Government of Western Australia

Department of **Mines, Industry Regulation and Safety**

REPORT 185

THE MAPPED STRATIGRAPHY AND STRUCTURE OF THE MINING AREA C REGION, HAMERSLEY PROVINCE

by DA Kepert

Geological Survey of Western Australia

Exploration Incentive Scheme

BHP

Government of **Western Australia**
Department of **Mines, Industry Regulation and Safety**

REPORT 185

THE MAPPED STRATIGRAPHY AND STRUCTURE OF THE MINING AREA C REGION, HAMERSLEY PROVINCE

by
DA Kepert

PERTH 2018

Geological Survey of Western Australia

REFERENCE
The recommended reference for this publication is:
Kepert, DA 2018, The mapped stratigraphy and structure of the Mining Area C region, Hamersley province: Geological Survey of Western Australia, Report 185, 282p.

ISBN 978-1-74168-814-6

A catalogue record for this book is available from the National Library of Australia

Grid references in this publication refer to the Geocentric Datum of Australia 1994 (GDA94). Locations mentioned in the text are referenced using Map Grid Australia (MGA) coordinates, Zone 50. All locations are quoted to at least the nearest 100 m.

Notice to the reader
The scientific content of this Report, and the drafting of figures, has been the responsibility of the author. No editing has been undertaken by DMIRS. BHP granted permission to publish this Report.

Published 2018 by the Geological Survey of Western Australia
This Report is published in digital format (PDF) and is available online at <www.dmp.wa.gov.au/GSWApublications>.

Further details of geological publications and maps produced by the Geological Survey of Western Australia are available from:
Information Centre
Department of Mines, Industry Regulation and Safety
100 Plain Street
EAST PERTH WESTERN AUSTRALIA 6004
Telephone: +61 8 9222 3459 Facsimile: +61 8 9222 3444
www.dmp.wa.gov.au/GSWApublications

Cover photograph: Asymmetric intrafolial folding modified by bounding flexural slip, Ophthalmia Orogeny, E Deposit, looking east

Preface

During the period 1994–2001, BHP conducted extensive detailed mapping of their tenement holdings at Mining Area C including adjoining Mudlark Well, and Weeli Wolli, covering some 590 km^2 at scales ranging from 1:5000 to 1:20 000. The results of this work, as well as some earlier work at Jimblebar and ongoing work at Newman, were documented in a comprehensive BHP report by Doug Kepert that is colloquially known as 'The Black Monolith'. The data and interpretations regarding the stratigraphy, structure, and tectonic evolution of this area were at the forefront of thinking at the time that the report was written in 2001. Despite the restricted circulation of this report, it has gone on to be widely cited by anyone working on the world-class iron ore deposits of the Hamersley Basin, and its findings have been widely applied. It remains one of the most comprehensive reports on this economically important region.

Following the commencement of a new Geological Survey of Western Australia (GSWA) project in 2016 to investigate the geochemistry of igneous rocks within the Fortescue and Hamersley Groups, and in consultation with BHP, it was agreed that this report should be publically released so that it can be legitimately referenced in future work, in particular in GSWA's Explanatory Notes System (ENS). Although the report now bears a 2018 date stamp, it is released in its original 2001 format, with minor redactions of superfluous appendices and data or conclusions that are considered 'commercial in confidence' by BHP. To this end, some of the interpretations and conclusions may now be out of date. However, 'The Black Monolith' remains an important record of the geology of the Hamersley province that deserves to be placed in the public domain.

The Mapped Stratigraphy and Structure of the MINING AREA C Region

An Eclectic Synthesis of Geological Mapping 1994-2001

The Black Monolith

Author: D A Kepert
2 February 2001

Approved: ____________________

Tout Change

Même Pierre

Oscar Claude Monet (1893)

EXECUTIVE SUMMARY

Introduction

This report is a compilation of the stratigraphy and structure of the greater Mining Area C region based on regional mapping programs from 1994 to 2001 at 1:10 000 or 1:20 000 and detailed mapping at 1:5 000 over Northern Flank deposits in 1995 and 2000. Additionally, it also includes geologic observations and ideas from elsewhere throughout the Hamersley Province where they differ or add to the greater understanding of the Province. As such its application is not limited to just the Mining Area C region, but the Province as a whole.

The project follows from BHP's acquisition of the area via Goldsworthy Mining Limited and the subsequent realisation that the entire area required a thorough remapping as a base to support ongoing exploration. A total of 590 km^2 of outcrop centred on the Marra Mamba and Brockman Iron Formations, over an aerial extent of 2650 km^2 was mapped (equivalent to an entire 1:100 000 sheet). It was instigated, guided and supported throughout by Mal Kneeshaw.

The main aims of the mapping project were:-

- to re-evaluate the region in terms of structure, stratigraphy and mineralisation,
- to aid in targeting current and future drill testing of prospective ground, and
- to determine areas that may be safely dropped as part of the partial conversion of TR3156H to ML status.

Regional mapping still to be completed in the future includes Brockman Iron Formation along the southern boundary of the Mudlark Well EL's, in the Karijini National Park in E47/17, and in the remainder of the Weeli Wolli and Coondewanna sections of M244SA. Further detailed 1:5 000 mapping should also be completed over other Deposits at the appropriate time.

Stratigraphy

The **Hamersley Basin** or Mount Bruce Supergroup is a late Archaean to Palaeoproterozoic platformal cover sequence of weakly metamorphosed sedimentary and volcanic rocks unconformably overlying the mid Archaean granite - greenstone terrain of the Pilbara Craton. It comprises the regionally conformable Fortescue, Hamersley and Turee Creek Groups. This report does not attempt to revisit the well documented BIFs of the Hamersley Group (in particular that of the Brockman Iron Formation), but rather focuses on some of the less widely known geologic features of the other stratigraphies in the Group, and in particular, observations from outcrop.

Preserved remnants of the **Fortescue Group** (*ca* 2770 to 2630 Ma) on the Pilbara Craton are terrestrial to shallow marine mafic volcanics and syn-volcanic dolerite sills, with interflow sediments (shales, cherts, carbonates), various tuffaceous sediments and shallow marine to deltaic and fluvial sediments. Within the Hamersley Province the upper part comprises laterally equivalent deep water submarine volcanic and sedimentary rocks.

In the Mining Area C region the Fortescue Group is limited to tuffaceous sediments and rare pillow basalts of the Jeerinah Formation exposed in the cores of the major anticlines. Mapping of the Group away from its upper contact was limited to traverses and airphoto interpretation. The upper Contact Tuff defined during mapping was dated at 2629 ± 5 Ma. A bolide derived layer seen elsewhere at about the same level could not be located.

The **Hamersley Group** (*ca* 2630 to 2450 Ma) is a 2.5 km thick sequence of dominantly deep water chemical sediments, with subordinate turbiditic sediments, and various intrusive and extrusive rocks. Sediments in order of decreasing abundance include banded iron-formation (BIF), hemipelagic shale, peri-platformal derived dolomite, chert, pyroclastic shale and tuff, turbiditic carbonate and turbiditic volcanics. Lithological banding of the Group is inherently fractal in nature comprising alternating bands of differing lithologies at all scales.

The Marra Mamba Iron Formation is relatively poorly described in literature with prior studies based mainly on limited fresh core with little immediate application to mapping. Based on down hole gamma signature, it is divided into three members that approximately coincide with changes in the relative proportions of BIF, chert and shale. The Nammuldi / MacLeod Member gamma defined contact in particular is not readily apparent on the ground as a mappable feature, instead mapping contacts were defined that approximate to the gamma defined contacts.

Unaltered Nammuldi Member consists of a lower relatively carbonate - rich sequence overlain by silicified cherty carbonate and cherty BIF, with minor interbedded (tuffaceous) shales and totals about 90 m in thickness. In outcrop it is typically well silicified dominated by poorly bedded, yellow chert and biffy chert, typically with broad pinch and swell structures, or undulating bedding. The basal contact is characterised by a 1 to 2 m thick band of dark coloured (brown, green or black) chert with crystal moulds. A persistent 10 m thick zone of 3 to 5 cm diameter D_1 chert rods with a regional elongation towards 045º to 060º, is located about 15 m above the base. A 2 m thick yellow - brown weathering carbonate turbidite near the top of the Nammuldi Member is very poorly preserved in outcrop.

A 74 m thick type section of the MacLeod Member was measured and described on the Southern Flank early in 1994 to assist with mapping. It is characterised by two major thick (Potato Bed and Football Chert) and two minor thinner, but prominent, podded units and a thick median red weathering dark green to black, tuffaceous stilpnomelane - rich bed. The lower contact of the MacLeod Member is defined at the base of the Potato Bed (approximately US12), rather than the base of the Football Chert on which earlier mapping was (loosely) based (the uppermost podded unit regardless of its true stratigraphic position was historically interpreted to approximate the contact).

The Mount Newman Member is characterised by very pronounced D_1 pods and stacked pods. S macrobands are composed of either well bedded white, pink, yellow and red shale after stilpnomelane - rich (tuffaceous) shale, and / or poorly bedded yellow to khaki rock after carbonate. At Mining Area C crocidolite in the Vivash Riebeckite Zone is better developed east of the Highway.

The lithology of the West Angela Member appears to vary significantly across the Province depending on its degree of “alteration”. In the west it is more “unaltered” comprising interbedded dolomite and shaly dolomite, compared with a "residual" of interbedded khaki, manganiferous shale and chert, with only rare dolomite beds in the central and eastern parts. Given the consistency, degree and depth of development of the shaly facies, it is unlikely that the regional variation is due to alteration or weathering, but probably represents an original facies change. Estimates of thicknesses vary from 0 to over 80 m, averaging 40 to 50 m for the central and eastern Province. The basal 10 to 12 m (A1) comprises interbedded biffy chert and shale. Rare occurrences of altered crocidolite have been identified in AB2 at C Deposit.

The Paraburdoo Member is a poorly exposed, monotonous sequence of well bedded, grey, crystalline, hemipelagic, deep water dolomitised carbonate with associated chert beds. Its thickness is poorly understood with regional measurements ranging from 110 m to over 420 m. Limited data from Mining Area C suggests a thickness of 350 to up to 500 m. The defined contact taken as the top of the uppermost thick dolomite bed proved a good mappable contact between it and the Bee Gorge Member.

Bee Gorge Member sediments are unique in the Hamersley Group in that they have a significant proportion of high energy turbiditic sediments, as opposed to the remainder of the Group, which mostly comprise very low energy sediments, with subordinate turbiditic beds. In outcrop the Member consists of thinly bedded, fissile turbiditic shale and dolomitic shales, with subordinate carbonate and chert beds. Sedimentary structures include intraclasts and flat pebble conglomerates, cross-bedding, ripples, concretions and roll-ups. A number of limited traverses identified several documented marker beds. Thickness varies regionally from 210 m thick in the northwest proximal to the Hamersley Range scarp, to an average 140 m in the central and southeast part of the Province, due mainly to variations in the interval above the Spherulite Marker Bed.

The Mt Sylvia Formation is characterised by its three relatively thin, but prominent BIF bands. Interbeds lithologically equivalent to the underlying Bee Gorge Member and the adjoining lower part of the Mt McRae Shale beneath the nodule zone comprise carbonate - bearing shale / mudstone sequence with many thin well banded chert or partly silicified weakly banded to massive turbiditic carbonate beds. The siltstone unit (S5) traceable from Newman to Giles Point is absent.

The Mt McRae Shale is subdivided into four facies here, of which the uppermost Colonial Chert Member (or D1) is included by BHPIO as part of the Dales Gorge Member. From the base up they are:-

- *Carbonate - massive chert facies* - similar lithotypes to the corresponding facies in the Mt Sylvia Formation, correlates with RL (lower) and RC (chert triplets),
- *Anoxic facies* - low energy pyritic carbonaceous shale and associated cherts, correlates with RN (nodule) and RU (upper),
- *Carbonate turbidite facies* - up to 15 m thick high energy, variably (poorly) preserved series of thick bedded turbidite flows progressively sourced from a chert / shale to a carbonate dominant sequence, broadly subdividable into a basal shaly conglomerate, massive carbonate and bedded carbonate, previously only recognised in the northern and central part of the Province, and
- *Colonial Chert Member or D1* - chert and biffy chert with shale interbeds.

The Dales Gorge Member is well documented elsewhere. It is a very well micro and mesobanded BIF interbedded with turbiditic to tuffaceous S macrobands. At Wittenoom Gorge the upper part of DS4 is a bolide derived partial Bouma sequence comprising a basal massive coarse grained unit with chert clasts in part after (rarely stromatolitic) carbonate and an upper fine grained unit. Riebeckite and associated crocidolite development at Wittenoom are not recognised throughout Mining Area C.

The Mt Whaleback Shale Member typically forms a topographic saddle of 30 to 50 m of fissile, red - brown to purple shales with yellow, brown and white chert mesobands. The most prominent of these is the 3 m thick Central Chert, with a characteristic large scale undulose to wavy banding about a third of the way up the Member.

BIF of the Joffre Member is less well banded than the Dales Gorge Member, with poorer defined microbands and minor podding / boudinage leading to individual mesobands being only traceable for a few metres. Stacked pods are locally developed in J6. No systematic attempt was made to subdivide the Member, although the characteristic J4 marker chert comprising two 5 to 10 cm thick, white / brown striped chert beds was mapped in places. It has now recognised as a Province wide mappable marker bed apparent from Jimblebar to Rocklea.

Five unbedded, black glassy porcelanites, previously described from Joffre Gorge, were located in prominent hills north of Tuckerbox Gorge. They were not apparent in the remainder of the area due to depth of weathering and enrichment.

Three clast supported carbonate debris flows, preserved in J3 to J5 at Mindy along the Hamersley Range escarpment to the northeast of Mining Area C, are the localised and highly proximal facies of a series of catastrophic collapses of a shallow water carbonate reef during deposition of the Joffre Member. They provide evidence on the history of carbonate sedimentation and original basin architecture.

The Yandicoogina Shale Member comprises alternating 10 to 30 cm thick, wavy banded, yellow and grey, and characteristic microbanded red / yellow striped cherts with subordinate interbedded shales. A well exposed 60 m thick section at the west end of Box Canyon should be measured for use as a standard section.

Detailed stratigraphy of the Weeli Wolli Formation is poorly documented but forms characteristic strike parallel ridges of resistant characteristic red / black microbanded BIF and valleys of extensive syn-sedimentary dolerite and (tuffaceous) shale. The red colouration of the BIF and chert is not primary being due to weak contact metamorphism. Mapping was only carried out up to the base of the Formation.

The Woongarra Rhyolite totalling about 400 m thickness can be subdivided into two main rhyolite units separated by a median raft complex. It is unclear if the rhyolites are intrusive or extrusive.

The Boolgeeda Iron Formation is approximately 200 m thick and comprises an upper and lower dark, flaggy to shaly BIFs, with a central shale - rich zone. It differs from all other BIFs in the Group in having no, to poorly defined mesobanding. The upper contact is gradational with the Turee Creek Group reflecting the increasing influx of clastic sediments from the south. Recent work in the western part of the Province also suggests the upper contact is also time transgressive based on the correlation of the glacial diamictite of the Three Corner Bore Member in the Turee Creek Group with recently discovered glacial drop stones in the upper Boolgeeda Iron Formation. No glacial lithologies at are known in the central and east parts of the Province.

Significant work by Trendall and others on the accurate dating of Hamersley Group strata has been carried out over the last decade. From this work the sedimentation rate for the dominant lithotypes of the Hamersley Group has been estimated at a very rapid 25 to 200 m/Myr for BIF, compared with about 5 m/Myr for carbonate and 2 m/Myr for shale. The difference in sedimentation rates is well illustrated by the lower more carbonate dominant half of the Hamersley Group spanning about 140 to 150 Myr, compared with the upper BIF dominant half spanning only 30 to 40 Myr.

Some BIF horizons are susceptible to massive riebeckite alteration and subsequent conversion to crocidolite. It is argued that riebeckite alteration is syn to late D_1, rather than between D_1 and D_2 as previously thought, with the localised conversion to crocidolite being associated with D_2. It is worth noting that within a susceptible zone, riebeckite is not always present and only if it is present can crocidolite then be formed. This requirement may provide some prior indication during mining of the potential for intersecting crocidolite, rather than just relying on certain stratigraphic intervals.

Dolerites occur as sills in the Jeerinah Formation (Karijini Dolerite), syn to late sedimentary sills in the Weeli Wolli Formation and underlying Yandicoogina Shale and Joffre Members ("Weeli Wolli" dolerite), and as several younger suites of sub-vertical dykes. A syn-sedimentary age for the Karijini Dolerite is favoured here over the previously proposed Ashburton Orogeny age. Evidence for syn sedimentary extrusive basalts in the Weeli Wolli Formation is discounted here.

Three main styles of **mineralisation** are recognised from mapping, of which the later two are near surface to supergene mineralisation that may be considered part of the greater Mesozoic to Cainozoic regolith as they form residual rocks. It should be noted that the mapped mineralisation only delineates areas of Fe enrichment rather than ore which implies a certain grade or degree of mineralisation. Many resources originally quoted by GML were not based on adequate drilling or mapping.

Earlier M-(mpl H) mineralisation formed by metamorphosed, Proterozoic supergene enrichment is not known from the Mining Area C region. An alternative model of genesis via possible hypogene carbonate alteration is also discussed.

M-G mineralisation is widely developed throughout the Mining Area C region in both the Marra Mamba and Brockman Iron Formations. It is spatially and genetically related to the Mesozoic - Tertiary palaeosurface, forming by near surface to moderately deep supergene enrichment of BIFs and to a lesser degree, of adjacent chert and shale. Some M-G mineralisation however, may be significantly older and part of the original Proterozoic supergene enrichment not converted to M-(mpl H).

Hardcap mineralisation is surficial ferricrete enrichment formed by Hamersley Surface processes and was only distinguished during 1994 mapping. Its delineation was found to be subjective and time consuming without providing additional useful information.

Hamersley Province contains a considerable diversity and history of **Cainozoic** sedimentary and residual rocks. Three broad sequences containing ore and non-ore bearing facies are defined as Tertiary Detritals 1 to 3. Each is separated by a hiatus with little erosion and sedimentation, and development of a ferricrete hardcap or Hamersley Surface. The sequences are:-

- Tertiary Detrital 1 (TD1) - dominantly fluvial sediments over 100 m thick, ranging from a proximal conglomerate to a distal fine facies, both with a characteristic fine hematite silt (red ochre) - clay matrix. It is mainly derived from the Marra Mamba Iron Formation and *terra rosa* soils developed over carbonate. Hematite is the dominant iron oxide present. Extensive exposure on the Southern Flank are described here and proposed as a type section for the sequence.
- Tertiary Detrital 2 (TD2) - fluvial and lacustrine sediments typically about 50 m thick dominated by bleached and mottled clays and micritic limestones. Goethite and limonite are the dominant iron oxides present. CID forms an important end member of this sequence.
- Tertiary Detrital 3 (TD3) - colluvial and alluvial sediments, about 50 m thick, ranging from proximal, cobble to pebble, alluvial / colluvial fans, to distal silty valley fills and playa deposits. The basal parts are more mature dominated by well rounded maghemite and hematite pisolites, grading to a more goethitic hematite clast - dominant upper half.

Structure

The regional structural and tectonic understanding of the Hamersley Province has increased exponentially in the last decade with the majority of work until then only recognising a single regional, east - west striking, folding event, followed by various faulting. In 1990 the GSWA were the first to really challenge this with the construction of a tectonic model for the southeast part of the Province which recognised an early orogeny comprising two tight, asymmetric to recumbent folding events (D_{1c} and D_{2c} - Capricorn Orogeny), followed by a more open upright folding event (D_{2a} - Ashburton Orogeny) restricted to the Ashburton Province not being recognised in the Hamersley Province. D_{2c} and D_{2a} folds were defined as approximately coaxial (ie east - west) but facing north and upright, respectively, with the Ophthalmia fold and thrust belt being produced principally by D_{2c}.

Detailed 1:5 000 mapping at Jimblebar during 1993 by BHPIO further refined this model, resulting in better definition of these events including the important recognition of D_{2a} (Ashburton) folds in the Hamersley Province, and also the recognition of two late cross folding events. Deformations were relabelled at this stage, removing the orogeny suffix and opting for a single numeric identifier. The Jimblebar structural model was the basis of mapping at Mining Area C and was further developed with the addition of an extra event between D_1 and D_2 referred to as $D_{1.5}$. This tectonic model (below) has since been exported by contract mapping geologists initially employed by BHPIO to all companies throughout the Province, including the critical recognition of thrusting in many Marra Mamba Iron Formation hosted deposits.

The $\mathbf{D_1}$ event (or D_{1c}) produced by vertical loading and northeast - southwest basin extension synchronous with diagenesis, resulted in a weak bedding parallel fabric and differential bedding-parallel extension producing boudinage and stacked pods, rare northeast - southwest trending intrafolial isoclinal folding and extensional shears all confined to specific horizons. A Province wide sense of imbrication (or stacking) and rotation of pods indicates an apparent southeast block down movement. In addition to tectonic pods, early diagenetic pods occur at specific horizons throughout the sequence.

Asymmetric south facing **$F_{1.5}$** folds of up to 20 m amplitudes first described in 1995, are very similar in style to the F_2 folds but with the opposite facing, and are not as well developed or intense. Whilst overprinting relationships are rare, where apparent $S_{1.5}$ and $F_{1.5}$ were inferred to precede D_2 structures. From 1995 mapping, these structures were thought to be relatively common but mapping since that time has progressively down grading their contribution and influence.

The **Ophthalmian Orogeny D_2** event (or D_{2c}) produced pervasive, scale independent, east - west, generally north facing, upright to recumbent, curvilinear, open to elastica folds in the Ophthalmia Fold Belt during peak metamorphism. At Mining Area C they developed in moderately narrow, linear to arcuate belts with intervening relatively undeformed long flat limbs. By comparison, at Newman the belts of folding are closer spaced to adjoining. Locally developed south facing folds do occur as parasitic folds on larger north facing structures. The age of D_2 is poorly constrained, commencing to the south during deposition of the Turee Creek Group (possibly as early as 2450 Ma) and continuing through deposition of the Lower Wyloo Group until at least 2200 Ma, but possibly considerably later. Around Tom Price, Hamersley Iron have limited the Ophthalmian Orogeny to syn Turee Creek deformation with late Lower Wyloo Group folding being separated out as the Panhandle event.

South over north D_2 thrusts along the Northern Flank preferentially developed on the Mount Newman / West Angela Members contact have an apparent movement of up to 200 m. They are also known elsewhere from drilling (eg Jaws). Thrusting in the Newman region has also been positively identified by recent mapping, including re-interpretation of some known faults previously interpreted as late normal faults (eg Homestead Fault). Here, they are not restricted to the upper Marra Mamba Iron Formation, but crosscut the entire sequence and with inferred displacement in the order of kilometres. It is important to note that whilst thrusts at Mining Area C and Newman have essentially the same geometry, conceptually they may have developed by quite different mechanisms. Small scale thrusts at Mining Area C and elsewhere are developed during folding at the West Angela / Mount Newman Member contact (or other similar strong rheological contrast) by over straining of an overturned fold producing localised detachment subparallel to the axial surface of the fold along the contact. They are unlikely to represent a shallow expression of a deeper detachment. By comparison, major thrusts at Newman represent the upper continuations of deep seated thrusts and sub-horizontal decollement surfaces and may act as conduits for fluid flow. Late extensional, sub-horizontal D_2 faults from the Newman region (eg Central Fault at Mt Whaleback) which are spatially (and genetically?) related to M-(mpl H) style mineralisation have not to date been identified in the Mining Area C region.

The *ca* 1800 to 1650 Ma **Ashburton Orogeny D_3** (or D_{2a}) event is less intense than D_2 and produced gentle to open east – west symmetric folds with upright axial surfaces coaxial to sub coaxial to $F_{1.5}$ and F_2 folds. Major megascopic range - forming folds such as the Weeli Wolli Anticline, which is slightly oblique to some macroscopic D_2 folds, are interpreted to be Ashburton. In the western Hamersley Province D_2 and D_3 are not coaxial, making positive differentiation easier.

Two late very weak cross cutting folding events locally deform the region. No definitive cross cutting relationships between $\mathbf{F_4}$ and $\mathbf{F_5}$ have been located, so their relative order is inferred. It is possible that they may be conjugates and part of the same deformation event. Some may also be the oblique ends of arcuate D_2 fold belts as per The Governor for example. Pd_5 dolerite dykes have previously been incorrectly linked to F_4 are only intrude up to, and are interpreted as feeders for, the late D_2 Cheela Springs Basalt.

Sinistral and dextral, sub-vertical, transcurrent faults with apparent movements of up to 3.5 km dominate Mining Area C Park and western Alligator. The regional geometry suggests late movement along major pre-existing crustal weaknesses (remnants of greenstone belts) in the southern half of Milli Milli Dome producing a giant pop-up or flower structure.

Late east - west, south block down, normal faults over 10 km long and with apparent vertical displacements of up to 400 m occur along Packsaddle Range. These and smaller normal faults elsewhere are consistent with gravitational slumping off the hills and may not be part of a true deformational event *per se*. They may be of variable age and as young as the Mesozoic or Cainozoic. Mineralisation is not preferentially developed on either transcurrent or normal faults.

Tectonic Synthesis

There has been an increase in discussion of fold styles over the last few years resulting in a comprehensive awareness of the change in character of folds along strike, style of parasitic folds and fanning cleavage, and juxtaposition of two different fold styles with little or no observable interference. This in turn has lead to some degree of confusion in assigning a particular fold to a given event. To minimise confusion by relabelling folds the previously defined deformational history (above) has been followed throughout the entire program. If nothing else it successfully discriminates between upright, north and south facing folds and comments on the tightness, associated cleavage etc.

As argued here, the Ophthalmian Orogeny was a protracted and complex event producing a diverse suite of structures at different scales, geometries and orientations. Due to its varied and diverse nature, it is difficult to classify on geometric criteria small to medium scale structures to other deformations and in particular, to locate unequivocal or even compelling evidence for $D_{1.5}$. Applying Occam's Razor, it is not necessary to have a separate north over south event prior to the Ophthalmian Orogeny as all such structures are shown to be compatible with D_2. The model proposed here for the development of D_2 is:-

- initial north - south compression produces symmetric to asymmetric, intrafolial, layer parallel shortening in susceptible units, with associated mineral cleavage development,
- continued compression produces larger folding, flexural slip, and reorientation of earlier and developing fabrics. This produced fanning cleavage and rotation of earlier folds into either fanning arrays, or possibly even refolds of earlier folds. Many of the resulting range of geometries and overprinting relationships have previously been interpreted as evidence for $D_{1.5}$.

- final compressive strain taken up by overturned to recumbent folding, and localised thrusting and associated low angle extensional faulting (Riedel shears), including 1 to 10 km displacements on the southern margin of the belt. Many anticlines associated with thrusting may have the general characteristics of F_3 folds, and
- relaxation of Ophthalmian compression produces late D_2 extensional faults as both low angle (eg Central Fault at Mt Whaleback) and high angle (eg Northern Flank, Southern Batter Fault at Tom Price) faults.

Resulting fold geometry was highly dependent on the relative proportion and thickness of adjacent beds. The differences are well illustrated by the development of broad relatively upright folds in the relatively thick bedded, stiff Fortescue Group compared with tighter overturned folds in the thinner, weaker Hamersley Group. A similar relationship is also developed at all scales, for example between the stiffer MacLeod and Nammuldi Members, and the weaker Mount Newman Member.

On a more regional crustal level, as a fold and thrust belt develops as a series of propagating fronts, the individual stages above will not occur throughout the belt at the same time. Furthermore, in some zones it is possible that the compressive deformation may be the result of more than one (incomplete) cycle or pulse.

The main controlling factors in the tectonic evolution of the Hamersley Province are:-

- the proto-Poonda Fault that formed the main growth fault between dominantly shallow water facies carbonates to the northeast and deep water facies carbonates and other sediments to the southwest,
- pre-existing tectonics of the underlying Pilbara Craton, which remained active post Hamersley Group deposition. The Rocklean Movement defined here to describe the on-going gravitational inversion of the underlying Pilbara Craton during deposition of the Mt Bruce Supergroup, produced dome and basin structures in the supercrustal rocks. Relative differences in the age and therefore tectonic stability of the east and west parts of the Craton may have been a significant controlling factor between tectonic styles in the east and west Hamersley Province,
- the Ophthalmian Orogeny marking the initial collision of the Pilbara and ?Yilgarn Cratons. It produced the majority of micro to megascopic structures apparent in the Province. The style of structures produced (and their relative geometry) were heavily dependent on the rheological properties, degree of D_2 development, including the relative degree of flexural slip and thrusting, and most importantly the highly anisotropic layering of the rocks. Much of the folding is scale dependent being intrafolial to intraformational. As rheological properties and degree of anisotropy change with both stratigraphy and scale, so too does the resulting fold style, and
- the Sylvania Inlier, which appears to have strongly influenced the regional divide between deformation styles of the east and west Hamersley Province. In the east it may have acted as a ram or indenter during the Ophthalmian Orogeny producing much of the intense folding now apparent that may have largely masked any earlier dome and basin tectonics.

Subsequent deformations had comparatively little impact on the region, mainly only modifying the orientation of previous structures by broad open folding and regional normal faulting.

This work also essentially completes the project initially commenced in 1994 at Mining Area C East to re-map the entire area Temporary Reserve and associated EL's using the increased stratigraphic and structural understanding acquired since the original GML mapping of the 1970's. The project itself also contributed in no small part to those advances.

M Kneeshaw
2002

CONTENTS

Part A INTRODUCTION

Part B STRATIGRAPHY

LIST OF TABLES

LIST OF FIGURES

LIST OF PHOTOGRAPHS pages 166 – 252

LIST OF APPENDICES

1.0 INTRODUCTION

This report is not just a summary of seven years of mapping programs in the Mining Area C region (Figures 1, 2) from 1994 to 2001 (Lipple *et al* 1994, 1995, Kepert *et al* 1996, 1999), but is also an eclectic synthesis[1] of geologic observations and ideas from here and elsewhere throughout the Hamersley Province where they differ or add to the greater understanding of the Province - a geologic odyssey, 2001. As such its application is not limited to just the Mining Area C region, but the Province as a whole. It primarily focuses on describing the advances in stratigraphic and structural understanding gained during the project into a single report. Prospectivity and prioritisation of areas is also briefly summarised.

Mapping was predominantly at 1:20 000 over Marra Mamba Iron Formation in the early years and 1:10 000 over the Brockman Iron Formation in subsequent years (Appendix 1). Additionally, Marra Mamba Iron Formation Northern Flank Deposits (C, D and E, and parts of A and B) were remapped at 1:5 000 during 1995 and 2000.

Previously, the only mapping available over much of the region was either reconnaissance style mineralisation outlines by Goldsworthy Mining Ltd (GML), with little to no stratigraphic and structural control or understanding, or stratigraphic airphoto interpretations by Mt Newman Mining Co (MNM) and BHP, with varying but limited ground truthing and only broad mapping of mineralisation. A regional historic account of the methodology, style and development of exploration including mapping is included in Kneeshaw *et al* (2002).

The mapping project was instigated by M Kneeshaw and remained under his direction and guidance for the duration of the project. Various mapping programs during the project were co-ordinated by S L Lipple (1994 - 95) and D A Kepert (1995 - 2001). The mapping teams (Appendix 1) comprised M C Benbow (1995 - 2001), A C Duncan (1994 - 97), D Hampton (1994), D Harris (1998), D A Kepert (1995 - 2001), S L Lipple (1994 - 96), D Pearcey (1997), M Pierini (1998), C M Sullivan (1994, 1999) and N Youngman (1994). All work was based out of Packsaddle (Photo 1).

The project greatly benefited from ground breaking 1993 detailed mapping at Jimblebar by O'Sullivan, Lipple and others (Lipple 1995), and from the variety of contract and Company geologists who contributed formally and informally to the mapping here. Additional structural insights gained from mapping in the Newman region (Kepert 2000a, Kepert 2000b) since 1999 by MCB (1999 onwards), D Harris (2000), DAK (1999 onwards), and CMS (1999) is also referred to here.

Regional mapping still to be completed in the future includes Brockman Iron Formation along the southern boundary of the Mudlark Well EL's, in the Karijini National Park in E47/17 and in the remainder of the Weeli Wolli and Coondewanna sections of M244SA. Further detailed 1:5 000 mapping should also be completed over other Deposits at the appropriate time.

[1] Eclectic synthesis - the result of the combining of elements borrowed freely from diverse sources into a whole.

Co-ordinates (in AGD66[2]) of all localities in this report are included as Appendix 3 and where possible are marked on Figures 1 and 2.

1.1 Aims

The main aims of the mapping project were:-

- to re-evaluate the region in terms of structure, stratigraphy and mineralisation,
- to aid in targeting current and future drill testing of prospective ground, and
- to determine areas that may be safely dropped as part of the partial conversion of TR3156H to ML status.

Mapping was typically targeted at the Marra Mamba and Brockman Iron Formations, and respectively confined to the intervals:-

- from the base of Nammuldi Member to the West Angela Member, and
- from the base of the Mt Sylvia Formation to the base of the Weeli Wolli Formation.

Reconnaissance mapping was carried out over the intervening Paraburdoo and Bee Gorge Members of the Wittenoom Formation. Mapping below the Nammuldi Member and above the base of the Weeli Wolli Formation was usually limited to airphoto interpretation. The stratigraphic column is included as Table 1.

Mapping in the Mining Area C Park area was more reconnaissance in style than elsewhere, mainly targeting the structure and potential of only the Mount Newman and Dales Gorge Members, and associated colluvium.

1.2 Methodology

Formal Mapping Standards were iteratively developed during the course of the project.

Mapping was guided by the previous mapping and airphoto interpretations where available. Mapping was conducted at photo scale (approximately 1:20 000 to 1:21 500) for 1994 - 95, and exactly 1:10 000 or 1:5 000 on photo enlargements for the remainder of the project.

Compilation base sheets were enlarged 1:50 000 AUSLIG digital topographic data or more recent BHP topography where available. In 1994, compilation was at 1:20 000 causing a great deal of angst due to the mismatch in scale between photo and compilation sheet. This method was improved on slightly in 1995 with the compilation scale being the average photo scale for each A1 sheet. Subsequent programs were mapped and compiled at 1:10 000 to increase accuracy, facilitate ease of location and compilation etc, but not to necessarily increase detail. The original scale of individual photos was estimated by comparing distances between creek junctions with the best

[2] For an approximate conversion of AGD66 to GDA94 (WGS84) add 138 m to the easting and 155 m to the northing.

available topography. This method of enlarging the photos to match the topography is recommended for future mapping with the additional initial cost easily being offset during mapping and compilation. The final map covering 27 A1 sheets, is designed to be produced at 1:20 000.

Various mapping programs within the project were stitched together by DAK, including airphoto interpretation of some areas, including unmapped Brockman Iron Formation and Cainozoic sediments. Authorship, scale and style of mapping of various areas are summarised in Figure 3.

Maps were digitised by BHP Engineering / Hatch Associates (Civil Drafting) and are stored digitally there, with copies on the BHPIO Geology GIS. Hard copies of maps are available through Civil Drafting.

Safe work practices were adopted throughout the project. Radio reception was difficult in the more rugged areas resulting in several false alarms due to missed schedules. These tested the initial phase of the safety system which responded well. No other type of incident has occurred since 1995.

Access to most areas was moderately good with well formed tracks along the base of most hills and a network of rough tracks, often constructed or re-opened with only a grader, over the hills. Original GML ground access tracks to the Mining Area C Park, West Alligator and Balgara areas were not re-opened, with access gained by helicopter.

1.3 Previous Mapping

A three day heliborne geological reconnaissance of the area from Weeli Wolli Springs to Turee Creek by GML on 24 – 26th March 1964 (Table 2) recognised that the most extensively mineralised area was the range extending west from Weeli Wolli Springs through to Packsaddle Mountain (now Packsaddle Hill). This range subsequently named C Range, but was renamed Packsaddle Range by BHPIO to avoid confusion between Mining Area C, C Range, its deposits C1 to C6 (now P1 to P6) and C Deposit on the Northern Flank. Packsaddle Range and surrounding ground that now makes up Mining Area C and Mudlark Well was subsequently applied for by GML (granted 15th October 1964), with MNM being granted the ground adjacent to Weeli Wolli Springs. Brockman Iron Formation ridges were progressively mapped (and drilled) from 1965 to 1971. With the recognition of the potential of the Marra Mamba Iron Formation following early reconnaissance and the first drill hole into it in mid 1971 (into what became F Deposit), the majority of Marra Mamba Iron Formation ridges were mapped in 1972. Other limited mapping occurred until 1980.

The majority of the GML mapping was both reconnaissance, and stratigraphic and structurally simplistic in style. In particular the Marra Mamba Iron Formation stratigraphy was poorly understood from both mapping and drilling. Mapped mineralisation boundaries were also simplistic. Mapping was generally compiled on to uncontrolled airphoto mosaics making both internal and external accuracy of the map questionable. Whilst providing a broad concept of the geology, little of their mapping has been incorporated in to the mapping here. The only area retained is the Mt Meharry massif, including Brockman Iron Formation in E47/17, which have not been remapped but have been modified by airphoto interpretation.

With the exception of Spring Hill, most of the MNM reconnaissance mapping of Weeli Wolli (M244SA) remains unchanged except for minor reinterpretation. Early airphoto interpretation by BHPIO of Packsaddle Range, Lamb Creek and Ministers North has been superseded over Packsaddle Range and Werriba Anticline in Ministers North by detailed mapping.

1.4 Environmental

During 1994 to1995 mapping, Pebble-mound mouse (*Pseudomys chapmani*) mounds located during mapping were recorded and classified to generate a data base on their historic and current distribution. This was not carried out in subsequent years due to time constraints, but mainly due to the recommendation that the Pebble-mound mouse be removed from the endangered species list.

Permission for all work within Karijini National Park during 1995 and 1996 was granted by CALM and carried out under their conditions.

During regrading of old MNM access tracks on the northeastern slope of Spring Hill in 1998, several small populations of *Lepidium catapycnon* (a declared rare flora) were located growing in and next to old windrows. The Newman Environmental group subsequently confirmed positive identification and cataloguing of its occurrence. During mapping other occurrences were noted down slope of this location.

Further very extensive occurrences of *Lepidium catapycnon* were located on Mt Robinson (1000's) and Eric's Point (100's) in 1999. Details were provided to Newman Environmental, and resulted in a feature and photograph in the *BHPIO Chronicle* newspaper. It prefers soils derived from shales (Mt McRae Shale, Mt Sylvia Formation, Bee Gorge Member).

2.0 MAPPED STRATIGRAPHY

Much has been written regarding the stratigraphy of the Hamersley Basin or Mount Bruce Supergroup over the years, and in particular that of the BIFs (eg Trendall and Blockley 1970, Trendall 1983). This report does not attempt to redo this work (in particular that on the Brockman Iron Formation), but rather focuses more on some of the less widely known geologic features, and in particular, observations from outcrop.

2.1 Geologic Setting

The Hamersley Basin[3] or Mount Bruce Supergroup is a late (Neo-) Archaean to Palaeoproterozoic platformal cover sequence of weakly metamorphosed (mainly prehnite - pumpellyite up to lower greenschist facies) sedimentary and volcanic rocks sitting unconformably on the mid (Meso-) Archaean granite - greenstone terrain of the Pilbara Craton. The Mount Bruce Supergroup comprises the regionally conformable Fortescue, Hamersley and Turee Creek Groups.

The Hamersley Province is an area of about 80 000 km^2 and covers the southern third of the Pilbara Craton, south and inclusive of the Chichester Range, to the margins of the various Mesoproterozoic sedimentary basins to the south. It is defined as and incorporates all of the deep water Hamersley Group deposited on the Hamersley Platform (see below). The depositional environment of the Hamersley Group is most likely a moderate to deep water platform, below the wave base (~ 100 to 200 m) and possibly as deep as 2000 m.

Further north on the exposed Pilbara Craton only erosional remnants of the once more continuous, shallow marine to terrestrial Fortescue Group remain.

Envisaged tectono-sedimentary models of the "Hamersley Basin" have varied significantly with time. Hypotheses put forward to explain the unique lateral continuity of the stratigraphy and lack of major siliclastic and other terrigenously derived clastic sediments have included:-

- an intracratonic silled basin (Trendall and Blockley 1970),
- a flooded Pilbara Craton restricting the extent of the source of detritus (Trendall and Blockley 1970),
- an arid Pilbara Craton providing minimal erosion and transportation (Trendall and Blockley 1970),
- an isolated platform or shelf on the continental margin (Morris and Horwitz 1983),
- a mid to outer shelf, wholly or partly isolated by a physiographic depression (McConchie 1987), and
- a continental shelf barred from the Pilbara Craton to the north by a fringing "barrier reef" or the "Fortescue Bank" (Morris 1993).

---

[3] "Basin" is used here in the same context as Trendall (1983) to denote the sequence of rocks, and makes no comment on the geometry of the original depositional area.

Along the eastern margin of the Pilbara Craton (Oakover Sub-basin or Syncline), shallow water carbonates of the Hamersley Group that also may once have onlapped on to a significant proportion of the Pilbara Craton are preserved. The Oakover Sub-basin contains mixed peritidal, stromatolitic, to moderately deep water, platformal carbonates defined as the Carawine Dolomite. Its exact stratigraphic correlative of the deep water Hamersley Platform is open to debate, but it probably represents at least the interval from the Wittenoom Formation to the Mt McRae Shale, and possibly also the Marra Mamba Iron Formation. The tectonic divide between the shallow and deep water facies is interpreted here to be the proto-Poonda Fault.

The Turee Creek Group is interpreted to be a foreland basin marking the initial collision, uplift and subsequent erosion between the Pilbara and Yilgarn Cratons (Horwitz 1982, Powell and Horwitz 1994).

2.2 Stratigraphic Nomenclature

Stratigraphic nomenclature and abbreviations adopted here follow that in general usage in the industry. Macrobands are labelled in the standard way by Member/facies/number (from base), thus SB3 is equivalent to Bruno's Band. In addition to the S ("shale") and B (BIF) facies macrobands, the following are also formally adopted here:-

- C - carbonate and carbonate turbidite dominant, and
- P - porcelanite (tuff) macrobands (Joffre Member only).

Carbonate (C) macrobands should not be confused with the system of labelling of chert bands in the Mt McRae Shale (eg Figure 12), or S macrobands with the subdivisions of the Mt Sylvia Formation (eg Figure 9) as used at Newman (eg Power 1998).

Series of macrobands within some Members of the Marra Mamba and Brockman Iron Formations (those of economic importance) can be further grouped into broad divisions (eg D1, N2 etc) as defined in Figures 4 and 12.

Banded iron-formation (BIF) is historically defined as being a banded rock with greater than 15% Fe chemical content. In order to better distinguish a mappable series of subdivisions between chert and BIF, a mineralogical definition is adopted here whereby:-

- *ferruginous chert* is a colour banded chert with no significant magnetite (or martite) but with Fe as finely disseminated goethite for example,
- *biffy chert* is a chert with magnetite microbands but only rare or diffuse magnetite mesobands (biffy is used here as an adjective to denote being BIF-like),
- *cherty BIF* is a well mesobanded silica-rich BIF and,
- *BIF* is a well mesobanded alternating silica and magnetite BIF.

BIF mesobands are referred to as either silica (ie chert rich) or oxide (ie Fe rich) mesobands. The corresponding *chert* and *chert-matrix* nomenclature of Trendall and Blockley (1970) is not adopted here as the term *chert-matrix* does not intuitively imply a silica poor, Fe rich lithology.

Informal and formal marker beds and horizons such as Football Chert, Central Chert and Main Tuff Interval are all capitalised here. Abbreviations of these used on the maps are however lowercase, that is fc, cc and mti for the above.

Similarly, labelling on the map of most Members and some Formations is as a single lowercase letter, being the last letter in its formal abbreviation (eg PHbd becomes d, AHr becomes r). This stratigraphic code may then be suffixed by a lithological code primarily to distinguish the mineralogy of mineralisation, thus M-G mineralisation of Dales Gorge Member becomes dh. Where mineralised, the mapping code may also be prefixed by H1, H2 or H3, being M-(mpl H), M-G / M-oG and hardcap respectively, to denote mineralisation type. With the exception of the 1994 mapping of Weeli Wolli Anticline, this distinction was not necessary as hardcap development (*senso stricto*) was not mapped, and M-(mpl H) (H1) is not known in the Mining Area C region. Member names in this report are used in full.

A complete listing of stratigraphic abbreviations, mineralisation and marker beds used in mapping is included in Table 1.

3.0 FORTESCUE GROUP (AF)

The Fortescue Group (*ca* 2770 to 2630 Ma) forms the lower most part of the Mt Bruce Supergroup. Current research on the Group has been released as a new Bulletin (Thorne and Trendall 2001) to accompany a previously released map (Thorne and Hickman 1998). Preserved remnants on the Pilbara Craton are shallow marine to terrestrial mafic volcanics and syn-volcanic dolerite sills, with interflow sediments (shales, cherts, carbonates), various tuffaceous sediments, and marine to deltaic and fluvial sediments. Within the Hamersley Province the upper part comprises laterally equivalent deep submarine volcanic and sedimentary rocks. Subdivisions of the Group and its distribution in the Hamersley Province is as follows (Thorne and Trendall 2001):-

- Bellary Formation (AFb) - comprising deltaic sediments and basalt is restricted to the core of the Bellary Dome near Paraburdoo and is not recognised elsewhere,

- Mt Roe Basalt (AFr) - comprising subaerial massive basalt and andesite and sandstone, is synvolcanic with Black Range Dolerite Suite (2772 ± 2 Ma, Wingate 1997) and in the Hamersley Province is only recognised in the Bellary, Rocklea and Wyloo Domes,

- Hardey Formation (AFh) - comprising fluvial sandstone, siltstone, shale, and conglomerate; in the Hamersley Province it is extensively developed in the west but poorly in the east being a correlative of the basal sedimentary unit in the east,

- Kylena Formation (AFk) and Boongal Formation (AFo) - comprising subaerial (Pilbara) and submarine (Hamersley) basalt and andesite and is the correlative of the lower mafic unit in the eastern Hamersley Province,

- Tumbiana Formation (AFt) - comprising lower tuffaceous sediments and upper biogenic dolomite in the north; in the Hamersley Province it is correlated with submarine basalt of the Pyradie Formation (AFp) in the west and the felsic pyroclastic unit in the east,

- Maddina Formation (AFm) - comprising lower (formerly Nymerina Basalt) and upper (formerly Maddina Basalt) basalts separated in part by a central tuffaceous sequence (Kuruna Member); in the Hamersley Province it correlates with submarine basalt of the Bunjinah Formation (AFu) in the west and the upper mafic unit in the east,

- Jeerinah Formation (AFj) - comprising marine shale, tuff, siltstone, pillow basalts and carbonate marks a major marine transgression over the remainder of the Pilbara Craton. Extensive dolerite sills intrude the Formation. The upper contact is dated at 2629 ± 5 Ma.

3.1 Jeerinah Formation (AFj)

In the Mining Area C region, outcrop of the Fortescue Group is limited to Jeerinah Formation in the cores of the major Weeli Wolli, Alligator and Wonmunna Anticlines, to the core of the Milli Milli Dome and to the south side of Parallel Ridge. Mapping of the Group away from the contact with the Hamersley Group was limited to traverses and airphoto interpretation.

In the Hamersley Province the Jeerinah Formation comprises felsic tuff, agglomerate, basalt, white and grey chert, brown (dolomitic) carbonate and distinctive white to red ?tuffaceous shale. Historically it has been divided in to three regional Members; the upper Roy Hill Shale, central Warrie Shale and lower Woodiana Sandstone Members. Thorne and Trendall (2001) however, no longer recognise the division of the two shale members as they can not reliably be differentiated in the field where the upper dolomite of the Warrie Member is absent. For simplification, they also opt for the removal of the lithological part of the Members names (eg Roy Hill Member). As only the uppermost part of the Formation is exposed at Mining Area C, and to avoid confusion and relabelling, the term Roy Hill Shale Member is however, retained here.

In the Mining Area C region the Formation is extensively intruded by dolerite sills (see Karijini Dolerite, Section 5.1) with typically only thin remnants of the Formation preserved.

3.1.1 Basalts (AFjb)

On airphotos near Dog Leg to Eterak (Mining Area C Park), the Jeerinah Formation is greenish and well banded, presumably reflecting different basalts and / or dolerite sills. It is unknown how much, if any, of the dolerite is Karijini Dolerite. Underlying the basalts to the northwest and at the limit of available photography, a massive brown unit occurs that may be either Karijini Dolerite or Bunjinah Formation basalt.

Massive basalts with a 5 to 10 m thick sequence of pillow basalts (Photo 2) exposed in a creek bed near Big Creek Fault (Mining Area C Park) are presumed to be part of the pillow unit of the Jeerinah Formation. Here the MacLeod Member has been thrust over the Jeerinah Formation, with an estimated 1 km of stratigraphy being removed (see Section 9.8.1).

3.1.2 Roy Hill Shale Member (AFjr)

The uppermost part of the Jeerinah Formation is the Roy Hill Shale Member, comprising distinctive white-weathering, massive to well bedded, cleaved felsic tuffs and tuffaceous shales, interbedded with pale green or white, pyritic chert. Finely laminated sulphides present locally in the upper cherts are inferred to indicate a volcanogenic origin (Davy and Hickman 1988). Locally, the black shales in the lower part of the Member have well developed pyrite balls to 2 cm that are commonly goethitised and well preserved at the surface (eg Wonmunna). This horizon is also commonly marked by surface copper blooms, which were mined in the middle of last century (1953 - Wonmunna).

The Member is apparent on airphotos as white scree at the base of prominent scarps capped by Marra Mamba Iron Formation. A road cutting on the Great Northern Highway just southeast of South East Corner exposes highly weathered tuffs and dolerites.

The upper contact is marked by a characteristic flaggy, cream tuff. Samples collected after 1995 mapping from the eastern end of North Alligator and dated by Trendall gave a zircon SHRIMP age of 2629 ± 5 Ma (see Section 4.9).

Other marker beds toward the top of the Member are described below.

<u>Marker Chert (jm)</u>

Near the top of the Member is the approximately 5 m thick Marker Chert, comprising well mesobanded, planar bedded chert with minor interbedded black shales. From DDH186, Davy and Hickman (1988) describe it as a chert - carbonate unit some 9 to 16 m below the top of the Roy Hill Shale, and as being technically a BIF.

Whilst recognised elsewhere, the Marker Chert is not readily apparent at Mining Area C due to the pervasive dolerite sills at this stratigraphic level. In the Alligator Anticline, there are at least three bands of well exposed, brown, banded carbonate, each overlain by white, brown or grey chert. Although these are here separated by dolerite sills, it is considered that this sequence is equivalent to either the lower carbonate rich Nammuldi Member or the Marker Chert. The bands are prominent features on aerial photographs, and outline the large scale folds within the Alligator Anticline.

Jeerinah Impact Layer (JIL)

The JIL (Simonson and Hassler 1997) is a thin, bolide derived, spherule bearing (see Section 4.2.3) bed about 1 to 5 m from the top of the Member, which to date has only been positively identified at two localities, both in the Fortescue Valley area - FVG1A (near Ilbianna Well) and Hester Siding rail cutting in the Chichester Range (Simonson and Hassler 1997, Simonson *pers comm* 2000). At Hester Siding, the interval is about 1.5 m thick.

It has also been tentatively identified in DDH186 and WRL1, which are also both marginal to the Fortescue Valley, where it is only 1 to 2 mm thick (Simonson *pers comm* 2001).

A similar occurrence intersected in drilling near the top of the Fortescue Group in the southern part of the Oakover Sub-basin at Billy Goat Bore and recently in outcrop near Woodie Woodie (about 10 m thick) may possibly be the same bed (Simonson and Hassler 1997, Simonson *pers comm* 2000, 2001). This may imply that the Dolomixtite near the base of the Carawine Dolomite is correlatable to the JIL rather than the SMB (see Section 4.2.3).

4.0 HAMERSLEY GROUP (AH / PH)

The Hamersley Group (*ca* 2630 to 2450 Ma) forms the central part of the Mt Bruce Supergroup and is regionally conformable with both the underlying Fortescue Group and overlying Turee Creek Group. It is a 2.5 km thick sequence of dominantly deep water chemical sediments, with subordinate turbiditic sediments, and various intrusive and extrusive rocks. Sediments include (in approximate order of decreasing abundance), banded iron-formation (BIF), hemipelagic shale, dolomite derived from peri-platformal ooze, chert, pyroclastic shale and tuff, turbiditic carbonate and turbiditic volcanics.

The Hamersley Group is inherently fractal in nature comprising alternating bands of differing lithologies at all scales (eg Figure 71 in Trendall and Blockley 1970). For example, excluding igneous rocks, the entire Group is broadly a BIF dominated sequence with a central relatively Fe - poor, chert / shale / carbonate sequence. Stepping progressively down in scale this relationship is repeated at the Formation scale (eg Mt Whaleback Shale Member in the Brockman Iron Formation), the Member scale (D3 in the Dales Gorge Member, NS3 to NS4 in the Mount Newman Member), the macroband scale (by definition), and through to the meso and microband scale. Trendall and Blockley (1970) defined the regular cyclicity of mesobanding seen in the Dales Gorge and Joffre Members as the Calamina and Knox cyclothems, respectively.

4.1 Marra Mamba Iron Formation (AHm)

The Marra Mamba Iron Formation[4] conformably overlies the Roy Hill Shale Member. In general, the Formation is poorly described in literature with only Morris (1991) and Blockley *et al* (1993) describing it in detail. Both however, are based mainly on limited fresh core and have little immediate application to mapping. Morris (1991) also describes the mineralogy and major element geochemistry in detail. Early independent work by various companies resulted in differently named and defined units with formal subdivisions into Members being finally resolved by Blockley *et al* (1993). The Member names (including the West Angela Member that was included by some companies in the Marra Mamba Iron Formation) reflect the three major companies and the GSWA. Based on down hole gamma signature, it is divided into three Members that approximately coincide with changes in the relative proportions of BIF versus chert versus shale / shaly BIF (Figure 4). The formal gamma defined contacts (in particular the Nammuldi / MacLeod Member contact) are not readily apparent on the ground as a mappable feature, instead mapping contacts were defined between the Members that approximates to the gamma defined contacts (Figures 4 and 6).

On airphotos there is little to no traceable internal bedding or subdivisions apparent, and as such the Formation is not reliably photo interpretable. Locally the MacLeod / Mount Newman Member boundary can be traced for a few 100's m as a break in slope but it is just as easy to be lead astray by other features such as a variation in the Hamersley Surface. Similarly, mineralisation in the Mount Newman Member is apparent in places as a colour variation, but again not reliably so. The upper part of the Football Chert may locally be apparent as an erosional feature.

Based on mapping and drilling data at Mining Area C, the Formation is approximately 220 m thick, which agrees well with data from other areas. By contrast, in the Newman area a much thinner sequence of 145 m is historically quoted from OB29 drill data (eg Willis 1978). Recent work around Newman (surface and pit mapping, and drilling Rhodes 1999, Kepert 2000a) and East Jimblebar (drilling only, Pudovskis 2000), however, suggests that the thicknesses, and in particular that of the MacLeod Member, may be closer to that at Mining Area C and elsewhere than was previously thought.

Based on mapping observations at Mining Area C, the lower 70% of the Formation (ie with the exception of the Mount Newman Member) is mostly not a BIF, containing only minor iron oxide micro and mesobands. This is consistent with the observations of Morris (1991, 1993) from fresh diamond drill core, that the Formation has a high content of iron silicates (rather than iron oxides) and carbonate (calcite).

---

[4] Curiously, both the Marra Mamba and Brockman Iron Formations both appear to be named after the same place - old references to Mount Brockman Homestead refer to it as either Marra Mamba Homestead (eg MacLeod 1966) or Murimamba (eg Mabel Tommy *in* Olive 1997).

Silicification

Fresh, unaltered exposure of the Formation is relatively rare, except in deep gorges in the Weeli Wolli and Alligator Anticlines; the remainder of the terrain is masked by superficial, but pervasive, development of ferricrete and silcrete. Much of the lower to central parts of the Formation appear to be in part a silicified carbonate - tuff (or tuffaceous shale) sequence, with many of the yellow or white chert mesobands typified by a granular weathering surface which is strongly indicative of some original carbonate component in the parent rock (eg Lipple *et al* 1995). Primary yellow - brown weathering (ferroan) carbonate is an important constituent of unaltered exposures of the lower half of the Marra Mamba Iron Formation.

The gently sloping contact between the fresh and silicified zones is discordant to stratigraphy and as seen in deep gorges, is generally related to the Mesozoic / Tertiary palaeosurfaces (ie the Hamersley Surface). Carbonate veins in partly silicified carbonate at Parallel Ridge formed along S_3 fracture cleavage, suggests that silicification occurred post D_3. Apart from the age constraint implied by the post D_3 veins, the best indication of the age of the silicification is the close conformity with the Hamersley Surface, suggesting it is genetically linked to it. Major silicification events during the Tertiary are also recorded elsewhere in Australia.

4.1.1 Nammuldi Member (AHmu)

The mapping definition of the Nammuldi Member as used here is from the base of the Marra Mamba Iron Formation to the base of the Potato Bed (approximately US12, Figure 4).

The unaltered Nammuldi Member consists of a lower carbonate - dominated sequence overlain by silicified cherty carbonate and cherty BIF, with minor interbedded (tuffaceous) shales. In outcrop it is dominated by poorly bedded, yellow chert and biffy chert, typically with broad pinch and swell structures, or undulating bedding. Previous subdivisions have defined 18 S macrobands based primarily on the down hole gamma signature. Recent mapping by Hamersley Iron subdivided the Member into eight units based on the character of the chert / BIF macrobands (Figure 5). Note that due to inaccuracies in measurement and possibly also the gradational nature of the top of the Nammuldi Member, the HI section is 118.45 m whereas from the same exposure in Blockley *et al* (1993) it is 126.5 m.

The Nammuldi Member has not been formally measured at Mining Area C. From sections from Hardey River Gorge, thickness to the base of the Potato Bed is 91.85 m (Figure 5) or 90.8 m (Blockley *et al* 1993). This agrees well with the interpreted stratigraphic thickness (based on down hole gamma signature) from piezometer hole CWB5 just south of C Deposit of 88 m.

Basal Chert with Crystal Moulds

The base of the Nammuldi Member is marked by a characteristic 1 to 2 m thick band of dark coloured (brown, green or black) chert containing lath - shaped crystal moulds (voids) parallel to bedding. Similar moulds occur in this chert throughout the eastern Hamersley Province.

None of the moulds were identified as cubic or nodular after pyrite. Various other mineral species have been suggested including gypsum, carbonate, barite, tremolite and K-feldspar, but no consensus has been reached. Potential origins suggested included evaporitic, diagenetic or low grade metamorphism. The widespread consistent occurrence of the moulds, regardless of the presence or not of locally well developed dolerite sills, implies that the horizon was not formed through contact metamorphism.

Considering the regional extent, systematic investigation of the origin of the crystals could yield evidence of a palaeoenvironmental marker. If a shallow water, evaporitic origin is indicated, this would conflict with the generally held view that most of the sequence was deposited in much deeper water.

Less spectacular crystal moulds are distributed throughout the Marra Mamba Iron Formation. Many of these are compatible with being due to solution of either pyrite or primary carbonate.

Lower Carbonate Facies

The lower carbonate facies is well exposed in scarps south of R Deposit (the Amphitheatre), and in deep gullies on South Alligator. It is characterised by 1 to 15 cm thick dark brown carbonate with a sandpaper surface etch texture. Elsewhere it is extensively silicified and is more apparent as yellow to brown chert with the same characteristic sandpaper texture. Secondary carbonate, including magnesite, is locally common. It is a correlative of HI's Unit 1 (Figure 5). The Rods mark the transition to the upper cherty facies.

Nammuldi Rods (ur)

A persistent zone of rodded chert / carbonate(?) and interbedded shale or tuff, about 10 m thick is located about 15 m above the base of the Nammuldi Member (Figures 4, 5). (*nb - these intervals are unmeasured estimates only.*) The Rods (Photo 3) are D_1 boudins with a regional elongation towards about 045º to 060º, with a diameter of 3 to 5 cm, and typically have an axis ratio well in excess of ten. Rods may show an apparent rotation that locally may change, but regionally gives a dextral (or southeast block down) sense of movement looking northeast. Orthogonal vein-filled radial fractures axial to compression planes are locally developed (see Photo 80). Bedding is attenuated around the rods, which may contain concentric banding. The zone is susceptible to limonite alteration or silicification. If seen only in two dimensional sections, the Rods may be mistaken for the Potato Bed.

At Hardey River Gorge, Blockley *et al* (1993) described a 16.6 m interval from 22.6 to 39.2 m above the basal contact of the Nammuldi Member, characterised by flattened pods in BIF, shaly BIF and yellow chert. In one part of this interval, "*Pods are elliptical in cross section but elongated down dip*." It correlates with HI's Unit 2 (21.3 to 35.5 m).

Carbonate Turbidite (uc or UC1)

A 2 m thick yellow - brown weathering carbonate turbidite near the top of the Nammuldi Member is very poorly preserved in outcrop being only known from a few localities, the best being in a deep gully on the Southern Flank of the Weeli Wolli Anticline (Photo 4). (Note, the stratigraphic position of the turbidite shown in Figure 4 is approximate only and its exact position requires verification.) At the Southern Flank it comprises a lower well laminated carbonate grainstone with isolated and local beds of pebbles of black silicified ?shales, and an upper cross bedded carbonate grainstone with asymmetric ripple marks (Photo 5). Soft sedimentary deformation of the turbidite has produced loading of the ripples in places (Photo 5b). Ripples indicate a north to south transport direction suggesting it is sourced from carbonate banks onlapping the Pilbara Craton (ie Carawine Dolomite equivalent).

A moderately large truncation surface apparent in some exposures (Photo 6) is probably due to dewatering of the underlying turbidity flow, followed by truncation and deposition by the subsequent turbidity flow.

A cross bedded carbonate at approximately the same level described at Jimblebar by Lipple (1995) could not be relocated by the author. Based on the photo in Lipple (1995) it appears to be somewhat different, however, given the variability of facies within a turbidite, it may conceivably be the same unit.

Upper (Carbonate -) Silica Facies

The upper 20 m of the Nammuldi Member is a cherty BIF with iron oxide mesobands (5 to 20 cm thick) that are locally strongly magnetic. The iron mesobands are interlayered with yellow chert (partly after carbonate), and form a useful guide to the proximity of the Potato Bed. The magnetite mesobands, including those with riebeckite replacement, may extend into the Potato Bed. Near the contact with the MacLeod Member, the BIF has a wavy to cuspate fabric. White chert bands with a crinkly lamination and red shale are locally exposed at the top of the Nammuldi Member. The upper few metres are also susceptible to silcrete formation.

HI recognise three subdivisions totalling 56.35 m between the Rods and the Potato Bed, being white / black banded BIF, yellow / black banded BIF and goethitic brown to green chert (Figure 5).

Well cleaved, deep blue riebeckite is locally developed in the top 5 m of the Nammuldi Member (Photo 7). It correlates with the Dun Horizon of the Marra Mamba Riebeckite Zone (see discussion in Section 4.1.3).

4.1.2 MacLeod Member (AHmm)

The mapping definition of the MacLeod Member as used here is from the base of the Potato Bed (~ US12) to MS13.

The lower contact of the MacLeod Member is placed at the base of the Potato Bed, as this is a recognisable marker unit in outcrop, and corresponds moderately with the formal boundary based on geophysical logs (Figures 4, 6). Placing the boundary here has the added advantage that it groups all the major podded units in to the one member, and also divides the Formation into three approximately equally thick members. Initial mapping in 1994 did not place it at the base of the Football Chert (that is nearer to the gamma defined boundary) as this was typically more difficult to trace in outcrop at Weeli Wolli Anticline[5].

A type section (Figure 6) of the MacLeod Member was measured and described in a gully on the Southern Flank early in 1994 to assist with mapping.

At Mining Area C Park the MacLeod Member is estimated to be somewhat thinner, with the distance between the base of the Football Chert and the top of the Potato Bed as little as 10 m. A generalised measured section about 2 km north of Eterak Fault is approximately 10 to 15 m thinner and shows considerable thinning throughout except for the Potato Bed.

Whilst less definite than in the Nammuldi Member, the weathering surface of much of the 'chert' in the MacLeod Member suggests some original carbonate component. On the southern side of Boundary Ridge, for example, a dark, laminated ?dolomite occurs in upper MacLeod Member well above the Football Chert.

The MacLeod Member is characterised by two major thick and two minor thinner, prominent, mappable, podded units and a thick median red weathering dark green to black, tuffaceous stilpnomelane - rich bed. Two of the podded units are in white chert partly after silicified carbonate. The other two are in limonitic cherty BIF. Pods may be used as local strain indicators.

Potato Bed (pb)

The basal 12 m of the MacLeod Member, is a sequence of abundant limonitic ellipsoidal pods in a shaly riebeckite - rich BIF, termed the Potato Bed[6] (Photos 8 to 10). The pods are typically more susceptible to weathering and are often eroded out leaving characteristic casts ('egg cartons') in the BIF

---

[5] Earlier mapping throughout the Province took the first mapped outcropping podded unit in the MacLeod Member as the Nammuldi / MacLeod Member boundary (eg Football Chert, Youngman Pods, etc) as the 'Potato Bed', and thus many of the stratigraphic interpretations may have been locally and regionally inconsistent.

[6] To maintain uniformity of terminology of marker beds the Potato Bed should be renamed the "Potato Pods". This would have the added advantage of removing confusion with the previously poorly defined usage of the Potato Bed name.

matrix. They are best seen in weathered cliff overhangs and may be discerned from a distance by an irregular surface on the cliff face (Photo 10). It is a correlative of HI's Unit 6 in the Nammuldi Member.

Although difficult to follow where hardcap alteration is intense, in general the Potato Bed provides a distinctive and mappable boundary with the underlying thick banded wavy yellow cherts. Sporadic larger pods may occur for about 4 m below the mapped contact.

Extending from the top of the Nammuldi Member is the local development in the basal 2 m of the Potato Bed are several 15 to 25 cm thick, prominent bands, of very tough, well cleaved, deep blue riebeckite of the Dun Horizon of the Marra Mamba Riebeckite Zone.

At Jaws Extended and elsewhere, the basal Potato Bed locally has a pronounced rodded fabric (eg Photo 77). The rods represent D_1 tectonic boudins, which have been attenuated along the principal axis of the rod by later deformation.

Well laminated yellow cherty BIF with minor shale comprises the next 30 m. This unit may form cliffs.

<u>Football Chert (fc)</u>

The Football Chert (Photo 11) comprises a 4 to 6.5 m thick unit of the large (up to 70 cm maximum axis) white chert ellipsoid - shaped pods with a characteristic etched sandpaper surface, probably formed during diagenesis from a carbonate rich bed. Diagenetic quartz - filled septarian fractures formed by dehydration are typically present in the pods. Chert laminations are seen to continue through some of the pods, especially the smaller ones. At and below the base is broad wavy banded chert with some very large pods.

Unlike the Potato Bed, the pods in the Football Chert are less susceptible to weathering than the matrix and usually weather out. Weathering may also remove part of the interior of some of the pods, leaving a shell surrounding a partial void with internal framework of septarian vein quartz and a central recrystallised sphere of quartz covered with radiating crystal protrudences. On well developed Hamersley Surface, the Football Chert is usually apparent as a lag of broken pods, and in extreme cases may only be apparent as remnants of septarian vein quartz.

From brief inspection by Lipple of the type section of the Marra Mamba Iron Formation (DDH 275), the Football Chert is readily discerned from MS1 to a point just below MS4. The core does not extend to the boundary as defined in the field (ie Potato Bed or about US12).

Stilpnomelane Bed

An approximately 11 m thick, red weathering, well - laminated, micro and mesobanded, dark green to black tuffaceous stilpnomelane - rich bed comprises the next major unit. It is relatively iron - rich with strongly magnetic laminae and appears BIF like where silicified. Historically, it has been referred to as the central chert or BIF of the MacLeod Member. Even planar banding and regular orthogonal fracturing of the unit make it prone to forming scarps and low cliffs in dissected terrain. Several massive bands 15 to 20 cm thick containing small nodules up to 2 cm diameter after pyrite, may be tuffs. Scattered pods may occur toward the base of the unit.

In down hole gamma logs, it does not coincide with any major peaks and has therefore had "shale" dropped from its original name - Stilpnomelane Shale Bed - proposed by Lipple *et al* (1994).

The Stilpnomelane Bed is overlain by about 8.5 m of interbedded 8 to 10 cm thick white chert and grey shale.

Youngman Pods (yp)

The Potato Bed may be confused with a similar feature, termed the Youngman Pods (Photo 12), named after the geologist who first mistakenly mapped them as the Potato Bed. It is about a 2 m thick unit with relatively less abundant, small (< 20 cm diameter) ellipsoidal, cherty to limonitic pods within a yellow cherty, limonitic BIF, than the Potato Bed.

The overlying, poorly exposed 3 m of grey, partially silicified pyritic shale is interbedded with bands of moderately laminated white chert, which may appear similar to the Stilpnomelane Bed.

Sullivan Pods (sp)

The grey and white chert / shale bed above the Youngman Pods is commonly characterised by large pods to 50 cm, which may be confused with the Football Chert bed. The Sullivan Pods[7] (Photo 13) may be spheroidal but are commonly elongate, irregular and comprised of white or grey chert after carbonate. It is usually more discernible and mappable as a form surface than the Youngman Pods, but has possibly been wrongly labelled on maps as the latter. Based on the measurements at the Hope Downs section, the Sullivan Pods lie at or just below MS9.

Relatively resistive pale yellow or brown cherty BIF with minor thin shale bands comprise the next 12 m. A distinctive marker horizon of white laminated chert bands about 5 to 10 cm thick with flattened pods occurs 6.5 m below the MacLeod / Mount Newman Member contact. The 'Tiger Eye' prospect south of A Deposit is located at this horizon.

[7] The Sullivan Pods were also briefly known as the Duncan Pods.

Upper Contact

The top 4 m of the Member is interbedded red shale and white laminated chert, commonly replaced by cream coloured silcrete. The contact is characterised by a fairly abrupt change from chert to martite - rich BIF of the Mount Newman Member. In places however, the mesoband between MS12 and MS13 may be moderately martite rich making the contact somewhat ambiguous and gradational over about 2 m. This is also the case at OB29 where mineralised MB12 and MB13 are mined with the mineralised Mount Newman Member. This zone may be represented by finely laminated fissile BIF with limonite - hematite mineralisation. Rare crocidolite occurs in khaki brown shale (MS12) in the reference section. MS13 is about 30 cm thick, characteristically red, and exposed mostly only in undercuts.

Other Reference Sections

The Marra Mamba Iron Formation type exposure is at Wonmunna Gorge. With the exception of the basal Potato Bed, much of the MacLeod Member is not well exposed along the creek bed, but most features are apparent on the eastern wall of the gorge. Exposure on the surrounding plateau from the Rods to the base of the Mount Newman Member has a very heavy ferricrete overprint that has destroyed all mappable features.

The MacLeod Member was measured by tape from the well exposed MS13 to the base the 12 m thick Potato Bed and was found to have the same true thickness (73.9 m based on 31º dip) as Mining Area C (74 m).

The labelled Hope Downs reference section, along the eastern wall of 'Hope Downs Gorge' (northwards from 708 000 E / 7 453 800 N) is about 1.5 km east of the Mining Area C reference section. The Potato Bed is from US12 to about 2 m above US16. US17 is a shale in planar bedded cherty BIF some 40 cm above the top of the Potato Bed. US18 is 1 m below the base of the Football Chert bed in thickly bedded chert and shaly, iron - poor BIF (by acknowledged error, Hancock Prospecting (HPPL) have painted two locations for US18 - the northeastern and uppermost marking is correct). From the base of the Football Chert bed to US17 is about 10 m (visual estimate). The base of the Football Chert is at MS1, with MS4 immediately above the main interval of largest pods. Widespread layer - parallel vein quartz occurs in the twin shale MS3. The 2 m transition zone above MS4 up to the Stilpnomelane Bed consists of small pods and carbonate - white chert lenses. MS6 lies 6 m above the Youngman Pods, and marks the top of the finely laminated, fissile, grey - white powdery chert and cherty shale.

In the Hardey River gorge section, Blockley *et al* (1993) describe the Potato Bed as 16.5 m of "ball - stack beds" consisting of very podded (circular) cherty BIF and thinner shaly BIF, which overlies black and yellow, thickly mesobanded BIF with thinner bands of shaly BIF, for a total thickness of the Nammuldi Member as defined here of 90.85 m. The upper 34.7 m of the measured section of the Nammuldi Member as described by Blockley *et al*

(1993), is included here as the MacLeod Member. It is also noted that the uppermost 16.0 m in the measured section (correctly assigned to the MacLeod Member), probably corresponds to the Football Chert and Stilpnomelane Bed.

4.1.3 Mount Newman Member (AHmn)

The Mount Newman Member is characterised by close spaced, oxide (dark) / silica - silicate (cream) mesobands. Microbanding is well developed in both types of mesobands. The most characteristic feature of the Mount Newman Member BIF compared with other BIFs of the Group is the very pronounced podding, especially stacked pods, developed in some beds (Photo 14). The origin of the pods has caused much debate over the years ranging from biogenic, to soft sedimentary deformation, to the currently favoured D_1 extensional structures (see Section 9.2).

Compared with BIF mesobands in the MacLeod or Nammuldi Members, the Mount Newman Member is more iron rich, better banded, and typically has cream cherts rather than yellow. It is the most deformed unit at Mining Area C, with tight to elastica, overturned D_2 folds developed at all scales.

The Member is divided into three subdivisions (N1 to N3, Figure 4) that separates the relatively martite - poor, shale - rich centre (N2) from the remainder.

Eight S macrobands are defined, but are relatively thinner than those in the Dales Gorge Member. From the type section (DDH275, *in* Blockley *et al* 1993), the proportion of S macrobands is 5% in N1, 24% in N2 and 4% in N3, or 10% for the entire Member (*cf* 26% for D2 to D4 in the Dales Gorge Member type section). In outcrop and near surface drilling, S macrobands are composed of either well bedded white, pink, yellow and red shale after stilpnomelane - rich (tuffaceous) shale, and / or poorly bedded yellow to khaki rock after carbonate (eg Figure 7). Morris (1991) describes the S macrobands as “SCC” macrobands for shale / chert / carbonate.

They are rarely apparent in outcrop except in some steep gorges. NS5 is often the best exposed and most characteristic of the S macrobands, being a 20 to 30 cm thick massive khaki rock with a load cast base and planar top. The regionally persistent layer (nodule band) of goethite balls after pyrite (2 to 5 mm diameter) is apparent in central NS3 (Figure 7) in both the 1975 GML and 2002 BHP bulk sample pit at C Deposit.

<u>Vivash Riebeckite Zone</u>

The Vivash Riebeckite Zone is one of two major zones in the Marra Mamba Iron Formation prone to replacement of BIF by riebeckite, which in turn, is prone to subsequent alteration to crocidolite (Trendall and Blockley 1970). The Zone there is described there as extending from a prominent green chert about 2.5 m beneath NS2 to about MS12 or MS11 (depending if NS1 is omitted from Figure 67 of Trendall and Blockley 1970). They argue that the alteration of BIF to massive riebeckite occurred post compaction and associated podding (ie D_1) and pre regional rippling (D_2), with the localised conversion of riebeckite to crocidolite being associated with D_2. Figure 53 of Trendall and Blockley (1970) shows massive riebeckite replacing BIF (Yampire Riebeckite Zone, Dales Gorge Member) along two NE trending "swells" that are compatible in orientation with D_1 structures. Trendall (*in* Hickman 1990) also describes northeast trending riebeckite swells with crocidolite in "duplicate structures" (Figure 8) in DB1 at Dales Gorge just downstream of Circular Pool. They are also associated with "compressed limbs" that appear identical to D_1 low angle, extensional shears structures well developed in the Mount Newman Member and elsewhere (eg Photo 75). It is more likely therefore, that the **development of riebeckite is syn to late D_1**, rather than between D_1 and D_2.

In outcrop, the Zone is usually only apparent between NS1 and NS2 as griqualandite or more rarely as tiger eye. Crocidolite is well exposed in the same interval along Blackwood Creek gorge south of C and D Deposits (Photo 15). South of A Deposit a number of old costeans have extracted tigers eye from a horizon approximately between MS12 and MS11, suggesting that the Zone is developed deeper in the stratigraphy here. This is in agreement with Robe River Iron Associates (RRIA) data from West Angelas where they consider the base of the Zone to be MS11. Crocidolite (fresh, or altered to tiger eye or griqualandite) was much more evident during mapping in the Weeli Wolli Anticline area than elsewhere in the region. At Mining Area C Park, no crocidolite was noted in the Mount Newman Member or elsewhere in the sequence. A stratigraphic compilation section mapping occurrences in Blackwood Creek gorge should be constructed prior to commencement of mining along the Northern Flank to aid in its prediction prior to intersection.

Drilling along the Northern Flank since 1993 has intersected fresh crocidolite in magnetite BIF between NS1 and NS2 at a number of localities. The stratigraphic depth extent of crocidolite here is unknown as drilling is usually abandoned immediately on intersection of crocidolite. Griqualandite in mineralisation has also been intersected at the same stratigraphic level, but not lower in the MacLeod Member.

The other riebeckite zone documented by Trendall and Blockley (1970) is the Marra Mamba Riebeckite Zone, interpreted here to extend from the Football Chert in the middle of the MacLeod Member to part way through the Nammuldi Member. It comprises the Mackay, Dun and Foxall Horizons (Figure 4), and apart from localised massive riebeckite development in the lower part of the Potato Bed (Photo 7) and two thin (< 1 cm) veins noted in the MacLeod Member reference section (Figure 6), does not appear to be well developed in the Mining Area C region. The type area is at Silvergrass where crocidolite in the Dun Horizon is very extensively developed (Duncan *pers comm* 2000).

It is worth noting that Trendall and Blockley (1970) stress that within a riebeckite zone, riebeckite is not always present, and only if it is present can crocidolite then be formed. This may provide some prior indication during mining, of the potential for intersecting crocidolite, rather than just relying on certain stratigraphic intervals. All that is required now is the ability to identify (weathered / altered) riebeckite during drilling!

In the Newman area (eg OB35, EKP0084 and adjacent holes) there may locally be a significant increase in K_2O (av 0.7%), MgO (av 1.6%) and CaO (av 0.9%) below MS7. (This compares with an increase in MgO and Na_2O, and static K_2O and CaO quoted by Trendall and Blockley (1970) for a single riebeckite altered mesoband from DB0). The increases at OB35 are not part of a weathering profile as the stratigraphic relationship can be seen to continue into weathered rock all be at a reduced elevation (eg EKP0081, 83). It is unclear if this variation is in fact due to localised riebeckite development or it reflects primary geochemical sedimentary change, such as the change from the lower carbonate rich to upper carbonate poor MacLeod Member. If it were the latter then it would be expected to be more widely developed and apparent in drill results. To properly assess the significance of the increase at OB35, Na_2O needs to be analysed for to rule out possible minor contained carbonates. **To potentially map areas of riebeckite alteration and therefore areas prone to crocidolite development, it is recommended that Na_2O be included in drill hole analyses**. This should initially be done as a trial in an area of known crocidolite development (eg parts of C Deposit).

4.2 Wittenoom Formation (AHd)

4.2.1 West Angela Member (AHda)

The lithology of the West Angela Member appears to vary significantly across the Province depending on degree of alteration or "weathering" (eg Blockley *et al* 1993). In the western part of the Province where it is more "unaltered" it comprises interbedded dolomite and shaly dolomite (eg in outcrop on the south limb of the Hardey Syncline, Rocklea, Kepert 2001b), compared with the central and eastern parts where it comprises a "residual" of interbedded khaki, manganiferous shale and chert, with only rare dolomite beds (eg between AS4 and AS5 at Western Ridge), or very rarely "original" dolomite (eg in EXP1033 at Prairie Downs). Given the consistency, degree and depth of development of the shaly facies in the central and eastern parts, it is unlikely that the regional variation is due to alteration or weathering, but probably represents an original facies change. Quoted thicknesses for the Member vary from 0[8] to over 80 m, with a generally accepted value of 40 to 50 m for the central and eastern Hamersley Province.

The basal 10 to 15 m below AS3 in the central and east is mainly biffy chert with shale interbeds (Figure 4). The approximately 20 cm thick Poulinett's pink shale (lower shale band of the AS1 doublet) defines the basal contact.

[8] A reported thickness of 0 m probably does not denote its absence, but rather that it is "unaltered" (dolomitic) and has been included in the Paraburdoo Member.

The West Angela Member is poorly exposed with typically only a few meters stratigraphic thickness of highly weathered, but distinctive, mineralised chert / shale apparent. Unmineralised biffy chert occurs as low scarps along Blackwood Creek and at western South Alligator (Photo 16). The basal 5 m are characterised by white, yellow or green chert bands up to 10 cm thick. The surface of the chert bands has a granular, sandpaper texture indicative of a carbonate-bearing precursor. Thin calcrete skins and veinlets are also a common feature. Chert interbedded with red and khaki shales is also well exposed at Death Valley. AS3 is well exposed at the east end of South East Corner as an extensive outcrop of red shale. Although rarely exposed, a 2 to 3 m thick BIF directly under AS3 is known from drilling.

Other good exposures of unmineralised West Angela Member occur at the entrance of Wonmunna Gorge, where about 10 m of well banded yellow, biffy chert are exposed. The interbedded shales are not exposed.

Griqualandite after crocidolite is only known from two single occurrences, a single intersection in E Deposit (GER0077, 81 to 84 m, Tehnas and Pudovskis 2000) and in the C Deposit West bulk sample pit in AB2 (Figure 4). It has not been documented from other localities due to either poor exposure of the Member and /or its limited geographic extent.

Manganese blooms (principally as pyrolusite - MnO_2) are common near to outcropping / subcropping West Angela Member, however it is also not an uncommon feature elsewhere in the stratigraphy and cannot be used reliably as a diagnostic feature for proximity to the Member. Minor psilomelane (MnO.OH) locally replaces goethitic khaki shales in AS2 at C Deposit West.

The upper two thirds of the Member comprising various khaki, manganiferous shales interbedded with dolomite and chert is not exposed in the region, nor is the contact with the Paraburdoo Member. Much of the upper shale - dominant part of the Member appears to have been removed (by tectonics or dissolution) on the west end of South Alligator where extensive Paraburdoo Member dolomite is apparent within 10 m of the lower part of the Member (A1, Photo 16). Alternatively, it may not have been developed by "weathering".

4.2.2 Paraburdoo Member (AHdp)

The Paraburdoo Member is a monotonous sequence of well bedded, grey, crystalline, hemipelagic, deep water dolomite with associated chert beds. Typically it is very poorly exposed, and forms the floors of the now - filled palaeovalleys between the Marra Mamba and Brockman Iron Formations. The thickness of the Member is poorly understood, with Trendall and Blockley (1970) quoting 110 m (360 feet) compared with at least 260 m at Paraburdoo and over 420 m from drilling at Range Gorge (Simonson *et al* 1993). Assuming no tectonic repetition, the exposed thickness at western South Alligator is some 350 to 500 m. This is also compatible with bedrock reconstructions of the Northern Flank valley from limited drill data.

The upper 50 m is very well exposed on the north face of The Governor (Photo 17) and south side of Mt Robinson. Here it shows well defined rhythmic banding (typically 2 to 5 cm) of clean grey dolomite with dirtier thinner brownish dolomite beds. Several horizons also have sets of multiple chert interbeds up to 10 cm thick over a 1 to 2 m interval, and these appear to increase upward in frequency (Photo 17). Moderately good exposures (but with no vehicle access) are also present at the west end of South Alligator. Similar exposures west of South Parmelia Hill have not been visited to date. Scattered exposures elsewhere in the region are more typical of the Member in outcrop, being a creamy to brown, partly brecciated and calcretised, poorly bedded dolomite. Brecciation (Photo 18) is probably a combination of diagenetic dolomitisation, various generations of karst development and more recent weathering.

Simonson *et al* (1993) describes some beds as locally having either lumpy laminations or roll-up structures, both suggesting the presence of a binding microbial mat during sedimentation. Due to depth constraints of deposition below the wave base (~ 100 to 200 m) however, any biogenic activity must have been non-photosynthetic.

Various workers have verbally and formally proposed that there is a break in sedimentation or a paraconformity somewhere within the Wittenoom Formation, probably in the Paraburdoo Member (eg Martin *et al* 1998a). Recent sequence stratigraphic frameworks (eg Krapez 1997) have postulated that the Member again represents a compressed section or lacuna. Whilst outcrop of this interval is less than comprehensive, there remains no stratigraphic or lithologic evidence for a break in sedimentation (eg Simonson *et al* 1993). Dating by Trendall (see Section 4.9.1) indicates a reduction in the sedimentation rate higher in the sequence between the Bee Gorge and Dales Gorge Members.

4.2.3 Bee Gorge Member (AHdb)

Sediments of the Bee Gorge Member are unique in the Hamersley Group in that they have a significant proportion of mainly high energy turbiditic sediments, as opposed to the remainder of the Group, which comprise very low energy sediments, with only minor turbiditic beds. There is evidence of similar, but relatively minor, sediments continuing upwards through the Mt Sylvia Formation to basal Mt McRae Shale (see Sections 4.3, 4.4).

Measured sections in Simonson *et al* (1993) indicate the Member varies significantly in thickness and lithology across the Province. The variation in lithology may be explained in part by the degree of weathering. From mapping completed here, the fresher exposures appear more carbonate rich, with the more weathered exposures appearing more shale dominant. By geographically regrouping the sections in Simonson *et al* (1993), the Member averages 210 m thick in the northwest proximal to the Hamersley Range scarp, to an average 140 m in the central and southeast part of the Province. The thickening to the northwest is due almost entirely to increases in the interval above the Spherulite Marker Bed (see below). At Bee Gorge this interval also contains six isolated carbonate layers with coarse clastic features suggesting that the interval in the northwest marks the toe of a sedimentary fan or wedge proximal to a carbonate shelf.

Kargel *et al* (1996) interpreted polygonal cracks from an unidentified / unspecified horizon in the Bee Gorge Member as being sub-aerial desiccation cracks, however given the mainly turbiditic nature of the Member, this interpretation appears unlikely as it would require large sea level changes that are not supported by evidence from anywhere else in the stratigraphy.

The contact between the Paraburdoo and Bee Gorge Members is defined by Simonson *et al* (1993) as the top of the uppermost thick (~ 2 m) dolomite bed. This proved a good mappable contact, except at Death Valley where it appears thinned (Photo 19) and the relative position of the dolomite appears to vary. It is unknown if this is due to real variation in stratigraphic thickness, localised development of more than one dolomite layer or (most likely) to tectonism (folding / faulting, eg Photo 101) and associated dissolution. The overlying Mt Sylvia Formation and Mt McRae Shale also appear to be somewhat variable in thickness, also suggesting a tectonic component.

Excellent carbonate - rich exposures of Bee Gorge Member occur on the north face of the west end of Fork South (Photo 20). Similar but more weathered and less well exposed outcrop also occurs on Spring Hill, Fork North, The Governor and Mt Robinson. A number of limited traverses across the Member identified several prominent marker beds including the Crystal Rich Tuff (CRT, Photo 21), Main Tuff Interval (MTI, Photo 22) and Spherulite Marker Bed (SMB, Photos 23, 24) of Simonson *et al* (1993). The majority of the Member in outcrop consists of thinly bedded, fissile turbiditic shale and dolomitic shales, with subordinate carbonate and chert beds. Shale and carbonate may locally contain intraclasts or flat pebble conglomerates. Other sedimentary structures include concretions, roll-ups, ripples and cross-bedding (Photos 24,25). Carbonate typically weathers yellow - brown indicating a likely ferroan calcitic to ankeritic composition, with only rare (grey - brown) dolomitic beds. Much of the carbonate is interbedded with (and / or replaced by) thin cherts giving several “striped” carbonate markers. Locally, many carbonate beds are also partly to totally replaced by massive chert (see Section 4.3).

On airphotos an orangish toned unit apparent toward the base (about 10 m above) of the Bee Gorge Member is a useful marker horizon when interpreting airphotos. The shale here is also usually more friable then the surrounding lithologies and forms a local change of slope.

A very good exposure of the top 90 m of the Member at Rocklea in the western Hamersley Province does not appear to have any of the above characteristic features being comprised of only well bedded shales with rare (< 1%) thin chert beds and no carbonate. It is unclear how much of the Member is present here however, as much of the Paraburdoo Member and therefore, potentially also the lower part of the Bee Gorge Member too, has been tectonically removed.

Crystal Rich Tuff (CRT)

The CRT is a thin (5 to 10 cm), grey, graded tuffaceous bed distinguished from similar tuff beds in the Member by the occurrence of abundant 1 to 5 mm white needle to plate like phenocrysts concentrated toward the base of the bed (Photo 21). At Fork South a second identical but slightly thinner bed is also exposed about 15 cm below the CRT. It occurs about 30 m (range 19 to 40 m) above the base (Simonson *et al* 1993).

Main Tuff Interval (MTI)

The MTI is 5 to 19 m thick (average 9 m), multiple, thin bedded, volcaniclastic turbidite of well to poorly bedded, green tuffaceous shales which usually form a prominent cliff in the middle of the Member (average 70 m above the base). It is distinct from other creamy fissile shales in the Member by colour and in having a biscuity to blocky and brittle texture (Photo 22). A complete description of the MTI can be found in Hassler (1993).

Spherulite Marker Bed (SMB)

The SMB is 0 to 10 cm thick, thin bedded, bolide - derived, turbidite bed occurring 20 m above the MTI. It is juxtaposed and overlain by a 0.5 to 3 m thick, cross bedded, thick bedded, carbonate turbidite. Subdivisions of the SMB and overlying carbonate are:-

- SMB - 0 to 10 cm, thin bedded turbidite comprising an impact derived bed of sand sized spherules[9] with some shale intraclasts. The local large variation in thickness over only several metres strike is compatible with deposition as low amplitude, long wavelength starved ripples on a shale substrate. Simonson (*pers comm* 2000) suggests that the spherule bed is not genetically related to the overlying carbonate turbidite due to the local preservation of a few centimetres of intervening shale. At Fork South, however, they are clearly gradational implying a more direct genetic link (Photo 23). In outcrop, the spherule bed has a distinct pitted appearance,
- lower, poorly to well bedded, yellow carbonate grainstone, about 0.1 to 1 m thick (Bouma sequence T_A to T_B, Photo 24)
- median, well cross bedded, yellow carbonate grainstone, locally with ball and pillow structures and convolute bedding due to water escape (Photo 24b), about 0.2 to 0.3 m thick (T_C),
- upper, 0.5 to 2 m thick distinct purple - brown, very poorly bedded ?carbonate mudstone (T_D).

A Glikson (*pers comm* 2002) recognises a second similar bed near Wittenoom Gorge 0.5 m above the SMB that is possibly due to a second, related impact rather than resedimentation of the earlier produced spherulites.

---

[9] Spherules, microkrystites and microtectites are used to denote quenched 0.5 to 2 mm spheres of glass created by molten ejecta from a bolide impact. Simonson had previously used the genetic term microkrystites in describing the SMB to distinguish them from microtectites, but now favours the more generic term spherules, also adopted here.

The SMB has been correlated by Simonson (1992, 1993b) with a similar but thicker unit (Dolomixtite) in the Carawine Dolomite (AHc). The Dolomixtite is a spherulite - bearing, carbonate debris flow. If the correlation is correct, then the mixed, predominantly shallow water Carawine Dolomite is in part equivalent to the Bee Gorge Member, and not just a direct correlative of the deep water Paraburdoo Member as historically thought. The Carawine Dolomite and the associated Fortescue Valley Reef (Morris 1993, Kepert 2001a, *in prep*), is the likely source for much of the carbonate ooze, mud and sand that comprise the Paraburdoo and Bee Gorge Members, and other subordinate carbonates from the Mt Sylvia Formation to the Brockman Iron Formation.

Recent field observations of the Dolomixtite (Glikson *pers comm* 2002) in mapping it through the Ripon Hills area (70 km northwest of Woodie Woodie) has found that it is about 120 to 150 m above the Jeerinah Formation / Carawine Dolomite contact. Elsewhere it is 4 to 12 m thick and much closer to the Jeerinah Formation contact providing some measure of the variability of the water depth and sedimentation rate as expected for a mixed, shallow water facies carbonate. Importantly, Glikson also recognises that as no spherulites are broken and locally it is forceful injection into the underlying dolomite imply a very high hydrolytic pressure during transport and deposition.

4.3 Mt Sylvia Formation (AHs)

The Mt Sylvia Formation is readily distinguishable by its three relatively thin, but prominent BIF bands, with the interbedded shales typically poorly exposed. It is also readily apparent and a very diagnostic character on airphotos. An excellent exposure of the entire Formation (Figure 9) occurs in a steep gully on the southeast face of Eric's Point, where the thinly bedded carbonate - bearing shale / mudstone sequence between the three BIF bands contain many thin (2 to 20 cm) chert and turbiditic carbonate beds (originally described by Trendall and Blockley 1970). Many of the carbonate beds here are lenticular to pipe like (eg Photo 78), but as the termination of the beds trend northeast, the beds were originally continuous but subsequently selectively partially dissolved during D_1.

Stratigraphic thicknesses at Eric's Point are similar to those at Mt Whaleback (eg Power 1998), with the exception of the absence of the pink tuffaceous siltstone unit (Kneeshaw 1975, S5 in Power 1998), and the thicker overlying S6 unit. Excluding the BIFs, the carbonate - bearing shale / mudstone sequence of the Formation is essentially lithologically equivalent to the underlying Bee Gorge Member and the adjoining lower part of the Mt McRae Shale beneath the nodule zone.

Bruno's Band (SB3) is a 5 m thick, very well microbanded BIF with dominantly dark coloured cherts. The upper contact is gradational over 10 cm becoming a less well banded, with yellow - white chert. Thin yellow carbonates also occur near the top at Eric's Point (Photo 26). It was first recognised by Stan Hilditch in the 1950's during investigation of the Ophthalmia Range and discovery of Mt Whaleback as a laterally continuous band beneath the main mineralised BIF, but was named instead after Bruno Campana, a Rio Tinto contract geologist.

The lower two BIFs (correctly SB1 and SB2, but colloquially the *Twins* or *Tramlines*) by comparison are less well exposed and chertier with distinct greenish cherts and characteristic shale mesobands.

The intervening carbonate - bearing shale / mudstone sequences can be broadly subdivided into two different facies depending on the type of chert and abundance of carbonate (Figure 9).

- *Laminated chert facies* - well laminated chert interbeds with little to no carbonate beds. It is primarily confined to the interval above SB2, and marginal to Bruno's Band. The interval above SB2 correlates well with unit S4 at Mt Whaleback (Power 1998), including a chert - rich lower half. The three well laminated BIFs may be considered as an iron - rich end member of this facies.

- *Carbonate - massive chert facies* - poorly laminated to massive chert interbeds, many with yellow – grey carbonate cores (ie silicified carbonate), and associated carbonate interbeds (Photo 27). This facies dominates most of the shale - rich part of the Formation. It also extends downward into the Bee Gorge Member and upward into at least the basal 15 m of the Mt McRae Shale at Eric's Point, before passing up in to the more typical very low energy anoxic pyritic carbonaceous shale (nodule zone) of the central Mt McRae Shale. The interval between Bruno's Band and the main laminated chert facies unit is significantly thicker than, but is a probable correlative of, S6 at Mt Whaleback. However given the turbiditic nature of the carbonates, it may also contain in part an unrecognised distal or lateral facies of the turbiditic siltstone (S5).

An isolated occurrence of a welded ignimbrite (Photo 28) between SB2 and Bruno's Band in highly folded Mt Sylvia Formation was discovered near Weeli Wolli Springs. It is well silicified, blocky and about 20 cm thick. A sample was provided to Trendall to date the ignimbrite by SHRIMP analysis, however no syn-volcanogenic zircons were found, with only a few anomalously young zircons separated. These are likely to be lab contamination.

Analysis of zircons from the pink tuffaceous siltstone unit (Krapez *pers comm* 2000) gives two broad populations at *ca* 2710 Ma (ie equivalent to Roy Hill Shale Member) and *ca* 2620 (lower Marra Mamba Iron Formation) that may be resolved in to three peaks and a single outlier at *ca* 2580 Ma (top of Marra Mamba Iron Formation).

4.4 Mt McRae Shale (AHr)

The Mt McRae Shale is subdivided into four facies here, of which the uppermost Colonial Chert Member (or D1) is included by BHPIO as part of the Dales Gorge Member and is referred to there. Trendall and Blockley (1970) describe three subdivisions, combining the lower two divisions here into a single shale member. The four subdivisions from the base up are:-

- *Carbonate - massive chert facies* - similar lithotypes to the corresponding facies in the Mt Sylvia Formation including yellow carbonate and purple carbonate bearing mudstone units comprise the lower 10 to 15 m. It is a correlative of RL (lower) and RC (chert triplets) at Mt Whaleback (Power 1998). Purple shales at Eric's Point also contain numerous irregular chert beds and isolated blebs (Photo 29). On the east end of International Hill adjacent to the proposed rail spur the blebs form distinct multi-zoned, flattened, ovoid "fish-eyes" up to 5 cm across (Garwood Pods[10]). The blebs do not appear to be after pyrite or carbonate.

- *Anoxic facies* - low energy pyritic carbonaceous shale and associated cherts. It is a correlative of RN (nodule) and RU (upper) at Mt Whaleback.

- *Carbonate turbidite facies* - high energy, variably (poorly) preserved series of thick bedded turbidite flows. It was previously recognised by Trendall and Blockley (1970) as being absent from Weeli Wolli Spring and confined to the "northern and central part" of the Province. It is not recognised at Mt Whaleback.

- *Colonial Chert Member or D1* - chert and biffy chert with shale (S macroband) interbeds. Its top approximates Trendall's Bed of Holes.

Exposure of the Mt McRae Shale is typically poor, being covered by a scree slope derived from the Dales Gorge Member, and as such outcrop is poorly described. Outcrop of the lower two facies at Mining Area C is usually limited to white to blue-grey cherts of which the 2 to 3 m thick Chert Triplets (ct) is the best exposed, and minor fissile cream shale. The anoxic or nodule zone may be apparent as ~ 1 cm size holes in the shale. Goethitised pyrite balls are apparent in outcrop at one locality at Ministers North (Photo 30).

4.4.1 Carbonate Turbidite (rc or RC1)

Extensive exposures of the Mt McRae Shale carbonate are documented by Trendall and Blockley (1970) from the northern side of the Hamersley Province. Exposures at Mining Area C considerably increase the previously known extent of the carbonate turbidite. A detailed measured section was made at Balgara (Figure 10) where first located, with subsequent generalised sections of some other exposures being estimated off photos taken of the outcrop (Figure 11). Whilst grossly similar, all exposures show significant lithological and thickness variations. Significantly all known occurrences are in the hinges of anticlines (Photo 31). The carbonates typically weather grey but are most commonly pink grey to maroon on a broken surface, suggesting some Mn component.

Four carbonate facies and three broadly correlatable units (Photo 31) are recognised and are described below. Additionally, a silicified breccia (presumably after carbonate) was also located in an anticline, and calcrete blooms are also locally common at this stratigraphic level, suggesting the carbonates were more

[10] After surveyor Wayne Garwood who discovered the locality.

extensive than now apparent in outcrop. In areas of folding the carbonates have only been preserved in low pressure anticlinal hinges (analogous to saddle reefs) with pressure dissolution removing it elsewhere. Some dissolution is also evident in preserved sections as sub-parallel to bedding stylolite surfaces (eg Photo 34b).

The sequence is broadly interpreted as a series of turbidites / debris flows progressively sourced from a chert / shale dominant to a carbonate dominant sequence. The three units are:-

- *Basal conglomerate* - poorly exposed, chert and / or shale clasts in a dirty ferruginous matrix that is often partly calcretised (Photo 32). Goethite pseudomorphs after pyrite nodules were identified in some large pink shale clasts, indicating local derivation from the Mt McRae Shale (Photo 32b). This unit is carbonate poor and may not be genetically related to the overlying carbonates. It is unclear if the unit comprises one or more turbidite beds. It has only been located at MAN and International Hill outcrops on Packsaddle Range.

- *Massive carbonate* - massive to moderately bedded carbonate grainstone to packstone, with carbonate and shale intraclasts typically less than 1 cm (Photo 33). It is equivalent to facies II at Balgara and varies in thickness from 3 m (Balgara) to 8 m (MAN). It appears to be a single, massive, turbidite flow that (assuming an original uniform distribution over the region from the Hamersley Range to Mining Area C), would imply a minimum volume of 20 km^3. Isolated clasts at MAN of up to 35 cm (dolomite), 75 cm (chert) and over 1 m (shale) occur in the centre of the unit (Photo 33b). Other clasts include abundant pyrite nodules at Governor Range (Photo 33c) and folded (soft sediment deformation) shale at Wildflower Mountain.

- *Bedded carbonate* - well bedded carbonate mudstone about 5 m thick (Photo 34). It comprises alternating beds 5 to 20 cm thick of massive to laminated carbonate mudstone (facies I) and rhythmite carbonate mudstone (facies IV). At Balgara it is about 12 m thick and also contains festoon cross bedded carbonate mudstone (facies III). Intraclasts are locally present at the base of some beds (Photo 34b). The sequence represents numerous comparatively small, thin bedded turbidites.

Four carbonate facies are seen in the upper two carbonate dominant units:-

I. *Finely laminated dolomitic mudstone* is the dominant carbonate facies. Minor argillaceous shale laminae may be present and numerous partings generally occur to impart a fissile habit.

II. *Fine grained, intraclastic, grainstone / packstone* with intraclasts up to 10 cm long but generally < 2 cm and very thin (ie plate - like). Orientation varies but is typically parallel to bedding. Clasts include those derived from laminated carbonate mudstone (facies I). It may pass up into fine grained carbonate with faint lamination and planar bedding.

III. *Festoon, current-bedded carbonate* of very fine grained packstone to mudstone (Photo 35b). Features include scour channels with erosional bases, and a current direction towards approximately 160º. Some large intraclasts occur toward the base.

IV. *Rhythmites* of interlaminated argillaceous carbonate and carbonate mudstones, and associated thin planar beds of carbonate mudstone and minor argillaceous shale laminae (Photo 35a).

Alan Thorne (GSWA, *pers comm* 1996) stated that where present the carbonate member is an incomplete Bouma sequence, grading from medium to fine grainstones with some symmetric ripples toward the top. He has not observed intraclastic units or festoon bedding, but was not surprised given the environment.

[Note: after completion of the 1997 mapping, an exposure of the carbonate in Wittenoom Gorge was visited by DAK. Here a massive channel - fill of intraclastic carbonate is apparent cutting over 1 m into well bedded carbonates (Photo 36). These basal bedded carbonates and their up slope equivalent may be the source of the massive and upper, well bedded carbonates described at Mining Area C. The exposure requires more detailed examination and confirmation.]

4.5 Brockman Iron Formation (PHb)

Unlike the Marra Mamba Iron Formation, the Brockman Iron Formation as a general rule can be photo interpreted, at least on a regional scale. It is normally marked by a steep slope to cliff marking the base of the Dales Gorge Member proper (ie D2), with the Colonial Chert Member (D1) usually poorly exposed at the base. The Mt Whaleback Shale Member is usually apparent as an erosional depression that may have a subdued ridge toward its base (Central Chert). The Joffre Member typically forms larger more rounded hills than the Dales Gorge Member. Yandicoogina Shale Member is typically poorly exposed as a dip slope on the back of Joffre Member hills. Cathedral Gorge on the Great Northern Highway just north of Newman is a typical, well exposed section for reference.

4.5.1 Dales Gorge Member (PHbd)

The Dales Gorge Member, whilst being economically important and laterally extensive, is not widely described from Mining Area C due to its relatively monotonous lithology. Regionally it varies in thickness from about 120 to 180 m (Trendall and Blockley 1970). It is divided into 17 B and 16 S macrobands (Figure 12). The macrobands can then be grouped into three divisions (D2 to D4) based on the relative abundance of S versus B macrobands. The Colonial Chert Member is included by BHPIO in the Dales Gorge Member as D1. The upper mapping contact was taken as that defined at Mt Whaleback with WS1 and WB1 are included in the Dales Gorge Member due to their relative thinness in the east.

The relative percentages of S macrobands in the D2 to D4 divisions varies from site to site but much of this appears to be due to mineralisation rather than possible original regional variations. From the type section (hole 47A[11], *in* Trendall and Blockley 1970) the percentage of S macrobands is 15% for D2, 47% for D3, 17% for D4, or 26% for D2 to D4 (*cf* only 10% for the Mount Newman Member). By comparison, HI's section from Tom Price has about half the proportion of S macrobands with 6% for D2, 31% for D3 and 7% for D4, or 12% for D2 to D4. Due to the degree of deformation at Whaleback, there is no documented standard thickness of individual S and B macrobands but only for D1 to D4 (Power 1988).

Bedding in the BIF is typically very well defined and planar, particularly proximal to its upper and lower contacts. D2 and D4 typically have a blocky fracture or outcrop pattern, with D3 somewhat more brownish, cherty and rounded in outcrop. Microbanding is well developed in both oxide and silica mesobands. Due to the planar nature of the bedding and the paucity of D_1 podding, individual mesobands are easily traceable for many metres in outcrop. Dehydration and compaction during diagenesis of flat round to less regular pods or macules[12] lead to an array of various patterns on adjacent bedding surfaces (eg Photo 37). Some B macrobands appear more susceptible to 1 to 5 cm, D_1 podding, but it is not known if these are regionally persistent mappable features.

The tops of D1 and D4 are marked by Trendall's and Huleatt's Beds of Holes, respectively with Trendall's between the CS6 doublet (Trendall and Blockley 1970, p 87) and Huleatt's about 20 cm beneath the top of DB16 (Photos 38, 40). Both are due to dissolution of small (~ 5 mm) carbonate nodules in the BIF. Less well defined beds of holes occur throughout the sequence, for example, at the base of DB0 (Photo 39), about 5 or 6 BIF macrobands part way down D1 (Blockley *pers comm* 2002) and a diffuse band 20 cm below Huleatt's Bed of Holes.

The fresh, unweathered composition of individual S macrobands in terms of varying proportions of chert - siderite, shale and carbonate are described by Trendall and Blockley (1970). When weathered most appear as kaolinitic clays with varying amounts of secondary iron cementation and staining. Based mainly on sedimentary structures in the carbonate beds of the S macrobands, Pickard *et al* (2001) described them as being produced by low density turbidity currents. They also infer a similar origin for the BIF, which appears less plausible.

Initially recognised by Tim Blake (UWA), near the base of Fortescue Falls in Dales Gorge in what is inferred as DS2, there is a thin turbiditic carbonate bed that contains small rounded carbonate and flat argillaceous intraclastic pebbles (Photo 42). Elsewhere the bed is apparent as a cross - bedded, carbonate grainstone. Similar cross - bedded, turbiditic carbonates also occur near the base of DS1 (Photo 41) and DS4.

[11] Whilst Director of the GSWA, Trendall arranged for a thin slab of the type section core from hole 47A spanning the entire Dales Gorge Member to be mounted for permanent public viewing on the wall of the lift foyer of the GSWA, 5th floor, Mineral House, Perth.
[12] Defined as nodule like thickenings of groups of mesobands in the BIF macrobands of the Dales Gorge Member by Trendall and Blockley (1970).

A 0.5 to 5 m thick bed of grey crystalline dolomite similar to the Paraburdoo Member is a feature of DS15 along the Hamersley Range scarp. This has not been recognised at Mining Area C, but is preserved in the core of anticlines further south at Coondewanna Ridge (Hollingsworth *pers comm* 2000) (*cf* preservation of Mt McRae Shale carbonate).

In summary, there is sufficient evidence from across the Province that much of the S macrobands are turbiditic in origin.

DS4 Bolide Derived Layer

Trendall and Blockley (1970) described part of DS4 (Photo 43) as a "breccia" based on exposures in Wittenoom, Calamina, Yampire and Dales Gorges, but also reportedly extending throughout the central and eastern parts of the Hamersley Range. It is described as being between 0.6 and 1.5 m thick with an erosional base, and comprises rounded to angular shale and chert cobble sized clasts that decrease in size upwards, in a structureless green groundmass. Some larger clasts occur near the top.

More recent investigations by Hassler and Simonson (1998, Hassler *pers comm* 1998) have identified abundant spherules (see Spherulite Marker Bed, Section 4.2.3) in the matrix, indicating it is likely to have formed by a bolide initiated, turbidite flow. Hassler (*pers comm* 1998) divided the layer comprising of partial Bouma sequences into two units (Photo 44):-

- basal massive coarse grained unit - is wide spread known from Dales Gorge to Western Ridge near Newman. At Wittenoom Gorge it varies from 50 to 90 cm thick (average 75 cm). It normally comprises almost pure, coarse sand - sized spherules, however, at Wittenoom Gorge the spherules have been highly diluted by shale and chert intraclasts of all size, from silt to boulders (Trendall and Blockley's breccia). The larger chert clasts are concentrated toward the top of the unit and locally have penetrated the overlying strata due to later compaction (Photo 45). Banded chert clasts (described as Dales Gorge Member - derived BIF by Hassler) are deformed in places, especially on their margins, indicating deformation and erosion of the poorly lithified clasts during transportation (Photo 46a). Many chert clasts appear to be, at least in part, after carbonate (Photo 46b) and do not appear typical of the Dales Gorge Member (*pers obs*). One silicified clast was identified as a likely stromatolite of unknown stratigraphic origin, this was subsequently confirmed by Kath Grey (GSWA, *pers comm* 1998).

- upper fine grained unit - is about 10 to 30 cm thick and present in all sections measured by Hassler and Simonson (1998). It comprises two beds of sand to silt sized intraclasts with no apparent spherules (eg Photo 44).

Riebeckite Zones

No crocidolite, or its alteration products, was noted anywhere in the Member during mapping at Mining Area C, however the Yampire Riebeckite Zone (Trendall and Blockley 1970) does show extensive riebeckite development (but no crocidolite) in the hills just north of Packsaddle Range. The Yampire and Junction Riebeckite Zones correlate with D2 and D4 respectively.

4.5.2 Mt Whaleback Shale Member (PHbw)

The Mt Whaleback Shale Member typically forms a saddle between the more resistant adjacent BIFs. In outcrop it comprises 30 to 50 m of fissile, red - brown to purple shales with yellow, brown and white chert mesobands. The most prominent of these is the 3 m thick Central Chert (cc), which usually has a characteristic large scale undulose to wavy banding (Photo 47). The Basin wide development of the wavy bedding here (and in other beds) irrespective of the local degree of deformation suggests it is not an interference structure between D_2, D_3 etc, but is more likely produced during diagenesis / D_1. It occurs about a third of the way up the Member.

In keeping with BHPIO convention, the basal contact is defined as the top of cherty WB1 macroband, in effect moving the contact about 2 m stratigraphically up, or rarely more than 5 to 10 m horizontally on the ground.

Compared with the sharp basal contact, the upper contact with the Joffre Member is gradational over a few metres as cherts progressively become more prominent and shales thinner. The contact is also poorly defined by down hole gamma signatures also indicating its gradational nature. Whilst not always accurate, the mapping contact was sometimes approximated as the first good outcrop, normally also coinciding with a break in slope.

4.5.3 Joffre Member (PHbj)

Compared with the Dales Gorge Member, BIF of the Joffre Member is less well banded, with poorer defined microbands in both the silica and oxide mesobands, and minor podding / boudinage leading to individual mesobands being only traceable for a few metres. Compared with the Dales Gorge Member, it also lacks true macrobands (Trendall and Blockley 1970). Unlike previous detailed mapping at Jimblebar, no systematic attempt was made to map J1/2, J3, J4, J5 and J6 subdivisions in the Joffre Member. At Mining Area C the Member is about 200 to 250 m thick.

Only the lower part of the Joffre Member (ie J1 and J2) is preserved on Mt Robinson, Governor Range, Fork North, Packsaddle Syncline, the eastern part of Fork South, and the western part of Packsaddle Range up to Tuckerbox Gorge (ie Iron Ore Ridge). The upper part of the Joffre Member (J6) is preserved on Wildflower Mountain, and the remainder of Packsaddle Range and Fork South.

A unique 2 to 3 cm thick single chert bed in J2 BIF with a characteristic radiating crinkled surface (Photo 48) was located at two sites about 4 km apart on Mt Meharry and Fork South. The texture is compatible with and is likely to having been produced by biogenic activity (Kath Grey *pers comm* 2002). Given that the deposition is below the wave base (~100 to 200 m) it also implies it is non-photosynthetic probably being produced by a chemoautotroph (eg sulphur bacterial mat). This however implies some form of hot spring activity or similar for which there is no supporting evidence. Similar radiating textures are unknown with its closest analogue being random wrinkling of "elephant skin" texture in much younger Neoproterozoic sediments.

The J4 marker chert[13] (Lipple 1995) comprising two sets (30 to 50 cm apart), each of two 5 to 10 cm thick, white / brown striped chert beds separated by a similar thickness of poorly exposed shaly chert (Photo 49) was mapped as a marker bed in places. The colour banding and slightly lumpy lamination is very characteristic, with the only similar striped cherts occurring in the Yandicoogina Shale Member and the Weeli Wolli Formation, but these are typically red and yellow. This multiple stripy chert marker has now been traced from Jimblebar through Newman to Mining Area C, and appears to be a Province wide, mappable marker bed.

Podding is best developed in J6 with boudinage of chert mesobands common. Locally stacked pods similar to those of the Mount Newman Member may also be developed. At a single stratigraphic level toward the top of J6 at Mindy, very large, cowpat - like, flattened pods over 30 cm in diameter and less than 5 cm thick are developed (Photo 50)

Porcelanites (JP1 - JP5)

Porcelanites, previously only described from Joffre Gorge by Trendall (1968), were located during MERIWA Project M282 field work in prominent Joffre Member hills north of Tuckerbox Gorge and just east of the Great Northern Highway (Hollingsworth *pers comm* 1998). They are black, unbedded and glassy, with a very characteristic bedding perpendicular, spaced blocky fracture. They appear grossly similar to parts of the black upper rhyolite of the Woongarra Rhyolite consistent with the Barley *et al* (1997) model of the Weeli Wolli dolerites and rhyolites marking a major period of bimodal volcanism. JP3 to JP5 are exposed in gorges on the south side, and JP1 to JP3 on the north (not visited) and west sides. JP4 and JP5 are both about 10 cm thick, with JP3 20 to 30 cm thick and just below a prominent 20 cm shale band in J2 (Photo 51). JP3 is also characterised by white, 1 to 3 mm phenocrysts. Except for further occurrences in the prominent hills above, the porcelanites could not be located in the mapping area due to depth of weathering and enrichment.

JP3 was later found by DAK at Cathedral Gorge in the Newman area where it crops out as a massive, blocky pink silicic rock with weathered white phenocrysts. It occurs about 5 m below J3 and about 18 to 20 m under the J4

[13] Drilling at OB24 midway through 2002 indicates that the J4 chert marker is actually interbedded with the shale triplet that marks the base of J5 rather than being the top of J4. It's name is retained here however for consistency with previous reports etc.

stripped chert, and may correlate with the prominent gamma peak near the top of J2. Further work is required to accurately stratigraphically locate and correlate the other porcelanites with respect to the standard stratigraphic section.

Unpublished SHRIMP dating of JP1, JP4 and JP5 from Joffre Gorge by W Compston (ANU) yield ages of 2462 ± 3, 2461 ± 4 and 2461 ± 2 Ma, respectively (Trendall *pers comm* 1998). That is, the porcelanites are effectively inseparable by SHRIMP analysis.

Recent dating by UWA has also confirmed these dates. They also recognise two further thin porcelanites above JP5 in J6 (Pritchard *pers comm* 2001). Up to seven porcelanites have also been located during current geotechnical mapping of the Mining Area C spur line along Yandicoogina Creek gorge (Benbow *pers comm* 2001).

Riebeckite

Trendall and Blockley (1970) do not define distinct riebeckite zones in the Joffre Member, but refer to patchy riebeckite development that is not restricted to any particular part of the Member. The Yandicoogina Horizon is described as being at the very top of the Member, however, from lithological descriptions of the hosting strata, it may be in the lower Yandicoogina Shale Member. It is only known from the Marillana and Yandicoogina Creeks area. Regionally, J6 BIF commonly appears riebeckite - rich where fresh.

Crocidolite was noted in cliffs along Yandicoogina Gorge at 718 400 E / 7 471 900 N further upstream of that reported in Trendall and Blockley (1970) in what is probably lower to mid J6, by DAK during early reconnaissance investigations. Syn D_2 quartz - riebeckite (crocidolite) veins also occur in lower to mid J6 at Cathedral Gorge.

Mindy Debris Flows (MDF or JC1 - JC3)

The Mindy debris flows (MDF, Kepert 2001a, *in prep*) are three multiple series of clast supported carbonate debris flows (JC1 - JC3) preserved to the northeast of Mining Area C along the Hamersley Range escarpment over approximately 4 km strike (Photo 52). Stratigraphically, they occur over an interval of 35 m in the J3 - J5 part of the Member, and vary in thickness from less than 1 m to about 8 m. They are the localised and highly proximal facies of a series of catastrophic collapses of a carbonate reef during deposition of the Joffre Member.

The MDF are unique within the Hamersley Group with no other known occurrence, and provide a unique opportunity to apply constraints on the original basin architecture, carbonate sedimentation and Morris' (1993) Fortescue Bank or Reef[14]. One bed may be proximal facies to a thin carbonate

[14] Morris coined the term Fortescue Bank, however, the term "Fortescue Reef" is favoured here due to the topographic relief implied by a debris flow of this nature.

bed seen elsewhere within the central Joffre Member (eg Trendall 1968a). Future study of the area also has the potential to provide unique evidence on the physical nature of the BIF precursor and the timing of diagenesis, a topic of much debate.

The lower two debris flows (JC1, JC2) are thinner and less well exposed but are similar to the uppermost flow, except they are not dominated by basal megaclasts and appear to be the result of a single rather than multiple collapse as per JC3.

The uppermost debris flow (JC3), the best exposed of the three, is characterised by the presence of basal megaclasts up to 21 by 6 m (eg Photo 52) and an upper multiple series of partial to complete Bouma Sequences between 10 and 50 cm thick. The main conglomeratic part of the upper flow (Photo 53) varies between 3 to 8 m thick and consists of a grossly graded, chaotic assemblage of clast supported carbonate debris (generally up to 20 by 20 cm), in a matrix of similar grey carbonate sand and silt sized particles.

The upper 20 to 50 cm of each cycle of the debris flows above the basal conglomerate can be divided into:-

- one or more graded beds of finer grey carbonate sand (T_A),
- weakly laminar bedded sand of similar composition (T_B),
- a rare bed of rippled grey carbonate sand in JC3 only (T_C),
- 1 to 10 cm of laminar bedded yellow ferruginous carbonate silt (T_D), and
- dark ferruginous cherty ferruginous silt (T_E).

The original lateral extent of the MDF is unknown, as along strike JC3 is replaced by recent goethitic silcrete and appears to thin (probably due as much to recent dissolution as original sedimentary extent) or is obscured by recent cover. Outcrop of JC1 and JC2 are very limited. The occurrence of three series of debris flows restricted to a tightly confined area that suggests the source area was locally unstable over a period of time, possibly due to a crosscutting fault or erosional feature. Based on an extremely rapid sedimentation rate of the Joffre Member of up to 200 m/Myr (see Section 4.9.1), this suggests an interval of less than 0.5 Myr between JC1 and JC3.

The basal contact of JC2 is broadly undulose with minor pinch and swell of the underlying BIF due to loading. The lack of significant erosional features or disruption of bedding suggests some degree of lithification of the BIF. Basal megaclasts in JC3 have deformed the underlying Joffre Member to a limited degree, producing simple downward drag and local truncation of the bedding (Photo 54). Given the upper surfaces are planar, the deformation is syn-depositional rather than later compaction of the BIF by loading. The lack of major disruption to the BIF by all but the largest megaclasts is contrary to that expected with the generally held hypothesis that BIF, and in particularly the silica - rich bands, are laid down as a soft water - rich gel many times thicker than the eventual sequence after lithification / diagenesis (eg Trendall and Blockley 1970, Lascelles 2001).

By comparison, the upper contacts of the MDF are planar and conformable with the overlying BIF (Photo 55). The top of JC3 is marked by upward fining cycles of sand to silt size carbonate sands with or without interbedded cherts indicating a gradual waning in activity (Photo 56).

Carbonate clasts are well bedded and banded white, dark grey to black and rarely brown carbonates, typically tabular to blocky, and angular to sub-rounded. Most clasts are micro-crystalline carbonate but some are composed of well graded silt to sand sized carbonate detritus. Diagenetic dolomite that now dominates the Paraburdoo Member and the Carawine Dolomite is absent, providing excellent preservation of original sedimentary features.

A wide range of internal fabrics including possible biogenic features, syn-sedimentary (and diagenetic) breccias, and replacement and displacement (carbonate) veins and pods are evident. Carbonate veining and brecciation indicates the carbonate source area had already undergone some diagenesis, but not dolomitisation, at the time of failure.

Rare banded ferruginous chert clasts up to 10 cm long also occur in the MDF. They are more blocky and less ferruginous than the underlying Joffre Member and are not locally derived from it, but represent original chert / silicified units within the dominantly carbonate source.

Potential sources of the carbonate clasts is problematical given they are unlike any known exposed carbonate in the region. Sources that could provide an essentially monolithic carbonate detritus are:-

- Paraburdoo Member, however, the type and great diversity of carbonate clasts is not compatible with being derived from the monotonous Paraburdoo Member,
- Carawine Dolomite, however, the nearest recognised outcrop of Carawine Dolomite is over 100 km away and except for one known locality, the clasts are also atypical of it,
- relatively thin Fortescue Group carbonates (eg Meentheena or Warri Members), however, other surrounding lithologies (basalts, shale etc) should also be present, or
- the Fortescue Reef.

Measurement of palaeocurrent directions from rare ripples within the upper debris flow are consistent with a source to the northeast from the same general region as other carbonate turbidites (eg Mt McRae Shale carbonate turbidite).

Sedimentary features apparent in some clasts that are consistent with and suggest a shallow water carbonate source are:-

- biogenic features including finely banded laminar carbonates with small to medium scale domal features (Photo 57a, c), and laminar and net fenestral -like voids filled by calcspar, are similar to those described in the Transvaal

Supergroup of South Africa (eg Beukes 1987). A clast (Photo 58) from the MDF was interpreted to be derived from a shallow water, low energy, enclosed system such as a lagoonal environment (K Grey, GSWA *pers comm* 1998),

- edge - on, flat pebble conglomerates indicative of a high energy environment,
- sea floor nucleating anhydrite crystal splays (Photo 57b),
- finely banded black and white zebraic dolomite (eg Simonson *et al* 1993),
- graded bedding in some clasts indicating a high energy environment (Photo 57c), including some infilling ?karst like structures,
- displacive precipitates (now carbonate) are very reminiscent of mosaic anhydrite growths that only form within the sediment pile in intertidal Sabkha environments (Photo 58). Some voids are also filled with radiating crystal splays that may be after inorganically precipitated aragonite or anhydrite, and
- rare poorly sorted peloidal and ooid rich units (Photo 57d).

Whilst not conclusive, the combination of these sedimentary textures is compelling evidence for a shallow water carbonate as the source of the MDF.

The nature of carbonates in the Fortescue valley are poorly known with core from FVG1a drilled by CRA in the centre of the Fortescue valley to the northeast of Mindy to Pilbara Craton basement being extensively brecciated limiting the recognition of possible similar shallow water features. It is also dolomitised. Upward terminating crystals from core of the Marra Mamba Iron Formation were interpreted as being after shallow water, swallow-tail gypsum by Morris (1993), however Krapez (*pers comm* 2000) interpret them as cone-in-cone pressure dissolution features.

A shallow water source is also indirectly implied by palaeobathymetry constraints. As the megaclasts lie at the base of the flow they were not greatly assisted by fluidisation, as with massive matrix supported debris flows (eg Carawine Dolomixtite). Insufficient study has been done to model the topographic relief, however for even a relatively short distance laterally it would have required a significant vertical component. Assuming the minimum 4 km distant source (minimum distance to carbonate source beyond the Poonda Fault as implied from magnetics and drilling) and an overall slope of 10º infers a vertical component of 700 m, or 3º for 200 m. Given that depth estimates of BIF deposition vary from just below the wave base (~100 to 200 m) to over 1000 m, with the figure of several hundred's of meters (eg Beukes 1987, Simonson *et al* 1993) gaining wide spread support, a slope as little as 3 to 5º effectively constrains the source carbonate to a relatively shallow water origin.

Fortescue valley carbonates cannot be stratigraphically assigned to the deep water, geochronologically constrained Wittenoom Formation. Similarly, they should not be assigned to the Carawine Dolomite, although predominantly shallow water facies and with a poorly defined upper age limit, the term Carawine Dolomite should be restricted to the Oakover Sub-basin. A sedimentary to early diagenetic age for the Carawine Dolomite (Jahn and

Simonson 1995) significantly earlier than the Joffre Member suggests they are not entirely correlatable, except possibly the lower parts where both overlie the Marra Mamba Iron Formation. Preserved carbonates in the valley are probably coeval with the Wittenoom Formation and Carawine Dolomite being from the lower half of the Fortescue valley carbonates, with the younger carbonates having been destroyed during karsting and formation of the Pinjian Chert Breccia.

The term 'Fortescue Reef carbonate' is proposed to cover carbonate sediments of the Fortescue valley until further constraints on the upper age limits of it and the Carawine Dolomite are available. Stromatolitic carbonates at Tubaddubudda (Simonson *pers comm* 1998) to the north of East Jimblebar but still within the Fortescue Valley and not the Oakover Sub-basin may belong to either. Ultimately, a new Formation may be required, comprising shallow and deep water facies carbonates, extending in age from the Marra Mamba Iron Formation to probably as young as the Joffre Member.

4.5.4 Yandicoogina Shale Member (PHby)

The Yandicoogina Shale Member was only mapped along the north side of Packsaddle Range. Elsewhere its location is based on various currencies of airphoto interpretation that may not always be consistent with each other.

In outcrop, it is mostly comprised of alternating 10 to 30 cm thick, wavy banded, yellow cherts and interbedded shales. Microbanded red / yellow striped chert beds are characteristic of the Member. About 5 m from the top a distinct 10 cm thick grey, poddy to wavy bedded chert is prominent. The Member is about 60 m thick at the west end of Box Canyon. Failing to locate a better exposure, a measured section should be made at this location for use as a standard. It appears that the name of Yandicoogina *Shale* Member is a misnomer as it is less than 50% shale and strictly speaking should be renamed to the *Yandicoogina Member*. The shale terminology is a hangover from the early days when the less well exposed strata between the main BIFs was assumed to be not only more shaly, but shale dominant. Likewise, the MacLeod Member comprising mainly chert to cherty BIF with interbedded shales was originally known as the Middle Shale Member.

The poorly defined boundary between the Joffre and Yandicoogina Shale Members caused some problems, especially as the interval is prone to intense yellow silcrete development. The mapping contact was taken as the base of the first thick (2 to 3 m) yellow chert with very characteristic waviness, termed the Trilobite Chert (Photo 59). A 10 to 20 cm shale lies between the BIF and the Trilobite Chert. Some thin and flaggy BIFs do occur above the Trilobite Chert, but it defines the major change from a BIF to a chert-shale dominant sequence.

Dolerite sills traditionally linked to the overlying Weeli Wolli Formation intrude over halfway down the Member along International and Spring Hills and Snake Gorge along Packsaddle Range, and also in the Newman area (see Section 5.2). In the western Province (eg Rocklea, Kepert 2001b) sills also regionally intrude in the central Joffre Member and locally in upper Mt Whaleback Shale Member.

4.6 Weeli Wolli Formation (PHj)

The detailed stratigraphy of the Weeli Wolli Formation is poorly documented but generally it consists of alternating beds of characteristic red / black microbanded BIF (up to 10 m thick), red chert and (tuffaceous) shale. The sequence is extensively intruded by numerous dolerite sills (see Section 5.2). In outcrop it is characterised by strike parallel ridges of resistant BIF and valleys of dolerite and shale. A measured section in Trendall and Blockley (1970) at Woongarra Pool in the western Province comprises a total of 184 m of BIF with minor shale and 269 m of dolerite in eight sills.

MacLeod (1966) originally included the basal 30 m, BIF - dominant sequence of the Weeli Wolli Formation in the Brockman Iron Formation as the now obsolete Coondiner Member. The base of the Weeli Wolli Formation was defined as the first major dolerite sill.

The base of the Weeli Wolli Formation was mapped along the north side of Packsaddle Range, with the remainder of the Formation airphoto interpreted there and at Mining Area C Park. Mineralisation at the P3 orebody on Packsaddle Range and at Paraburdoo 4E extends upward through the Joffre Member into BIF bands of the Formation.

As with the base of the Yandicoogina Shale Member, the exact contact between it and the Weeli Wolli Formation is poorly documented, often being defined as the first dolerite sill. Due to the inaccuracies involved with using an intrusive as defining a sedimentary contact, the mapping contact was taken as the first planar banded, finely red - black banded BIF directly overlaying yellow wavy cherts. As previously noted, a distinctive grey chert occurs about 5 m under this contact.

Mapping of the lower to central part of the Weeli Wolli Formation at Yandi (Brady 1988) recognised ten subdivisions, which are grouped into three units based on the dominance of BIF over dolerite. Due to the regional variation in the stratigraphic level of dolerite intrusions an exact correlation is not possible, but MacLeod's Coondiner Member probably correlates with Unit Two.

Geotechnical mapping of the Yandi to Mining Area C rail corridor (Kennedy and Benbow *pers comm* 2001, 2002) mapped two BIFs and two dolerite sills at Yandi, which are broadly correlatable with Units One, and Two below. Stratigraphically higher units confined to the Yerrabiddy Syncline to the south are tentatively correlated with units that make up the Three Sisters at Yandi. Brady's subdivisions in ascending order (with their likely correlation to the geotechnical mapping units *in italics*) are:-

Unit One - 115 m thick dolerite dominant sequence, intruded into a "weak" shaly BIF sequence, subdivided into:-

- PHja - 0 to 10 m thick medium to coarse dolerite sill, base not exposed (dolerite 1 or '*D1*' – not to be confused with subdivisions of the Dales Gorge Member),

- PHjb - 0 to 45 m thick shaly, flaggy BIF, easily eroded (*B1*),
- PHjc - 0 to 60 m thick, medium to coarse dolerite sill (*D2*).

Unit Two - 53 m thick BIF (*B2*) sequence comprising:-
- PHjd - 0 to 10 m thick shaly, flaggy BIF,
- PHje - 0 to 8 m thick cherty BIF, commonly silicified,
- PHjf - 5 to 25 m thick shaly, flaggy BIF,
- PHjg - 2 to 10 m thick (average > 5 m) resistate BIF, this is the main BIF marker.

Unit Three - 112 m thick dolerite dominant sequence that at Yandi is confined to the Three Sisters and comprises:-
- PHjh - 40 m thick, medium to coarse dolerite sill (*D3*),
- PHji - 10 m thick resistate BIF, second BIF marker (*B3*),
- PHjj - 62 m thick, medium to coarse dolerite sill, top not exposed (*D4*).

4.7 Woongarra Rhyolite (PHw)

The Woongarra Rhyolite can be subdivided into three main units totalling on average about 400 m thickness:-

- lower rhyolite - pale green, massive rhyolite with a rough fracture and is relatively susceptible to weathering,
- median raft complex - a stratigraphically impersistent unit comprising various proportions of BIF, dolerite and shale, and
- upper rhyolite - dark grey, massive, commonly porphyritic rhyolite with a subconchoidal fracture and overlain by 10 to 20 m of interbedded tuff and chert.

The two rhyolites vary in thickness with the upper typically thicker than the lower. Trendall (1995) interpreted the two rhyolites as of intrusive rather than extrusive origin based on a number of forms of evidence including the variation in the median raft complex, and the presence of peperites marginal to both contacts of both rhyolites. He coined the term "*giant lava - like felsic sheet* (GLFS)" for similar global occurrences. At Eagle Rock Falls[15] the weathered faces of the upper rhyolite show a well developed rhythmic layering and locally developed vertical columnar jointing (Photo 60).

The Woongarra Rhyolite was not mapped, but is apparent on air photos as a poorly exposed, characteristic orangey toned unit, between the more resistive BIFs of the Weeli Wolli and Boolgeeda Iron Formations. It is limited in occurrence to the southern side of Mining Area C Park, on the south dipping limb of the regional Turee Creek Syncline. The median raft complex is not readily apparent on the air photos and was not distinguished.

[15] Referred to as Coondiner Falls by Trendall (1995)

4.8 Boolgeeda Iron Formation (PHo)

The Boolgeeda Iron Formation is approximately 200 m thick and comprises an upper and lower dark, flaggy to shaly BIFs, with a central shale - rich zone. It differs from all other BIFs in the Group in having no, to poorly defined mesobanding (Trendall and Blockley 1970). The upper contact is gradational with the Turee Creek Group reflecting the increasing influx of clastic sediments.

Mapping and drilling by MNM north of Jimblebar and east of OB31 for magnetite BIF in the Boolgeeda Iron Formation (Shrivastava 1975, 1977) also divided the Member into three units summarised below (thicknesses in *italics* are true thicknesses calculated from core (EXD17, Shrivastava 1977) by DAK, others are from outcrop and RC drilling):-

- Lower member - over 90 m thick (base not seen, *over 63 m*) of interbedded BIF and shale. The basal 10 to 20 m of interbedded shale and (red) chert probably correlates with the uppermost tuff - rich part of the Woongarra Rhyolite,

- Middle member - 45 m thick (*74 m*) massive BIF, which may have a prominent shale 24 m (*44 m*) from the base. The Lower and Middle member as defined by Shrivastava correlate with the lower BIF of Trendall and Blockley (1970), and

- Upper member - 100 m thick (*69 m*) interbedded BIF and shale. It can be further subdivided into a basal 35 m (*26 m*) of predominantly shale with a distinct 5 m thick green chert just above the base and an upper 65 m (*43 m*) of interbedded BIF and shale. These correlate with the central shaly and upper BIF divisions of Trendall and Blockley (1970), respectively.

Recent work in the western part of the Province, based on the assumption that different glacial derived units are correlatable representing a single event, suggests the upper contact with the Turee Creek Group is time transgressive (Martin 1998). Traversing northward from the Hardey Syncline, Martin correlates the diamictite of the Three Corner Bore Member in the Turee Creek Group with glacial drop - stones within the upper Boolgeeda Iron Formation at Duck Creek Syncline and the central Boolgeeda Iron Formation at Yeera Bluff (adjacent Mesa H, Deepdale). Martin concludes the upper Boolgeeda Iron Formation in the northwest part of the Province is coeval with the lower Turee Creek Group near the Hardey Syncline. No glacial lithologies at this stratigraphic interval are known to exist in the east part of the Province.

As with the Woongarra Rhyolite, the Boolgeeda Iron Formation is limited to the Turee Creek Syncline and was only photo interpreted.

4.9 Geochronology

Significant work driven in main by Trendall on the accurate dating by SHRIMP of Hamersley Group rocks (principally interbedded tuffs / tuffaceous shales) and other greater Gondwana BIFs has been carried out over the last decade by various researchers. Published, unpublished and provisional Hamersley Group age determinations are summarised in Table 3. Pickard (in press) detailing further dating of the Joffre Member porcelanites was not available at the time of compilation. Further Fortescue Group dates are summarised in Thorne and Trendall (2001). Contrary to popular belief, Trendall's work indicates that not all of the greater Gondwana BIFs were deposited synchronously. For example, the Carajás Formation in Brazil (Trendall *et al* 1998a) and Mulaingiri Formation in India (Trendall *et al* 1997) are significantly older than the 2.63 to 2.45 Ga Hamersley Group with both of the above being deposited in a narrow but separate time interval between 2.7 and 2.8 Ga.

4.9.1 Sedimentation Rates

A primary aim of Trendall's research was to provide a geochronological framework on which to estimate the true rate of deposition for the dominant lithotypes of the Hamersley Group (ie BIF versus (chert /) shale versus carbonate). Surprisingly, the sedimentation rate of lithified BIF is very rapid and of the order of 19 to 225 m/Myr (eg Trendall *pers comm* 1996, Trendall 1997, 2002), compared with about 10 m/Myr for carbonate bearing rocks and 3 m/Myr for shale (Figure 13). Barley *et al* (1997) subsequently inferred a similar rate for BIF sedimentation. Sedimentation rates for the generally accepted thicker hydrous gel (?90%) precursor to the BIF would obviously have been even higher. Depending on the relative timing of sedimentation versus dehydration and compaction this could potentially rapidly fill the depositional platform. Trendall's preferred model for the rate of sedimentation (Figure 13) remains unproven, for example, there is no evidence on geochronological or lithological grounds to infer vastly different sedimentation rates for the Nammuldi and MacLeod Members. Regardless, the difference in sedimentation rates is well illustrated by the lower carbonate dominant 50% of the Hamersley Group (after removal of major igneous components) spanning about 140 to 150 Myr, compared with the upper BIF dominant 50% spanning only 30 to 40 Myr.

Trendall's calculated rate of deposition for BIF of 19 to 225 m/Myr is in very good agreement with estimates made by Trendall and Blockley (1970) based on the assumption that a microband pair (or *aftvarve*[16]) reflects an annual cycle, of 23 to 230 m/Myr (for reference, a deposition rate of 100 m/Myr equates to an aftvarve thickness of 0.1 mm). Aftvarves are therefore likely to be the result of a seasonal variation or event such as temperature or salinity controlled iron solubility, or the flourishing of biogenic activity oxygenating a ferrous bearing water column thereby precipitating a ferric - rich silica gel during bloom and a ferric - poor silica gel otherwise. Unfortunately, due to inaccuracies of estimating the number of microbands over a large interval together with an error of 2 to 3 Myr for even the best SHRIMP date, it is not possible to further resolve the sedimentation rate and establish the exact correlation between aftvarves and annual cycles.

By comparison, Cisne (1984) suggested that aftvarves may be related to a diurnal cycle, however this implies an extreme sedimentation rate. Williams (2000) went

[16] Aftvarve for AF Trendall varve.

further suggesting that micro / mesobanding in the Weeli Wolli Formation is either diurnal cycles in monthly groups or fortnightly cycles in annual groups.

4.9.2 Correlation to the Transvaal Province

Based on lithological, tectonostratigraphic and geochronological grounds many authors (eg Trendall 1968b, Button 1976, Trendall *et al* 1990, Jahn and Simonson 1995, Martin *et al* 1998a, Nelson *et al* 1999) have drawn comparisons between the Mt Bruce Supergroup and the Ventersdorp and Transvaal Supergroups in southern Africa. Tectonic reconstruction (Cheney *et al* 1988, Cheney 1996) suggests they were joined during that period to form the *Vaalbara* continent. Recent work has also possibly correlated the spherule bearing dolomixtite and SMB with a similar bolide - derived bed in the lower Cambellrand Subgroup (Simonson *et al* 1997, 1998).

As with the Mt Bruce Supergroup, the Transvaal Supergroup (Beukes 1983, 1987) comprises a lower mafic volcanic package (Schmidtsdrif Subgroup) overlain by either well exposed platformal (Cambellrand Subgroup) or coeval basinal (Nauge Formation) carbonates equivalent to the Carawine and Paraburdoo Member dolomites, respectively. Both carbonate facies in turn are overlain by BIF of the Asbesheuwels Subgroup and its correlatives, which are equivalent to the Brockman Iron Formation. Beukes (1983) went one step further in the degree of correlation proposing correlation of 16 stilpnomelane rich beds in the lower Kuruman Iron Formation at the base of the Asbesheuwels Subgroup with the 16 S macrobands of the Dales Gorge Member.

The platformal and basinal carbonates are separated by the Griquiland Fault Zone interpreted as a synsedimentary growth fault. As with the Cambellrand Subgroup (Beukes 1987), the facies relationships are well explained by a relatively thick carbonate platform containing stromatolites, interfingering with deeper water basinal facies shales, turbidites, and even BIFs.

As with the Griquiland Growth Fault, the proto-Poonda Fault probably marks the transition from predominantly shallow water carbonates to deep water carbonates and other sediments, and as such is probably also a growth fault (see Section 11).

4.10 Sequence Stratigraphy

There have been several attempts in the last decade to describe the Hamersley Basin in terms of sequence stratigraphic concepts (Blake and Barley 1992, Krapez 1996, 1997), that is, defining the sedimentary record into a number of periods of similar length marking regular oscillations of the sea level producing unconformity bounded packages (or sequences) of rocks. To date this work has not resulted in any significant increase in understanding of the Basin, but instead has led to a confusing and ever changing system of nomenclature. For example, the Carawine Supersequence contains the Paraburdoo Member, but not necessarily the Carawine Dolomite. For reference, the most recent version is included as Figure 14 (Krapez 1997).

Lithofacies mapping of the interval from the Mt Sylvia Formation to the Yandicoogina Member to support sequence stratigraphy by Krapez and others under sponsorship by MERIWA is nearing completion. Krapez *et al* (2001) and Pickard *et al* (2001) referred to in Section 11 are early publications of parts of this work.

5.0 INTRUSIVES

Dolerite intrusives occur as sills in the Jeerinah Formation, sills in the Weeli Wolli Formation and underlying Yandicoogina Shale and Joffre Members, and as several younger suites of sub-vertical dykes.

5.1 Karijini Dolerite (PKd)

The Jeerinah Formation contains thick sills of medium to dark green, fine to medium-grained, and locally microporphyritic dolerite and diorite. The dolerite is well exposed under only several metres thickness of Roy Hill Shale Member in the core of the Alligator and Weeli Wolli Anticlines, and in small erosion windows elsewhere at Alligator and South East Corner. In some areas (eg South Alligator), it appears that the dolerite is emplaced higher than the Roy Hill Shale Member with the lower part of the Nammuldi Member removed by stoping. This is also apparent at Western Ridge / OB35 at Newman where a sill is intruded above the Rods about a third of the way up the Nammuldi Member (Kepert 2000a).

The sills may be slightly discordant to the adjoining cherts and carbonate beds. Thin apophyses can also be seen intruding several metres into the Nammuldi Member at South Alligator.

Lipple *et al* (1995) argued the paucity of contact metamorphism / hornfelsing in the rafts of chert and carbonate in the core of Alligator Anticline indicates that the sills were intruded successively, and essentially cooled before further magma emplacement occurred. Photo interpretation and limited ground truthing of exposure in the core of the Alligator Anticline indicates a minimum of twelve separate sills with an estimated total thickness of 680 m (Appendix 2). Minor igneous differentiation is indicated by the presence of feldspar phenocrysts near the top of several sills. Some of the lower sills show a prominent rhombohedral joint pattern on aerial photographs.

Interpretation of field relationships during 1994 and 1995 suggested that massive dolerite sills intruded into the Jeerinah Formation were probably syn D_3. This was based on:-

- at The Amphitheatre south of R Deposit, apophyses have apparently intruded axial plane fractures of small scale D_3 folds, and

- the sill appears to lack tectonic fabric earlier than D_3. The dolerite varies from massive and apparently undeformed, to a sub vertical weak fracture cleavage, to a moderately schistose mineral cleavage approaching contacts with Jeerinah

Formation chert and carbonate, and F_3 fold hinges. In contrast, the tuffs and shales of the Jeerinah Formation have an earlier south dipping S_2, overprinted by S_3.

The dilation of the sedimentary pile was interpreted to be probably due to early D_3 compression, with deformation continuing after dolerite intrusion, as indicated by the formation of tight F_3 folds, and the development of an intense S_3 mineral cleavage near the F_3 fold hinges. It was argued by Lipple *et al* (1994), that considering magma buoyancy, then the presence of dolerite implies a certain common tectonic level in the crust.

From subsequent experience and reinterpretation of the data, which casts further doubt on the previously proposed syn D_3 model, it should be noted that:-

- the "apophyses" at The Amphitheatre are along strike of open fractures to the north west that are parallel and about 1 to 1.5 km south of the younger dolerite dyke array that passes through C and R Deposits, and as such may not be related to the Karijini Dolerite,

- the typically upright cleavage in the dolerite may, in part or in total, be a refracted, upright D_2 fabric. Additionally, the sill intruding the Nammuldi Member at OB35, which is part of the same suite has a very well developed south dipping D_2 fabric.

Although the possible correlation of the dolerite with D_3 is based on poor evidence and is yet to be confirmed, the dolerite sills have been separated from the Jeerinah Formation and are referred to here as the Karijini Dolerite (Lipple *et al* 1994). Regardless of structural correlation, it is appropriate that the dolerite be defined as a separate stratigraphic unit as there appears to be little lithological, genetic or chronological association with the Jeerinah Formation.

5.2 <u>"Weeli Wolli" Dolerite (Pds)</u>

Regionally extensive dolerite sills intrude much of the Yandicoogina Shale Member and Weeli Wolli Formation. Previously they have been included in the Weeli Wolli Formation, but given they can intrude both lower and higher in the sequence they should be described separately from it. They can occur stratigraphically as low as Mt Whaleback Shale Member at Rocklea (Hardey Syncline) or J3 to J5 in the Joffre Member (eg Rocklea, Brockman Anticline etc), up to the median raft complex of the Woongarra Rhyolite (Trendall 1995). They vary in thickness from less than 10 cm to over 100 m, and in outcrop vary from massive mottled red and yellow clays to hard, fresh, rounded dolerite boulders. The thicker sills are better exposed, being less weathered and altered. Individual sills can clearly be seen to transgress the stratigraphy over 100's to 1000's of metres of strike and north of Box Canyon also include metre thick rafts of Weeli Wolli Formation BIF over 50 m long.

The characteristic red colouration of the silica bands of the Weeli Wolli Formation BIFs has previously been proposed as being due to fine hematite in the silica produced by heat from the thicker dolerite sills. This likely genetic link is supported by similar alteration being present in Joffre Member BIF adjacent to a thick sill between J3 and J4 at Rocklea (Kepert 2001b).

At Coondiner Gorge about 2 km below Eagle Rock Falls, Barley *et al* (1997) described an outcrop of igneous rock in the Weeli Wolli Formation as a pillowed lava flow with hyaloclastic flow front breccias overlain by BIF which *"provides unequivocal evidence of eruption of basalt on to the sea floor during BIF deposition"*. Whilst the recognition of a hyaloclastic breccia with internal pillows (complete with marginal radiating vesicles) is correct (Photo 61), the top of this unit also has **unequivocal** apophyses intruding into overlying BIF indicating it can not be extrusive (Photo 62). Interestingly, these apophyses are shown diagrammatically in Barley *et al* (1997) but were not described there. Moreover, there are no pillows (or vesicles) at the top of the unit as suggested but a simple quenched contact with small scale columnar jointing. Minor drag of the jointing proximal to the upper contact and the intense red colour of the BIF also implies an intrusive contact. The **entire outcrop is therefore more consistent with intrusion at a shallow level into a wet sediment soon after its deposition but before diagenesis** rather than being extrusive as interpreted by Barley *et al* (1997).

Based on trace element geochemistry, Barley *et al* (1997) also genetically links the dolerites with tuffs and of the Weeli Wolli Formation, the Woongarra Rhyolite and possibly also S macrobands of the Dales Gorge Member, forming a significant, bimodal, volcanic province. SHRIMP dating of a tuff, the upper rhyolite and a tuffaceous shale between the Woongarra Rhyolite and the Boolgeeda Iron Formation all have the same age within error (see Section 4.9), indicating that at a minimum, the felsic igneous rocks are related.

From evidence above, their conclusion that BIF deposition is linked to major coeval submarine magmatic / hydrothermal activity rather than reflecting a gradual increase in oxygen content of the oceans is however open to interpretation with the vast majority of magmatic activity post dating at a minimum the Brockman Iron Formation and Weeli Wolli Formation.

Unfortunately, this is yet another example of geologic misinterpretation to enter the public arena via a highly reputable journal under the guise of being "unequivocal" evidence and it, together with associated conclusions, are thus elevated to "fact" status. Question everything you read - including this tome!

5.3 Dolerite Dykes (Pdd)

Based on orientation and cross cutting relationships, Tyler (1991) defined eight generations or suites of "late or post tectonic" dolerite dykes in the southeast Hamersley Province and Sylvania Inlier (Appendix 2). Suite 1 (Pd_1), or the Black Range Dolerite is synvolcanic with the Mt Roe Basalt at the base of the Fortescue Group and forms part of the controlling structure of the Sunrise Hill deposits at Yarrie. Three of the eight suites are recognised in the Mining Area C region.

Dykes are highly weathered and recessive, forming prominent airphoto lineaments and steep-sided gullies through both the Marra Mamba and Brockman Iron Formations.

Exposure is commonly restricted to the walls of gullies where they are micro-jointed and deeply weathered, and generally consist of pink or orange coloured clay or silicified porcelanite replacement material. Margins are weakly sheared locally, but typically there is stratigraphic continuity across the fracture and no apparent fault movement on the lineament. A notable exception to this is the dyke cross cutting Roundtop Hill at Weeli Wolli that from airphoto interpretation, has an inferred vertical displacement of about 40 m on the Mt Whaleback Shale Member. Laterite caps developed over dykes have an abundance of characteristic yellow - orange nodular limonite. Dykes form low ridges where they intrude the Karijini Dolerite in the core of Alligator Anticline. Here they are less than 10 m in width, fine-grained, massive, and non-porphyritic.

Suite Pd_4

A single poorly exposed dolerite dyke and associated photo linear trending at 285º, at South Alligator is assigned to the Pd_4 suite.

Suite Pd_5

Pd_5 dykes are the dominant suite in the region. Western Alligator Anticline and Mining Area C Park are dominated by the eastern edge of a 100 plus km wide swarm of dykes trending 325 to 340º. Two smaller, but strike persistent, *en echelon* arrays of Pd_5 dykes are also developed - one crosscuts the western end of C Deposit, the other just north of Weeli Wolli Springs. A number of other isolated Pd_5 dykes occur within the region. One dyke in this suite has formed a lateral sill within a shale band of the Mount Newman Member (703 600 E / 7 460 650 N).

It is traditionally quoted that these dykes (and other suites) may form the initial aquiclude / structural trap for the initiation of mineralisation (eg at C Deposit West). It is however, just as likely that the dyke is an aquiclude up to which mineralisation front has progressed, with the dyke halting, not initiating mineralisation. Some small pods of surficial ore on the up - dip and down - dip side of dykes are locally developed.

Pd_5 dykes intrude as high as the Beasley River Quartzite and are regarded as probable feeders for the overlying Cheela Springs Basalt (eg Lipple 1997, Martin *et al* 1998b). (Pd_4 dykes also intrude to this level.) SHRIMP dating of zircons from a volcaniclastic breccia bed in the Basalt have a youngest population of 2209 ± 15 Ma, interpreted by Martin *et al* (1998b) as being derived from the Basalt. Powell *et al* (1999), however, now ascribe it to a coeval source of unstated nature, whilst Trendall (*pers comm* 2000) believes that given the complexity of the zircon populations, there is insufficient evidence to state even a coeval source with any degree of authority. Clearly, the significance of the date is open to much interpretation, although it does provide a maximum age for the Basalt.

Suite Pd_7

Dykes of this suite are comparatively rare, but very continuous in length. They post date the Bangemall Basin. The main Pd_7 dyke in the area trending 050º is traceable from West Angela (Two Sisters) Hill, across Jaws Extended, Governor Range, Southern Flank, to E Deposit. A mapped fault on Fork South (and associated airborne magnetic linear) has a similar orientation to the Pd_7 suite. Also of note, is a single dyke trending 070º traceable on airborne magnetics from Waterloo Bore on the north end of Mindy Mindy through Yandi, Lamb Creek, under Packsaddle Camp, south of Mining Area C Park, and through Channar, where it has locally recrystallised the mineralisation there. A pair of dykes that cross cut North and South Parmelia Hills are probably also of this suite.

6.0 MINERALISATION

Mineralisation is strictly not part of the stratigraphic sequence but is included here in its appropriate geochronological position for ease of reference. Three main styles are recognised from mapping, of which the later two are near surface to supergene mineralisation that may be considered part of the greater Mesozoic to Cainozoic regolith. That is, they form "residual rocks" and thus may be broadly considered as part of the stratigraphic sequence. The earlier mineralising event is generally considered to be a metamorphosed, Proterozoic supergene enrichment, and therefore, it too can be broadly included in the stratigraphic sequence.

It should be noted that the mapped mineralisation is only meant to delineate areas of Fe enrichment. Mapped mineralisation is not necessarily equivalent to ore which implies a certain Fe grade or degree of mineralisation.

6.1 Martite - Microplaty Hematite (M-(mpl H) or H1)

M-(mpl H)[17] or Whaleback - Tom Price type mineralisation is not definitively known from the greater Mining Area C region[18]. The only possible occurrence is from early surface sampling of Weeli Wolli Sections of M244SA, where a polished section from OB13 (Chevron Hill) appears to be genuine M-(mpl H), and not just recent goethite dehydration to very fine mpl H (Tehnas *pers comm*).

It is generally thought that M-(mpl H) is the result of dehydration during regional burial metamorphism of an early Proterozoic M-G supergene mineralisation (Morris 1985). Abundant ore clasts in the Mt McGrath Formation indicate that mineralisation predates the Ashburton Orogeny (D_3). Province wide, M-(mpl H) mineralisation is distributed along two broad linears that may have marked the exposed part of the Province during Proterozoic times, and therefore, that part open to supergene enrichment (Morris 1985). These linears mark the edges of the so called McGrath Trough.

The known distribution of M-(mpl H) mineralisation in the southeast Hamersley Province is confined to a relatively thin zone that extends from Inlier Hill at East

[17] Mineralisation types, nomenclature and shorthand abbreviations (with the exception of iron-carbonate) follow the industry standard AMIRA-CSIRO model developed during the 1980's (Morris 1985, CSIRO 1995).
[18] A single piece of M-(mpl H) ore sourced from Mt Whaleback, painted white and with the inscription *"Don Eade, Mt Robinson, Western Australia, 28th Sept 1975"* is part of an old cairn on The Governor!! Another lost surveyor?

Jimblebar to Hope Downs 3 (south of Coondewanna Ridge), termed the Homestead Linear. Ore occurrences along the Linear are typically spatially (and genetically?) associated with low angle faulting (thrusting and / or normal). The Homestead Linear has been modified by late cross-cutting faults (eg Whaleback Fault). At OB28 West and at Lido on the Homestead Linear M-(mpl H) mineralisation is also spatially associated with completely leaching of BIF to a white chert (Kepert 2000b). Similar alteration of the Mount Newman Member intersected in drilling at eastern Arrowhead in the Rhodes Ridge area has no known associated M-(mpl H) mineralisation.

Current researchers are attempting to revise the Morris metamorphosed - supergene model of ore genesis with a hypothesis of a hydrothermal / hypogene origin (Figure 15). To date, they remain just that, a hypothesis, with little substantiated evidence to support them and no comment on Morris' wealth of petrographic data. Small isolated ore clasts in the Beasley River Quartzite that have a similar texture have been quoted by Powell *et al* (1999) as evidence for a syn Ophthalmian Orogeny (D_2) age for the mineralisation, however, they are atypical of "normal" M-(mpl H) and are most likely residuals of mpl H bearing BIF (Morris 1980, 2001). Similarly, the very limited occurrence and small grain size of the clasts in the Beasley River Quartzite when compared with the Mt McGrath Formation do not suggest being sourced from a major or wide spread mineralisation event.

By comparison, Barley *et al* (1999) infer a post D_2 hydrothermal model related to Wyloo rifting (see below).

6.1.1 Iron - Carbonate (ic)

Recent work by Hamersley Iron (HI) (Hagermann *et al* 1999 and Barley *et al* 1999) and BHPIO (Kepert 2000b) have recognised a magnetite - carbonate rich zone marginal to M-(mpl H) mineralisation. The transition zone is also often marked by elevated P (> 0.2%). At Tom Price (Southern Batter and North Deposits) the following zonation apparent over a few metres at the BIF to M-(mpl H) transition is attributed by Hagermann *et al* (1999) and Barley *et al* (1999) to be the mineralising process of the entire Tom Price ore body:-

- unaltered magnetite - chert BIF (25 - 35% Fe), to
- magnetite (± hematite) - siderite (± iron silicate) BIF (50 - 60% Fe), to
- magnetite - mpl H mineralisation (~ 60% Fe), to
- M-(mpl H) mineralisation (65% Fe).

The mechanism of ore genesis hypothesised by HI (Figure 16, Taylor *et al* 2001a, b) to produce the zoned alteration assemblage above and therefore inferred to have produced the entire M-(mpl H) mineralisation of the Tom Price ore body is:-

- hypogene leaching of the silica from the parent BIF by warm, highly saline, bicarbonate saturated fluids derived from the underlying Wittenoom Formation, leaving a thinned residual of original iron oxides (magnetite), carbonates, magnesium silicates and apatite. Fluids travelled along pre-existing normal faults (Southern Batter Fault) probably formed during Wyloo rifting at about

2.0 Ga (ie post D_2, Barley *et al* 1999) (does this make the proto Whaleback Fault part of the controlling structure for Mt Whaleback?, eg see Ronaszeki 1997),

- oxidising of the magnetite - siderite rock to a hematite (ie M-(mpl H)) - ankerite rock by moderately warm, low salinity, possibly supergene fluids,

- further leaching removed all carbonates from both the magnetite and hematite zones resulting in porous iron bands with a high apatite content interbedded with unaltered (Mg - rich) S macrobands, and

- supergene leaching (indistinguishable from modern weathering but more deeply penetrating) altered and thinned S macrobands to kaolinitic residues and removed apatite from the ore.

This final step of removing all remaining excess (soluble) P by deep supergene leaching is based on the observation that at Tom Price all the high P M-(mpl H) ore lies beneath a surface defined by the oxidation of the S macrobands. It is not known if deep high P ore at Mt Whaleback shows the same relationship to fresh S macrobands. Based on structural re-orientation, Taylor *et al* (2001b) attempted to force this genetic model on Mt Whaleback, this was however refuted as being baseless by Kneeshaw and Kepert (2002).

By comparison, based on polished sections previously collected from the same specific areas as part of the AMIRA-CSIRO study[19], Morris (2002) concludes that the alteration at Tom Price is post M-(mpl H) mineralisation. This is based on:-

- the localised reduction of mpl H to magnetite rather than *vica versa*,

- that other phases interstitial to mpl H which form various stages in proto-ore as detailed above are all post mpl H. The mpl H here is also typically coarser indicating some post mineralisation recrystallisation by later fluids, and

- that "syn" ferroan chlorite alteration of dolerites and rare pyrite interstitial to mpl H would not survive the pervasive oxidising conditions required.

An alternative mechanism suggested by Morris (2002) to explain localised carbonate alteration adjacent to faults is one of a circulating fluids driven by the exothermic decomposition of the pyritic, carbonaceous Mt McRae Shale producing carbonate alteration of the overlying BIF and associated expulsion of silica into adjacent pre-existing porous M-(mpl H) mineralisation.

Other possibly similar occurrences of carbonate alteration / metasomatism adjacent to M-(mpl H) mineralisation are discussed below:-

- remapping of <u>OB26 and 28 West</u> located zones of carbonate alteration of BIF transitional to <u>martite - carbonate</u> mineralisation adjacent to M-(mpl H)

[19] HI blocked all attempts by Morris to view more recent specimens and exposures from which their genetic model is based upon.

mineralisation (Kepert 2000b, Photo 63). Both drilled and mapped occurrences at OB26 and 28 are faulted adjacent to Paraburdoo Member dolomite, and therefore, the carbonate alteration may only represent a reaction selvage against the dolomite rather than being representative of the actual mineralising process *per se*. Local decomposition of the dolomite may have provide enhanced fluid mobility / pathways to drive the alteration. Its genetic relationship, if any, to M-(mpl H) mineralisation remains unclear,

- recent deep drilling in BIF on Eastern Ridge at Newman has intersected a recrystallised dolomite - altered magnetite BIF in two holes about 4 km apart. Hole ECP0531 drilled on a Falcon gravity target in the Dales Gorge Member on the west end of Eastern Ridge intersected the dolomite BIF in D2 adjacent to and beneath a major fault. The dolomite altered BIF was partially enriched (Fe > 40%) and dense (av 3.7 to 3.8). ECP0533 targeting extensions of M-(mpl H) mineralisation in J2 at OB25 Pit 1E, intersected similar material in the Joffre Member, but with a 10 m thick siderite - rich transition zone. The significance of the recrystallised, dolomite - altered BIF is currently unknown, as is whether similar occurrences elsewhere have been overlooked in the past,

- carbonate alteration of J1 locally occurs at Werriba Anticline near a minor fault of unknown affinity where chert micro and mesobands have locally been replaced by dolomite and siderite adjacent to small lenses of possible M-(mpl H) mineralisation (Photo 64),

- carbonate alteration adjacent to the Giles Fault (part of the Homestead Linear) beneath unmineralised BIF at the east end HI's Giles Mini (Dalstra *et al* 2002), and

- dolomite alteration and replacement of magnetite BIF recently described from Carajás in Brazil has also been interpreted as forming the proto-ore there (Guedes *et al* 2002 (co-authored by Barley)).

The spatial relationship of M-(mpl H) overlying dolomite apparent at some occurrences is reminiscent of the Sishen style of deposit in South Africa, but there the contact is a karst related unconformity (eg Beukes 1983, Schalkwyk and Beukes 1986). Some HI geologists consider the loss of Wittenoom Formation between outliers of M-(mpl H) Dales Gorge Member and Marra Mamba Iron Formation at the southern end of Tom Price (SE Prong) to be due to karsting during mineralisation rather than tectonics (Dalstra *pers comm* 2001), even though the area is extensively faulted. There is no apparent evidence for karsting on the tectonic contact at OB 26 and 28 and in other occurrences above, there is no proximal carbonate substrate.

Whilst the relationship of iron carbonate alteration to M-(mpl H) mineralisation remains unclear, the alteration does appear to have a strong spatial relationship to (late) D_2 faulting.

6.2 Martite - Goethite (M-G and M-oG or H2)

M-G mineralisation is widely developed in both the Marra Mamba and Brockman Iron Formations, and distributed throughout the Mining Area C region and much of the Province (Figure 17). It is spatially and genetically related to the Mesozoic - Tertiary palaeosurface, being due to near surface to moderately deep (200 to 300 m) supergene enrichment of BIFs and to a lesser degree, of adjacent chert and shale (Morris 1985, Harmsworth *et al* 1990). Clasts of M-G mineralisation in the Yarraloola Conglomerate define a Cretaceous or older age. Some M-G mineralisation however, may be significantly older being part of the original Proterozoic supergene enrichment that was not converted to M-(mpl H) (eg Morris 1985, Nemchin and Cawood 2001). Unverified reports of M-G clasts in the Beasley River Quartzite (Marisa Worth *pers comm* 2002) implying a syn D_2 age seem unlikely.

At Mining Area C in the Marra Mamba Iron Formation, it is best developed in the upper Mount Newman Member (and lower West Angela Member), but near surface, it may continue downwards to a few metres above the Football Chert of the MacLeod Member. Mineralisation stratigraphically lower than this is typically thin, patchy and discontinuous along strike. Mineralisation in the Nammuldi Member may locally resemble that of the Mount Newman Member but is of very limited extent. As such, mapping of the mineralisation boundary, especially where patchy or poorly developed, was not always systematically traced and recorded in the MacLeod and Nammuldi Members.

In the Brockman Iron Formation, it is best developed in the Dales Gorge and lower Joffre Members. Mineralisation in the Dales Gorge Member is best developed in D2 and D4, with D3 less well developed, and D1 typically poorly developed. It is best developed in J2 of the Joffre Member, with mineralisation elsewhere being patchy, especially from J3 upwards. The notable exception to this is the P3 orebody, where it is well developed in the entire Joffre Member extending in to the lower BIFs of the Weeli Wolli Formation. Locally M-G mineralisation may also be developed as low as Bruno's Band and rarely in SB1 and SB2 of the Mt Sylvia Formation.

Mineralisation appears to preferentially develop in areas of intense D_2 folding, however, there are a number of significant exceptions to this (eg Fork North, see Section 11).

M-G mineralisation usually results in some stratigraphic thinning (20 to 30%) of the Dales Gorge Member and also presumably a similar loss in the Joffre Member. On a local scale this thinning appears to have been mainly confined to originally silica rich mesobands. In contrast, there appears to be no corresponding thinning in mineralised sections of the Mount Newman Member. This may potentially be due to a greater original content of felted needles of silicates in the silica mesobands of the Mount Newman Member that acted as a framework helping to hold the mesobands open during Fe replacement.

6.3 Hardcap (H3)

Hardcap mineralisation is essentially surficial enrichment or ferricrete development due solely to Hamersley Surface processes, and was only distinguished during 1994 mapping. Its delineation was found to be very subjective and time consuming and did not provide much additional useful information and was thus discontinued in subsequent programs.

It typically comprises vermiform goethite that destroys most sedimentary features, including podding in the MacLeod Member, making the MacLeod / Nammuldi Member boundary very difficult to map in places. In dissected terrain it is usually seen to be less than 5 m thick.

7.0 CAINOZOIC GEOLOGY

Mining Area C and the Hamersley Province as a whole contain a considerable diversity and history of Cainozoic sedimentary and residual rocks. Three broad sequences have been recognised separately by various companies and institutions. Morris (1994) formally named the sequences Tertiary Ore Detritals 1, 2 and 3 (TOD1 to 3, Figure 18). BHPIO have adopted this nomenclature but changed the names to Tertiary Detritals (TD 1 to 3) to allow for inclusion of non-ore bearing facies within the sequences. Each is separated by a hiatus with little erosion and sedimentation, and development of a ferricrete hardcap or Hamersley Surface.

The three sequences (Figures 18, 19) are broadly defined below:-

- Tertiary Detrital 1 (TD1) - dominantly fluvial sediments over 100 m thick (up to 200 m at Hope Downs North and S Hill), ranging from a proximal conglomerate to a distal fine facies, both with a characteristic fine hematite (martite) silt (red ochre) - clay matrix. It appears to be mainly derived from the Marra Mamba Iron Formation and *terra rosa* soils developed over Paraburdoo Member carbonate (Morris 1994). Hematite (martite) is the dominant iron oxide present.

- Tertiary Detrital 2 (TD2) - fluvial and lacustrine sediments typically about 50 m thick dominated by bleached and mottled clays and micritic limestones. CID forms an important end member of this sequence. Goethite and limonite are the dominant iron oxides present.

- Tertiary Detrital 3 (TD3) - colluvial and alluvial sediments, also about 50 m thick, ranging from proximal, cobble to pebble, alluvial / colluvial fans, to distal silty valley fills and playa deposits. The basal parts are more mature dominated by well rounded maghemite and hematite pisolites, grading to a more goethitic hematite (martite) clast - dominant upper half.

7.1 The Hamersley Surface(s)

The Hamersley Range landscape is dominated by a well developed, typically well rounded mature land surface (the Hamersley Surface, MacLeod 1966, Horwitz *in* Morris *et al* 1993 and references therein), which has been eroded in part during more recent times. This surface is best described as a ferricrete and not as a lateritic surface as it is not associated the remainder of a laterite profile (ie saprolite, mottled zones etc). Whilst often described as a single entity, the Hamersley Surface is a composite of several periods of maturation (Morris 1994). From drilling (eg Kepert 1994) it is known that there is not a single surface in the Tertiary sediments, but is best developed at the upper contact of each series of detrital and also the top of the bedrock. The earliest Hamersley Surface must therefore, at least predate TD1 as many of the clasts in it are derived from the hardcap carapace. It was probably initially developed during M-G mineralisation (Morris 1985, 1994).

In drilling it is possible to separate the generations of Hamersley Surfaces into HS1, HS2 etc (Figure 18, Morris 1994). This is not possible or relevant in bedrock outcrop with the superposition of at least three overprinting ferricrete Hamersley Surfaces developed at times of little erosion / deposition to produce the resulting mature land surface.

Different generations of the Hamersley Surfaces may be reflected in outcrop as one or more undulating terraces or surfaces apparent on many of the ridges (Photo 65). The older surface defines the top of plateaus and high ridges. The subsequent surface(s) are denoted as wide gently sloping terraces cut into the upper slopes of plateaus and ridges. The terraces are readily discernible on airphotos and as marked gradient changes on topographic plans.

These palaeosurfaces have since been eroded from Pliocene times to form deep gorges and associated large terminal alluvial scree fans. Deposits associated with the evolution of the Cainozoic landscape include early to mid-Miocene alluvial fan hematite conglomerate, lithified colluvial canga, calcrete, lacustrine micritic limestone, and Pliocene indurated alluvial fan BIF and hematite conglomerates, and pebbly mudstones.

7.2 Tertiary Detritals 1 (TD1) - Miocene Conglomerate (Tmco)

An extensive sequence of hematite conglomerate and siltstone infills palaeovalleys adjacent to mineralised Mount Newman Member throughout the Hamersley Province. Correlation between drilled and mapped sediments throughout the Province (from Nammuldi to Mining Area C, Hope Downs, Wunna Munna Flats and Newman - OB29) indicates that the conglomerate is part of a significant regional lithostratigraphic marker. From drilling it overlies lignite and pyrite bearing clays (eg S Hill, Hope Downs) and / or siderite of indeterminate origin (eg Hope Downs).

The conglomerate is a correlative of terminologies variously used by different companies over time as listed below:-

- Hematite Siltstone - by GML at R Deposit etc,
- Red Ochre Detritals (ROD) - by CRA IOD at Bakers, S Hill and Arrowhead etc, by HPPL at Hope Downs and BHPIO at Mining Area C,
- Superband (or superimposed band) - by HI at Nammuldi and Silvergrass where similar but often coarser material was inferred to occur within palaeokarstic features

in the Paraburdoo Member. All such occurrences have now been reinterpreted to be tectonically (thrust) juxtaposed Mount Newman Member bedrock over Paraburdoo Member rather than detrital derived from it (Duncan *pers comm* 2001),

- TOD1 / TD1 - by CSIRO / Morris and BHPIO,
- Koodaideri detritals, which are derived from the Brockman Iron Formation, are not considered to be TD1 as they are rumoured to be significantly older (?Cretaceous).

Despite the wide spread occurrence, the economic importance of TD1 appears to be low due to an overall low lump content and a relatively high proportion of shale in the matrix both proximal to the West Angela Member and also in more distal fine grained deposits. Detailed drilling of the more proximal conglomeratic facies at L Deposit on the Southern Flank indicates that even here it has a highly variable lump and shale content (Figure 20). Lump grades are typically in the 58 to 60% Fe, but over 1 m intervals locally may be greater than 65% but with low lump recovery (<20%).

Extensive areas of Miocene conglomerate crop out along a narrow, confined palaeovalley within the Southern Flank. The area of exposed conglomerate is approximately 2 km^2 and with a maximum exposed thickness of about 40 m. Conglomerate occurs as a moderately bedded alluvial sequence with marginal massive colluvial deposits in a palaeovalley. It is also less well exposed as onlapping alluvial fans along the Southern Flank margins (< 0.2 km^2), west of R Deposit (~ 4 km^2), South East Corner (~ 1 km^2), and North and South Alligator (< 0.2 km^2). A small mesa of hematite conglomerate between Balgara and South Alligator has no apparent local source, with both Mount Newman and West Angela Members being fresh BIF. Dales Gorge Member mineralisation however, occurs nearby. TD1 is also exposed in upper benches of OB29 at Newman where it is confined to the synclinal core (Photo 66).

The remainder of the description of TD1 hereafter focuses mainly on the relatively conglomeratic facies as seen in outcrop at Mining Area C. In the main it is a highly condensed and edited version of Lipple (1994) based mainly on exposures in the confined, internal valleys along the Southern Flank and subsequent RC drilling (Kepert 1994). Brief observations are also made from Hope Downs North (HPPL) drill core.

The conglomerate mostly overlies the West Angela Member and mineralised Mount Newman Member, with a moderate-dipping unconformity of 25º to 30º (locally steeper) on an irregular gullied surface similar to the modern topography.

Outcrop of the conglomerate is generally affected by Tertiary alteration / weathering, especially marginal occurrences of pebble conglomerate, with alteration of the matrix to limonite or goethite. Pisolite gravels may also be present, either as a surface capping or in - filled solution pipes in the conglomerate. The relatively impermeable hematite siltstone is less affected by weathering, apart from a 5 to 10 cm oxidised orange brown carapace. The horizontal fabric imparted by weathering helps mask any sedimentary fabric that may be present.

Apart from the unstructured basal metre or so of conglomerate, which may represent a palaeoregolith, the sequence is moderately stratified.

Minor yellow silcrete has replaced conglomerate north of M Deposit indicating that at least some silcrete development post dates the conglomerate.

7.2.1 Lithologic Facies

The conglomerate sequence variously consists of interbedded massive coarse conglomerate, pebble conglomerate, coarse bedded sandstone with massive pebbly siltstone, and siltstone. Massive siltstone, with or without pebble trains and sporadic clasts comprises, about one third of the sequence in outcrop. Conglomerate (*sensu stricto*) makes up the remainder. Sandstone beds are rare. By comparison, from drill data at Mining Area C and elsewhere throughout the Province, siltstone with or without pebbles is the dominant facies both proximal and distal to Mount Newman Member mineralisation.

Coarse Conglomerate

Coarse conglomerate (Photo 67) is widespread in outcrop consisting of a matrix - supported, massive to weakly bedded assemblage of unsorted (up to 10 m across), angular to subrounded, tile to discoid-shaped clasts of hematised and subordinate unaltered martite - goethite ore in a matrix of sand to silt-sized grains of similar composition. Conglomerate overlying West Angela Member commonly also contains angular shale clasts. Chert nodules (MacLeod Member derived), BIF clasts and other non-ore pebbles are rare, although the conglomerate locally includes clasts of low grade ore.

There is a weak to moderate imbricate sedimentary fabric developed conformable to bedding. Larger blocks disrupting the imbricate fabric suggest movement of the blocks across the bedding surface.

Pebble Conglomerate

Pebble conglomerate consists of clast-supported hematite pebbles in a hematite silt groundmass. The unit is massive, well-sorted and lacks any apparent sedimentary fabric. Clasts are dominantly in the size range of 1 to 3 cm (up to 10 cm) and mostly sub-angular and equant, with lesser discoid shapes. The unit thickens from a 10 to 30 cm veneer on the upper slopes of Mount Newman Member to 2 to 3 m thickness on West Angela Member. Pebble conglomerate mostly overlies mineralised basement, but locally rest on unmineralised basement. It appears to merge with coarse conglomerate by the progressive increase in the proportion of larger clasts, and a slight increase in the degree of clast roundness.

The uniform, well cemented, angular, clast-supported nature of the pebble conglomerate is very similar to material generally referred to as ‘canga’ (Czcg) in the Hamersley region.

Hematitic Sandstone

Thin (< 1 m) and laterally impersistent, rare hematitic sandstone beds show a variety of associations including as channel fill, and as single to sets of interbeds within the conglomerate facies (Photo 68).

Exposures along the Southern Flank include:-

- sandstone and granule conglomerate (grit) beds within the coarse conglomerate have dips up to 40º generally towards the south,
- sandstone beds occur at both sporadic intervals, and as zones up to 1 m thick of interbedded sandstone and massive conglomerate,
- cliff exposures of a maroon, massive hematitic pebbly sandstone with a silty matrix and moderately laminated siltstone beds occur near the base of the conglomerate, and
- sandstone lens as migrating alluvial channels truncating the internal fabric in conglomerate beds. Sandstone beds also show scour channels infilled by coarse conglomerate and bedding truncation due to channel migration (Photo 68).

Hematite Siltstone

The siltstone consists of over 80% pink to dark red hematite silt and minor aluminous clay matrix, with the remainder of matrix-supported pebbles of ore and rare BIF. Clasts are angular to rounded, with moderate sphericity. Locally shale - derived clay interbeds are developed. From drill data (Photo 69), the siltstone is the dominant facies developed in broad (unconfined) valleys such as the Northern Flank valley. Conglomerate facies are typically only significant adjacent to the source (< 50 m).

In outcrop, hematite siltstone is typically pink to dark maroon forming beds 20 cm to 2 m thick within conglomerate. Apart from sporadic pebble trains, the unit is mostly massive. A very poorly sorted, randomly distributed, angular grit to small pebble size clasts occur through out the siltstone.

Samples from GML diamond drill holes at C Deposit were described by Morris (*in* O'Sullivan, 1992). The core consists of an assemblage of martite, martite-goethite, spongiform goethite (hardcap) and BIF clasts in a hematite mud matrix. Individual clasts are generally angular to rounded, and of moderate sphericity. The relatively uniform grain size distribution has a mode at about 100 μm, representing the predominance of individual martite grains. Limited transport of the material is inferred from the abundance of fine, sand-sized individual martite crystals, which retain an octahedral magnetite form. Some larger goethite clasts have hematite rims indicating prolonged exposure. Reworking of the siltstone is illustrated by the ghosted boundaries and hematite rims.

Clastic Dykes

Massive clastic dykes identical in composition to the pebbly sandstone and siltstone beds lower in the sequence are most notably apparent at Poxy Leg

Gully, where three curvilinear dykes, 0.1 to 1 m thick, are apparent in cliff sections (Photo 70). Forcible plastic injection through the conglomerate mass is indicated by well defined striations along the dyke margins. Hematitic siltstone lenses elongate oblique to bedding elsewhere, may be of similar origin.

The dykes probably formed when pore pressure exceeded the tensile strength of the poorly consolidated sediment. Intrusion may have been triggered by the impact of very large blocks from scarps to the north, or from compaction and dewatering due to over pressuring of the sediment by lithostatic loading.

7.2.2 Basement Controls

The distribution of TD1 and the conglomerate sequence and unconformity surface are strongly controlled by the stratigraphy and structure of the underlying bedrock. Deposition was in palaeovalleys within the West Angela Member, proximal to and with detritus derived from, mineralised Mount Newman Member, and the clay component of the matrix from the West Angela Member.

Erosion of the middle and upper shaly parts of the West Angela Member (and possibly minor Paraburdoo Member) formed valleys parallel to the west trending D_2 (and D_3) synclinal fold axes. Double plunging synclines led to locally internally drained basins of deposition, with the shape of the unconformity mimicking the folded bedding in West Angela Member. Drilling along the Southern Flank (Kepert and Tehnas 1995) suggests internal basins may be over 100 m deeper than any apparent surface outlet (at Hope Downs North toward Weeli Wolli Springs it is over 200 m). A similar internally draining palaeovalley beneath Whaleback Creek adjacent to Mt Whaleback is also interpreted from drilling (Kneeshaw *pers comm* 2001). At the Southern Flank, the more resistant M-G mineralisation in the Mount Newman Member formed prominent dip slopes hills, locally incised by deep gullies. The overall dip of the unconformity is 25º south, ranging between about 5º and (locally) 70º.

7.2.3 Environment of Deposition

<u>Colluvial facies</u> of massive pebble conglomerate scree developed as a thin (~ 2 m) veneer on the hill slopes, passing laterally down slope into coarse conglomerate interbedded with hematitic sandstone and pebbly siltstone comprising a diverse <u>alluvial valley facies</u>. The colluvial facies merge with the alluvial facies at the break in slope (ie West Angela / Mount Newman Member contact).

Thin, restricted hematitic sandstone beds are interpreted to represent minor fluvial tops and channel fills during waning floods which transported the conglomerate clasts down an alluvial fan and trunk drainage system, and as the distal facies of the alluvial system. Megaclasts probably slumped off cliffs and rolled or slid across the unconsolidated, water-saturated conglomerate. Chaotic imbricate fabric around such megaclasts and the conformable orientation of internal bedding of the slabs with overall conglomerate bedding suggest that sliding rather than rolling was the mode of movement. Injection of clastic dykes was triggered by over pressuring of pore fluid by block impact and / or dewatering and consolidation of the conglomerate under lithostatic load.

Migrating fluvial channels are indicated from scours of hematitic sandstone / siltstone, and truncation of the imbricate fabric of flat clasts on gravel bars. Sufficient near surface induration occurred during sedimentation resulting in intraformationally derived conglomerate clasts. Material in the alluvial fan system experienced sufficient transport and / or chemical corrosion to transform many of the initially angular pieces to subrounded, and in rare cases, well-rounded shapes.

7.2.4 Structural Features

Features that are deformation related include:-

- zones of close-spaced, near-vertical, east / west trending joints (other joint orientations also occur), commonly with slickenside development,
- moderate to weak zones of shearing, especially in the siltstone, and
- locally steep to very steep dips, particularly proximal to deposition margins.

At M Deposit on the Southern Flank, outcrop disposition, bedding parallel clast fabric and minor thin sandy and silty pebble conglomerate and siltstone layers (10 to 30 cm thick) indicate a consistent dip of about 40º northwards (Photo 71). The unconformity between the conglomerate and gently north-dipping (15 to 25º) mineralised Mount Newman Member consists of an abutment against steep (near - vertical) palaeosurface on the north face of a west-trending palaeoridge.

Deposition of continuous beds with dips of 25 to 40º is improbable since the unconsolidated mass would slump and be prone to erosion. Various origins for the steep dip have been debated, including folding, faulting, compaction and mass movement. No evidence has been observed for faulting of the contact, such as shearing, brecciation or veining. The unconformity angle asymptotes towards the ridge crest suggesting some primary draping of the bedding over the unconformity. The basal conglomerate lacks a fabric near the unconformity, possibly due to alteration (weathering) or disturbance during compaction.

The preferred model for the generation of the steep dips and other tectonic features by Lipple (1994) was tightening of a pre-existing D_2 anticlinal fold in the underlying Mount Newman Member. Problems in fold geometry relative to the unconformity could be accounted for by a subparallel fold tightening the moderate north limb dips of the D_2 anticline, and reversing low angle, south limb dips. Such a modification of dips would also account for the change in dips in the conglomerate from 70º north to 40º north further east along the unconformity. Although modification of D_2 structures by D_3 folds (*ca* 1800 Ma) is well documented for the project area, the conglomerate is of Cainozoic age. Based on the symmetry of moderate dips elsewhere in the palaeovalley between K and M Deposits, local zones of strong near-vertical jointing and one location with sheared siltstone, Lipple (1994) suggested that the conglomerate has been affected by Tertiary deformation.

This is not considered the most likely scenario by the current author. The preferred model here is one of dewatering and compaction whereby the unconsolidated conglomerate mass would tend to steepen the dips of the sediment deposited at the margins of the palaeovalley, also resulting in the strike parallel, weakly tectonised nature of the sequence. Due to the confined and in places internally draining palaeovalleys, it is likely that the sediment would have been completely saturated at the time of deposition. Continued deposition would have led to progressive dewatering and compaction centred on the deepest parts of the palaeovalley and generation of injection dykes. Bedding steepening toward to the lateral unconformity surface consistent with compaction is also apparent at OB29 (Photo 66).

7.2.5 Contained Biogenic Material and Age

The conglomerate was formed after the development of M-G ore (generally regarded as Mesozoic), but prior to Tertiary ferricrete (and silcrete) development and deposition of mid to late Miocene CID. Several horizons (up to 40 cm thick) of lignite and carbonaceous clay in both hematite siltstone and CID occur in large diameter drill core from Hope Downs North. Palynological studies by Dr B Balme included in Morris (1994) conclude an **early to mid Miocene age**.

Lignitic wood fragments are also known from RC drilling by CRA IOD west of S Hill that intersected over 150 m of red ochre detritals (with a basal 10 m of white clay with lignite and pyrite balls), before bottoming in West Angela Member. The wood was positively identified by polished section but not palynological examined.

Goethitised wood fragments typically 1 to 5 cm long (ie larger than those in CID) are locally well preserved in the conglomerate. At one locality on Blackwood Creek, abundant goethitised wood occurs as rounded pieces of fibrous wood ranging from twigs 1 to 2 cm diameter, to 5 to 15 cm long to small logs 10 cm in diameter and almost 1 m long. Some smaller fragments show branch nodes. Fragments appear to have been deformed by compaction.

7.2.6 Type Sections

Lipple (1994) suggested the regional extent, importance as a lithostratigraphic marker (and possible though not yet substantiated economic potential of the hematite conglomerate) warrants a formal stratigraphic definition for the unit. The name Chabbledoo Conglomerate was proposed after the Aboriginal name for the major hills along the northern limit of the Southern Flank. Note, however, given the dominance of siltstone to conglomerate in drilled sections, Chabbledoo Formation would be a more appropriate name.

The proposed type section for the conglomerate by Lipple (1994) is along a major creek just north of M Deposit where it cuts an eroded basement syncline backfilled with the sequence. The section extends 500 m between the northern basal contact at 697 980E / 7 455 660N and the southern basal contact at 698 300E / 7 455 270N. The total thickness from drilling 500 m to the west is about 130 m (Figure 20). The section consists of moderately stratified interlayered conglomerate, pebbly conglomerate and coarse sandstone, and massive to pebbly siltstone. Bed thickness varies between 0.1 to 2.5 m. Conglomerate near the base contains some megaclasts. Dips vary from 30 to 45º south, increasing southwards from the northern contact with West Angela Member. A similar sequence, though more steeply dipping (60 to 70º north), occurs on the southern limbs of the syncline, though lacking megaclasts in the basal coarse conglomerate.

Additional reference sections include:-

- a steep - sided, southeast - draining gully (710 100E / 7 453 400N to 710 500E / 7 453 200N. The section features good exposures of conglomerate with megaclasts, hematite sandstone and siltstone (pebbly and massive varieties), alluvial channelling, reworked conglomerate boulders and sedimentary injection dykes. Above the unconformity with the underlying West Angela Member, an unstructured zone 50 cm thick appears to represent a palaeoregolith.

- a gully north of L Deposit (695 100E / 7 454 600N to 695 800E / 7 454 900N). Dip slopes and overhangs on conglomerate preserving alluvial channels, and massive and pebbly siltstone occur along the southern margin of the gully. The northern side of the gully provides a cross-sectional of interbedded conglomerate and siltstone.

- the synclinal keel of OB29. In the top benches of the keel area permanent (pit limit) faces of massive to bedded pebble siltstone with only minor conglomerate beds occur. Bedding can also be seen to steepen toward the unconformable contact with the West Angela Member. **This siltstone dominated sequence at OB29 is probably more representative of the regional TD1 sequence than more conglomeratic facies deposited in confined palaeovalleys along the Southern Flank.**

7.3 <u>Tertiary Detritals 2 (TD2)</u>

Tertiary Detritals 2 variously comprise abundant white and mottled (transported saprolitic) clays, CID, and fluvial to lacustrine limestone and associated calcrete. At Mining Area C the sequence is dominated by clays etc, with CID only occurring in minor uneconomic amounts. Unlike the other two Tertiary sequences, which are dominated by iron in the form of hematite and maghemite, Tertiary Detritals 2 is dominated by iron as goethite and limonite. From drill data (Figure 22) the extensive clay deposits are the oldest part of the sequence, but do not crop out. The closest exposed parallel is probably the Eastern Clay horizon near the top of the CID sequence at Yandi. The sequence appear to have been deposited in a period of intermittent high rainfall and / or waterlogging, and leaching, as evident by the mottled clays, dominance of iron hydroxides over oxides, lacustrine limestone and deep lateritic weathering profile in the underlying basement.

7.3.1 Channel Iron Deposits (Robe Formation) (CID)

The geology and genesis of CIDs is well described in Morris (1994) and Morris *et al* (1993) and is not repeated here. The sedimentology of the Yandi CID (Marillana Formation) is the focus of a BHPIO sponsored PhD commenced in 2001 by Michelle Stone through UWA.

Except for near Hope Downs / Weeli Wolli Springs area and at Death Valley, CID is poorly developed in the Mining Area C region. It is typically restricted to thin veneers and creeks on hill sides rather than being transported to, and accumulating in a palaeovalley. Drilling has not located any significant buried deposits.

Thin (~ 6 m) erosional remnants of CID between North and South Parmelia Hills can be traced downstream under Oakover Formation cover, re-emerging at and downstream of Weeli Wolli Springs. Drilling along that drainage has not located any significant thickness of CID. Other CID of note in the same broad palaeo-catchment is the 30 to 40 m thick buried CID shown on schematic cross sections of Hope North (it is unknown how much of this is genuine CID as opposed to other vitreous goethite - bearing detritals), and erosional remnants of CID upstream of Box Canyon. It is unlikely that Box Canyon itself has any buried CID, as remnants of the palaeochannel are preserved on the top of the south lip of the Canyon, and instead it probably contains only TD3 sediments. It should however, still be drill tested at the appropriate time. CID in the Weeli Wolli Creek drainage eventually joins the more significant Marillana Creek CID further downstream.

At the west end of Death Valley, a 30 to 40 m thick sequence of CID is evident in a gorge before it dips westerly under recent sediments is of high interest. Isolated erosional remnants occurring further upstream in Death Valley indicate a more extensive deposit that has been eroded away since pre-Oakover Formation times. The Death Valley CID may continue under Oakover Formation cover in the main Turee Creek valley 2 km downstream. Thin CID caps, which form mesas on the Fortescue Group along Big Creek, also indicate potential for buried CID downstream in Turee Creek.

Isolated CID outcrops between Balgara and South Alligator are probably not of great interest, but should be drilled when the Marra Mamba Iron Formation in the area is investigated.

7.3.2 Oakover Formation (To)

In the southwestern part of the survey area along Turee Creek, there are excellent exposures of late Cainozoic sediments, lithologically similar to the Oakover Formation of the Canning Basin and Fortescue River Drainage. Along Turee Creek over 60 m thickness of the Oakover Formation equivalent is exposed in mesas and as the base is not exposed, a greater maximum thickness is indicated. There are less extensive occurrences in Death Valley, North Alligator and elsewhere throughout the area. Extensive calcrete (Czk) with massive opaline silica mapped by GSWA along the drainage lines may cap similar sediments (eg south of Weeli Wolli Springs). At North Alligator the limestone abuts pisolitic gravel over a canga on a north-sloping basement palaeosurface.

Climate during deposition of the Oakover Formation and equivalents was wetter than currently exists for much of Australia, although a degree of aridity is implied by the lacustrine carbonates (ie evaporative conditions), red brown colouration of the ferruginous clastics and the superimposed, stacked calcrete palaeosols. Continental palaeodrainage systems were reactivated a number of times during the late Cainozoic. The sediments deposited within them reflect the overall increasing aridity as Australia drifted towards the equator and as global climates deteriorated with the expansion of the polar ice sheets. Thus late Cainozoic sediments that were deposited in the palaeodrainage of the Pilbara Craton and Hamersley Basin for example, are distinctly less carbonaceous and commonly include lacustrine limestone and dolomite.

A number of lithofacies were recognised from a brief visit to a mesa along Turee Creek, Mining Area C Park:-

- basal (~ 10 m thick) white micritic carbonate limestone / mudstone (Czm) (possibly dolomitic), bedding is poorly developed and an irregular vertical rodding structure is superimposed, very likely the result of weathering. Degree of induration is moderate.

- conglomerates and red beds (Tog), fluvial bed - load conglomerates and alluvial flood plain, red beds, with stacked calcrete palaeosols, dominate the sequence (~ 40 m thick). The conglomerates are matrix to framework - supported, and clasts of well rounded pebbles to boulders predominantly derived from a variety of Fortescue Group volcanics. Minor vein quartz pebbles also occur, as do rare granitoid basement clasts derived from Milli Milli Dome to the north. Significantly there are also rare wood-bearing CID pebbles. Matrix of the conglomerates ranges from sandy mud to quartz - rich sand.

  The conglomerates are variously interfingered with poor to well sorted, mud and sandy mud, to quartz sand red beds. In the lower part of the exposures, relict green colour and mottling is apparent. In part, the sands are free of clay and are free-flowing to weakly indurated. Cross-bedding is also locally apparent indicating southward current directions.

  Stacked calcareous (calcrete) horizons are superimposed, particularly in the clastic red beds. These are groundwater and palaeosol carbonates and include horizontally disposed, irregular wavy sheets, massive indurated crusts, and vertically oriented lumpy horizons.

- capping the mesas is 3 to 4 m of similar but purer lacustrine carbonate limestone / mudstone (Czm). The mesa tops thus mark the floor of an extensive old lake bed. The carbonate mudstone is variably silicified by chalcedony and ?opaline silica.

There is very little evidence for an age for this sequence in Turee Creek, however CID clasts indicate an age younger than the Robe Formation (mid to late Miocene). This is in keeping with regional observations that the Oakover Formation overlies the Robe Formation.

7.4 Tertiary Detritals 3 (TD3)

7.4.1 "Pliocene" conglomerate (Tpco)

Conglomerates, canga and other indurated detrital at Mining Area C Park caused some degree of confusion during mapping. The apparent TD3 (Figure 21) sequence at Mining Area C Park from the base up is:-

- goethite and ochre cemented pebble conglomerate (Tpco here) forming elongate outcrops, overlying either older Tertiary sequences or perched on low Marra Mamba hills,
- consolidated to well cemented ore and BIF detrital and canga in the base of the fans (Czc(g)), cement typically soil derived, typically only exposed by recent erosion of major Brockman fans, and
- unconsolidated BIF (and ore) detrital in fans (Czc etc).

This lowermost unit was initially interpreted as Miocene Conglomerate (Tmco) due to similarities including elongate as opposed to fan shaped outcrops, rare boulder sized clasts and goethitic to ochreous cement. Differences in the lesser degree of rounding and polishing of the pebbles, and some difference in the matrix was ascribed to being essentially Brockman Iron Formation derived instead of wholly Marra Mamba Iron Formation derived (as appears the case with true Miocene Conglomerate). Lacustrine limestone (Czm) also appeared to abut and onlap eroded banks of the conglomerate, indicating that the limestone is younger. Unfortunately, only at the very end of the program was the conglomerate found to unconformably overlie CID (Photo 72), and as such has been renamed as Pliocene conglomerate (Tpco), although its exact age is debatable. Assuming that the Oakover Formation (To) and lacustrine limestone (Czm) are coeval, then the conglomerate lies between the two (Figure 21). Alternatively, lacustrine limestone may not be all of one age or correlatable to the Oakover Formation.

7.4.2 Canga (Czcg)

Canga has historically been defined as goethite - cemented, to well indurated, ore pebble, colluvial deposits of no particular age or stratigraphic association. Whilst still open to misuse, it is used here to describe only those colluvials of apparent TD3 association. This is of course open to interpretation, as in outcrop it is similar to and difficult to distinguish from the pebble conglomerate facies of the Miocene

Conglomerate, or the more alluvial "Pliocene conglomerate". In reality there is probably a near continuous history of canga sedimentation / development.

7.4.3 Colluvium (Czc)

Piedmont colluvial / alluvial fans form at the out flow of most creeks draining the hills. They grade laterally and vertically into distal silty valley fills (Cza). Mapping subdivisions based on the varying proportion of ore versus non-ore clasts are:-

- Czc - undifferentiated,
- Czcb - clasts mainly non-ore (BIF),
- Czcm - mixed clasts,
- Czco - clasts mainly ore (> 90%).

This subdivision is however, is based only on the upper most recent detritus and does not necessarily reflect the composition of older buried parts of the fan. Other subdivisions of colluvium include:-

- Czcg - cemented or indurated Czco (see Section 7.4.2),
- Czci - indurated Czc, Czcb and Czcm,
- Czpi - pisolite rich regolith typically developed over Tmco, Czcg and Czco.

7.4.4 Colluvium Drill Subdivisions

The colluvial fans have been further separated into five major and two associated subdivisions or facies based on drilling (Figure 22, Potter 1993, Kepert 1994). The basal parts are more mature, dominated by maghemite and hematite pisolites grading to a more goethitic hematite clast - dominant upper half. This differentiation is apparent whether or not the majority of the clasts are ore or non-ore, that is, it is primarily due to changing rates of weathering, erosion and deposition, and does not reflect the source. The drill subdivisions from the base up are:-

- *Aluminous Scree (AZ)* - gibbsitic coated, well rounded goethitic pisolite in a pinkish shaly matrix. It is locally apparent in outcrop as a moderately to well indurated rock, but is not subdivided.

- *Fine Scree (FZ)* - red, very well rounded fine maghemite pisolite in a red soil matrix that may be clayey in part. It is a basal and distal facies of Compact Scree. Generally correlates to pisolite (Czpi).

- *Compact Scree (CZ)* - red, well rounded maghemite and hematite pisolite and pebble clasts in a red to brown-red soil matrix that may be clayey in part. May contain some hematised BIF.

- *Loose Scree (LZ)* - red-brown, rounded hematite and BIF pebble clasts in a red-brown soil matrix.

- *Low Lump Scree (LLZ)* - similar to Loose Scree, but with a higher proportion of brown soil matrix

- *High Matrix Scree (HMZ)* - distal facies of Loose and Low Lump Screes with a dominant orange-brown soil matrix. Generally correlates to mapped alluvium (Cza).

- *Surface Scree (SZ)* - semi-rounded, brown goethitic hematite pebbles and cobbles in a brown soil matrix. By definition this is mapped as colluvium (Czc), but can be further subdivided depending on proportions of ore to non-ore clasts.

All units (with the exception of High Matrix Scree) can be locally indurated or cemented by secondary goethite, particularly near the bedrock contact to form a canga (Czcg).

7.4.5 Alluvium (Cza)

Red-brown to orange brown, soil to clayey alluvial silt, locally with pebble horizons, covers large areas in the centre of most valleys. It may have a surficial veneer of very fine maghemite lag.

7.4.6 Playa Deposits (Czp)

Heavy rain from Cyclone Bobby (Feb 1995), and from Cyclone John (Dec 1999) and other abnormally heavy monsoonal activity (Jan - Feb 2000) resulted in the flooding of a large playa located between Parallel and Boundary Ridge in the west, and Mount Robinson in the east. The playa is locally referred to as 'Lake Robinson' or more correctly as Coondewanna (note, this was previously reported as *Gundawuna* by Brown 1986). The surface consists of clay and silt. Several other smaller playas also occur within the region.

7.5 Quaternary Deposits

Quaternary deposits include:-

- Qa - active alluvials, typically only differentiated in major creeks,
- Qc - landslips / cliff failures, block failures are described below, and
- Qs and Qd - sand sheets, and dunes, only recognised on a more regional scale.

Large scale coherent slips and failures of blocks 10's m in size are a common feature of dip slopes in lower Joffre Member and more rarely in lower Dales Gorge Member. They develop by gravitational creepage of BIF on underlying shale, initially apparent as vertical tension cracks. Critical failure may lead to the blocks travelling 10's m. Partly upward trajectory paths, mega-scour marks and troughs in recent alluvials and cataclastic deformation of the blocks (Photo 73) all infer a significant a significant velocity during critical failure. Individual blocks may be over 50 m long and weigh 50 000 t. On Mt Robinson blocks have rotated 30 to 40º with respect to the vertical, implying a listric detachment surface that crosscuts bedding.

8.0 STRUCTURE

8.1 Historical Perspective

The structural and tectonic understanding of the Hamersley Province has increased exponentially in the last decade. Until then the majority of work (eg MacLeod *et al* 1963, Trendall and Blockley 1970), with the exception of in - pit studies at Mt Whaleback (and presumably also Tom Price), only recognised a single major, east - west striking, fold forming deformation, followed by various faulting. Tyler and Thorne (1990) and Tyler (1991) building on a tectonic framework proposed by Gee (1979) were the first to really challenge this with the construction of a regional tectonic model for the southeast part of the Province which recognised an early orogeny comprising two tight, overturned to recumbent folding events (D_{1c} and D_{2c} - Capricorn Orogeny), followed by a more open upright folding event (D_{2a} - Ashburton Orogeny). D_{2a} however, was restricted to only the Ashburton Province by Tyler, and was not recognised in the Hamersley Province. D_{2c} and D_{2a} were defined as being approximately coaxial (ie east - west) but with differing axial plain orientations (inclined to the south and upright, respectively). Styles (1991) who worked with Tyler in the field reached a similar conclusion. Tyler and Thorne (1990) and Tyler (1991) were also the first to describe the Ophthalmia Fold Belt as a fold and thrust belt produced principally by D_{2c}.

Detailed 1:5 000 mapping of Jimblebar during 1993 by BHPIO and contract geologists (Lipple 1995) further refined Tyler's model, resulting in better definition of these events including the important recognition of D_{2a} (Ashburton) folds in the Hamersley Province, and also the recognition of two late cross folding events. Deformations were relabelled by Lipple (1995) at this stage, removing the orogeny suffix and opting for a single numeric identifier (Table 4). Similar parallel and partly independently studies, principally by Powell (eg Powell and Horwitz 1994), were also being run at this time, although typically with some time lag behind the evolving BHPIO structural model. This subsequent work has not greatly altered the model derived from Jimblebar.

The structural sequence from Jimblebar was successfully applied to the mapping at Mining Area C, with the only significant addition being the possible recognition in 1994 (Lipple *et al* 1994) - and the further substantiation in 1995 (Lipple *et al* 1996) - of a possible additional asymmetric fold event between D_1 and D_2 (Figure 23). This deformation was internally referred to as $D_{1.5}$ in order to save confusion resulting from renumbering subsequent deformations. Mapping by BHPIO and others (eg Gregory 1998, Kepert *et al* 1999, Hollingsworth and Cawood 1999, Hollingsworth *in prep*, and 1:5 000 mapping of Northern Flank orebodies in 2000) since that time has clouded the water to a large degree with the important recognition that much of the folding earlier attributed to $D_{1.5}$ and also D_3, may have been produced by D_2. This is discussed further in Section 10.3.

The evolution in structural understanding from the 1970's on is well illustrated by Figure 24 showing the structural and stratigraphic interpretation of a drill section at C Deposit.

The structural model resulting from the BHPIO Jimblebar mapping (and further developed at Mining Area C), has since been exported by way of various contract mapping geologists initially employed by BHPIO to Hamersley Iron, Robe River Iron Associates and Hancock Prospecting. It is now in common usage by companies throughout the Province. Unfortunately all have however, adopted the renumbering system favoured by Duncan, that is where $D_{1.5}$ becomes D_2, D_2 becomes D_3 etc (Table 4). BHPIO however, have retained $D_{1.5}$ and the Jimblebar based numbering scheme.

This generally accepted structural model was used during the majority of the mapping discussed in this report, and forms the basis of the definition and description of the various deformations outlined in Section 9 and shown in Figure 23. Alternative models for the generation of some features are discussed later in Section 10.

8.2 Nomenclature

Structural nomenclature used here for describing the geometry of folds includes:-

- vergence - is defined as the horizontal direction towards an antiform. South verging folds are equivalent to "S" and north verging to "Z" parasitic folds, but it removes the potential ambiguity if folds are viewed from the wrong direction (correct convention is from the north or west, ie same as for cross sections).
- facing - is defined as the younging direction along a hinge surface, that is, F_2 are typically north facing and F_3 upward facing.

Structural measurements of planar fabric (ie bedding, cleavage etc) are recorded as dip / dip direction, and linear or vector fabrics (ie fold axes, slickensides etc) as plunge / plunge direction. Azimuth (directional) measurements are taken at waist height to minimise the influence of magnetic BIFs (in particular, Bruno's Band, the top of D4 and J6).

Orogeny names adopted here follow those in current public usage, that is, the Ophthalmian and Ashburton Orogenies for D_2 and D_3, respectively (Table 4, Figure 15). They are used in preference to the poorly defined Capricorn Orogeny. This was originally defined by Gee (1979) to include *all* tectonism and associated sedimentation between the Yilgarn and Pilbara Cratons (including the onlapping Hamersley Basin). The Capricorn Orogeny term was then adopted by Tyler (1991) and widened to include the deformed margins of the Cratons, including D_1 basin compaction (D_{1c}), but excluding D_3 (D_{2a}), which had been included by Gee (1979). Hamersley Iron (Taylor *et al* 2001) has further confused the terminology using Capricorn rather than Ashburton Orogeny for D_3. They also remove late D_2 folds from the Ophthalmian Orogeny referring to them as Panhandle folds.

The assigning of various folds and associated fabrics to various generations of deformations that are approximately coaxial, is open to significant interpretation when, as is the case in a majority of circumstances, no definitive overprinting relationships are apparent. During mapping folds have typically been assigned to a deformation based mainly on the geometric characteristics summarised in Table 5, with the most important criteria being the orientation of the axial plane and associated cleavage. This has also led to some folds being assigned as hybrid, for example where the geometry suggests an F_2 is further tightened during D_3, then it is labelled $F_{2/3}$. If nothing else, this flags folds as having a certain geometry regardless of any genetic consideration.

The convention used in this report for referring to folds is that **folds of a specific geometry but without a well defined association to a particular deformation event or orogeny are referred to as "F_x", whereas those that are associated with an orogeny regardless of geometry are "D_x folds"**. For example, for a south facing fold (ie $F_{1.5}$) that is recognised as being produced by the Ophthalmian Orogeny, it is referred to here as a "D_2 fold" or "D_{2S} fold", with the additional (optional) subscript "S" denoting the facing direction where it differs from the norm. In general, in Section 9 only "F_x" is used, whereas depending on the context both "F_x" and "D_x folds" are used in Section 10. A similar naming convention has also been applied to other fabrics.

9.0 MAPPED STRUCTURE

9.1 Early Structures ("Pods I Have Known")

Many of the rocks of the Hamersley Group have a wide range of various features that historically have informally and formally been attributed by various authors to "soft sediment deformation" (eg Ewers and Morris 1981). However many may be in part or total due to diagenetic concretions and / or tectonism. These features are dominated by various styles of elongate to spherical podding, and stacked pods (or boudins). Pods can be divided into four end members:-

- bedding penetrates the pod indicating they formed by nondisplacive diagenetic nodules. Examples of this type of podding are the Youngman Pods,

- bedding wraps the pods but are spherical and / or without a preferred orientation are most likely due to basin floor sedimentary and / or displacive diagenetic nodules. Subsequent compaction and / or tectonism may also accentuate the wrapping of the bedding around the more competent pod. Examples are pyrite nodules of the Mt McRae Shale (eg Kakegawa *et al* 1999), Football Chert, (?)Potato Bed and Huleatt's Bed of Holes,

- bedding wraps a pod, and pinch and swell structures of a primary lithology may be produced by differential compaction, lithification, and / or dehydration during diagenesis. Examples are macules, many of the irregular small scale podding and pinch and swelling of chert mesobands in a less competent iron oxide matrix, in the BIFs,

- bedding wraps a pod with a preferred orientation or sense of rotation are principally due to extensional tectonic forces (D_1) resulting in boudinage or similar of more competent layers. Examples are elongate pods and rods throughout the sequence, most noticeably in the Nammuldi and Mount Newman Members, and locally significant in J6.

The three diagenetic end members may all be subsequently modified by D_1.

9.2 D_1 - Basin Compaction and Extension

The D_1 event (or D_{1c}) was defined by Tyler (1991) as being a bedding parallel fabric with minor northeast - southwest trending isoclinal folds confined to specific horizons. It did not produce any major thickening or overturning of the stratigraphic sequence, with all known folding being intrafolial. The existence of a weak, bedding parallel, D_1 slaty cleavage is indicated by the development of a crenulation cleavage by subsequent deformations. Powell and Horwitz (1994) attribute the orientation of D_1 to pre-existing, northeast - southwest basement faults.

The kinematics of the D_1 event indicates vertical loading and northeast - southwest basin extension, producing vertical collapse of the stratigraphic pile, and associated differential bedding extension. This differential extension locally produced shearing parallel to the bedding foliation, boudinage of bedding, intrafolial folding and extensional shears or crenulation cleavage. D_1 was probably synchronous with late diagenesis.

Few if any F_1 folds were unequivocally identified during mapping, with the most common and obvious D_1 structures developed being various styles of tectonic podding and other extensional features. Some intrafolial isoclinal D_2 folds may have been incorrectly identified as F_1 folds (eg those in Poxy Leg Gully).

D_1 boudinage structures parallel to bedding are best developed in the Mount Newman Member (Photo 74). Closely associated with the boudinage, again most commonly found in the Mount Newman Member, are shear band structures or extensional crenulation cleavage (stacked pods) which usually have a consistent dextral shear sense looking northeast, although locally they may also show an opposite shear sense (Photos 75, 76).

Pods in the Potato Bed may be elongate in the same direction as the Rods indicating that they have been tectonically modified by either coalescence or elongation (Photo 77). Modification of diagenetic podding implies that the pods predate D_1. Carbonate beds in the Mt Sylvia Formation at Eric's Point have also been modified by D_1 to produce northeast trending lenses and pipes (Photo 78). D_1 rods may also develop as sinuous chert pods as locally developed in the Joffre Member (Photo 79) implying some other controlling force syn to post their formation.

The mechanism for the generation of D_1 structures such as the Nammuldi Rods (Photo 3) or stacked pods in the Mount Newman Member (Photo 14) is problematical. Both show a consistent, Province wide sense of imbrication and rotation of pods (Photos 75, 80), indicating an apparent southeast block down movement (ie dextral). If the apparent thickness as defined by microbanding in stacked chert pods in the Mount Newman Member is assumed to be the original maximum thickness of the hydrous silica(gel) mesobands, then the original Member would have been several times thicker. Whilst this in itself is not unlikely, it is difficult to envisage a process that is so heterogeneous on a small scale, where a given mesoband may vary from 20 mm to 2 mm over less than 2 cm, but on an outcrop and Province scale, can produce a homogenous band and Member with very little lateral variation in its thickness or composition. Alternatively, the high angle fabric in the stacked chert pods defined by isolated oxide lamellae that is assumed to be S_0, may instead be refracted S_1 (or C_1), with S_0 of the pod parallel to its long axis (Photo 76).

As previously noted in Section 4.1.3, riebeckite alteration of BIF is interpreted here to be syn D_1 as it preferentially developed in northeast - southwest trending structures consistent with being D_1 (Figure 8), and predate "regional rippling" (ie D_2, Trendall and Blockley 1970, Trendall 1983). Riebeckite development may also be associated with low angle, extensional D_1 shears.

Powell (*pers comm* 1998) identifies D_1 structures only up to the base of the Boolgeeda Iron Formation, which he interprets to indicate that they formed prior to deposition of the remainder of the Formation, possibly by seismic activity associated with emplacement of the Woongarra Rhyolite and / or "Weeli Wolli" dolerites. However, as D_1 structures are only developed in certain horizons and as the Boolgeeda Iron Formation does not have well developed alternating chert / oxide mesobands (Trendall and Blockley 1970), it is just as likely that no susceptible horizons occur above this point. It is also difficult to envisage that seismic activity alone would produce such well defined rodding.

The origin of rodding remains problematical, especially given that the precursor bed in the Nammuldi Member (*ca* 2620 Ma), for example, would have still have to have been plastic enough by (say) Boolgeeda times (*ca* 2440 Ma), but "lithified" by the start of the Ophthalmian Orogeny (*ca* 2450 Ma) very soon after. Alternatively, D_1 may well have developed progressively during sedimentation although some change in orientation with respect to stratigraphic position might then be expected. As no measurable change is indicated, it implies that the extension direction must have been controlled by long lasting, synsedimentary down warping or (growth) faults. Similarly, as there is no Province wide documented measurable change in the orientation, it also implies that there is no variation in the orientation of warping / faulting.

9.3 $F_{1.5}$

The $F_{1.5}$ folds are very similar in style to the F_2 folds but with the opposite facing (Photo 81), and are not as common or intense. Folds are minor south facing, asymmetric folds with amplitudes typically less than 20 m, a southerly vergence and a northerly dipping axial surface (ie north over south tectonic motion) and with or without a well developed crenulation to solution cleavage. Whilst overprinting relationships are rare, where apparent $S_{1.5}$ and $F_{1.5}$ are inferred to precede D_2 structures (Photos 82 to 84). From the 1995 mapping this group of structures was thought to be much more common and significant than initially noted in 1994. From 1995 data they have an average orientation for the axial surface of $49^o \rightarrow 006^o$ and fold axis of $02^o \rightarrow 275^o$ (Table 6). Mapping since that time has progressively down rated their contribution and influence.

At Alligator, folds of this geometry appear to be quite pervasive with amplitudes of over 100 m occurring on the southern flank of the Alligator Anticline (Photo 81). Here, $F_{1.5}$ may be more dominant than the F_2 folds and appear to be the controlling geometry of this part of the Alligator Anticline.

Although these folds do not greatly affect the overall geometry of stratigraphic contacts, the $F_{1.5}$ style fold may locally be as significant as the F_2 fold for providing the necessary geometry for iron enrichment where the folds are well developed. Its probable greatest significance with respect to mineralisation is in structural thickening and fluid mobility enhancement.

The asymmetry of $F_{1.5}$ suggests north over south, non-coaxial tectonics produced by north - south compression. Possible driving forces are early compression between the Pilbara Craton and an unidentified block to the south, which subsequently locked up and changed symmetry to become F_2. Alternatively, Lipple (1997) suggested they may be produced by gravity driven slumping of the Hamersley Basin, southwards off the Pilbara Craton.

9.4 D_2 - Ophthalmian Orogeny

The D_2 event (D_{2c}) was described by Tyler (1991) as pervasive, generally north facing open to elastica folds with upright to recumbent fold axial surfaces produced by the southeast part of the Ophthalmia Fold Belt. It is the most intense tectonic event and is probably associated with peak metamorphism.

The age of the Ophthalmian Orogeny is relatively poorly constrained, commencing to the south during deposition of the Turee Creek Group (possibly as early as 2450 Ma) and continuing through deposition of the Lower Wyloo Group until at least 2200 Ma, but possibly continuing considerably later. A volcanogenic breccia bed in the syn D_2 Cheela Springs Basalt gives an age of 2209 ± 15 Ma (Martin *et al* 1998b), however the relevance of this date is open to interpretation (see Section 5.3).

The typical overall asymmetry of the D_2 folds is north facing, indicating a non-coaxial, south over north motion tectonic movement.

By comparison, around Tom Price Hamersley Iron (eg Taylor *et al* 2001b) recognise two separate sets of folding in the Ophthalmian Orogeny, the first being syn Turee Creek Group (east – west Ophthalmian folds), followed by relaxation and rifting, and deposition of the Lower Wyloo Group with further compression (northwest – southeast Panhandle folds, Figure 25). The absence of these younger sediments in the central and east Hamersley Province makes any such subdivision impossible.

9.4.1 Folding

D_2 is marked by scale independent, doubly plunging (or curvilinear), east - west, north facing, open to tight asymmetric folds (Photos 85 to 88). At Mining Area C they developed in moderately narrow, linear to arcuate belts with intervening areas (or the long flat limbs) relatively undeformed and relatively unaffected by F_2. By comparison, at Newman the belts of folding are closer spaced to adjoining. Locally developed south verging folds do occur as parasitic folds on larger north verging structures (Photo 89).

Different styles and degree of D_2 folding between adjacent layers results in the localised development of bedding parallel detachment surfaces (Photos 90, 91).

Regionally, the orientation of the axial surface of range - forming megascopic D_2 folds varies from near recumbent in the south at Newman, to progressively asymmetric and upright north on Mining Area C (Figure 26). By comparison, lesser mega to microscopic folds do not show the same well defined geographic change in axial surface with the majority of these folds having a moderate south dipping axial surface. Locally they exhibit a less systematic change due in part to rheological differences.

S_2 is variably developed typically as a fine crenulation to solution cleavage. Closely associated with S_2 is the local development of relatively rare D_2 shear zones, best developed in the Mount Newman Member.

Slickensides defined by quartz fibre growth (ie slickenfibres) on the bedding surface are often associated with F_2's, suggesting a flexural slip folding mechanism.

As part of MERIWA Project M282, Cunneen (1997) estimated the degree or amount of shortening produced by folding during D_2. From review of data presented there, the degree of shortening estimated is highly dependent on the scale it is being measured at. This is due in part to the more deformed sections being measured at each scale, without making provision for less deformed sections (ie long flat limbs). As such:-

- at hand specimen scale where no flat lying undeformed limb is included, shortening is estimated at about 50%,
- hill-side to range-side scale with some undeformed component is about 25 to 40%, and
- on a regional scale where a significant proportion is undeformed is about 10 to 20%.

In combining the contribution of shortening at each scale to calculating the total apparent shortening, and making no provision for undeformed parts, a figure of 74% total shortening was reached by Cunneen (1997). However, this degree of shortening would also lead to an average four-fold gross thickening of the stratigraphic pile, which is not supported by observation. Using the same data, but assuming that at each step up in scale only 25% of the rock is significantly deformed at that scale (probably still an overestimate), the total apparent shortening is only 29% (or 1.4 fold thickening).

The cleavage and fold axial surfaces for F_2 (S_2) show a considerable scatter in orientation due to the later folding events and fanning cleavage etc, in the fold closures. In the Weeli Wolli Anticline, the overall pattern of the S_2 distribution is that of a loose point cluster, but with some tendency towards a great circle distribution oriented at 85º→274º (Table 6), compatible with refolding by F_3. Dividing the Weeli Wolli Anticline along its east / west axis, there is a subtle trend in S_2 data suggesting it is steeper on the southern side (59º→186º) than on the northern side (49º→176º), again compatible with F_3.

If the S_2 data for the Weeli Wolli Anticline is divided into a western and eastern half, the average S_2 orientation is the same (49º→181º and 51º→181º respectively). There is however, a subtle difference in the pole of the best fit great circle to the S_2 data from 89º→271º in the west to 82º→277º in the east indicating a change in plunge along the Weeli Wolli Anticline from near horizontal at the western end, to a shallow easterly plunge at the eastern end. This change in plunge agrees with the general outcrop shape and again is probably due to F_3, or alternatively the curvilinear nature of F_2.

By comparison, from data to the west of the Highway, there is little variation in geometry of F_2's except for a subtle reversal of plunge with the average orientation of S_2 (cleavage and axial surface) of 52º→182º and the fold axis of 04º→096º. This lack of variation of the average orientations of F_2's between Mining Area C East and West is also apparent for other structures (Table 6).

The F_2 fold hinges tend to be nearly coaxial to the $F_{1.5}$ fold hinges, although there does appear to be a weak trend with F_2's slightly east southeast – west northwest compared with $F_{1.5}$'s , which tend to be more east - west (Table 6). An exception is at Alligator South where the $F_{1.5}$'s tend to be the more east southeast – west northwest in orientation, implying a similar orientation of the major stress field as F_2 elsewhere.

9.4.2 Thrusting

Minor south over north thrust faults consistent with being F_2 related, were first positively identified from drilling at C Deposit (Kepert and Tehnas 1995), and subsequently identified in outcrop during 1995 detailed mapping. From drill data they have an apparent movement of up to 200 m and develop preferentially on the Mount Newman / West Angela Members contact. Thrusts in a similar geological setting have now also been positively identified along the remainder of the Northern Flank and elsewhere in the Mining Area C region (eg Jaws). Transfer of this BHPIO structural model via contract geologists has also been responsible for the recognition of thrusting regionally at Hope Downs, West Angelas, Silvergrass and Nammuldi.

From drilling at C Deposit and elsewhere along the Northern Flank, the orientation of the thrusts is south dipping (10 to 40º) and approximately axial planar (eg C West and C East Thrusts, Figures 27 to 29). Associated with the thrusts are gently north dipping splays (eg C Central Fault). These were originally termed thrusts (Kepert and Tehnas 1995), but strictly speaking are low angle extensional faults and compatible with forming as D_2 Riedel shears. Faults with a similar geometry are also known from Paraburdoo 4 East and 32 East (eg Harmsworth *et al* 1990) and Mt Whaleback (eg Ronaszeki 1997, Figures 3.8, 3.10 etc).

There is a strong spatial relationship between the thrusts and faults along the Northern Flank but there is comparatively little overlap between them (Figures 27 to 29). This is probably due to once a structural break initiates, all strain is partitioned in to it and any other break is therefore unlikely to develop. The apparently simple pattern may also be influenced by what can be interpreted from drill data.

Also apparent in the structural contours of the thrusts and faults (Figure 29) are some local sub-horizontal sections where the thrusts are presumably following the bedding rather than the foliation. This is also seen in outcrop in areas of intense flexural slip induced shearing, with the shear surfaces stepping in and out of the enveloping surface of the bedding (see Section 10.3). A similar geometry is also apparent in the C West Thrust in the east wall of the bulk sample pit where the orientation varies between a shallow and a moderate southerly dip over a wavelength of about 20 to 30 m (ie smaller than the drill spacing in Figure 29). Small scale faults and thrusts are also apparent stepping in and out of bedding is AS3 shales at OB29 (Photo 92).

The geometry of a fault complex apparent from airphoto interpretation at Jump Up Bore south of Juna Downs Homestead is consistent with a well developed stacked thrust sheet (Jump Up Thrust, Photo 93). Here, a single Karijini Dolerite sill is repeated 5 times by thrusting with a total minimum inferred movement of over 400 m. The location has not been ground checked (note, this would also imply that the dolerite is pre D_2, and not syn D_3 as argued by Lipple *et al* 1996, see Section 5.1).

With the exception of thrusting interpretated at W4 (Jimblebar) from down hole gamma logs (Kerr *et al* 1994), thrusting has also long been suspected to occur in the Newman – Jimblebar region (eg OB33) but no cohesive agreement could be made on the data. Mining has since exposed a number of thrusts at W4 (Photo 94).

More recent mapping (Kepert 2000a, b) has positively identified medium (Photo 95) to large scale thrusting (including re-interpretation of some known faults previously interpreted as late normal faults, eg Homestead Fault), that are not only localised in the upper Marra Mamba Iron Formation, but crosscut throughout the sequence with over 500 m of stratigraphy removed in places. Minimum inferred displacements are not readily apparent as no source for the allochthonous or transported blocks are preserved, but are in the order of kilometres. The source of the allochthonous blocks may either have been removed or overthrust by continuing D_2 thrusting, or other subsequent tectonics, uplift and erosion. Some of these mapped faults may also have an unrecognised (late) D_2 extensional component.

It is important to note that whilst thrusts at Mining Area C and Newman have essentially the same geometry, conceptually they may have developed by quite different mechanisms. At Mining Area C they have preferentially developed during folding at the West Angela / Mount Newman Member contact by over straining and extension of a fold, leading to localised breaking or detachment of the fold along the contact (or other similar weak layer) subparallel to the axial surface. The thrust may then have splayed off the sheared contact and propagate several 100's m into the adjacent stratigraphy but remain essentially intraformational. As such, they are unlikely to represent a shallow expression of a deeper detachment. Smaller scale thrust at Newman and Jimblebar are also likely to have developed by a mechanism similar to that described above. By comparison, major thrusting at Newman probably represents the upper extensions of deep seated thrusts and subhorizontal detachment surfaces. The different mechanisms resulted in an order or two of magnitude greater relative movements and thrust - out stratigraphy at Newman. Deep seated structures may also act as conduits for fluid flow.

9.4.3 Late Extensional Faulting

Whilst not apparent in the Mining Area C region, late extensional (south off north), sub-horizontal D_2 faults are known from the Newman region (eg Central Fault and East Footwall Fault Zone, Mt Whaleback). All such faults have been located by deep drilling with none having a mappable surface expression prior to mining and therefore, their apparent absence from Mining Area C can not be presumed. In the Newman region they appear to be spatially (and genetically?) related to M-(mpl H) style mineralisation.

Although of very different geometry (north block down, high angle, normal), the late D_2 extensional Southern Batter Fault at Tom Price is also interpreted to be genetically linked to M-(mpl H) and / or iron - carbonate mineralisation there (see Section 6.1.1). Further, Taylor *et al* (2001b) argued by association that the low angle extensional faults at Mt Whaleback were originally developed as high angle faults as per the Southern Batter Fault but were subsequently rotated by listric faulting along the D_5 Whaleback Fault. This hypothesis of rotation (apart from being irrelevant to their model as all that is required is late D_2 extension) was based on no hard facts and was refuted by Kneeshaw and Kepert (2002).

From non-intuitive reinterpretation of extensional shearing in anisotropic high grade metamorphic terrains, Harris (2002a) has proposed an alternate model for the development of folding between parallel extensional shears solely via extension, rather than early compression (folding) followed by late extension (shearing) along pre-existing structures (S_2 here). The model requires for the initial back rotation of the shear bounded block as per the development of extensional crenulation cleavage. Continued but currently unexplained back rotation which is supported by observation in outcrop, progressively rotates strata in the block perpendicular to the regional shortening field resulting in the development of folding parallel to the bounding shears (Figure 30). Resulting folds have the opposite sense of asymmetry than is predicted from current models of folding associated with shearing (ie drag folding).

From extrapolation of his model up in scale but down in grade, Harris (2002b) has proposed that it is possible (but **not** proven) that some of the D_2 folding observed at Mt Whaleback which as a whole geometrically fits the model, may have developed during extension between subhorizontal extensional faults (Figure 31). Additionally, it has the potential to influence fluid movement that may, for example, be linked to ore genesis.

Importantly, this model of extensional folding does not invoke a different tectonic regime during the Ophthalmian Orogeny as a fold and thrust belt can produce local to regional domains of syn to late extensional structures such as those documented at Mt Whaleback, Mining Area C and Tom Price.

As described above (Section 9.4.2), the geometry of the shallow, north dipping faults along the Northern Flank is consistent with it being a possible late extensional fault, that is, sub-horizontal to north dipping and north off south movement (Figures 27, 28). However, as they appear (from interpretation of drill data only) to be associated with the thrusting, they are interpreted to be a Riedel shear developed during the main D_2 thrusting. They also have the opposite sense of movement to other known late extensional faults. We should know in about 5 to 10 years time!

9.5 D_3 - Ashburton Orogeny

The Ashburton Orogeny D_3 (or D_{2a}) event is considered to be less intense than the D_2 event, but it is responsible for the development of the major map scale folds such as the Weeli Wolli Anticline and Packsaddle Syncline, which cross cut earlier D_2 folds. The *ca* 1800 to 1650 Ma Ashburton Orogeny is post Upper Wyloo Group (June Hill Volcanics 1843 ± 2 Ma, Pidgeon and Horwitz 1991) and pre Bangemall Group (1638 ± 14 Ma, Nelson 1995). Note, HI refer to this period of deformation as the Capricorn Orogeny (Figure 25).

Folds are approximately coaxial to F_2, and as such it is only possible to positively identify F_3 when there is an overprinting relationship (Photo 96) or when locally there is some angle between the two sets of fold axes (as in the western Hamersley Province).

In the eastern Hamersley Province, F_3 has generally produced gentle to open symmetric folds with upright axial surfaces oriented 90º→000º and fold axes coaxial to sub coaxial to $F_{1.5}$ and F_2 folds with an average orientation of 00º→090º. There does however, appear to be a general weak trend in that some $F_{1.5}$ and F_2 folds are more east southeast - west northwest in orientation than the F_3, folds which tend to be more due east - west. By comparison, this is the opposite relationship to the western Province (eg Figure 32) and at Mt Newman (Gregory 1998) where F_2 folds trend east - west and F_3 folds more east southeast - west northwest, but the same as OB35 compared with Western Ridge syncline (Kepert 2000a).

The maximum fold amplitude of the largest F_3 folds is difficult to estimate, but it is possible that it may be in the order of 200 to 500 m (eg Photo 97), with a wavelength of about 10 to 20 km. The kinematics of F_3 indicates that it was formed by a north - south horizontal compression.

The F_3 folds are often associated with the development of a moderate to weak, crenulation cleavage, to spaced fracture cleavage. From data from the Weeli Wolli Anticline, the S_3 pole data shows minimal scatter in its orientation, with a slight tendency to lie on a great circle with an orientation of 05º→087º. This suggests little or only localised, minor later deformation.

In the Ashburton Basin to the south of the Hamersley Province, the Ashburton Orogeny can be seen to be a protracted episodic multiple deformation event. This is evidence by several ages of folded unconformities as the Yilgarn and Pilbara Cratons collided producing various episodes of sedimentation, deformation and erosion.

9.6 F_4

Two late cross cutting events locally deform the region. Both events are very weak and only cause minor folding or warping of pre-existing surfaces. No definitive cross cutting relationships between F_4 and F_5 have been located, so their relative order is yet to be proven. The inferred order defined at Jimblebar (Lipple 1995) has been retained. It is possible that they may be conjugates and therefore, may be part of the same deformation event. Historically, Pd_5 dolerite dykes have been linked to F_4 (eg Lipple *et al* 1994), however, as these only intrude up to, and interpreted as feeders for, the late D_2 Cheela Springs Basalt this is can not be correct (see Figures 15, 25).

The age of F_4 is unknown, but it may be associated with tectonics of the Blair and / or Bresnahan Basins prior to *ca* 1650 Ma. The apparent overlap with the generally accepted age of the Ashburton Orogeny (ie D_3) above, suggests that F_4 may be a later part of the broader Ashburton Orogeny.

The average orientation of S_4 is 90º→044º. Cleavage is typically poorly developed, except for a spaced fracture cleavage in the hinges of rare tight folds.

Several major F_4 folds with locally overturned bedding at Fork South and Governor Range are traceable for up to 500 m. Along the southwest face of The Governor, D_2 folds (Photo 86) were interpreted to have possibly been rotated into an F_4 orientation by D_4 folding and / or faulting. From experience gained during 1:5 000 mapping along the Northern Flank however, it is more likely that these folds are part of an arcuate zone of D_2 folds (see Section 10.3). Similarly, an asymmetric north / south fold at North Alligator (Photo 98) may also be D_2 in origin.

The broad, undulose nature of many of the ridges when viewed looking either north or south is interpreted to be due to either regional F_4 and / or F_5 structures. For example, on Packsaddle Range, broad anticlinal crests of indeterminate strike direction coinciding with MAN, International and Spring Hills. Depending on the strike of the fold axis, they have a wavelength of between 5 (oblique) to 10 km (perpendicular).

Note that F_4, as defined here, is not the same as that locally defined at Mt Whaleback (Ronaszeki 1992, 1997), which may also be (another) part of the broader Ashburton Orogeny.

9.7 F_5

F_5 folds are interpreted to be associated with the opening of the Bangemall Basin at about 1638 ± 14 Ma (Nelson 1995). In the eastern Hamersley Province, the period was marked by extensive and prominent northeast - southwest regional normal faulting (eg Whaleback and Wheelarra Faults), and less widespread but prominent northwest - southeast normal faulting (eg Poonda Fault). Pd_7 dolerite dykes that crosscut the Bangemall Basin have historically been linked to F_5.

Folding is less frequent and less well developed than F_4 folds. From the limited data collected, the average orientation of S_5 is 90º→128º.

9.8 Faulting

9.8.1 Thrust Faults

The majority of thrusting appears to be directly related to D_2 and is described there (Section 9.4.2). The possible exception to this is the interpreted southeast over northwest Pillow Thrust at Big Creek (Mining Area C Park), adjacent to and possible related to the transcurrent Big Creek Fault (see below).

9.8.2 Transcurrent Faults

Sub-vertical, transcurrent faulting (Figure 2, Photo 99) dominates Mining Area C Park and western Alligator, with apparent lateral movements of up to 3.5 and 2 km on Big Creek and Eterak Faults, respectively. Where exposed, the faults are narrow (10 to 30 cm) and brittle, and except for minor brecciation up to 2 m away, do not deform the surrounding rocks. The majority of the major faults have an apparent dextral movement, although the northern most major faults (Dog Leg and North Alligator Faults) and some of the smaller splays have an apparent sinistral movement. Big Creek Fault develops into a flower structure of four main splays as it transects the Marra Mamba Iron Formation. In the Joffre Member along Eterak Fault, very limited magnetite recrystallisation and associated cleavage and quartz fibre pressure shadows around the magnetite indicates locally elevated temperatures.

Mineralisation is not preferentially developed along the any of the faults, with only minor surficial M-G mineralisation present.

There is evidence of possible thrusting along the Marra Mamba Iron Formation / Fortescue Group contact in the Big Creek Fault area, where parts of the Nammuldi and MacLeod Members are absent. The sense of movement is consistent with D_2 but may also have been re-activated during transcurrent faulting. A structural reconstruction of the area also suggests some removal of the Wittenoom Formation by similar thrusting.

The relative age of the transcurrent faulting is somewhat problematical, as no good overprinting relationships between faults and folds or cleavages were observed. Similar faulting around Paraburdoo is interpreted to be re-orientated, low angle, normal, listric, D_1 faults (Duncan *pers comm* 1996). If true, then at Mining Area C Park there has also been subsequent movement(s). The apparent movement and regional geometry is consistent with a general north - south compression, which is taken up in the east by east - west orientation folding (F_2 and / or F_3). However, due to competency / rheological differences in the underlying basement to the west, transverse faulting has developed. The north - south compression and vertical attitude are consistent with D_3, and therefore it is probable that the faults are D_3 related. The regional geometry suggests a giant splay or flower structure developed on the southern half of Milli Milli Dome with predominantly sinistral movement to the north, and dextral to the south. The apparent transcurrent displacement is likely to be only the final movement along major pre-existing crustal weaknesses (remnants of greenstone belts) between more competent blocks (granites).

Different crustal competencies are also reflected by the refraction of the folding and increase of late dolerite dykes to the west. It may be due to either differences in the underlying Pilbara Craton, or thicker, graben - filling Fortescue Group to the east resulting in a more ductile basement. The change in tectonic style also coincides with the western limit of the Sylvania Inlier, suggesting that it may have had having some influence.

9.8.3 Normal Faults

No major normal faults were mapped in 1994 and 1995 in the Marra Mamba Iron Formation, but it is unclear whether this is a real feature or is due to a lack of easily mappable marker beds. The only faults mapped were associated with a linear intruded by a Pd_5 dolerite dyke extending southeast from C Deposit West. In part, this linear forms a narrow zone of *en echelon* faults, with one fault having an apparent normal motion of about 10 m.

In comparison, major east - west striking, south block down, normal faulting was mapped over much of the length of Packsaddle Range from MAN Hill to Weeli Wolli Spring. Strike lengths of individual faults may be over 10 km and with apparent vertical displacements of up to 400 m. The majority of the faults mapped were in either the upper part of the Joffre Member (most easily recognised where it is faulted against overlying strata), or in strata beneath the Dales Gorge Member. Faulting may also be present in the Dales Gorge to lower Joffre Member interval, but as much of this is at least surficially enriched, no major faults were recognised. Offsets noted in the Whaleback Shale Member however, indicates that some faulting must also be present in this interval.

Mineralisation does not seem to be preferentially developed along the mapped faults, with the only area of significant (M-G) mineralisation at orebody P3 (Snake Gorge) along Yeerabiddy Fault. Surficial mineralisation is developed along much of the Fault’s length, but much of this is only due to minor canga development in a weak topographic low associated with the fault. The north face of Box Canyon (Box Canyon Fault) is marked by a 10 m thick silicified yellow breccia containing BIF clasts (Photo 100).

Minor faulting mapped elsewhere include:-

- a northeast - southwest fault cutting across Fork South (also apparent on airborne magnetics for over 10 km strike length),
- northwest - southeast, southwest block down faulting between Governor Range and The Governor,
- various normal faulting on the flanks of Mt Robinson, and
- locally developed faulting of Bruno's Band.

It is worthy of note that the majority of faults mapped are strike parallel to the ridges and have an apparent normal movement with the down thrown block being that closest to the Wittenoom Formation. That is, the faulting may be reflecting gravity driven slumping off the hills into the valleys or dissolution of the Paraburdoo Member (eg Photo 101) and may not be part of a true deformational event *per se*. As such, they may also be of variable age, and as young as the Mesozoic or Cainozoic. Recent landslips and block failures (see Section 7.5, Photo 73) are similar in style to faulted Dales Gorge Member in the southeast part of Mt Robinson. It is unclear if this faulting is related to minor deformation apparent in the Miocene Conglomerate along the Southern Flank (see Section 7.2.4), as it is geographically remote from any mapped faulting of this type.

Interpretation of drilling at C Deposit postulated the existence of medium scale, tensional, north block down, normal faults, possibly related to late D_2 (Kepert and Tehnas 1995). The subsequent shaft sinking program intersected small scale faulting with a similar geometry (Tehnas 1997).

Detailed mapping along the Northern Flank in 2000 located similar normal faults at C and E Deposits in the MacLeod Member (Photo 102). They are parallel with, but have an opposite sense of movement to, syn D_2 shears in the Mount Newman Member produced by over tightening of folds and associated flexural slip. As such, they may have preferentially developed along such pre-existing weaknesses.

They may also be related to faulting in the Brockman Iron Formation and surrounds, described above. Whilst still open to interpretation as to their relative timing, there is little doubt of their existence, and the effect they have on the geometry of the Northern Flank orebodies.

9.9 Other Features

Kink folds and conjugate kink folds are rare but do occur (Photo 103). Insufficient data has been collected on kinks and so very little can be said about their spatial and temporal relationships. A significant proportion do however tend to trend north, with no clear relationship to other deformations and have at times been colloquially referred to as F_6.

Various joint sets are developed throughout the region, but again insufficient data has been collected to interpret the relationship of these structures. Typically the orientation of these joints has only been measured where they are associated with either dolerite dykes or sub vertical faulting. Similarly, the orientation of quartz veins has only been measured where they are associated with faulting or flexural slip. The majority of other quartz veins are subparallel to bedding and were not measured.

10.0 DISCUSSION AND TECTONIC MODELS

There has been an increase in discussion of fold styles over the last few years resulting in a more comprehensive awareness of the change in character of folds along strike (eg Photo 85), style of parasitic folds and fanning cleavage, and juxtaposition of two different fold styles with little or no observable interference. This in turn has lead to some degree of confusion in assigning a particular fold to a given event. To minimise confusion by relabelling folds (or even worse, not labelling folds), the previously defined deformational history has been followed throughout the entire program. If nothing else it groups similar folds together, successfully discriminates between upright, north and south facing folds and comments on the tightness, associated cleavage etc. It also allows for the relabelling of south facing (ie $F_{1.5}$) folds as D_{2S} folds at appropriate the time when consensus can be reached.

It should also be noted, that as there are very real and obvious differences in the regional style of tectonics in the western and eastern Hamersley Province, a single tectonic model may not be applicable across the entire Province. This difference has more recently been explained by thin - skinned (in the east) versus thick - skinned tectonics (eg Hackney *et al* 2001).

10.1 On the Shape of Folds

The geometry of a fold is principally controlled by the orientation of the stress field. However (and critically importantly) in the case of well layered, anisotropic rocks such as those of the Hamersley Group, the geometry is also very dependent on the ratio of relative thicknesses of, and competency contrast between, the adjacent layers. Thus, a classification system based primarily on the geometry of a fold in a well layered, anisotropic rock, as presented in Section 9 above, may lend itself very open to misclassification and misinterpretation of any given fold. Other characteristics of folds such as scale, degree of development, interlimb angle, type and orientation of associated fabric etc can and have also been used above. However all of these are also ultimately controlled not only by primary characteristics of the deformation such as the stress field, confining pressure and temperature etc, but also by the rheological properties of the rock.

Examples of an apparent conflict of fold style versus broader geometric relationships that have previously led to a probable misinterpretation of the generation of folds are:-

- tight to isoclinal overturned folds (ie F_2) developed in Mt Sylvia Formation are spatially and therefore presumably genetically associated with, broad open approximately upright folds in the Dales Gorge Member (ie F_3) which occur on The Governor (Photo 86) and elsewhere, and

- arcuate, overturned tight syncline (ie F_2), paired with and parallel to, open upright anticlines (ie F_3) along the Northern Flank.

In both cases the upright folds should be reclassified as D_{2U} folds.

Ramsey's fold classification (Ramsey 1967) recognises three main classes of folds based on the relative curve of the inner and outer arcs, hinge to limb thickness ratio, and the convergent to divergent nature of dip isogons. Ramsey and Huber (1987) also classified the deformation style of multilayered anisotropic rocks with respect to the ratio of thickness and the competency contrast between relatively less and more competent layers. The style of folding predicated by Ramsey (1967) is in good agreement with field observation of folds in the Hamersley Group (eg Gregory 1998), with single layers typically forming Type 3 or 1(B) folds.

In terms of multilayer classification of folds (Ramsey and Huber 1987), Class D, E and F (high competency contrast with varying ratios of stiff and weak layers) ranging from parallel to chevron and box (or conjugate) folds are all predicted for Hamersley Group strata. Of particular note is that box folds are likely for much of the sequence, that is the production of opposite facing folds from a single compressional event (eg Photo 89).

The change in fold shape with thickness versus stiffness is also well illustrated by the difference between the Fortescue and Hamersley Groups whereby the Fortescue Group comprising relatively thick and stiff basalt units folds broadly at a relatively long wavelength compared with the weaker sedimentary parts of the Hamersley Group which fold at a significantly shorter wavelength, with much of the additional folding developed as intrafolial to intraformational folds.

Based on field evidence, the relative stiffness verses weakness of interlayered units as defined by their resulting fold style is not what may have been intuitively reasoned. Obvious thick bedded and stiff units are the Fortescue Group (as above), Woongarra Rhyolite and the Weeli Wolli Formation, particularly when dominated by thick dolerite sills. At the opposite end of the spectrum the shale dominant West Angela Member, Mt Sylvia Formation and Mt McRae Shale are the weakest.

Within the Marra Mamba Iron Formation, the Nammuldi and MacLeod Members often behave more stiffly, presumably because they are dominated by thick cherts but possibly also as they may not have decoupled from the underlying Fortescue Group. By comparison, the Mount Newman Member is significantly weaker, often preserved in a tight syncline between more open anticlines. This implied weakness is opposite to what may be expected given the relatively few and thin interbedded shales compared with the MacLeod Member, for example. Equally surprising is that the weakest part of the Mount Newman Member appears to be N1 (or more specifically between NS1 and NS2) rather than the relatively more shale dominant N2. Whilst yet to be proven, here there is a good empirical relationship between the relative weakness of a given BIF compared with either interbedded BIF or chert and its riebeckite content.

The Joffre Member, which has a similar percentage and relative thickness of shale bands as the Mount Newman Member, also appears to be weaker (ie deformed) where more riebeckitic. High strain zones identified by Gregory (1998) at specific horizons in the Joffre Member across the Mt Newman Anticline may be reflecting this (Figure 33). BIF of the Dales Gorge Member, by comparison, behaves more stiffly regardless of riebeckite content with more of the strain being partitioned in to the thicker and more abundant S macrobands.

Another group of folds that may also potentially be important in understanding the observed geometry are fault bend folds produced where a layer parallel thrust steps up obliquely through the strata (see Figure 35). The allochthonous block progressively folds and unfolds as the fold axes propagate through the sequence as it alternates between ramps. Folding developed during south over north compression by this method may be both north (F_2) and south ($F_{1.5}$) facing.

10.2 "Duncan" Model

The "Duncan" Model[20] was initially developed in the eastern Hamersley Province, but has since been downgraded in likelihood there due to subsequent conflicting evidence. It may however, still be applicable in the west where early dome and basin style of tectonics dominate. The model requires for two generations of asymmetric thrust-like folding, one from the north ($D_{1.5}$), then one from the south (D_2), and is now principally championed by ACD.

Recent mapping by Duncan, Benbow and others for Hamersley Iron in the western Hamersley Province (Silvergrass, Nammuldi) suggests that the major dome and basin features (eg Jeerinah Anticline, Brockman and Turner Synclines) may be formed during the $D_{1.5}$ event (Duncan *pers comm* 1999, 2000). Evidence includes:-

- that the D_2 folds cross cut the larger dome and basin structures without any apparent deviation and therefore postdate the doming,
- that the domes and basins have a weak but measurable asymmetric skewing compatible with $D_{1.5}$, and
- rare, but consistent overprinting relationships, principally $S_{1.5}$ being folded by F_2, ie similar to those at Mining Area C.

In the eastern Hamersley Province there are no well defined regional dome and basin structures so the first two points above can not be critically addressed. Note however, that sense of timing implied by the first point above was originally proposed by Tyler (1991), but with the doming being pre Lower Wyloo Group and D_2 (D_{1c} and D_{2c}) being pre Upper Wyloo Group (see Figure 15).

Rare overprinting relationships as above, and numerous examples of north dipping foliations and south facing folds that are consistent with the "Duncan" Model do however occur in the eastern Province. Alternative methods of generating these

[20] After AC Duncan, ADAW Pty Ltd.

structures are discussed below. Possibly the best example of this at Mining Area C is an outcrop on Fork South (Photo 84) which has two cleavages, one dipping shallowly to the north, juxtaposed (?crosscut) by the other dipping moderately to the south (ie S_2).

By comparison, the majority of dome and basin structures were originally considered by Powell and others to be interference structures between D_2 and D_3 folds (eg Figure 32), rather than predating D_2. More recently Powell (*pers comm* 1997 – 1999) has proposed an alternate hypothesis whereby the basement domes are D_2 in origin being tectonically emplaced by subhorizontal ramping detachments or thrusts in the basement (see Section 10.4 for the model preferred here).

10.3 The Diverse Nature of D_2

The D_2 event produced by south over north compression, was the most intense event throughout the Hamersley Province, producing relatively narrow, commonly arcuate zones of medium scale, tight, overturned, north facing, asymmetric folding and associated thrusting. From available age constraints and comparison of similar continent - continent collisions, it is also likely that D_2 is a complex and protracted orogenic event rather than a simple, single phase of deformation.

10.3.1 Fold Geometry

From recent detailed mapping on the Northern Flank, the Mount Newman and West Angela Members are seen to be particularly susceptible to development of tight overturned (and thrust) folds. The underlying units being more rigid and typically only form more open, apparently symmetrical, upright folding. As previously mentioned, this is similar to the crustal scale differences between the thick bedded, stiff Fortescue Group and the thinner, weaker Hamersley Group. This upright folding in the lower Marra Mamba Iron Formation has historically been (mis-) interpreted as D_3. However, based on the strong empirical relationship that the fold axes of the open, upright anticlines and north facing, tight to thrust, overturned folds are parallel arcs, it can be demonstrated that the anticlines are produced during D_2.

This empirical relationship between the pairing of an open, upright anticline to the south of a tight overturned syncline is not only confined to the Marra Mamba Iron Formation, but is also apparent at various stratigraphic levels throughout the eastern Hamersley Province. It follows then, that if D_2 produced open and upright anticlines, why not also upright anticline / syncline pairs? Unfortunately, due to the relative similarities in geometry between D_2 and D_3, no unequivocal evidence that indicates open anticline / syncline pairs may be linked to D_2 has been found. In summary, **many of the open upright anticlines (and synclines) are likely to be D_2 and not D_3 as previously / currently interpreted.**

Axial collapse is a common characteristic of folds developed in highly anisotropic rocks. It is developed where a contrast in rheologies produces relatively rounded open to more angular and tighter anticlinal closures in adjacent units. Resulting areas of low pressure in the hinge may then either develop saddle reefs (or mobilisation of shales into the hinge zone for example), or axial collapse producing a curved axial surface (eg Photos 83, 88). The resulting curved axial surface has been mistakenly interpreted in the past as being due to the axial surface being folded by subsequent folding (ie $S_{1.5}$ by F_2 or F_3, S_2 by F_3).

Box folds are also commonly developed at all scales in anisotropic rocks (Ramsey and Huber 1987). Many of the mapped fold hinges of $F_{1.5}$ are subparallel to a F_2 of the same form (ie syncline to syncline, anticline to anticline), suggesting they are more likely box folds developed by the same deformation rather than being unrelated (eg Photos 83a, 85). This is well illustrated by the 1995 detailed mapping of B Deposit where the mapped, paired $F_{1.5}$ and F_2 axes are both significantly outside their usual range (trending between 100 / 280º to 130 / 310º), but remain subparallel to each other ("*…a priori premise, that the large northwest - trending panel of enrichment between B and C Deposits was an interference structure between $D_{1.5}$ and D_2. Although technically demanding to obtain the evidence to substantiated this model, it was clearly established it is correct.*" - Lipple *et al* 1996). Note, that it is not possible to produce the geometry seen at B Deposit by refolding the earlier folds with D_3. The maximum deviation of the $F_{1.5}$ and F_2 fold axes from their norm coincides with the axis of a possible, broad (but unsubstantiated) F_3 anticline. Being on the F_3 axis no rotation will take place.

10.3.2 Cleavage and Axial Plane Orientation

The orientation of D_2 cleavage is similarly <u>not</u> a good discriminator to the deformation as it varies significantly at all scales from microscopic to regional. Cleavage is commonly refracted in well layered anisotropic rocks between layers of varying rheological properties, particularly in fold hinges where a markedly fanning cleavage may also be developed. Small scale examples are ubiquitous. Large scale to regional examples of this are:-

- upright D_2 anticline with convergent fanning arrays occurs in the Joffre Member in a gorge just north of Box Canyon (Photo 104).

- Saper Vedere[21] Gully at the west end of C Deposit, in lower Mount Newman Member BIF, where D_2 cleavage and axial surfaces fans convergently across a macroscopic, upright anticline (wavelength of over 200 m) from dipping about 70º north on the north limb, through to vertical in the hinge, and to 50º south on the south limb (Figure 34, Photo 105). Parasitic folds developed here also have a similar geometric relationship. The north limb was one of the type exposures of $S_{1.5}$ located during detailed mapping in 1995 (Photo 106b).

- Parallel Ridge, where the all cleavage is steeply to the north on a regional north dipping limb, ie the same geometry as above except that only the north limb is apparent. Again, this was a type exposure of $S_{1.5}$, with Parallel Ridge supposedly being interpreted as an interference between approximately coaxial

[21] *Saper vedere* meaning "know how to look" were Leonardo da Vinci's watchwords

$D_{1.5}$ and D_3 anticlines (Lipple *et al* 1996), instead of the north dipping limb of a D_2 as interpreted here.

- cleavage refraction in the Jeerinah Formation between dolerite sills and inter-sill sediments, where with the dolerite sills have a variably developed upright cleavage and the sediments a more typical south dipping cleavage. This relationship is apparent regionally in the cores of Alligator, Wonmunna and Weeli Wolli Anticlines. Upright cleavage was also used as evidence that the dolerite sills (ie Karijini Dolerite) were probably syn D_3 (Lipple *et al* 1996), something that is now very open to re-interpretation.

- local intense folding and associated axial planar shearing has produced vertical (limbless) D_2 folds at Ando's Gorge east of Newman (Photo 107). Several hundred metres down stream S_2 dips about 50 to 60º south.

- the regional variation of the range - forming megascopic folds form near recumbent (at Newman) to more upright (Mining Area C, Figure 26).

The orientation of cleavage and associated small scale intrafolial folding may also vary significantly across a fold, ranging from sub-vertical on the sub-horizontal limb, to sub-horizontal on the sub-vertical limb. That is, the axial plane of the intrafolial folds are at a high angle to perpendicular to the enveloping surface rather than having a regionally consistent orientation. This geometry is compatible with initial layer parallel shortening producing small scale folding, which were subsequently reorientated by larger scale folding.

In some broad, open, upright folds it is difficult to gain a true three dimensional perspective of the axial plane. For example, an anticline on the northeastern part of Mt Robinson appears symmetrical and with a vertical axial plane when viewed over a relief of 50 m, however, when viewed over the entire exposure of over 200 m of relief the axial plane dips about 70º to the south. Even at this scale, however, the limbs still appear symmetrical. This subtle asymmetry may also be true of many other broad "upright" folds such as the previously described anticlines south of C Deposit. Incorrect axial planes may also be inferred if only one limb and part or all of the closure is apparent in outcrop such as some broad $D_{1.5}$ folds mapped at South Alligator (eg Photo 81). That is, **the apparent symmetry and therefore classification, of many broad open folds is dependent on how much of the limbs, closure and axial surface is apparent in outcrop.**

10.3.3 Fold Axis Orientation

As a general comment, mapped F_2 fold axes at Ming Area C trend about 80 / 260º whereas F_3 are more due east / west, but there is a considerable overlap between the two populations. As previously mentioned (Section 9.3), this angular relationship is not regionally consistent. Additionally, in areas outside of any significant F_3 influence that may have reorientated earlier structures, D_2 fold axes are observed to be inherently non-linear in nature (eg Photo 85), providing further scatter of the population. For example, on the Southern Flank arcuate synclinal keels of Mount Newman Member vary from bearing 80 / 260º to 120 / 300º. That is, **regionally and locally D_2 folds do not have a consistent axial hinge direction and therefore, classification based on either their absolute or relative orientation is flawed**.

It is even possible that some folds assigned to F_4 (and F_5) may be D_2. For example, tight to overturned folds bearing 130 / 310º to 150 / 330º on Governor Range and The Governor (Photo 86) mapped as having a F_4 component, are more likely to be part of arcuate D_2 fold. They are similar in orientation to proven D_2 folds at the northwest end of B Deposit that trend 120 / 300º to 140 / 320º.

10.3.4 Flexural Slip

In certain stratigraphic units, flexural slip during D_2 between adjacent beds locally played an important role in accommodating strain and in modifying the geometry of earlier and developing structures. Flexural slip is developed during folding of alternating stiff and weak layers with strain principally being partitioned into the weak layers. The unevenness of its development to specific stratigraphic horizons is well illustrated by Gregory (1998) where the degree of strain or flexural slip in the Joffre Member on the shallow and steep limbs of the Mt Newman Anticline show a strong stratigraphic correlation (Figure 33). Interestingly, the shallow south dipping limb which is generally considered to be "relatively undeformed", is as deformed (if not more) and has accommodated as much strain as the "more deformed" upright limb.

Stratigraphic partitioning is also evident on the Northern Flank where it is preferentially partitioned into the Mount Newman Member compared with the remainder of the Marra Mamba Iron Formation. Within the Mount Newman Member it also appears to be better developed in the lower part (beneath about NS2), but this may only be an artefact of the amount of outcrop and degree of mineralisation above this stratigraphic level. Well developed flexural slip is apparent only in some of the better outcrops of mineralisation.

Flexural slip is developed throughout the region with the best studied examples along the Northern Flank. Here **flexural slip has produced a range of structural features, some of which have previously been interpreted to be due to $D_{1.5}$** (Figure 34). Features include:-

- <u>rotation of earlier features</u> (Photos 106, 108, 109), in particular, that of small scale folds produced by layer parallel shortening. This has resulted in early folds on north dipping limbs having an asymmetry that was previously interpreted as due to $D_{1.5}$. However where outcrop allows for them to be traced across to the opposite limb, they are clearly D_2 related,

- <u>shearing of earlier features</u> (Photos 109, 110), producing curved axial surfaces previously interpreted as D_2 refolding $S_{1.5}$, and truncation of small scale folds,

- quartz fibre growths (Photo 108) developed on bedding surfaces indicate that the flexural slip is approximately parallel to dip direction,

- flexural slip on north dipping limbs produce a reverse sense of shear (ie north over south, Photo 110), and upright to south facing parasitic folds that have previously both been interpreted as $D_{1.5}$ structures, however, they clearly postdate D_2 layer parallel shortening,

- reverse, high angle shears (Photo 111) dipping at about 60º are developed as splays off bedding parallel shear in areas of more intense flexural slip on either limb. They are compatible with general north / south compression and probably develop as P shears viewed in the local reference frame of the sheared limb (Figure 35),

- locally, some beds bounded by intense flexural slip develop a S/C like fabric (Photo 110). This may, however, be due to the complete truncation of the closures of early intrafolial folds resulting in obliquely stacked bedding giving an apparent S/C fabric, and

- localised shears of various geometry and sense joining adjacent planes of flexural slip.

Planes of bedding parallel flexural slip also divide the strata into different structural domains where the degree of strain in each may be different. This results in differing amounts of re-orientation, shearing and truncation of early fabrics such as layer parallel folding in each domain (Photo 109). High angle, reverse shears together with flexural slip may further divide stratigraphically continuous domains into numerous small domains (Photo 111). In extreme cases, the axial planes in adjacent domains may differ by up to 90º (Photo 112).

The degree of slip or shear can be estimated by the relative thicknesses of the stiff versus the weak layers (Ramsey 1974, Gregory *pers comm* 2000). From measurements taken from outcrop of the Mount Newman Member on the Northern Flank, the calculated relative displacement between adjacent stiff layers (ie in the weak layers) and degree of angular distortion is in the range of 20 to 60 cm and 60 to 85º, respectively. Whilst the relative displacement is fairly modest, over a stack of 10 to 20 layers (over about 10 m stratigraphic thickness), it becomes significant. The angular distortion corresponds to a theoretical bedding to cleavage angle of 30 to 5º that, for a limb angles of only 30º, would result in a vertical to north dipping cleavage. That is, ignoring any possible influence from the development of fanning arrays or refracted cleavage, **the amount of flexural slip observed is sufficient to produce a moderate to steeply, north dipping cleavage or tight, south facing folds on gently, north dipping limbs.**

Intense flexural slip may lead to high strain zones where the axial planes of isoclinal folds are rotated parallel to bedding and hinges may be sheared out leaving only remnant closures (Photos 107, 109b).

Taking flexural slip up a level in scale, North and South Alligator Faults are high angle reverse faults sub-parallel to bedding and therefore are compatible with having been produced by flexural slip during folding of the Alligator Anticline. The core of Karijini Dolerite acted as a relatively rigid block, around which the Marra Mamba Iron Formation was forced upwards from the north and south (note, that the Alligator Anticline has previously been interpreted as a D_3, and not as a D_2 by Lipple *et al* (1996)). It is unclear which other regional faults may be due to flexural slip, for example the kinematics of the Central Fault at Mt Whaleback is compatible with being (albeit late) flexural slip on the Sylvania Inlier (note, that this would make the Central Fault compressional rather than extensional).

10.3.5 A Model for the of Development of D_2

Any model must attempt to explain the geometry and relative timing between all structural elements. Evidence for the style and nature of development of D_2 remains open to interpretation, with the model proposed here likely to be altered or superseded in the near future.

Folding probably initially formed as near symmetric, disharmonic, intrafolial to intraformational, layer parallel shortening producing local thickening of the sequence (Figure 35, Photo 106a). The axial surfaces of many of the small scale folds are (sub-) perpendicular to the enveloping bedding surface indicating that for the main part, they predate much of the larger scale folding, being produced by layer parallel shortening. Medium to large scale folding within discrete zones initially developed syn to post with the shortening, and by accommodating much of the strain, would have decreased the contribution of the layer parallel shortening with time. Rotation by folding of bedding planes out of the principle compression direction would also have decreased the component of layer parallel shortening, but would also tend to make it more asymmetric.

Continued tightening of the larger scale folding produced flexural slip on both limbs resulting in bedding parallel and associated higher angle shearing (Figures 34, 35, Photos 105, 106, 109 to 111). Bedding parallel shearing locally truncated, refolded and re-orientated some earlier small scale folds to the opposite asymmetry (ie south facing folds, Photo 110). Until recently these modified folds were interpreted to be a separate earlier event ($D_{1.5}$) due to their opposite symmetry and the overprint by D_2 shearing (and late D_2 folding), but are now best explained as being produced by D_2. Folds of this nature along the Northern Flank are typically small and do not impact in the overall geometry of the orebody. The high angle shears are compressional and are compatible with being a P shear in the local reference frame of the flexural slip of each limb.

A logical extension of the model is for asymmetric folds produced by layer parallel shortening to be progressively refolded by larger scale folds, such that in places, an incorrect vergence will develop. The resulting <u>refolded folds</u> are produced in a single deformation rather than two as is typically assumed. A similar conclusion but for higher strain zones was reached independently by Hollingsworth and Cawood (1999). A possible example of this is the well known and much studied "type exposure" of a F_2 / F_3 refold in Weeli Wolli Formation BIF at Cathedral Gorge (Photo 113). Evidence that suggests it may not be a F_2 / F_3 refold is:-

- that the geometry of the tight, overturned (D_2) syncline and open, upright (F_3) anticline is the same geometry as observed regionally for a D_2 syncline / anticline pair,
- the (F_3) anticline fold axis trends 124 / 304º (Gregory 1998) which is more akin to F_2, and
- the apparent juxtaposition of the F_3 anticline just north of the D_2 syncline is repeated 2 km west at Homestead Gorge (D_2 fold trending 125 / 305º, F_3 131 / 311º Gregory 1998, ie effectively the same). Apart from being a striking coincidence, it implies that regionally the two folds (or their *en echelon* sets) are exactly parallel implying they are related. Indeed, the majority of examples of "F_2 / F_3 refolds" are in the Weeli Wolli Formation (eg Eastern Ridge, Johnson 1994).

[Note, that Gregory (*pers comm* 2001) attributes this juxtaposition of a D_3 anticline adjacent to and just north of a D_2 syncline as being due to similar rock mechanics, that is similar geometry and rheology. Gregory also notes that for the second point above, this apparent fold axis trend may be due to inclusion of some F_2 data.]

It is argued here, that for some occurrences **an alternative mechanism for the development of a "F_2 / F_3 refold" in a package of interlayered thinner, weaker units (eg Weeli Wolli Formation BIFs) and relatively thicker, stiffer units (eg dolerite sills) is for smaller scale intrafolial folds developing in the thinner, weaker units being reorientated by synorogenic, relatively broad open folding or buckling of the thicker, stiffer units.** The degree of "refolding" apparent is then dependent on the original degree of asymmetry of the intrafolial folding and also the relative timing of when the thick, stiff unit changed from deforming mainly by shortening to buckling. This relationship of thin and weak versus thick and stiff is repeated many times at various scales through the entire sequence.

The structural complexity of the Weeli Wolli Formation BIF at Cathedral Gorge is also indicated by folds of different orientation that have been interpreted as F_1 and F_5. The F_1 is a layer parallel, isoclinal fold identical to other D_2 isoclinal folds, but with an northeast - southwest orientation (Liens *pers comm* 1999). It is identical in style to other similar scale F_2's and is probably a F_2 reorientated by flexural slip, for example. The open F_5 trending towards 339º (Gregory 1998) may be a local D_2 space accommodating flexure.

Alternative models of development for observed small to medium scale "$D_{1.5}$" structures and their apparent overprinting relationship with D_2 structures by flexural slip and other methods have been outlined above. At a larger scale, there are many examples of open to tight, south facing folds that have not been adequately explained by models presented so far (eg fanning arrays). Possible mechanisms (Figure 36) for the development of these folds are:-

- <u>box or conjugate folds</u> are a likely to be produced in layered anistropic rocks (see Section 10.1). A majority of mapped south facing folds are, for example paired with a similar formed, but opposite facing fold, south facing anticlines often have a north facing anticline directly to the north of them. This spatial relationship suggests they are a single, large scale box fold rather than two separate generations of folds. An open syncline may develop between an anticline pair but is usually comparatively broad and open, and probably represents further compression after development of the box fold. The open nature of the syncline is also against the norm (ie a tight syncline adjacent to an open anticline),

- axial collapse can produce a similar geometry to box folds. Axial collapse during folding will form an additional flexure of the south facing limb adjacent to and south of the main anticline axis. Further tightening of the fold during deformation will also result in tightening of the flexure producing a subordinate south facing fold,

- blind reverse thrusts that may have propagated upwards as reverse facing folds are a common feature in many fold and thrust belts. Evidence that may suggest their local development, is that where south facing folds occur, they dominate on a hill sized scale, usually at the virtual exclusion of north facing folds. That is, they are developed instead of, rather than as well as north facing folds. Examples of this are South Alligator and southern Coondewanna Ridge (Hollingsworth *pers comm* 1999) west of M244SA Section 22. This suggests they developed as an alternative to north facing, rather than as an earlier or different event,

- south over north fault bend folds can also produce an open south facing fold (see Section 10.1), and

- unfolding of D_2 folds by D_3 to produce a north dipping ("$S_{1.5}$") cleavage, this is however, mechanically very unlikely (eg Gregory 1998).

South facing folds produced by box folding should occur as an anticline / anticline pair etc, where as reverse thrusting and fault bend folds will produce syncline / anticline pairs.

Whilst not completely discounting the possibility of a $D_{1.5}$ event, alternate models for the development of "$D_{1.5}$" structures have been outlined here. If $D_{1.5}$ exists at all, it is probably as a ("earlier?") reverse thrust phase of the Ophthalmian Orogeny that locked up prior to D_2 proper.

Increased partitioning of the strain into confined zones during D_2 resulted in late detachment and thrusting, preferentially developed at specific stratigraphic horizons (eg Mount Newman / West Angela Members contact), and low angle, north dipping faults subparallel to bedding and / or shears produced during flexural slip. From there thrusting propagated through the surrounding sequence. Tight, overturned D_2 folds and associated thrusts of up to 200 m apparent displacement are the main control on the geometry of Northern Flank orebodies. Differential rates of propagation of a given part of either a fold or thrust led to the development of arcuate fold axes and zones of deformation. Along the Northern Flank, the broader, apparently upright folds to the south (exposed lower in the sequence) mirror this curve indicating they are D_2 and not D_3 folds as historically interpreted.

Regionally, the best developed zones of tight to over extended, detached and thrust D_2 folds also occur on the north dipping limb of broad open upright anticlines such as the Weeli Wolli Anticline compared with the corresponding south limb which by association suggests that the open folds are also D_2. There is no strong cohesive evidence backing the previous model (Figure 23) depicting equal development of D_2 folds and thrusts on both limbs.

The relative timing of the low angle, north dipping, extensional faults interpreted from drilling along the Northern Flank is problematical given there is no known definitive exposure. Only the C Central Fault is known to extend to the surface. It has removed much of the upper MacLeod Member with less than 10 m stratigraphic thickness remaining between the Mount Newman / MacLeod Member contact and the top of the Football Chert (normally 38 m, Figures 4, 6). Due to paucity of outcrop, it is not possible to locate the exact position of the fault in this interval, but it is assumed to be at the base of the Mount Newman Member. Possible models for the timing of the faults are:-

- they predate the thrusting, but this is not supported by evidence as they crosscut the major overturned folding that are pre to synchronous with the thrusting. If they predate thrusting they also have the opposite inferred movement to the flexural slip in the same structural setting,

- they are synchronous with, and genetically and spatially related to the thrusting. Evidence for this timing includes that their orientation and sense of movement are compatible with being Riedel shears produced during thrusting, and that empirically the faults and thrusts appear to be spatially related (Figures 27 to 29). For this model the faults will not have a consistent crosscutting relationship with respect to the thrusts, but both will splay off each other, and

- they postdate the thrusting and are more akin to low angle extensional faults. There is no evidence for or against this model except for the apparent spatial relationship above suggesting they are related.

Following the majority of the folding and thrusting, relaxation of the compression produced localised, small scale, high angle, normal faulting that preferentially developed, in part, along bedding planes and / or the pre-existing high angle flexural slip induced shearing. They are consistent with D_2 having formed in its extensional direction (Figure 35). Small scale faults of this nature are apparent in some of the BHPIO and GML C Deposit shafts. Possible extensional crenulation is also apparent at C Deposit (Photo 114).

In summary, the preferred structural model (Figure 35) presented here for the generation of the various fold geometries and related shearing and faulting seen along the Northern Flank is for the majority (if not all) of deformation to by due to a single, complex and protracted D_2 Ophthalmian Orogeny (Table 7). This structural model is consistent with deformation elsewhere in Mining Area C region, and can be extrapolated throughout the eastern Hamersley Province:-

- initial north - south compression produces symmetric to asymmetric, intrafolial, layer parallel shortening in susceptible units, with associated mineral cleavage development,

- continued compression produces larger folding, flexural slip, and reorientation of earlier and developing fabrics. This produced fanning cleavage and rotation of earlier folds into either fanning arrays, or possibly even refolds of earlier folds. Many of the resulting range of geometries and overprinting relationships have previously been interpreted as $D_{1.5}$.

- final strain taken up by overturned to recumbent folding, and localised thrusting and associated low angle extensional faulting (Riedel shears), including 1 to 10 km displacements on the southern margin of the belt. Many anticlines associated with thrusting may have the general characteristics of F_3 folds,

- relaxation of Ophthalmian compression produces late D_2 extensional faults as both low angle (eg Central Fault at Mt Whaleback) and high angle (eg Northern Flank) faults.

The subsequent <u>Ashburton Orogeny</u> is not readily distinguishable (and / or developed?) on the outcrop scale, but regionally may have produced much of the megascopic folding such as the Weeli Wolli Anticline. Much of the eastern Hamersley Province may have been effectively shielded from the Ashburton Orogeny by the Sylvania Inlier, but its impact intensifies to the west (Figure 37).

The Sylvania Inlier may have also acted as a ram or indenter during D_2 producing characteristic tight folding of the eastern Hamersley Province compared with the west.

Note however, that for the proposed framework above, the relative timing of events during deformation is applicable only to a local geological and / or geographical reference frame. As the deformation front of a fold and thrust belt propagates through a package of rocks, not all parts of the package will undergo the same style of deformation at the same time. For example, recumbent folding and thrusting in the south may be synchronous with initial layer parallel shortening in the north. Similarly, differing rheological properties of stratigraphic units will also affect the relative timing and style of deformation producing stratabound structural domains. Differences in strain and shortening between these domains will produce local to regional, bedding parallel detachments (eg Photos 90, 91).

Fluid flow during the Ophthalmian Orogeny would have been regionally from the south to the north, or more locally from the sub-horizontal to the steeper limbs as they rotated into the maximum elongation direction.

10.4 Pilbara Craton (Gravity) Driven Tectonics

The generally excepted model for the tectono-sedimentary history of the Pilbara Craton is for a relatively simplistic model of producing granite dome and greenstone keel by crustal inversion driven principally by density contrasts (Hickman 1983, van Kranendonk *et al* 2001), rather than by one of accretionary growth more akin to Phanerozoic plate tectonics favoured by some authors (eg Bickle *et al* 1985). That is, it is one dominated by vertical rather than horizontal tectonics. Current mapping and geochronology by the GSWA over much of the Craton has strengthened Hickman's model and refined it into a number of more discrete episodic periods of sedimentation and volcanism / intrusion with associated tectonism (eg van Kranendonk *et al* 2001). Each unconformity - bound "greenstone" group was deposited in a local to regional basin that was subsequently down-folded by coeval, episodic granite emplacement in the batholith complexes prior to the next cycle of sedimentation. Contacts between Formations in each Group are also typically unconformity bound in the tighter keels etc, indicating ongoing tectonism during deposition. The tectonics are driven by, and / or result in, the relatively denser sedimentary / volcanic greenstone sequences sinking in to tight to pinched, syncline keels between hot, up-welling, less dense, buoyant, granite plumes. In the East Pilbara Granite Greenstone Terrain (EPGGT), three major, widespread "greenstone" groups are developed with a periodicy of about 200 million years:-

- Warrawoona Group (3.47 to ~ 3.4 Ga),
- Gorge Creek Group (~ 3.2 Ga), and
- De Grey Group (~ 3.0 to ~ 2.9 Ga).

The last major granite activity in the eastern Pilbara Craton occurred at about 3.24 Ga (Strelley event), but less voluminous granite activity until about 2.85 Ga ("tin granites") as the Craton progressively cooled and become more stable and rigid. Tectonism however, had not completely ceased as evidenced by the Fortescue Group (2.77 to 2.63 Ga) being deposited in active grabens, typically overlying the synclinal greenstone belts. The basal Fortescue Group (Mt Roe Basalt) was deposited in keels formed by continuing isostatic adjustment between the greenstone and granite terrains, and represents a continuation of the steady accumulation of greenstone (Trendall 1983). This was followed by uplift, erosion and deroofing of the granites, deposition of the Hardey Sandstone and continuing volcanism. Subsequent and ongoing synclinal folding centred over older greenstone belts is well exemplified by the geographic distribution of remnant Fortescue Group preserved on the Pilbara Craton (Thorne and Trendall 2001, van Kranendonk *et al* 2001). Locally this produced dips up to 40º (Williams *pers comm* 2001). A comparison of the regional variation of the thickness of the Group by Hackney (2001) shows a marked thickening above some greenstone keels (Figure 38).

The Fortescue Group is equivalent to the fourth cycle of the development of the greenstone sequence, but due to the lack of plutonic activity, remains comparatively undeformed in the northern part of the Pilbara Craton and retains much of its original flood basalt or platformal character. The main tectonic difference between the earlier greenstone belt sequences and the Fortescue Group is the lack of syn to post tectonic / plutonic activity of the granitic basement.

During Hamersley Group deposition (2.63 to 2.45 Ga) there appears little direct or indirect evidence of any basement tectonic activity, such as grabens, growth faults or local to regional unconformities. One possible exception to this is the proto-Poonda Fault that may have been the bounding structure between the shallow water Carawine Dolomite to the northeast (Oakover Sub-basin) and the deeper, shelf sediments in the main part of the Basin (Kepert 2001a).

Trendall and Blockley's (1970) isopach map of the Dales Gorge Member suggests that the thickness of the Member increases gradually toward the centre of the current extent of the Hamersley Group. It does not suggest any major discontinuities that may indicate whether basement tectonics were active during and affected the thickness of the Dales Gorge Member. However, as the sample spacing is approximately equal to the frequency of basement doming with measurements typically coinciding with the edges of the domes, the data is compatible with, but inconclusive of any synsedimentary basement tectonics.

The interpreted asymmetry and timing of the major basin and dome structures in the western Hamersley Province is compatible with being part of an earlier north over south $D_{1.5}$ event (Duncan *pers comm* 1999). This north dipping asymmetry is also apparent by the offset of the major anticlinal axes with the underlying axis of the domes as defined on regional magnetic and gravity data sets (Figure 39). This asymmetry, however, could have developed during D_2 in a similar manner to fault bend folds, where the initial folding produced in the allochthonous block by a south over north movement was obstructed by a more competent feature (for fault bend folds this is the ramping of the fault, here it is the relatively competent underlying granite dome ramping up it and structures around its edges). The resulting broad regional folding will develop an apparent incorrect vergence.

Alternatively, this post depositional asymmetry may be reflecting an inherent, older, pre-Hamersley asymmetry of the basement doming (such as that of the Mt Edgar Batholith). Here uplift has continually been much more active along its southern rim than the northern rim giving a distinct structural asymmetry to the dome (Hickman *pers comm* 1999). Had a similar structural asymmetry occurred in the Hamersley Province, it could have been (mis-) interpreted in this instance as being due to $D_{1.5}$.

The preferred model here for the genesis of the doming in the Hamersley Province is that it directly relates to pre-depositional basement domes that have been reactivated prior to D_2, and not to various north - south compression (ie $D_{1.5}$, D_2, D_3), although D_2 and D_3 may have since modified the doming. Deformation was by way of passive isostatic readjustment or vertical tectonics of the granite / greenstone terrain along pre-existing structures.

It is well established that in the EPGGT this style of deformation continued to be very active long after the last major Strelley event. A period of activity in the order of 500 million years is indicated (from 3.24 until at least 2.77 Ga). Given that much of the granitic activity in the West and Central Pilbara Granite Greenstone Terrains (WPGGT and CPGGT, respectively) is significantly younger than in the EPGGT, and assuming vertical tectonics continued for the same period, then doming may well have still been active until at least 2.5 Ga, that is, syn to late Hamersley Group deposition. If the difference in ages between the EPGGT compared with the WPGGT and CPGGT is assumed to continue further south under the Hamersley Province, then it may account for the differences in the tectonic styles in the east versus the west Hamersley Province. That is, the eastern Hamersley Province may be underlain by older, more rigid basement than in the west.

Comparison by the author of the distance between the geometric centres of adjacent domes in the Pilbara Craton with those in the Hamersley Province indicates they are identical (58 ± 9 km, 56 ± 10 km, respectively). This includes less well defined domes in the more deformed parts of the southeast Province such as the Wonmunna Anticline, where regional gravity data indicate coincidence with a basement dome.

The term Rocklean Movement is proposed here to describe the on-going gravity driven inversion of the underlying Pilbara Craton during deposition of the Mt Bruce Supergroup producing dome and basin, or more correctly dome and keel, geometry in the supracrustal rocks. The duration and timing of the cessation of the doming is uncertain, however it was well developed by Ophthalmian Orogeny times but it is unclear if it continued to a lesser degree after this. As the doming appears to have been relatively passive deformation and due to its extended period of development, the term Rocklean Movement is preferred here rather than Rocklean Orogeny[22]. This terminology has been suggested to other workers (eg Hollingsworth, Duncan) to try and avoid a profusion of confusing terminologies. Describing the doming as a more passive movement rather than defining it as a deformation *per se* is also in keeping with recent practice by GSWA where the major partial convective crustal inversion of the eastern Pilbara Craton from *ca* 3280 to 3020 Ma is not included in their more discrete D_3 at *ca* 3240 Ma (van Kranendonk *et al* 2001).

Other major tectonic features controlled by the underlying Pilbara Craton include large scale transcurrent faulting as occurs in Mining Area C Park. Here the post Hamersley Group faults are developed on pre-existing basement faults wrapping the southern half of the Milli Milli Dome. The geometry of the faulting is compatible with compression between adjacent domes, creating a giant flower or pop-up structure similar to the Yarrie area (the marginal to tangential Elephant Rock and Kennedy Gap Faults mark the east - west compression between the Muccan and Warrawagine Batholiths). Other examples of basement controlled faulting are the Weeli Wolli and Prairie Downs Faults, which are both southern extensions of the Nullagine Linear (eg Hackney *et al* 2001).

10.5 Conclusions

Based on simple geometric criteria, it is difficult to distinguish between various structures caused by different episodes of north - south compression. D_2 or the Ophthalmian Orogeny was a protracted and complex event that produced a diverse suite of structures at different scales, geometries and orientations. Due to its varied and

[22] The name Rocklean is borrowed from Halligan and Daniels (1964) who first coined the name to distinguish the west northwest trending folds (Ophthalmian folds) from the more open, east – west folds such as the Brockman Syncline (Rocklean folds). They did not specify an order of deformation but from the order presented in the table implied that Rocklean was possibly younger.

diverse nature, it is difficult to classify small to medium scale structures to other deformations and in particular, to locate unequivocal or even compelling evidence for $D_{1.5}$. Applying Occam's Razor, **it is not necessary to have a separate north over south event prior to the Ophthalmian Orogeny** as all such structures can be shown to be compatible with D_2. The majority of mapped structures including some D_1 folds, all $D_{1.5}$ structures, some D_3, D_4 and possibly D_5 folds and some D_5 faults have been shown to be wholly compatible with being produced during D_2. Reclassification of various mapped structures with respect to a particular deformation event are summarised in Table 7.

The main controlling factors in the tectonic evolution of the Hamersley Province are therefore:-

- pre-existing tectonics of the **underlying Pilbara Craton** which remained active post Hamersley Group deposition (ie **Rocklean Movement**), in particular the geometry of the granite domes including their marginal, tangential faults. Relative differences in the age and therefore tectonic stability of the east and west parts of the Craton may have been a significant controlling factor between tectonic styles in the east and west Hamersley Province,

- the **Ophthalmian Orogeny** marking the initial collision of the Pilbara Craton and an unknown continental block to the south. It produced the majority of micro to megascopic structures apparent in the Province. The style of structures produced (and their relative geometry) were heavily dependent on the rheological properties, degree of D_2 development, including the relative degree of flexural slip and thrusting, and most importantly the highly anisotropic layering of the rocks. Much of the folding produced is scale dependent and intrafolial to intraformational. As rheological properties and degree of anisotropy change with both stratigraphy and scale, so too does the resulting fold style, and

- the **Sylvania Inlier**, which appears to have strongly influenced the regional divide between deformation styles of the east and west Hamersley Province. In the east it may have acted as a ram or indenter during the Ophthalmian Orogeny producing much of the intense folding (ie "thin - skinned" tectonics) now apparent that may have largely masked any earlier dome and basin tectonics (ie "thick - skinned"). Additionally, it may also have acted as a baffle during the Ashburton Orogeny minimising the impact of it in the eastern Hamersley Province.

Subsequent deformations had comparatively little impact on the region, mainly only modifying the orientation of previous structures by broad open folding and regional normal faulting.

11.0 DEPOSITIONAL TECTONIC SYNTHESIS

In modelling the tectonosedimentary history of the Hamersley Group, evidence should not be forced to fit either a yet to be substantiated geochronological framework based on regular and predictable sea level changes or on Phanerozoic plate tectonic settings, which together form the basis of sequence stratigraphy based reconstructions (eg Krapez 1996, 1997, 1999).

The remarkable regional lateral continuity of the Hamersley Group is unique amongst the known geology of the world regardless of lithology, age or tectonic setting and sets it apart from other similar platformal BIF - dominant basinal Archaean to Lower Proterozoic sedimentary sequences elsewhere. This feature together with the almost total absence of terrigenous derived clastics is perhaps both the hardest to envisage and explain, and the pivotal characteristic that must be incorporated in any model on the development of both the Hamersley Basin and Group. Continuity is not only developed on a macroband scale (ie dominantly chemical sedimentation punctuated by volcanic or turbiditic events), but is also apparently just as well developed Basin – wide at a meso to microband scale (eg Trendall and Blockley 1970, Trendall 1983, Morris 1985, 1993). It would be unlikely for this level of lateral continuity to be produced by suspension currents whether density driven or contourites as postulated by Krapez *et al* (2001) and Lascelles (2001). There is however, good evidence that the more laterally variable S macrobands are turbiditic in part or whole (eg Trendall and Blockley 1970, Hassler and Simonson 1998, Pickard *et al* 2001).

Lateral continuity not only places constraints on the stillness and therefore the depth of the water (below storm base or about 30 m), but also on both the trigger controlling the precipitation or deposition of various components, and on the mechanism of their replenishment to the water column.

11.1 Carbonates of the Group

Carbonates which occur as a major to minor component in the sedimentary pile up to the middle of the Joffre Formation, can provide much indirect evidence as to the architectural development of the Group. For the most part they occur as thin turbidite beds with all palaeocurrent indicators regardless of stratigraphic position giving a source of the carbonate to the north. This is compatible with a very long lived (spanning at least 180 million years) shallow water carbonate factory on the Pilbara Craton possibly akin to the Carawine Dolomite. Other evidence for a northerly source includes the geographic distribution of these horizons, the intraclast filled channel cut into well bedded carbonates at Wittenoom Gorge as being (one of) the feeders to the Mt McRae Shale carbonate turbidite and partly silicified stromatolitic clasts in DS4 at Wittenoom Gorge. The geographic variation of the stratigraphic thickness of turbiditic carbonate shales above the SMB in the Bee Gorge Member, which increases to the northwest proximal to the Fortescue Valley, is suggestive of the toe of a submarine fan, again sourced from the Pilbara Craton to the north.

By comparison, the Paraburdoo Member does not appear to be turbidite rich, being deposited as periplatformal derived pelagic carbonate ooze or mud. A significant part of the Marra Mamba Iron Formation has several percent of carbonate dispersed through its matrix, which may have the same pelagic origin as the Paraburdoo Member mud, however during Marra Mamba Iron Formation it was highly diluted by precipitation / deposition of silica and proto-BIF.

The Bee Gorge Member marks the largest volumetric pulse of carbonate turbidites, followed by the gradually waning of carbonate input over time to the thin carbonate beds in the Dales Gorge Member. With the exception of Mt McRae Shale carbonate, all subsequent, widely distributed carbonate beds are thin bedded distal turbidites indicating a major change in the nature of the carbonate platform to the north. This may mark either a change in climate or sea level with the platform being either flooded or exposed.

The Mindy debris flows (MDF) in the central Joffre Member provide strong evidence that to the north east of the Poonda Fault, the carbonates in the eastern Fortescue valley are not deep water Paraburdoo Member but are more equivalent to the mixed platformal Carawine Dolomite in terms of sedimentary environment and type of carbonate. Stratigraphically and chronologically, there is also parallels with both being underlain by a thin to absent, atypical Marra Mamba Iron Formation, and with a poorly defined to open age limit (although a diagenetic age of the Carawine Dolomite coeval with Bee Gorge Member deposition suggests they are not wholly compatible as the eastern Fortescue valley carbonates may in part be equivalent to the Joffre Member). The lack of other known fine grained turbiditic carbonates above the MDF suggest that the platform was no longer an active carbonate factory, but it is unclear if it were dormant, buried, sub aerially exposed or in a state of decay.

11.2 <u>On Banded Iron-Formations</u>

The origin of BIFs remains enigmatic (eg Trendall and Blockley1970, Ewers and Morris 1981, Cloud 1983, Morris 1993, Trendall 2002), as there are no modern equivalents due to the lack of dissolved silica and ferrous in modern oceans and also that no part of the resulting BIF is in the same physical state as it was originally deposited in. Trendall (2002) concludes on their origins that *"BIF have often been described as bizarre or unusual rocks, and correspondingly exceptional conditions have been advanced to explain their presence in the stratigraphic record, ... it should not be asked what strange circumstances led to the deposition of BIF, but instead in what respects were the* ordinary *environments of the Precambrian Earth radically different from those now existing"* and that *"It is useless in any present considerations of the origin of iron formation to confine attention to the iron formation itself"* (requoted from Trendall 1965).

The following are just a few of the variables and arguments in modelling the origin of BIFs in the Hamersley Province and elsewhere:-

- lengthy tectonic stability – total of 180 Ma for the Hamersley Group (although individual BIF events are much shorter) together with associated lack of terrigenous input,

- the timing and rate of oxidation of the Earths early atmosphere as driven by the evolution of life – a single oxygenating event (the Cloud hypothesis) corresponding with the greater Gondwana BIFs at *ca* 2.5 Ga has more recently been modified by Trendall (2002) to reflect better geochronological data. The atmosphere need not be significantly oxygenated if oxygenating biogenic activity is in equilibrium with iron in the water column rather than the atmosphere, that is any oxygen produced is preferentially scavenged by ferrous ions prior to release to the atmosphere. Trendall (2002) also accounts for the apparent lack of expected biogenically derived carbon in the Dales Gorge Member BIF (*ca* 1.5 %) required to oxidise ferrous to ferric is equivalent to the amount of carbon now present as carbonate in the fresh BIF,

- stability of supply – possible long lived sources of dissolved (or suspended) iron and silica include black smokers or upwelling currents from deep basinal sources (eg direct leaching of iron from a bare basaltic oceanic floor, Trendall 2002). If it is as a suspended load of very fine particles then no trigger is required for precipitation, but a mechanism is still required to produce alternating iron and silica rich laminae,

- cyclical microbanding or aftvarves – due to either seasonal factors that alter the solubility of iron (eg seasonal algal blooms oxygenating part of the water column, temperature changes altering solubility, storm events providing mixing of waters across a thermocline or chemocline, etc) or alternatively the iron and silica may both (precipitate out) of the water column at the same time but settle at different rates (eg Lascelles 2001). Cyclical banding produced by different rates of settling is plausible for BIF but would not produce similar microbanding seen in cherts or silica mesobands, for example,

- the origin of mesobanding – from Trendall and Blockley's 1970 model of silica removal from a *chert* mesoband to leave a residual *chert-matrix* (oxide) mesoband, to one reflecting a primary compositional difference, with the most likely scenario being a combination of the two. Mesobanding has recently been modelled by Krapez *et al* (2001) and Lascelles (2001) as being produced by a siliceous hard band marking the top of a sedimentary cycle but neither attempt to explain the cyclic Calamina or Knox cyclothem mesobanding, for example, documented by Trendall and Blockley (1970). Bedding truncations described by Krapez *et al* (2001) associated with this postulated hard pan are likely to be no more than long wavelength / low amplitude D_1 podding,

- the rapid increase in sedimentation rate / influx of BIF in the upper half of the Group requires a very large continually renewing supply of both iron and silica in the water column. Based on similar geochemistry, this has been related to a large igneous event incorporating Weeli Wolli dolerites, Woongarra Rhyolite and the volcanogenic S macrobands of the Dales Gorge Member (Barley *et al* 1997). If the iron is added as the ferrous ion it also implies a correspondingly high oxygen (or other oxidising agent) input. Various mass balance calculations have been attempted by Trendall and Blockley (1970), Morris (1993) and others,

- the physical state of the BIF is commonly believed to have been a thick hydrous rich (?90%) colloidal gel or similar (eg Trendall and Blockley 1970, Lascelles 2001, Trendall 2002). This is indirectly supported by large volume loss associated with the development of some stacked pods (eg Photos 14, 75, 76), but is not compatible with the basal contacts of the MDF where a moderately competent sediment with no post depositional volume loss suggested (Photo 54). The lack of significant erosion on the base of other turbidites also supports this interpretation. It may be that Joffre Member BIF, for example, was deposited in a relatively more indurated state with less post deposition compaction compared with the highly podded Mount Newman Member BIF. Lack of post sedimentary compaction is also indirectly supported by the very rapid sedimentation rate of the Joffre Member.

Meso to megascopic syndiagenetic mineralisation argued by Findlay (198?) and Lascelles (2001) by mega boudinage and expulsion of silica by compaction, respectively, is considered highly unlikely to have occurred in the Hamersley Province.

11.3 Original Extent of the Hamersley Group

Thorne and Trendall (2001) modelled the tectonostratigraphic evolution of the Fortescue Group recording a major marine transgression over the southern third of the Craton but with the Sylvania Inlier (Figure 37) acting as a palaeotopographic high over much of that period. They recognise:-

- early deltaic sediments (Bellary Formation) in the south west, followed by subaerial to rarely lacustrine pillow basalts (Mt Roe Basalt) restricted to the northern and south western parts of the Craton, but absent from the central Craton and Sylvania Inlier,

- fluvial sediments and felsic volcanics (Hardey Formation) again mainly restricted to the northern and south western parts of the Craton, but with the addition of the western Sylvania Inlier,

- subaerial to submarine basalts and sediments (Kylena / Boongal to Maddina / Bunjinah Formations) ranging from continental in the north, progressively through coastal, offshore and deep marine facies to the south. On the Sylvania Inlier they are poorly developed west of the Fortescue River Fault and absent east of the Jimblebar Greenstone Belt (from Falcon data), which formed a palaeotopographic high restricting deposition in the east, and

- predominantly marine sediments and volcanics (Jeerinah Formation) marking a northward propagating marine transgression. Extensive synsedimentary dolerite sills best developed south of line from the Sylvania Inlier to the Jeerinah Anticline (ie all exposures in the Hamersley Province) may be controlled by south block down growth faults. This line also effectively marks the deep verses shallow water facies carbonates of the overlying Hamersley Group (ie proto-Poonda Fault). Tyler and Trendall (2001) also argue for a series of syn Fortescue Group, mainly east – west, *en echelon* growth faults underlying the Province.

The lack of continental to shallow marine facies (with the exception of the Carawine Dolomite) and the apparent lack of any growth faults limits the tectonostratigraphic reconstruction that is possible over the Hamersley Group. Indirect lines of evidence that apply some constraints to the depositional and original extent of the Group are:-

- the proto-Poonda Fault is almost certainly the major growth fault marking the boundary between deep water facies in the main part of the Group and mixed shallow water carbonates in the eastern Fortescue valley and Oakover Sub-basin as described above (Figure 40). North of the remainder of the Chichester Range also appears to have been a shallow water carbonate factory sourcing much of the Group's carbonate including the MDF. The shallow water carbonates also had the dual roll of acting as a barrier to terrigenous input from the Pilbara Craton,

- from palaeocurrent directions in the MTI of the Bee Gorge Member, Hassler (1993) argues that there was an east – west palaeoridge near the current southeast extent of the Group that may have marked the original southeast limit of deposition. The geographic extent of the pink tuffaceous siltstone in the Mt Sylvia Formation also implies a source to the southeast. As per during deposition of the Fortescue Group, it therefore appears likely that the Sylvania Inlier was also a topographic high during Bee Gorge Member to Mt Sylvia Formation deposition, although it is unclear if it were submarine or subaerial, and if submarine, whether it is also the limit of deposition,

- further indirect evidence supporting a limit of deposition against the Sylvania Inlier is that only rare "atypical" Marra Mamba Iron Formation occurs along the Inlier's east and south sides akin to the Oakover Sub-basin and possibly also parts of the Fortescue valley (note, there is no information as to the nature of overlying sediments if any including carbonate facies, south and east of the Inlier). The atypical nature however, may only be due to poor knowledge of the area in much the same way as the poorly exposed Marra Mamba Iron Formation along the north edge of the Inlier was thought to be until recent drilling (Pudovskis 2000),

- from regional magnetic data the Brockman Iron Formation wraps the west end of Sylvania Inlier from Prairie Downs through to Deadmans Hill suggesting deposition was open to the south and west of there,

- proposed syn deposition plate tectonic reconstructions (eg Vaalbara in Cheney *et al* 1988, Cheney 1996, or Krapez 1997) do not have a (continental) plate adjoining the southern half of the Pilbara Craton,

- Lascelles (2000) argued Marra Mamba Iron Formation along the Chichester Range is a typical sequence based on reconstruction of the stratigraphy by down hole gamma logs with the MacLeod Member being about 40 m thick (MS13 to MS1), although if the gamma correlations are correct, it shows a larger than expected variation in the stratigraphic thickness given the simple structure. Further, whilst gamma signatures from the two areas west of the extrapolated extension of the proto-Poonda Fault are largely recognisable, those from Mulga Downs to the east are not, casting doubt on how standard the Formation is northeast of the Fault, and

- Trendall and Blockley's (1970) isopach map of the Dales Gorge Member indicates a thinning toward all current outcrop limits suggesting the current limits approximate the original limits, however given the poor understanding of structural effects the apparently thinned, more tectonised southern edge may be open to re-interpretation.

In conclusion, apart from compelling evidence for the proto-Poonda Fault marking the northeast margin between deep and shallow water, and possibly also the Sylvania Inlier marking the southeast margin, there is little strong evidence for modelling the original tectonostratigraphic architecture of the Hamersley Group. If there were other growth faults, the question as to where would they be and what would they look like still requires answering.

12.0 RECOMMENDATIONS

The following work is recommended to complete the mapping and geologic understanding of the Mining Area C region:-

- mapping of Brockman Iron Formation of Mudlark Well including the northern parts of the West Angelas Hill ranges along the southern edge of the tenements and the south west parts of Mt Meharry massif to the north in E47/17,

- mapping of Brockman Iron Formation throughout the remainder of the Weeli Wolli Sections of M244SA, this should also incorporate mapping of Coondewanna Ridge,

- detailed mapping of the remainder of the Northern Flank area, that is, the remainder of A and B, and F and R Deposits,

- measured stratigraphic sections of the poorly documented Bee Gorge, Paraburdoo and Yandicoogina Shale Members and others as warranted, to aid in mapping and understanding of the stratigraphy,

- measured section(s) with respect to a standard gamma log, of crocidolite development in the Vivash Riebeckite Zone in Blackwood Creek Gorge to the south of D and E Deposits to gain a better understanding of the stratigraphic distribution of crocidolite prior to the mining of C Deposit,

- re-analysis of the substantial structural data base (over 13 000 readings) in light of the increase in structural understanding since it was first collected,

- comparison of the structural styles between Newman, Mining Area C and Rocklea to document differences in the tectonics between the southeast, east to central and west Hamersley Province, and

- incorporation of additional structural and stratigraphic features noted during development of C Deposit.

13.0 ACKNOWLEDGEMENTS ("Bods I have known!")

This report began its life in late 1999 initially being a photographic and diagrammatic record of geologic features of Mining Area C with some brief text to help put the figures in context. Over two years the text grew to a "brief" plus 62 000 words (69 000 including captions) with there still remaining much left that could be documented.

As with a work of this nature there has been input from many different people at different times during the project. Of individual note are the field contributions of Steve Lipple, Andrew Duncan and Mark Benbow who through the course of mapping provided much stimulation in proving, disproving, proving again, etc etc etc, various and varied hypotheses, and to Mal Kneeshaw who provided a tempering force and degree of sanity to that process. Sections of the text have also gained from discussions with Alec Trendall (to whom I unofficially dedicate this), Dick Morris, Ilmar Tehnas, Bruce Simonson, Sean Gregory, Dave Hollingsworth, Chris Powell, Ian Williams and others, all of whom, I hope, I have quoted in context.

Figures were drafted by Nick from BHP Engineering / Hatch Associates or Merrison and Assoc / Ord Street Digital. Maps were digitised over the years by Faye, Mel, Stu, Yvonne, Ralph and Dean all from BHP Engineering / Hatch Associates. Colleen scanned hundreds of photos and had the joy of converting the entire report to the .pdf version.

The project was instigated, guided and supported throughout by Mal Kneeshaw.

Finally, a thanks to our "mules" Zamberlan, Scarpa, Rossi *et alia*, who carried us over more than 10 000 accident free kilometres during our odyssey.

15.0 REFERENCES

Arndt, NL, Nelson, DR, Compton, W, Trendall, AF and Thorne, AM, 1991. The age of the Fortescue Group, Hamersley Basin, Western Australia: from ion probe zircon U-Pb results. Aust J Earth Sci, 38, 261-281.

Barley, ME, Pickard, AL and Sylvester, PJ, 1997. Emplacement of a large igneous province as a possible cause of banded iron-formation 2.45 billion years ago. Nature, 385, 55-58.

Barley, ME, Pickard, AL, Hagemann, SG and Folkert, SL, 1999. Hydrothermal origin for the 2 billion year old Mount Tom Price giant iron ore deposit, Hamersley Province, Western Australia. Mineralium Deposita 34, 784-789.

Beukes, NJ, 1983. Palaeoenvironmental settings of iron-formations in the depositional basin of the Transvaal Supergroup, South Africa. *In* AF Trendall and RC Morris (eds), Iron Formations: Facts and Problems. Elsevier, 131-209.

Beukes, NJ, 1987. Facies relations, depositional environments and diagenesis in a major early Proterozoic stromatolitic carbonate platform to basinal sequence, Cambellrand Subgroup, Transvaal Supergroup, southern Africa. Sedimentary Geology, 54, 1-46.

Bickle, MJ, Morant, P, Bettenay, LF, Boulter, CA, Blake, TS and Groves, DI, 1985. Archaean tectonics of the Shaw Batholith, Pilbara Block, Western Australia: structural and metamorphic tests of batholith concept. *In* LD Ayres, PC Thurston, KD Card and W Weber (eds), Geol Soc Canada Special Pub 28, 325-341.

Blake, TS and Barley, ME, 1992. Tectonic evolution of the Late Archaean to Early Proterozoic Mount Bruce Megasequence Set, Western Australia. Tectonics, 11, 1415-1425.

Blockley, JG, Trendall, AF, de Laeter, JR and Libby, WG, 1980. Two anomalous isochrons from the vicinity of Newman. GSWA, 1979 Report, 93-96.

Blockley, JG, Tehnas, IJ, Mandyczewsky, A and Morris, RC, 1993. Proposed stratigraphic subdivisions of the Marra Mamba Iron Formation and the lower Wittenoom Dolomite, Hamersley Group, Western Australia. GSWA Prof Papers, Report 34/4, 47-63.

Brady, AC, 1988. Yandicoogina Pisolite Project, reconnaissance mapping of basal stratigraphy, Weeli Wolli Formation (BHP CR6107).

Brown, S, 1986. Toward a prehistory of the Hamersley Plateau, northwest Australia. Occasional Papers in Prehistory 6.

Button, A, 1976. Transvaal and Hamersley basins - review of basin development and mineral deposits. Minerals, Science and Engineering, 8, 262-293.

Cheney, ES, 1996. Sequence stratigraphy and plate tectonic significance of the Transvaal succession of southern Africa and its equivalent in Western Australia. *In* A Danielson and AJ Kaufman (eds), Geology and geochemistry of the Transvaal Supergroup. Precambrian Research 79, 3-24.

Cheney, ES, Roering, C and Stettler, E, 1988. Vaalbara. Geological Society of South Africa Geocongress Extended Abstracts, 85-88.

Cisne, JL, 1984. A basin model for massive banded iron-formation and its geophysical applications. J Geol 5,471-489.

Cloud, P, 1983. Banded iron-formations – a gradualists dilemma. *In* AF Trendall and RC Morris (eds) Iron-formation: facts and problems. Developments in Precambrian geology 6. Elsevier. 401-416.

CSIRO, 1995. Bedded iron ores derived from banded iron-formation (interactive CD). CSIRO Division of Exploration and Mining.

Cunneen, J, 1997. Structural analysis of the Wonmunna Anticline, Hamersley Province, Western Australia. UWA BSc (Honours) Thesis (unpub).

Dalstra, HJ, Harding, AE, Riggs, T and Taylor D. Banded iron formation hosted high-grade hematite deposits, a coherent group? Proceedings of Iron Ore 2002 Conference, AusIMM Pub Series 7/2002, 57-61.

Davy, R and Hickman, AH, 1988. The transition between the Hamersley and Fortescue Groups as evident in a drill core. GSWA Prof Papers, Report 23, 85-97.

Ewers, WE, 1983. Chemical factors in the deposition and diagenesis of banded iron-formations. *In* AF Trendall and RC Morris (eds) Iron-formation: facts and problems. Developments in Precambrian geology 6. Elsevier. 491-512.

Ewers, WE and Morris, RC, 1981. Studies on the Dales Gorge Member of the Brockman Iron Formation. Econ Geol, 76, 1929-1953.

Findlay 198?. ??

Gee, RD, 1979. Structure and tectonic style of the Western Australian Shield. Tectonophysics, 58, 327-369.

Goldsworthy Mining Limited, 1984. Proposal for the development of Mining Area C. Prepared for: China Metallurgical Import Export Corporation.

Gregory, SM, 1998. Structural evolution of Mt Newman, Hamersley Province, Western Australia. UWA BSc (Honours) Thesis (unpub).

Guedes, SC, Rosière, CA, Barley, ME and Lobato, L, 2002. The importance of carbonate alteration associated with the Carajás high-grade hematite deposits, Brazil. Proceedings of Iron Ore 2002 Conference, AusIMM Pub Series 7/2002, 63-66.

Hackney, RI, 2001. Gravity constraints on Palaeoproterozoic thin-skinned tectonics at the southern margin of the Pilbara Craton, Western Australia. Powerpoint presentation.

Hackney, RI, Hollingsworth, DA and Kepert, DA, 2001. Archaean basement structure beneath the Hamersley Province (Western Australia) inferred from gravity data (abs). 4th International Archaean Symposium (withdrawn).

Hagermann, SG, Barley, ME, Folkert, SL, Yardley, BWD and Banks, DA, 1999. A hydrothermal origin for the giant BIF-hosted Tom Price iron ore deposit (abs). SGA 5th Biennial Meeting, London.

Halligan, R and Daniels, JL, 1964. The Precambrian geology of the Ashburton valley region. GSWA Annual Report 1963, 38-46.

Harmsworth, RA, Kneeshaw, M, Morris, RC, Robinson, CJ and Shrivastava, PK, 1990. BIF - derived iron ores of the Hamersley Province. *In* FE Hughes (ed) Geology of the mineral deposits of Australia and Papua New Guinea, AusIMM, 617-642.

Harris, LB, 2002a. Folding in high-grade rocks due to back-rotation between shear zones. Journal Structural Geology (in press).

Harris, LB, 2002b. Folding between extensional detachments at Mt Whaleback, Hamersley Province. Applied Structural Geology for Mineral Exploration and Mining International Symposium, Sept 2002. Aust Inst Geoscientists (submitted).

Hassler, SW, 1993. Depositional history of the Main Tuff Interval of the Wittenoom Formation, Late Archaean-Early Proterozoic Hamersley Group, Western Australia. *In* TS Blake and A Meakins (eds), Archaean and Early Proterozoic Geology of the Pilbara Region, Western Australia. Precambrian Research, 60, 337-359.

Hassler, SW and Simonson, BM, 1998. Are wave-formed sedimentary structures and large rip-up clasts in early Precambrian microkrystite horizons diagnostic of oceanic impacts? (abs). Lunar and Planetary Science XXIX.

Hickman, AH, 1983. Geology of the Pilbara Block and its environs. Geological Survey Western Australia Bulletin 127.

Hickman, AH, 1990. Excursion number 5, Pilbara and Hamersley Craton. *In* SE Ho, JE Glover, JS Myers and JR Muhling (eds), Third International Archaean Symposium, excursion guidebook, Perth 1990, 1-60.

Hocking, RM, 1990. Geology and mineral resources of Western Australia. GSWA Memoir 3.

Hollingsworth, DA, in prep. Curtin Uni Tech, PhD Thesis (unpub).

Hollingsworth, DA and Cawood, PA, 1999. Deformation in the southeastern Hamersley Province: a question of timing (abs). SGTSG Symposium, Geol Soc Aust, Feb 1999.

Horwitz, RC, 1982. Geological History of the Early Proterozoic Paraburdoo hinge zone, Western Australia: a discussion. Precambrian Research 19, 191-200.

Jahn, B and Simonson, BM, 1995. Carbonate Pb-Pb ages of the Wittenoom Formation and Carawine Dolomite, Hamersley Basin, Western Australia (with implications for their correlation with the Transvaal Dolomite of South Africa). Precambrian Research 72, 247-261.

Johnson, TM, 1994. Structural studies of the SE Ophthalmia Fold Belt, 1993 field report (unpub draft).

Kakegawa, T, Kawai, H and Ohmoto, H, 1999. Origins of the pyrites in the ~2.5 Ga Mt McRae Shale, the Hamersley District, Western Australia. Geochemica et Cosmochemica Acta, 62, 3205-3220.

Kargel, JS, Schreiber Jr, JF and Sonett, CP, 1996. Mud cracks and dedolomitization in the Wittenoom Dolomite, Hamersley Group, Western Australia. Global and Planetary Change, 14, 73-96.

Kepert, DA, 1994. Drilling report, C Range Scree and Southern Flank, TR3156H (internal BHPIO report).

Kepert, DA, 2000a. Annual report Western Ridge, E52/170, Period 5 July 1999 to 4 July 2000 (internal BHPIO report).

Kepert, DA, 2000b. Western Homestead Linear mapping and drilling report, 1999 - 2000, OB26, 28, 32 & 36, ML244SA Sec 11 & 12 (internal BHPIO report).

Kepert, DA, 2001a. Carbonate debris flows in the Brockman Iron Formation, Western Australia. *In* KF Cassidy, JM Dunphy and MJ van Kranendonk (eds). Fourth International Archaean Symposium 2001, extended abstracts. AGSO – Geoscience Australia Record 2001/37, 238-240.

Kepert, DA, 2001b. Rocklea E47/16 Annual Report 4th October 2000 – 3rd October 2001 (internal BHPIO report).

Kepert, DA, in prep. Carbonate debris flows in the Joffre Member, Brockman Iron Formation, Western Australia: evidence for a coeval shallow water barrier reef (unpub draft).

Kepert, DA and Tehnas, IJ, 1995. Drilling report on C Deposit and MAC East, TR3156H (internal BHPIO report).

Kepert, DA, Lipple, SL, Duncan, AC and Benbow MC, 1996. Geological Mapping Project, MAC Park, TR3156H, E47/15 (internal BHPIO report).

Kepert, DA, Benbow, MC, Duncan, AC, Harris, D, Pearcey, D, Pierini, M and Sullivan, CM, 1999. Geological Mapping Project, Brockman Iron Formation, TR3156H, E47/13 & 14, ML244SA Sections 1 & 2 (internal BHPIO report).

Kerr, TL, O'Sullivan, AP, Podmore, DC, Turner, R and Waters, P, 1994. Geophysics and iron ore exploration: examples from the Jimblebar and Shay Gap regions, Western Australia. *In* MC Dentith, KF Frankcombe, SE Ho, JM Sheperd, DI Groves and A Trench (eds), Geophysical signatures of Western Australian Mineral Deposits. ASEG Special publication 7, 355-367.

Kneeshaw, M, 1975. Mount Whaleback Iron Orebody. In CL Knight (ed), Economic Geology of Australia and Papua New Guinea. AusIMM Monograph 5, 910-916..

Kneeshaw, M, 2000. Guide to the geology of the Hamersley and North East Pilbara Iron Ore Provinces (internal BHPIO report).

Kneeshaw, M and Kepert, DA, 2002. Discussion of 'Genesis of high-grade hematite orebodies of the Hamersley Province, Western Australia' by Taylor, D, Dalstra, HJ, Harding, AE, Broadbent, GC and Barley, ME, 2001, Econ Geol (in press).

Kneeshaw, M, Kepert, DA, Tehnas, IJ and Pudovskis, MA, 2002. From Mt Goldsworthy to Mining Area C – reflections on forty years of iron ore exploration in the Pilbara. AusIMM Iron Ore Conference (in press).

Krapez, B, 1996. Sequence-stratigraphic concepts applied to the identification of basin-filling rhythms in Precambrian successions. Aust J Earth Sci, 43, 355-380.

Krapez, B, 1997. Sequence-stratigraphic concepts applied to the identification of depositional basins and global tectonic cycles. Aust J Earth Sci, 44, 1-36.

Krapez, B, 1999. Stratigraphic record of an Atlantic-type global tectonic cycle in the Palaeoproterozoic Ashburton Province of Western Australia. Aust J Earth Sci, 46, 71-87.

Krapez, B, Barley, ME and Pickard, AL, 2001. Banded iron formations: ambient pelagites, hydrothermal muds or metamorphic rocks? In KF Cassidy, JM Dunphy and MJ van Kranendonk (eds). Fourth International Archaean Symposium 2001, extended abstracts. AGSO – Geoscience Australia Record 2001/37, 247-248.

Lascelles, DF, 2000. Marra Mamba Iron Formation stratigraphy in the eastern Chichester Range, Western Australia. Aust J Earth Sci, 47, 799-806.

Lascelles, DF, 2001. A new model for the origin of banded iron-formations. *In* KF Cassidy, JM Dunphy and MJ van Kranendonk (eds). Fourth International Archaean Symposium 2001, extended abstracts. AGSO – Geoscience Australia Record 2001/37, 251-253.

Li, ZX, Guo, W and Powell, CMcA, 2000. Timing and genesis of Hamersley BIF-hosted iron deposits: a new palaeomagnetic interpretation. MERIWA Report 199.

Lipple, SL, 1994. Miocene Conglomerate at Mining Area C (unpub BHPIO draft).

Lipple, SL, 1995. 1993 mapping report, Wheelarra Hill - East Jimblebar, ML266SA (internal BHPIO report).

Lipple, SL, 1997. Geological history of the Hamersley Region with special reference to structural events and controls on iron mineralisation. *In* Advances in Understanding the Hamersley Province, a short course, 28 Jan 1997. Key Centre for Teaching and Research in Strategic Mineral Deposits, UWA.

Lipple, SL, Sullivan, CM, Duncan, AC, Youngman, N and Hampton, DJ, 1994. Geological Mapping Project, Weeli Wolli Anticline, TR3156H (internal BHPIO report).

Lipple, SL, Duncan, AC, Benbow, MC and Kepert, DA, 1996. Geological Mapping Project, MAC West, TR3156H, E47/13-15 (internal BHPIO report).

MacLeod, WN, 1966. The geology and iron deposits of the Hamersley Range area, Western Australia. GSWA, Bull 117.

MacLeod, WN, De La Hunty, LE, Jones, WR and Halligan, R, 1963. A preliminary report on the Hamersley Iron Province, NW Division. GSWA Record 1963/11.

Martin, DMcB, 1998. Depositional setting and implications of Palaeoproterozoic glaciomarine sedimentation in the Hamersley Province, Western Australia. Geol Soc Am, Bull 111, 189-203.

Martin, DMcB, Clendenin, CW, Krapez, B and McNaughton, NJ, 1998a. Tectonic and geochronological constraints on late Archaean and Palaeoproterozoic stratigraphic correlation within and between the Kaapvaal and Pilbara Cratons. J Geol Soc, 155, 311-322.

Martin, DMcB, Li, ZX, Nemchin, AA and Powell CMcA, 1998b. A pre-2.2 Ga age for giant hematite ores of the Hamersley Province, Australia? Econ Geol, 93, 1084-1090.

McConchie, D, 1987. The geology and geochemistry of the Joffre and Whaleback Shale Members of the Brockman Iron Formation, Western Australia. *In* PWU Appel and GL LaBerge (eds), Precambrian Iron-Formations. Theophrastus.

Morris, RC, 1985. Genesis of iron ore in banded iron-formation by supergene and supergene - metamorphic process - a conceptual model. *In* KH Wolf (ed) Handbook of strata-bound and stratiform ore deposits, vol 13, 73-235.

Morris, RC, 1991. The Marra Mamba Iron Formation of the Hamersley Group of Western Australia. CSIRO Restricted Report 158R.

Morris, RC, 1993. Genetic modelling for banded iron-formation of the Hamersley Group, Pilbara Craton, Western Australia. *In* TS Blake and A Meakins (eds), Archaean and Early Proterozoic Geology of the Pilbara Region, Western Australia. Precambrian Research, 60, 243-286.

Morris, RC, 1994. Detrital Iron Deposits of the Hamersley Province. CSIRO Restricted Report 76R.

Morris, RC, 2001. Reply to Powell *et al* 1999 - Synorogenic hydrothermal origin for giant Hamersley iron oxide ore bodies. Geology (in prep).

Morris, RC, 2002. Iron ore genesis and post-ore metasomatism at Mount Tom Price. Proceedings of Iron Ore 2002 Conference, AusIMM Pub Series 7/2002, 3-13.

Morris, RC and Horwitz, RC, 1983. The origin of the iron-formation - rich Hamersley Group of Western Australia - deposition on a platform. Precambrian Research, 21, 273-297.

Morris, RC, Ramanaidou, ER and Horwitz, RC, 1993. Channel Iron Deposits of the Hamersley Province. CSIRO Restricted Report 399R.

Nelson, DR, 1995. Compilation of SHRIMP U-Pb zircon geochronology data, 1994. GSWA Record 1995/3.

Nelson, DR, Trendall, AF and Altermann, W, 1999. Chronological correlations between the Pilbara and Kaapvaal Cratons. Precambrian Research, 97, 165-189.

Nemchin, AA and Cawood, PA, 2001. Direct dating of goethite. AMIRA Project 616, confidential report.

Olive, N (ed), 1997. Karijini Mirlimirli: Aboriginal histories of the Pilbara. Fremantle Arts Centre Press.

O'Sullivan, AP, 1992. Hematite siltstone petrography (unpub BHPIO memo).

Pickard, AL, Krapez, B and Barley, ME, 2001. Dales Gorge Member S macrobands – what are they and why are they important? *In* KF Cassidy, JM Dunphy and MJ van Kranendonk (eds). Fourth International Archaean Symposium 2001, extended abstracts. AGSO – Geoscience Australia Record 2001/37, 256-258.

Pickard, AL, 2002. Aust J Earth Sci (in press).

Pidgeon, RT and Horwitz, RC, 1991. The origin of olistoliths in Proterozoic rocks of the Ashburton Trough, Western Australia, using zircon U-Pb isotopic characteristics. Aust J Earth Sci, 38, 55-63.

Potter, B, 1994. Wheelarra Hill scree 1993 drilling report (internal BHPIO report).

Powell, CMcA and Horwitz, RC, 1994. Late Archaean and Early Proterozoic tectonics and basin formation of the Hamersley Ranges. 12th Australian Geological Convention, GSWA, Excursion Guidebook 4.

Powell, CMcA, Oliver, NHS, Li, ZX, Martin, DMcB and Ronaszeki, J, 1999. Synorogenic hydrothermal origin for giant Hamersley iron oxide ore bodies. Geology, 27, 175-178.

Power, M, 1998. Stratigraphic update to the standard section used at Mt Whaleback (internal BHPIO report).

Pudovskis, MA, 2000. Marra Mamba Iron Formation, East Jimblebar, gamma log reference and stratigraphic column (internal BHPIO section).

Ramsey, JG, 1967. Folding and fracturing of rocks. McGraw-Hill, New York.

Ramsey, JG, 1974. Development of chevron folds. Geol Soc Am Bull, 85, 1741-1754.

Ramsey, JG and Huber, MI, 1987. The techniques of modern structural geology. Academic Press.

Rhodes, D, 1999. Mapping and structural modelling of Orebody 29 (internal BHPIO report).

Ronaszeki, J, 1992. Structural geology and its controls on iron ore mineralisation at the Mt Whaleback Mine, Newman, Western Australia. *In* Excursion guide to the southern margin of the Pilbara Craton, SGTSG, Geol Soc Aust (unpub).

Ronaszeki, J, 1997. Structural geology, and relationship between structure and ore genesis, Mt Whaleback. *In* Geology Report - Mt Whaleback, Newman satellite orebodies and Mining Area C, Sections 3.3 and 3.4, 19-26 (internal BHPIO report).

Shrivastava, PK, 1975. First report on TR5789H (internal MNM report).

Shrivastava, PK, 1977. Third report on TR5789H (internal MNM report).

Simonson, BM, 1992. Geological evidence for a strewn field of impact spherules in the early Precambrian Hamersley Basin of Western Australia. Geol Soc Am Bull 104, 829-839.

Simonson, BM, Hassler, SW and Schubel, KA, 1993a. Lithology and proposed revisions in stratigraphic nomenclature of the Wittenoom Formation (Dolomite) and overlying Formations, Hamersley Group, Western Australia. GSWA Prof Papers, Report 34/4, 65-79.

Simonson, BM, Schubel, KA and Hassler, SW 1993b. Carbonate sedimentology of the Early Precambrian Hamersley Group of Western Australia. *In* TS Blake and A Meakins (eds), Archaean and Early Proterozoic Geology of the Pilbara Region, Western Australia. Precambrian Research, 60, 287-336.

Simonson, BM, Beukes, N.J. and Hassler, SW, 1997. Discovery of a Neoarchaean impact spherule horizon in the Transvaal Supergroup of South Africa and possible correlations to the Hamersley Basin of Western Australia (abs). Lunar and Planetary Science, XXVIII, 1323-1324.

Simonson, BM and Hassler, SW, 1997. Revised correlations in the Early Precambrian Hamersley Basin based on a horizon of resedimented impact spherules. Aust J Earth Sci, 44, 37-48.

Simonson, BM, Hassler, SW and Beukes, NJ, 1998. Discovery of a Neoarchaean microkrystite horizon in South Africa and possible correlation with similar layers in Western Australia. Geol Soc Am, Special Paper (Sudbury 1997).

Stone, M, in prep. Stratigraphy of CID at Marillana Creek. UWA PhD Thesis.

Styles, M, 1991. Structural evolution of the south-eastern margin of the Hamersley Basin, Western Australia. UWA BSc (Honours) Thesis (unpub).

Taylor, D, Dalstra, HJ, Harding, AE, Broadbent, GC and Barley, ME, 2001a. Genesis of high-grade hematite orebodies of the Hamersley Province, Western Australia. *In* Iron Ores, MSc short course, 2 Feb 2001, Centre for Global Metallogeny, UWA.

Taylor, D, Dalstra, HJ, Harding, AE, Broadbent, GC and Barley, ME, 2001b. Genesis of high-grade hematite orebodies of the Hamersley Province, Western Australia. Econ Geol 96, 837-873.

Tehnas, IJ, 1997. Report on shaft sinking, C Deposit, 1996, Mining Area C, TR3156H (internal BHPIO report).

Tehnas, IJ and Pudovskis, MA, 2000. Mining Area C drilling report (internal BHPIO report).

Thorne, AM, 1990. Ashburton Basin. *In* Geology and mineral deposits of Western Australia, Memoir 3, 210-219.

Thorne, AM and Hickman, AH, 1998. Geology of the Fortescue Group, 1:500 000. GSWA non-series map.

Thorne, AM and Trendall, AF, 2001. Geology of the Fortescue Group, Hamersley Basin, Western Australia. GSWA, Bull 144.

Trendall, AF, 1965. Discussion of 'Origin of Precambrian Iron Formations'. Econ Geol, 68, 1065-1070.

Trendall, AF, 1968a. The Joffre Member in the gorges south of Wittenoom. GSWA Annual Report 1968, 53-57.

Trendall, AF, 1968b. Three great basins of Precambrian banded iron-formation deposition: a systematic comparison. Geol Soc Am, Bull 79, 1527-1544.

Trendall, AF, 1983. The Hamersley Basin. *In* Trendall, AF and Morris, RC (eds) Iron-formation: facts and problems. Developments in Precambrian geology 6. Elsevier. 69-129.

Trendall, AF, 1995. The Woongarra Rhyolite - a Giant Lavalike Felsic Sheet in the Hamersley Basin of Western Australia. GSWA Report 42.

Trendall, AF, 1997. A model for the depositional chronology of the Hamersley Basin, based on zircon U-Pb ages. *In* Advances in Understanding the Hamersley Province, a short course, 28 Jan 1997. Key Centre for Teaching and Research in Strategic Mineral Deposits, UWA.

Trendall, AF, 2002. The significance of iron-formation in the Precambrian stratigraphic record. Special Publications of International Association of Sedimentologists, 33, 33-66.

Trendall, AF and Blockley, JG, 1970. The iron formations of the Precambrian Hamersley Group, Western Australia, with special reference to the associated crocidolite. GSWA, Bull 119.

Trendall, AF, Compston, W, Williams, IS, Armstrong, RA, Arndt, NT, McNaughton, NJ, Nelson, DR, Barley, ME, Beukes, NJ, De Laeter, JR, Retief. EA and Thorne, AM, 1990. Precise zircon U-Pb chronological comparison of the volcano-sedimentary sequences of the Kaapvaal and Pilbara Cratons between about 3.1 and 2.4 Ga. *In* JE Glover and SE Ho (eds), Third International Archaean Symposium, Perth 1990. Department of Geology UWA, extended abstracts, 81-83.

Trendall, AF, Basei, MAS, de Laeter, JR and Nelson, DR, 1998a. SHRIMP zircon U-Pb constraints on the age of the Carajás Formation, Grâo Pará Group, Amazon Craton. J Soc Am Earth Sci, 11, 265-277.

Trendall, AF, Nelson, DR, de Laeter, JR and Hassler, SW, 1998b. Precise zircon U-Pb ages from the Marra Mamba Iron Formation and Wittenoom Formation, Hamersley Group, Western Australia. Aust J Earth Sci, 45, 137-142.

Trendall, AF, de Laeter, JR, Nelson, DR and Mukhopadhyay, D, 1997. A precise zircon U-Pb age of the base of the BIF of the Mulaingiri Formation (Bababudan Group, Dharwar Supergroup) of the Karnataka Craton. Geol Soc India J, 50, 161-170.

Tyler, IM, 1991. The geology of the Sylvania Inlier and southeast Hamersley Basin. GSWA Bull 138.

Tyler, IM and Thorne, AM, 1984. The northern margin of the Capricorn Orogeny, Western Australia, example of an Early Proterozoic collision zone. J Struct Geol 12, 685-701.

van Kranendonk, MJ, Hickman, AH, Williams IR and Nijman, W, 2001. Archaean geology of the East Pilbara Granite–Greenstone Terrain – a field guide. GSWA Record 2001/9.

Williams, GE, 2000. Geological constraints on the Precambrian history of Earth's rotation, and the moon's orbit. Rev Geophys 38, 37-59.

Willis, WB, 1978. Marra Mamba Handbook (internal MNM report).

Wingate, MTD, 1997. Testing Precambrian continental reconstructions using ion microprobe U-Pb baddeleyite geochronology and palaeomagnetism of mafic igneous rocks. ANU PhD thesis (unpub).

Woodhead, JD, Hergt, JM and Simonson, BM, 1998. Isotopic dating of an Archaean bolide impact horizon, Hamersley Basin, Western Australia. Geology 26, 47-50.

TABLE 1

Stratigraphic Column

	STRATIGRAPHIC NAME	STRAT CODE	COLOUR Civils	COLOUR GIS	COLOUR Derwent	MAP CODE prefix	MAP CODE code	MAP CODE suffix min	MAP CODE suffix non-min	COMMENTS	marker beds
	alluvium	Qa	32	973	19.02	-	Qa	-	-		
	colluvium/talus	Qc	33	974	19.60	-	Qc	-	-		
	sand in dunes /sheets	Qs	34	975	19.05	-	Qs	-	-		
TD1	*playa*	Czp	60		19.39	-	Czp	-	-		
	alluvium	Cza	35	730	19.03	-	Cza	-	-		
	colluvium/alluvial fans	Czc	37	733	19.57	-	Czc	-	-		
	bif	Czcb	38	732	19.58	-	Czcb	-	-		
	ore	Czco	40	258	19.27	-	Czco	-	-		
	mixed	Czcm	39	328	19.62	-	Czcm	-	-		
	canga/cemented	Czcg	61	733	19.64	-	Czcg	-	-		
	indurated	Czci	37	733	19.57	-	Czci	-	-		
	pisolite	Czpi	36	933	19.52	-	Czpi	-	-		
	laterite	Czl	42	933	19.52	-	Czl	-	-		
TD2	*calcrete/silcrete*	Czk	44	22	19.44	-	Czk	-	-	capping To, Czm, AHd etc	
	Oakover Formation	To	44	22	19.44	-	To	-	-	includes Czm	
	conglomerate	Tog	63	22	19.44	-	Tog	-	-		
	lacustrine limestone	Czm	44	22	19.44	-	Czm	-	-	partially equiv to To	
	Pliocene conglomerate	Tpco	64			-	Tpco	-	-		
	Robe Formation	CID	45	782	19.54	-	CID	-	-	equiv to GSWA's Tp	
TD3	*silcrete*	Czb	43	811	19.07	-	Czb	-	-	bedrock only, otherwise Czk	
	hardcap ore	H3	46	-	-	H3/	-			not coloured	
	Miocene conglomerate	Tmco	47	247	19.21	-	Tmco	-	-	formerly Mzco, equiv to ROD	
	martite - goethite ore	H2	52	113	19.13	H2/	-		-	PHbj and AHmm only	
	"	H2	48	143	19.20	H2/	-		-	PHbd and AHmn only	
	"	H2	50	183	19.26	H2/	-		-	AHda only	
	dolerite dykes	Pd	65	359	19.43	-	Pd	-	**d** 4 5 7		
	Karijini Dolerite	Pkd	25		19.45	-	Pkd	-	-	partially equiv to AFjd	
	microplatey ore	H1	49	309	19.32	H1/	-		-		
HAMERSLEY BASIN	**Turee Creek Group**	PTu	77			-	PTu	-	-		
	Boolgeeda Iron Formation	PHo	2	384	19.24	-	o	-	-		
	Woongarra Rhyolite	PHw	3	86	19.22	-	v	-	-		
	dolerite sills	Pds	70		19.45	-	Pds	-	-		
	Weeli Wolli Formation	PHj	4	994	19.17	-	PHj	-	-		
	Brockman Iron Formation	PHb	6	200	19.29	-	PHb	-	-		
	Yandicoogina Shale Mb	PHby	5	409	19.59	-	y	-	-		
	Joffre Member	PHbj	6	200	19.29		j	**h** g	**b** c		J4
	Whaleback Shale Member	PHbw	12	14	19.47		w	**g** h	**s** c		cc
	Dales Gorge Member	PHbd	13	140	19.11		d	**h** g	**b** c		
	Mt McRae Shale	AHr	17	694	19.49	-	r	-	-		ct
	Mt Sylvia Formation	AHs	18	20	19.50	-	s	-	-		bb
	Wittenoom Formation	AHd	19	614	19.38	-	AHd	-	-		
	Bee Gorge Member	AHdb	20	614	19.38	-	b	-	-		
	Paraburdoo Member	AHdp	66		19.41	-	p	-	-		
	West Angela Member	AHda	21	871	19.51		a	**l** h g	**s b** c		
	Marra Mamba Iron Formation	AHm	54	977	19.06	-	AHm	-	-		
	Mount Newman Member	AHmn	22	734	19.10		n	**h** g ib l	**b** c		
	MacLeod Member	AHmm	23	35	19.48		m	**g** h l	**c** b		sp dp yp fc pb
	Nammuldi Member	AHmu	24	977	19.06		u	**g** h l	**c** b		ur
	Jeerinah Formation	AFj	28	14	19.69	-	AFj	-	-		
	Roy Hill Shale Member	AFjr	27	994	19.71	-	AFjr	-	-		mc
	chert	AFjc	67			-	AFjc	-	-		
	basalt	AFjb	26			-	AFjb	-	-		
	dolerite	AFjd	25	948	19.45	-	AFjd	-	-	includes Pkd	
	Bunjinah Formation	AFu	79			-	AFu	-	-		
	granites	Age	31	108	19.19	-	Age	-	-		

NOTE

MAP CODE prefix
- use only if mineralised
- if mineralised and blank assume H2/

MAP CODE suffix
- multiple suffixes are not permitted, eg ngh
- if blank assumed to be non-mineralised
- preferred suffix in bold

ABBREVIATIONS

suffixs

b	BIF
c	chert
g	goethitic ore
h	hematite, goethitic hematite ore
i/ib	interbedded limonite hematite ore
l	limonitic ore
s	shale

marker beds

cc	central chert
ct	chert triplets
bb	Brunos Band (base)
sp	Sullivan pods
dp	Duncan pods
yp	Youngman pods
fc	football marker chert
pb	potato bed (top)
ur	rods
mc	marker chert

TABLE 2

Summary of Previous Mapping

Date	Name	Drawing Number	Alternate Number	Coverage	Method	Compilation Scale	Mappers	Comments
Mar 1964				Weeli Wolli Springs to Turee Creek	reconn	-	RTB, WRL	first heliborne reconn by GML (3 days)
1965	Mining Area C (sheet 1)	MAC/G-1	CEX-O/A-2	Mining Area C East	reconn	~1:39 600	RMS, RTB	includes detailed mapping from MAC/G-4
1965	Mining Area C (sheet 2)	MAC/G-2	CEX-O/A-2	Mining Area C West	reconn	~1:39 600	RMS, RTB	
1965	Mining Area C (sheet 3)	MAC/G-3	CEX-O/A-2	Mining Area C Park	reconn	~1:39 600	RMS, RTB	
1966	Part of Mining Area C	MAC/G-4		Packsaddle Range	mapped	~1:24 000	RMS, RTB	included in MAC/G-1
1967	General Surface Map	EX-MAC-8A		P1 - P6, Packsaddle Range	mapped	~1:24 000	RMS, RTB	mineralisation boundary only
1970	Area C1	MAC-EX-		P1, Packsaddle Range	mapped	~1:24 000	NJA	
1970	Geological Features on Lease	MAC-CONT-3		Govenor Range, Mt Robinson	reconn	~1:37 260	RG	
1971	The Noose	-		The Noose	mapped	1:2 400	AJW, NJA	
1971	Wildflower Mt	MAC-EX-1/	MAC-EX-33	west half Wildflower Mntn	mapped	1:4 800	AJW	
1971	Floodplain	MAC-EX-1/		Floodplain	reconn	1:2 400	AJW	
1971	Hill 65	HILL-EX-00		east half Hill 65	mapped	1:9 600	JW	
1972	Marra Mamba Area (sheet 1)	-		E and F Deposits, Northern Flank	mapped	~1:12 000	GD	
1972	Marra Mamba Area (sheet 2)	-		A, B, C, D and Q Deposits, Northern Flank	mapped	~1:12 000	NJA	
1972	Marra Mamba Area (sheet 3)	-		G, H, I, J, K, and L Deposits, Southern Flank	mapped	~1:12 000	NJA	
1972	Marra Mamba Area (sheet 4)	-		L, M, N, O, P, and R Deposits, Southern Flank	mapped	~1:12 000	NJA	
1972	Camp Hill	CEX-CH-2	MAC-EX-43	Camp Hill	reconn	~1:39 600	RG	
1972	Mt Robinson	-		Mt Robinson	mapped	~1:12 000	GD	
1972	Alligator Anticline	CEX-AA-2	MAC-EX-10	Alligator Anticline, Brockman to north and Balgara	reconn	~1:38 000	RG	mineralisation on Balgara not mapped
1972	Yandicoogina Creek	MAC-Misc-07		Lamb Creek and Ministers North	reconn	~1:39 600	RG	
1972	Parallel and Boundary Ridge	CEX-BR-2a		Parallel and Boundary Ridge	reconn	~1:36 000	GD	
1972	Fork South	MAC-EX-42	MAC-Misc-08	Fork South	mapped	~1:39 600	RG	
1972	North West Range	MAC-EX-34		Wildflower Mountain	reconn	~1:39 600	RG	
1972	Dog Leg	C-MMM-47		Dog Leg to Turee Creek	reconn	~1:38 000	GD	Marra Mamba only
1972	Turee Creek	CEX-TC-2		Dog Leg to Turee Creek, incl Brockman	reconn	~1:38 000	GD	Marra Mamba mineralisation not shown
1972	Mt Meharry massif	MAC-EX-37		Mt Meharry massif	reconn	~1:39 600	RG	mineralisation not mapped
1973	Governor Range	MAC-EX-38		Governor Range, The Governor, SE Corner	reconn	~1:39 600	RG	
1977	South East Corner	CEX-SE-2		South East Corner	reconn	1:25 000	SB	unlabelled
1977	Parallel Ridge	CEX-PR-2		Parallel Ridge	reconn	1:25 000	SB	taken from 1972 mapping?
1978	Southern Flank (2 sheets)	CEX-SF-2		Southern Flank	mapped	1:25 000	DH, SB	
1978	Weeli Wolli	015-G-032 A		Spring Hill to South Parmelia Hill	reconn	1:25 000	WK et al	includes older reconn compiled by WK
1980	Yandicoogina Ck	-		Ministers North	reconn	1:50 000	SB,RT	
1993	C Range	-		P1 to P6, Packsaddle Range	interp	1:10 000	APO	
1994	MAC North	810-G-1260, 70, 71, 72, 75, 77		Packsaddle Range, Lamb Creek, Ministers North	interp	1:20 000	DAK	

NJA	NJ Altheer, GML	DH	D Hackett, GML	RMS	RM Simon, GML
RTB	RT Brandt, GML	DAK	Doug Kepert, BHPIO	RT	R Trotter, GML
SB	S Burton, GML	WK	Bill Knox, MNM	AJW	?, GML
GD	G Donzelli, GML	WRL	WR Liddicoat, GML	JW	J Ware, GML
RG	R Geijskes, GML	APO	Tony O'Sullivan, BHPIO		

TABLE 3

Geochronology of the Hamersley Basin

			HORIZON	DATE	Method	LOCATION	COMMENTS	REFERENCE
BANGEMALL BASIN								
				1638 ±14			post Ashburton Orogeny	
ASHBURTON BASIN								
			Boolaloo Granite	1680 ±??	3		cooling age, late Ashburton Orogeny	
			"	1786 ±5	1		syn Ashburton Orogeny	Krapez and McNaughton
			June Hill Volcs	1843 ±2	4		pre Ashburton Orogeny	Pidgeon and Horwitz (1991)
			Cheela Sp Basalt	2209 ±15	1	north of Wyloo Dome	xenocrysts in volcaniclastic breccia (max age)	Martin *et al* (1998)
			Sylvania Inlier	2235 ±57	3	Ophth Dam Granitoid	cooling age, late Ophthalmian Orogeny	Blockley *et al* (1980)
HAMERSLEY BASIN								
PHo		~200						
PHw		~400	upper shale	2446 ±6	1	Woongarra Pool	17m above last massive rhyolite	Trendall *pers comm* (1996)
			upper flow	2449 ±3	1	Woongarra Pool		Barley *et al* (1997)
			uncertain	2451 ±5	1	Woongarra Pool	within error of Barley's date	Trendall *pers comm* (1996)
PHj		~400	uncertain	-	1	core	no zircons in 3 samples processed	Trendall *pers comm* (1997)
			tuff in 2nd BIF	2449 ±3	1	W of Cathedral Gorge	?Homestead Creek Gorge	Barley *et al* (1997)
PHby		40	basal	?2458	1	OB 25, pit 3	very poor zircons, only one good grain	Trendall *pers comm* (1997)
PHbj	J6	90	P5	2461 ±2	1	Joffre Gorge	provisional date	Compston unpub / prov
	J3-J5	30	P4	2461 ±4	1	Joffre Gorge	provisional date	Compston unpub / prov
	J2	50	P1	2462 ±3	1	Joffre Gorge	provisional date	Compston unpub / prov
	J1	30						
PHbw		30	WS1 or 2?	2463 ±5	1	Tom Price pit	large, fragile (? high U) zircons	Trendall *pers comm* (1997)
PHbd	D4	50	DS14	-	1	Tom Price pit	no zircons	Trendall *pers comm* (1996)
			DS13	2473 ±4	1	Wittenoom Gorge		Trendall *et al* (1990)
	D3	30	DS9	2479 ±3	1	Tom Price pit	abundant zircons, provisional date	Trendall *pers comm* (1996)
	D2	40	DS5	-	1	Tom Price pit	few cloudy zircons, not suitable	Trendall *pers comm* (1996)
			DS2	-	1	?Dales Gorge	very complex population (ie turbiditic)	Trendall *pers comm* (1996)
	D1	30	CS5	-	1	Tom Price pit	few, poor zircons, not suitable	Trendall *pers comm* (1997)
AHr		50						
AHs		40	ignimbrite	-	1	Weeli Wolli Springs	no zircons	Trendall *pers comm* (1998)
AHdb		140	SMB	2541+18/-15	4		diagenetic age	Woodhead *et al* (1998)
			SMB (Spherulites)	~2553	1	5km WNW Mt Bruce	remaining zircon after removing inherited CRT	Trendall *pers comm* (1996)
			CRT	2561 ±8	1	5km WNW Mt Bruce		Trendall *et al* (1998b)
				2346 ±38	4	Millstream 10 core	diagenetic age	Jahn and Simonson (1995)
(AHc)				2541 ±32	4	various outcrops	diagenetic age	Woodhead *et al* (1998)
AHdp		280		2505 ±37	4	Millstream 10 core	diagenetic age	Jahn and Simonson (1995)
AHda		40						
AHmn		60	NS3	2597 ±5	1	Marandoo pit		Trendall *et al* (1998b)
AHmm		70						
AHmu		90						
AFjr			CT (contact tuff)	2629 ±5	1	North Alligator	collected by DAK	Nelson *et al* (1999)
			~1m below contac	-	1	Parallel Ridge	poor zircons, collected by DAK	Trendall *pers comm* (1996)
AFj			ignimbrite	2684 ±6	1	S of Paraburdoo	exact stratigraphic position uncertain	Ardnt *et al* (1991)
			tuffaceous sst	2690 ±16	1	S of Paraburdoo	exact stratigraphic position uncertain	Ardnt *et al* (1991)
AFr			basalt	2775 ±10	1			Ardnt *et al* (1991)
			Black Range Dyke	2772 ±2	2		feeder to the Mt Roe Basalt	Wingate (1997)

Methods
1 U-Pb SHRIMP zircon
2 U-Pb SHRIMP baddeleyite
3 Rb-Sr whole rock / mineral isochron
4 Pb-Pb whole rock / mineral isochron

TABLE 4

Correlation of Deformations and Orogeny Names

GSWA		**UWA**	**BHPIO**				**HI**	
WA	SE Hamersley	Hamersley	Jimblebar	Mining Area C		Whaleback	Hamersley	Tom Price
Gee 1979	Tyler 1991	Powell *pers comm*	Lipple 1995	Lipple *et al* 1996	Kepert 2001	Ronaszeki 1992, 97	Duncan *pers comm*	Taylor *et al* 2001
			D_5	D_5	D_5		D_6	
			D_4	D_4	D_4		D_5	
						D_4		
Capricorn	D_{2a} Ashburton	D_3	D_3	D_3 Ashburton	D_3	D_3	D_4	D_4 Capricorn
	D_{1a}							
								D_3 Panhandle
	D_{2c} Capricorn	D_2	D_2	D_2	D_2 Ophthalmian	D_2	D_3	D_2
				$D_{1.5}$			D_2	
	D_{1c}	D_1	D_1	D_1	D_1 extension / compaction	D_1	D_1	D_1

TABLE 5

Fold Styles and Deformational History as Mapped

Event	Orogeny and Age	Tectonic Regime	Typical Fold Characteristics: Style	Axial Surface		Macroscopic Folds		Interlimb Angle	Cleavage	Other	Associated Faulting
				Strike	Dip	Wavelength	Amplitude				
D_1	2450 Ma	basin extension / sag / compaction	recumbent, rootless	40-60	subhorizontal intrafolial		<1 m	isoclinal	bedding parallel mineral	boudinage, podding and rodding trending 40 - 60	Turee Ck Group growth faults?
$F_{1.5}$		N over S compression ?fold and thrust belt ?Lower Turee Ck closure	asymmetric to overturned	E - W	50-70 north	<1 km	20-200 m	tight to open	mineral to crenulation		
D_2	Ophthalmian 2200 Ma	S over N compression fold and thrust belt Upper Turee Ck closure	asymmetric to overturned, rarely recumbent	90-110	50-70 south	0.2-5 km	20-200 m	tight to open, rarely isoclinal	strong mineral to crenulation	flexural slip qtz fibres, intrafolial parasitics, N limb highly deformed	local thrusting, transverse faults
D_3	Ashburton 1650 Ma	N - S compression Ashburton Basin closure	upright	80-100	subvertical	1-20 km	20-500 m	open	crenulation to fracture		
D_4		NE - SW compression ?Mt Minnie Basin closure	upright	140-160	subvertical	>1 km	50-200 m	open to broad	spaced fracture		strike slip, normal?
D_5		NW - SE compression ?Breshnahan Basin closure	upright	30-60	subvertical	> 2km	100? m	broad	spaced fracture		regional normal mostly S block down

NOTE

D_2 and D_3 together form the Capricorn Orogeny

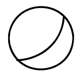
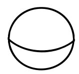
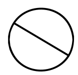
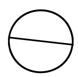
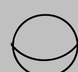
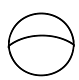
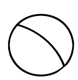
TABLE 6

Average Orientation of Structure by Area, 1994 to 1996

Structure	1994			1995							1996				
	Weeli Wolli Anticline														
	Regional	Northern Flank	Southern Flank	Parallel Ridge	Boundary Ridge	North Alligator	South Alligator	South East Corner	Camp Hill	Regional	western South Alligator	Balgara	Juna Downs	Dog Leg to Death Valley	Regional
S_0	08→188			25→356	12→188	14→007	29→077	05→320	14→165		34→189	41→187	25→185	21→150	
$F_{average}$	90→095										06→270	06→269	11→120	17→113	
L_1				18→056	15→238	04→052	01→052	05→048							02→072
$S_{1.5}$				57→357	53→006	56→003	38→012	53→003		49→006		61→356		56→028	
$F_{1.5}$				17→268	09→268	05→275	06→099			02→275		24→276		16→126	
S_2	50→181	49→176	59→186	54→185	60→184	57→185	50→176	49→177	47→192	52→182		65→182		51→193	
F_2	03→272			04→095	02→098	03→101	07→092	03→091	14→096	04→096		03→274		17→109	
S_3	89→001			90→178	90→003	89→182	89→002	90→002				89→181		86→189	
F_3	04→271			00→090	02→091	02→093	10→094	07→088	02→098			04→092		13→108	
F_4	03→136													31→136	
F_5	04→227														

NOTE Planar features defined as dip→dip direction
Linear features defined as plunge→plunge direction

TABLE 7 Revised Interpretation of Mapped Structures with respect to Deformation

MAPPED STRUCTURE		PREVIOUS INTERPRETATIONS	REVISED INTERPRETATION			
Whaleback style fault NE-SW broad folding		D_5 fault F_5	D_5 fault F_5	**D_5**	?reactivated D_2 inpart ?arcuate F_2 inpart	
Homestead style fault		D_5 fault	D_2 thrust			
NW-SE folds usually upright but may face NW		F_4	F_4	**D_4**	arcuate F_2	
domes and basins in the west		$F_{1.5}$ / F_2 / F_3 interference	dominately pre D_2			
upright, open larger scale folding refolds F_2, incongruous vergence vertical fracture to mineral cleavage		F_3 S_3	F_3 S_3	**Ashburton Orogeny D_3**	upright F_2 ?progressive D_2 inpart fanning S_2	absent?
N facing folds N and S verging S dipping mineral cleavage S over N thrusting		F_2 S_2 D_2 thrust		**Ophthalmian Orogeny D_2**		weak
S facing folds, S verging N dipping mineral cleavage N over S shear		$F_{1.5}$ $S_{1.5}$ $D_{1.5}$ shear	south facing F_2 fanning S_2 D_2 flexural slip			moderate
intrafolial isoclinal folds, mostly NE-SW NE-SW cross pods and rods		F_1 L_1	F_1 L_1	**D_1**	early F_2 inpart	strong
pre Mt Bruce Supergroup			**Rocklean Movement**			

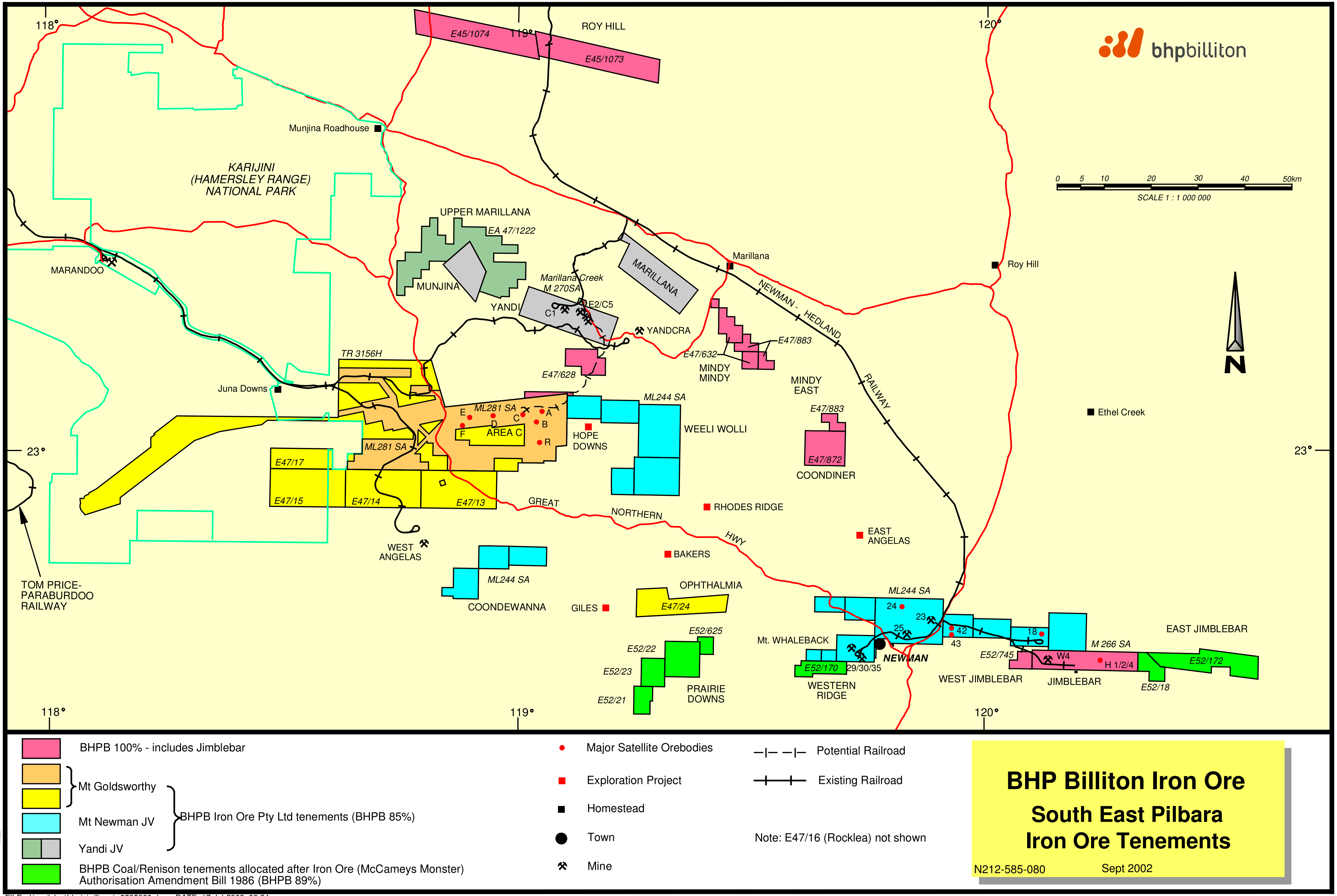


Figure 1

FILE: d:\proj\dgn\bhpio\pilbara\n2585080.dgn DATE: 17-Jul-2002 09:24

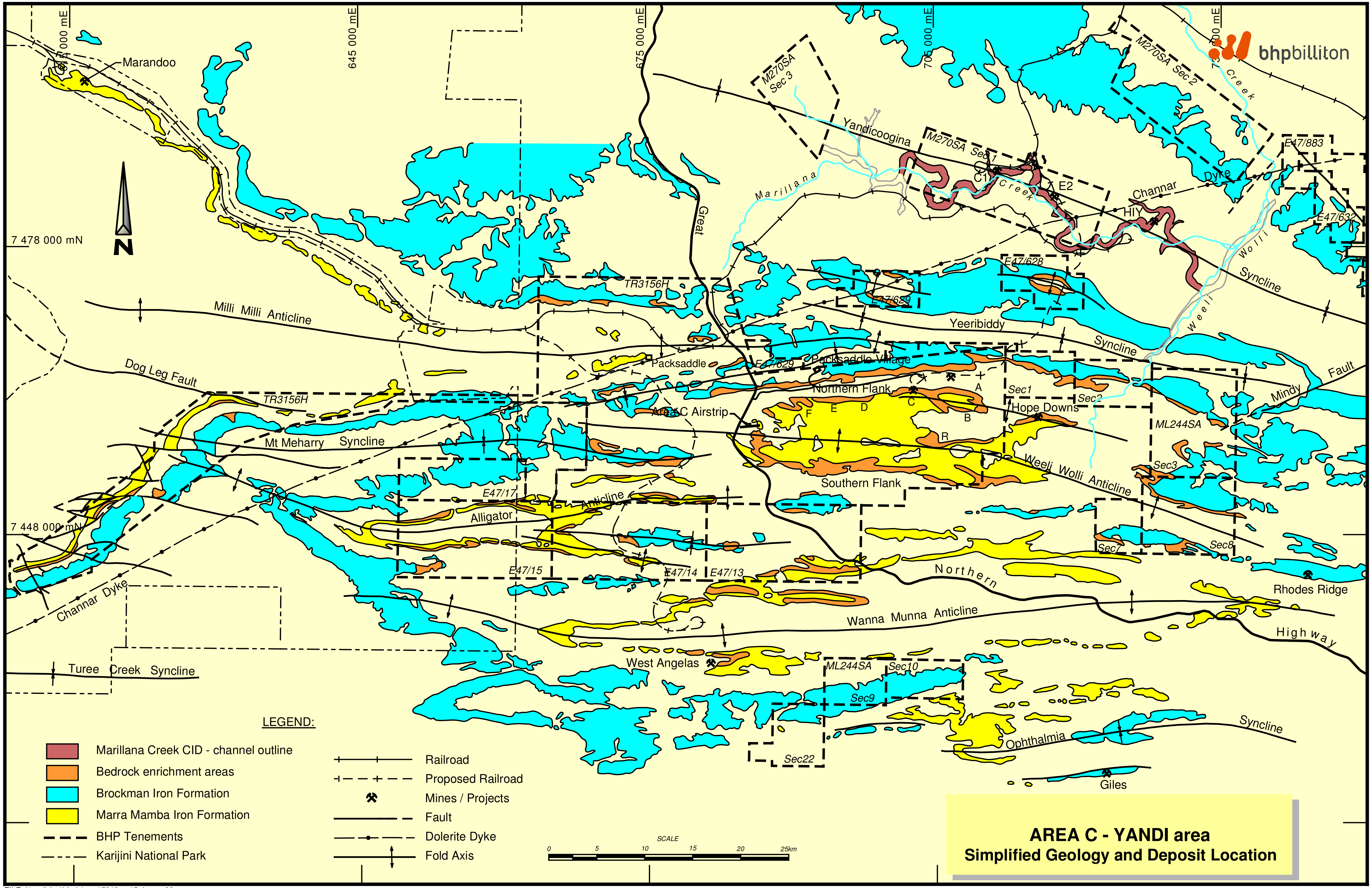
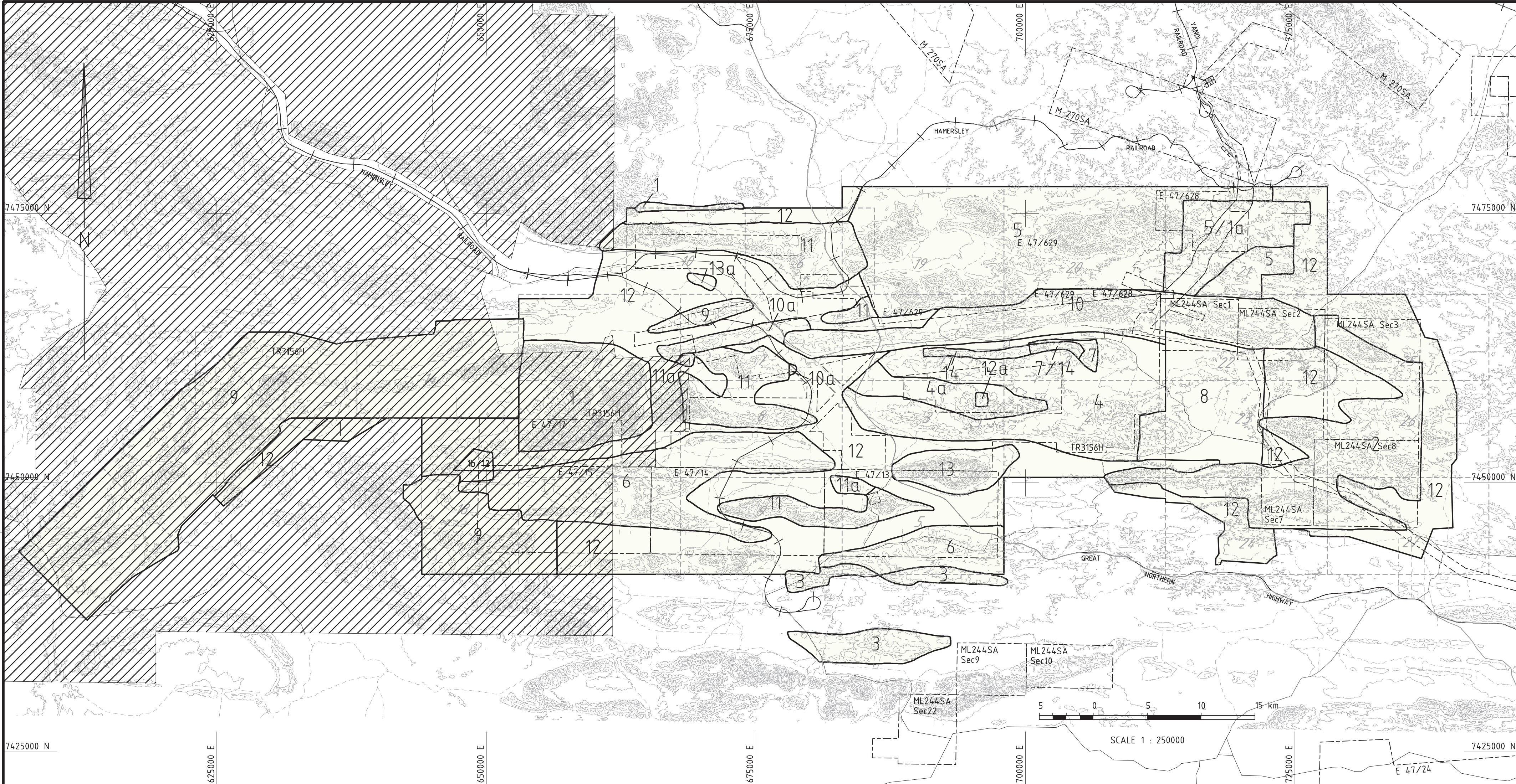


Figure 2

FILE: I:\proj\dgn\bhpio\mac\5348ms15.dgn A3
DATE: 17-Feb-99 12:57



Area	Date	Name	Mapping Report	Method	Compilation Scale	Photography Series	Photography Scale	Mappers	Comments
1	1972	Meharry massif	nil?	reconn	~1:40 000	GML	?	RG	mineralisation not mapped
1a	1972	Yandicoogina Ck	nil?	reconn	~1:40 000	GML	~1:40 000	SB,RT	structural readings only added to MAC North interp
1b	1972	part of Alligator	nil?	reconn	~1:40 000	GML	?	RG	mineralisation from GML map added to photo interp
2	1978	Weeli Wolli	nil	mapped	1:25 000	WW	~1:25 000	WK and others	includes older reconn compiled by WK, AHdb/Ahdp and Cz interp by DK
3	pre 1994	West Angela	JSM	mapped	1:10 000?	WA	?	RRIA	digitised by BHP from simplified figure in JSM document
4	1994	MAC East	SLL et al 1994	mapped	1:20 000	MAC	~1:20 000	SLL,CMS,ACD,NY,DH1	
4a	1994	MAC East	SLL et al 1994	reconn	1:20 000	MAC	~1:20 000	SLL,ACD,NY,DH1	Weeli Wolli Anticline axis is mainly reconn only
5	1994	MAC North	nil	interp	1:20 000	MAC	~1:20 000	DK	mineralisation not mapped, limited ground checking
6	1995	MAC West	SLL et al 1995	mapped	~ 1:20 000	MAC	~1:20 000	DK,SLL,ACD,MCB	
7	1995	ABC Deposits	nil	mapped	1:5 000	MAC	~1: 5 000	SLL,ACD,MCB	
8	1995	Hope	nil	interp	1:20 000	MAC	~1:20 000	ACD	mineralisation not mapped
9	1996	MAC Park	DK et al 1996	mapped	~ 1:20 000	MAC	~1:20 000	DK,SLL,ACD,MCB	heliborne, Brockman mainly reconn
10	1997	Packsaddle/Weeli	DK et al 1999	mapped	1:10 000	MAC,NF,WW	1:10 000	DK,MCB,ACD,DP	
10a	1997	Packsaddle/Weeli	DK et al 1999	mapped	1:20 000	MAC	~1:20 000	DK,MCB,DP	
11	1998	Wild/Fork/Gov	DK et al 1999	mapped	1:10 000	MAC	1:10 000	DK,MCB,DH2,MP	
11a	1998	Wild/Fork/Gov	DK et al 1999	mapped	1:20 000	MAC	~1:20 000	DK,DH2,MP	
12	1999	Big MAC	nil	interp	1:20 000	MAC,WW	various	DK	includes stitching of all other mapping along boundaries
12a	1999	Big MAC	nil	interp	1:20 000	MAC	~1:20 000	DH3,DK	interp by DK after comments by DH3
13	1999	Mt Robinson	DK et al 1999	mapped	1:10 000	MAC	1:10 000	DK,MCB,CMS	
13a	1999	16 Mile Hill	nil	mapped	1:20 000	MAC	~1:20 000	CMS	
14	2000	North Flank	DK 2000	mapped	1:5 000	MAC	1:5 000	MCB,DK	includes remapping of C and part of B Deposits

Mappers

MCB	Mark Benbow, contractor
SB	S Burton, GML
ACD	Andrew Duncan, contractor
RG	R Geijskes, GML
DH1	Danny Hampton, contactor
DH2	Dave Harris, contractor
DH3	Dave Hollingsworth, CUT
DK	Doug Kepert, BHPIO
WK	Bill Knox, MNMCo
SLL	Steve Lipple, contractor
DP	Dave Pearcey, contractor
MP	Melanie Pierini, contractor
RRIA	Robe River Iron Assoc, various
CMS	Chris Sullivan, contractor
RT	R Trotter, GML
NY	Noel Youngman, contractor

Photography

GML	unknown vintages and/or scales
WW	Weeli Wolli, May 1978, ~1:25 000
WA	W Angela, unknown vintage and/or scale
MAC	MAC, April1993, ~1:20 000
NF	N Flank, Nov 1996, ~1:30 000

GML and MNM mapping geographically referenced and digitised by BHP

LEGEND

24 MAC 1:20000 DRAWING SHEET INDEX

3 MAC GEOLOGICAL MAPPING INDEX AREA

KARIJINI NATIONAL PARK

TENEMENT BOUNDARIES

NOTES

1. HORIZONTAL DATUM: AMG (ZONE 50)

BHP Iron Ore Pty Ltd ABN 46 008 700 981

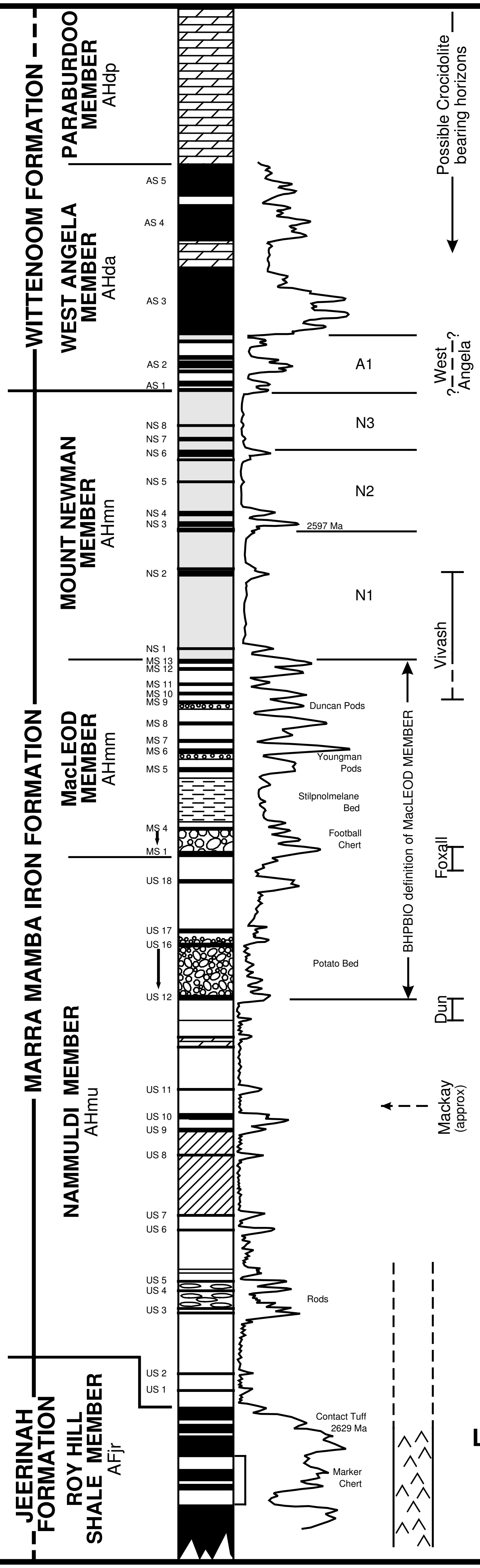
MINING AREA C & SURROUNDS
GEOLOGICAL MAPPING INDEX

SCALE	DATE		DRG. NO.
1:250 000	25.10.1999	A2	810 - G - 1325/C

REV	INIT
C	MH

FILE: p:\Common\civil\geomap\Mac_All\dgn1\810g1325.dgn
DATE: 23-Jan-01 08:35

0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200



bhpbilliton

LEGEND

- Dolomite
- Shale / tuff / dolomitic shale
- Banded iron - formation (BIF)
- Ferruginous chert and cherty BIF
- Cherty BIF
- Pods and rods
- Stilpnolmelane "shale / tuff"
- Dolerite sills

NOTES :-

- internal sub-divisions (AHmn) and shale band numbering system shown.
- A1 , N1 - 3 thickness from drill data (C Deposit) , other thicknesses from mapping.
- much of the Nammuldi and lower MacLeod Members have relict carbonate textures in outcrop.
- thick dolerite sills typically intrude the Roy Hill Shale Member , rarely extending as high as the Rods.
- thickness at Newman (OB29) are approximately AHda 45m , AHmn 45m , AHmm 25m and AHmu 75m.
- ages shown refer to SHRIMP dating.

0 50m

Scale in metres

BHP Billiton Iron Ore

MINING AREA C

MARRA MAMBA IRON FORMATION

LITHOSTRATIGRAPHIC and GAMMA LOG REFERENCE SECTION

D.Kepert. Mar. 2002

DRWG No D:\DGN\BHPIO\MAC\5355MS46.DGN DATE 11-3-2002

Figure 4

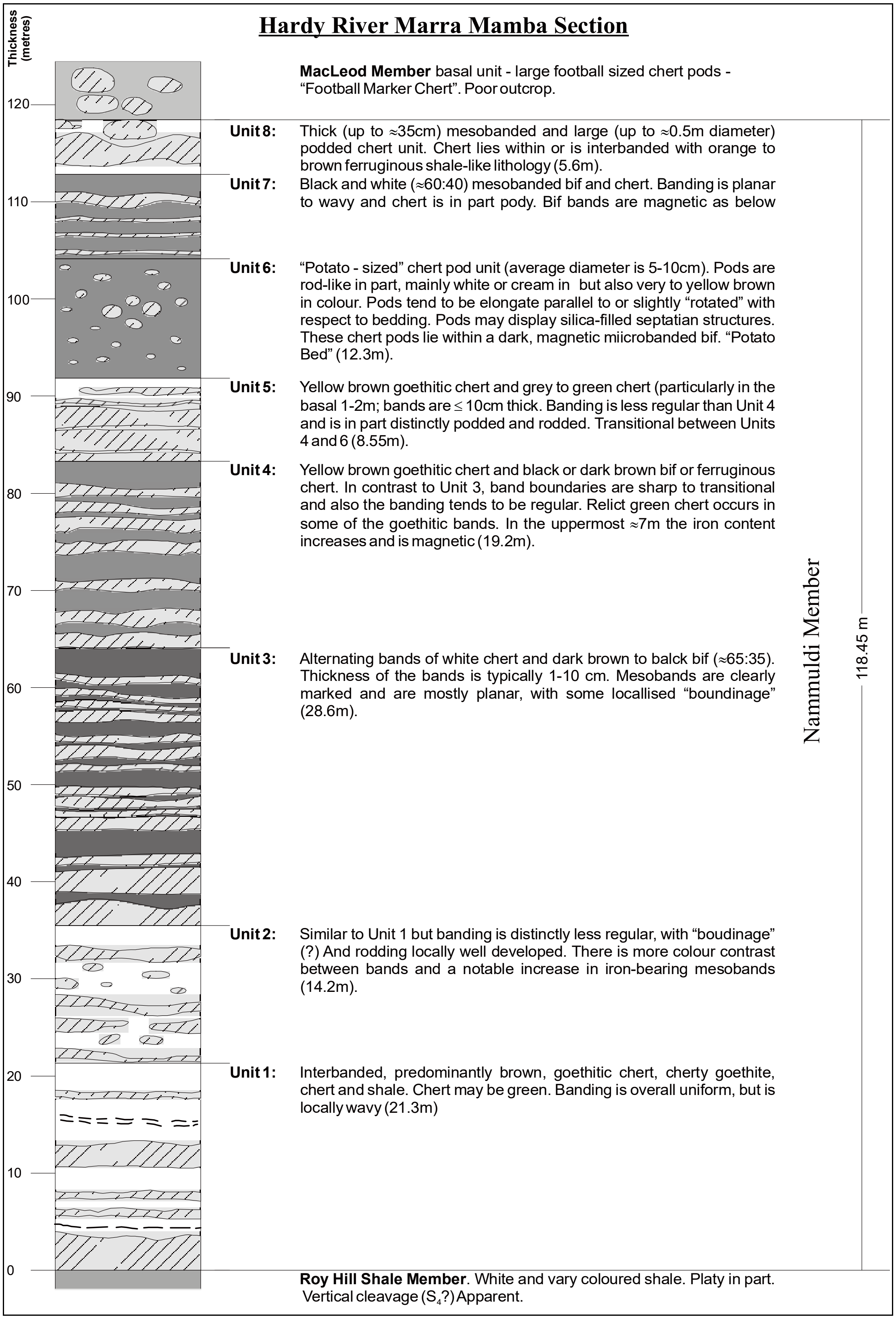
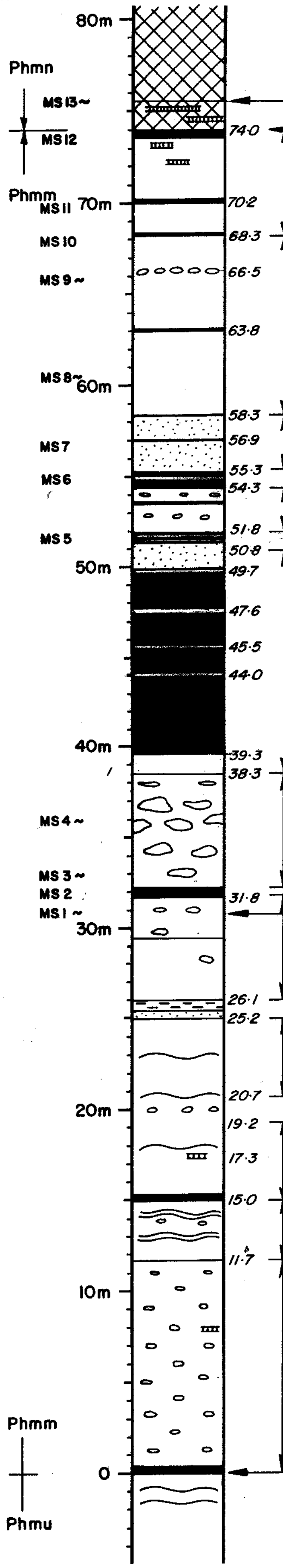


Figure 5. Hamersley Iron's standard mapping section of the Nammuldi Member. Units 6 to 8 are included by BHPIO in the MacLeod Member giving the Nammuldi Member a thickness of 91.85 m. Unit 2 includes the Rods, Unit 6 is the Potato Bed (Duncan *pers comm* 1996).



Dark grey/white hematitic BIF – wavy banding with flattened podded chert mesobands. Numerous thin crocidolite horizons occur between NS2 (+20m) and contact.

GSWA CONTACT

MAPPING CONTACT

White (bleached) laminated chert and red shale. In less weathered sections this portion can be a finely laminated platy BIF with interbedded limonite-hematite mineralization. Uppermost shale marked by prominent undercut. Rare thin (1cm) crocidolite bands in brown-khaki shale.

White laminated chert (silicified carbonate BIF) with 'sandpaper' weathered surface. Characterised by regular ellipsoidal pods ('SULLIVAN PODS') with 15cm diameter in S_0 and 10cm axis. Laminations penetrate pods which may have quartz-filled septarian fractures.

Pale yellow/brown cherty BIF with minor thin shale bands. (Dip 14°)

Grey/white moderately laminated chert and partially silicified pyritic (?) shale.

Dark brown laminated shale with 10cm chert band.

Limonitic spheroidal pods in yellow iron-poor cherty BIF with shale partings and bands. Pods typically 5cm diameter, up to 10cm ('YOUNGMAN PODS').

Shale and chert with two prominent 10cm massive chert bands at 51·3 and 51·6m.

Well laminated red-weathering, dense black stilpnomelane shale and thin iron-rich laminae
Massive 10-20cm tuff bands with nodule horizons (after pyrite) at 44·0, 45·5, 47·6 and 49·7m.
Minor thin finely laminated (fissile) BIF and chert bands, especially in upper 2m.

Finely laminated, fissile yellow chert

'FOOTBALL MARKER CHERT.' Well laminated yellow/brown BIF with large (up to 70cm long x 30cm diam) distorted ellipsoidal chert pods. Pods have distinctive sandpaper (carbonate) weathered surface. Silicified carbonate BIF laminations penetrate pods, chert mesobands pinch out along bed. Pods have quartz-filled septarian fractures and are probably diagenetic. Conformable quartz veins up to 5cm thick.

30 - 40cm red shale band.

GSWA Phmm/Phmu CONTACT

Fissile yellow cherty BIF with occasional pods and thin shale partings. Bedding continues through pods.

Granular red/buff shale with thin interbedded BIF. Massive green-brown chert below.

Well laminated yellow cherty BIF. Resistant to erosion, forms prominent cliff. Platy appearance due to thin shale partings. Low amplitude wavy banding.

Shaly BIF with lensoid/elliptical pods to 10cm diam. (radial slickenslides on surface of pods.)

Well laminated yellow cherty BIF with 0·5cm crocidolite horizon.

Wavy banded yellow BIF with fine hematite laminae and rare pods.

'POTATO BED'-podded chert horizon-generally spherical/ovoid chert pods in finely laminated yellow BIF. Pods generally more spherical than in rest of Phm-some elongated in direction 265°. Pods appear to have rotated clockwise. Frequency of pods decreases upwards.
7·5-8·0m-Harder, more resistant wavy BIF horizon with 4 thin altered crocidolite seams over 10cm interval.

MAPPING CONTACT - marked by 30cm shale band - undercut.

Wavy banded (pinch & swell) iron-rich, finely laminated BIF with minor pods formed from boudinised chert mesobands.

0 5 10 15 20m

SCALE 1:250

LEGEND

- Shale / Shaley BIF
- BIF - Iron rich
- Wavy banded, iron-poor cherty BIF
- Interbedded chert and shale
- Chert pods spherical, ovoid
- Crocidolite (altered)

BHP Iron Ore (Goldsworthy) Pty. Ltd.

MINING AREA C

MEASURED STRATIGRAPHIC SECTION

MacLEOD MEMBER OF THE MARRA MAMBA IRON FORMATION

from 706740 E 7453400 N (base)
to 706550 E 7453820 N (top)

Geology: CMS/SLL/MK	Date: December '94	FIGURE 6

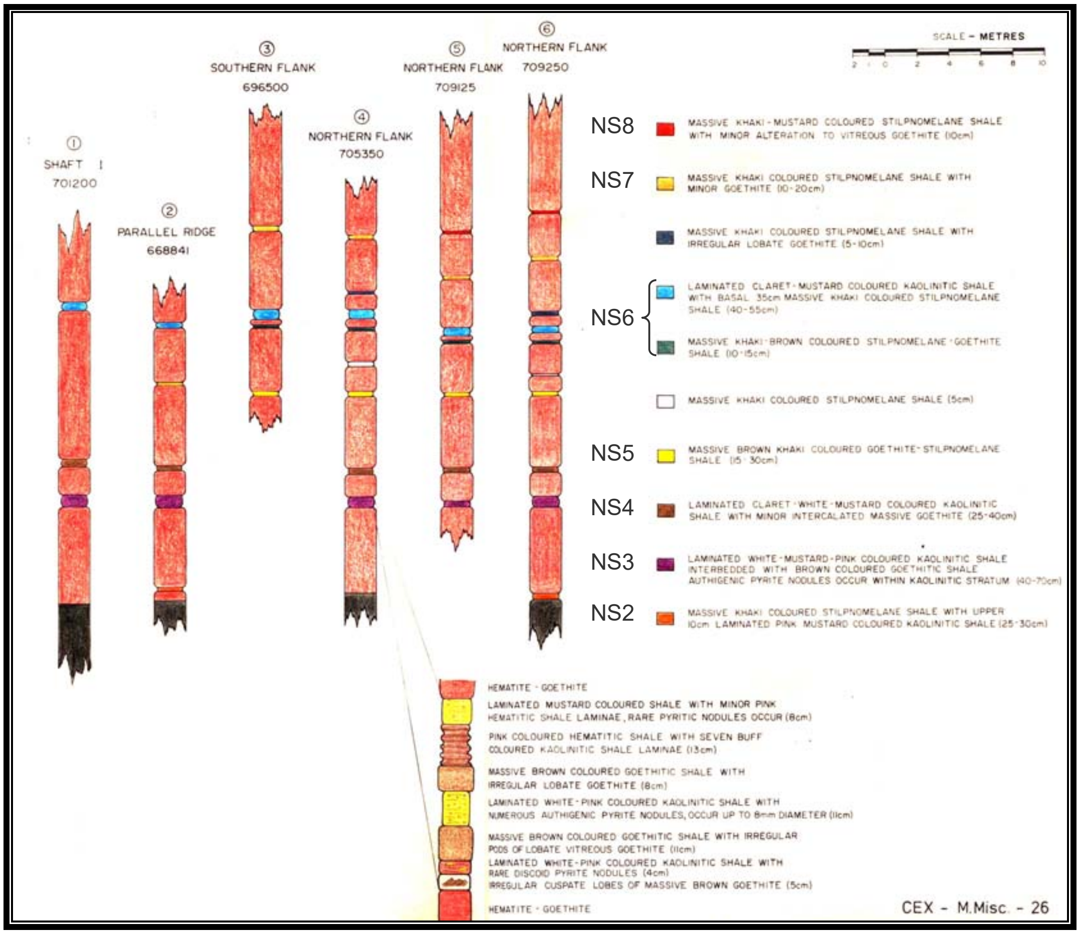


Figure 7. Lithology of the S macrobands of the Mount Newman Member from C Deposit and elsewhere. The detailed division of NS3 has a main central zone of (ex)pyrite balls and upper and lower less well developed pyritic beds. The two thin shales immediately below NS3 are not described. Red is mineralisation, black is BIF (modified after GML 1984).

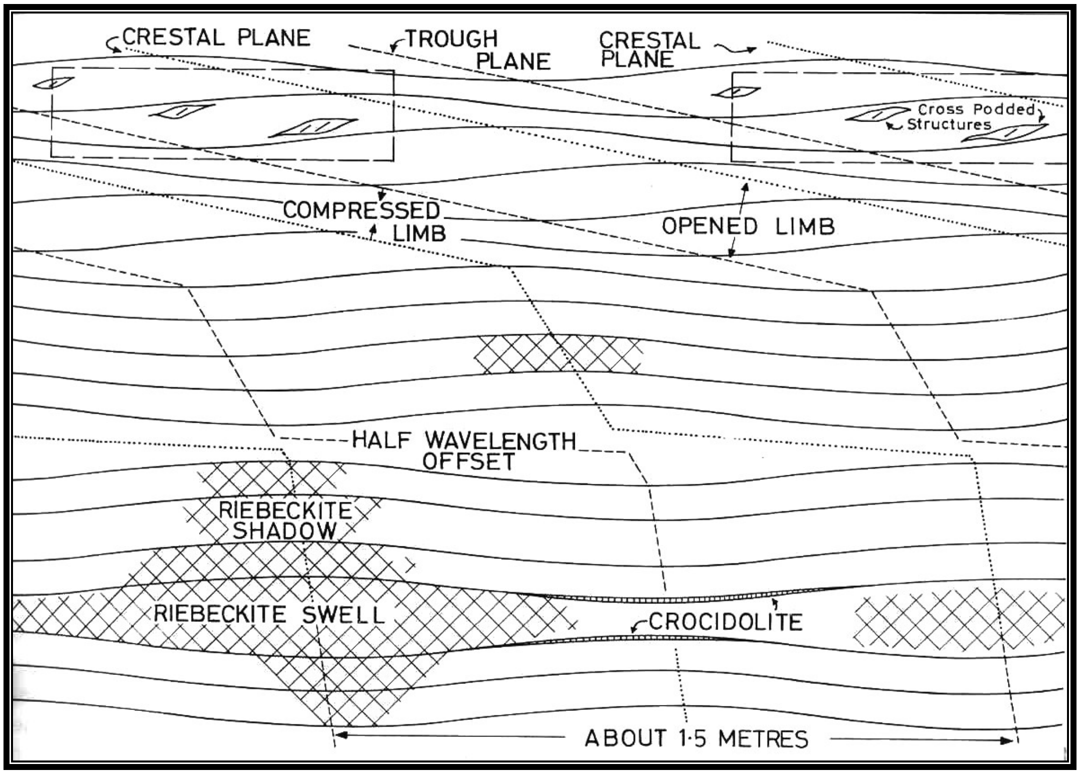
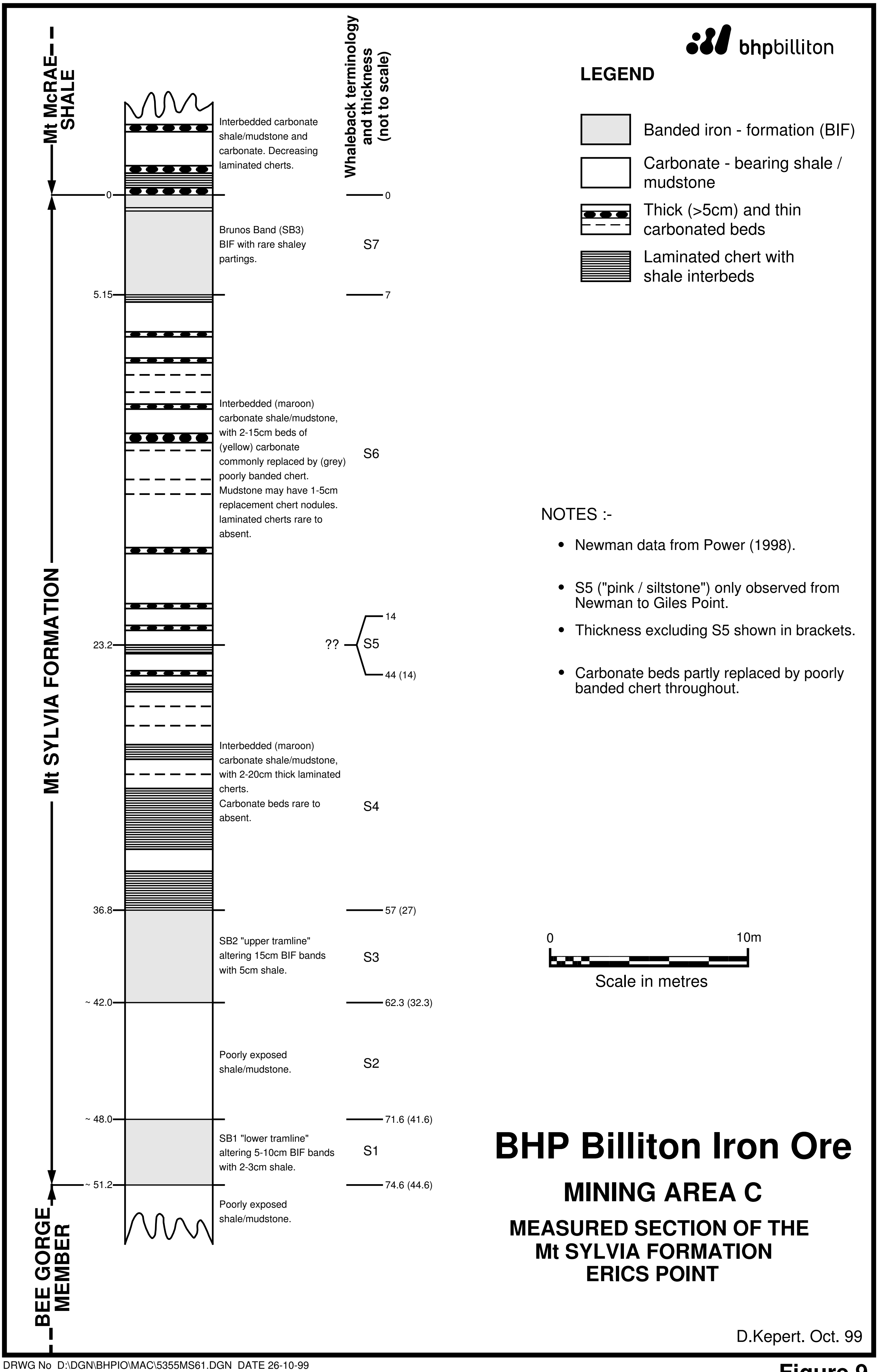


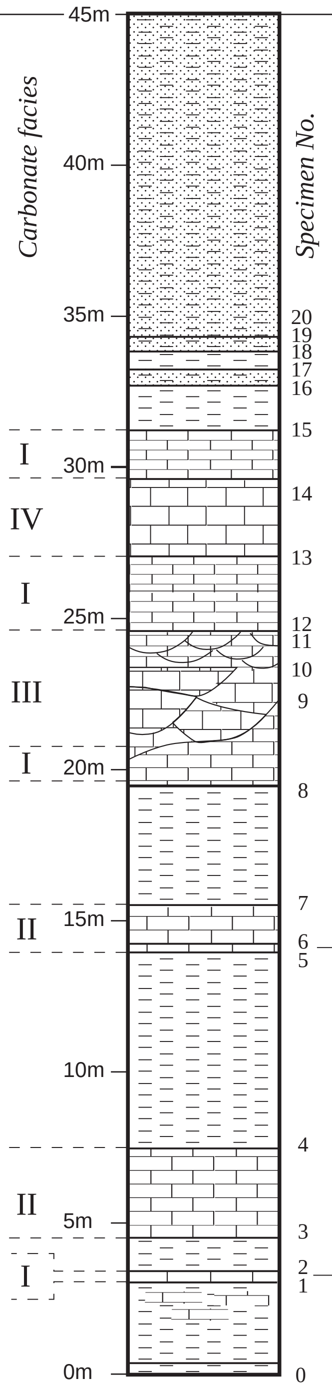
Figure 8. D_1 structures controlling the zones of riebeckite alteration during diagenesis of DB0 in Dales Gorge (looking north, from just downstream of Circular Pool). Note, that what is labelled as a (vertically) compressed limb corresponds with, and more correctly termed, a low angle horizontal extensional shear (from Trendall *in* Hickman 1990).



DRWG No D:\DGN\BHPIO\MAC\5355MS61.DGN DATE 26-10-99

Figure 9

DEPTH **LITHOLOGY** **DESCRIPTION**



COLONIAL CHERT MEMBER (D1)

MT McRAE SHALE

Red brown argillaceous shale
Banded white chert
Redbrown shale

Carbonate mudstone.Laminated,very fine partings(fissile).
Very minor argillaceous content

Carbonate mudstone.Grey and pale red brown weathering.
Planar bedding,laminated.Slightly argillaceous and non argillaceous carbonate mudstone,thick laminae alternate in rhythmically laminated sequence

Carbonate mudstone,laminated,very fine partings(fissile).
Very minor argillaceous content

Carbonate mudstone.Planar,laminated.maroon fresh grey(weathered)

Carbonate mudstone.Pink grey.Festoon bedding 10-20cm thick,beds display internal current bedding

Carbonate mudstone.Grey.Massive appearance,but trace discontinuous laminae.
Festoon beds~60cm thick,Scour channels,erosional base where it may be intraclastic

Carbonate mudstone.Laminated,very fine(papery) partings.Grey,maroon

Pale yellow,off white,argillaceous shale.Silicified in part

Very fine 'grainstone'/'packstone'.Indistinctly laminated. Pale grey

Very fine 'grainstone'/'packstone'.Trace lamination.Ripup clasts of laminae of mudstone up to 2-3cm diameter.Grey

Pale yellow,white,argillaceous shale.Some laminae of maroon,grey carbonate mudstone near top and bottom.Some intraclasts

Very fine to ? medium grained 'grainstone'/'packstone'.Intraclastic.Base is erosional in part.Clasts up to 5cm long,generally ≤1cm

Argillaceous shale.Maroon.Fibre infills pull aparts parallel to bedding

White carbonate mudstone.Faint lamination.Dolomitic

White,pale yellow argillaceous shale with carbonate mudstone bands becoming more evident upwards.Minor sculpturing

Cherty shale.Yellow brown.Heisegangs.Below lies at least 20m of shale, below which are chert triplets(in creek)

SCALE 1:250

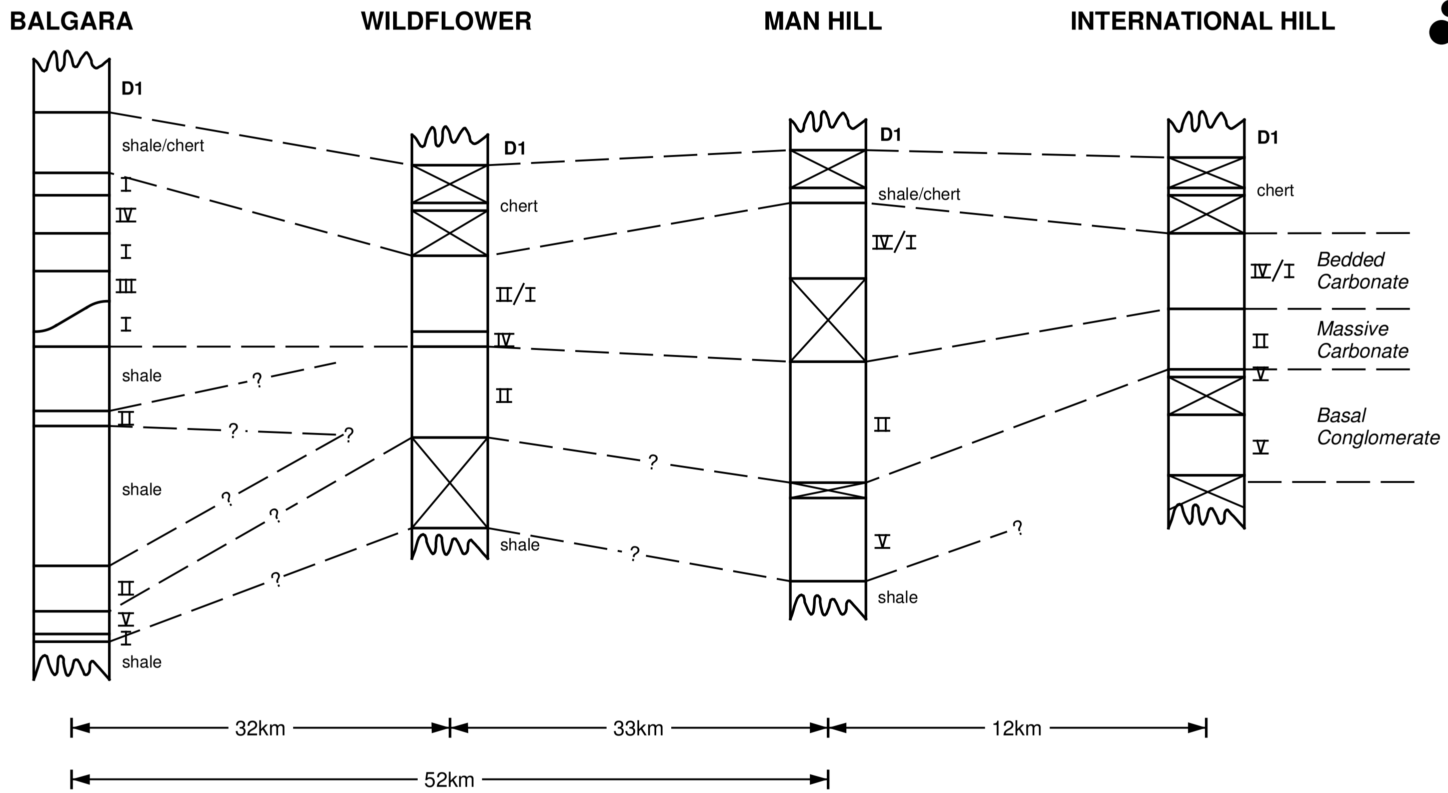
BHP Iron Ore (Goldsworthy) Pty. Ltd.

MUDLARK WELL
E47/15

MEASURED SECTION OF PART OF MT McRAE SHALE

10/599/25

Compiled: M.Benbow	Date: Sept. 1995	FIGURE 10



BHP Billiton Iron Ore

AREA C

Correlation of Mt McRae Shale Carbonate Turbidite

Facies

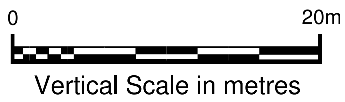
I carbonate mudstone , well bedded

II carbonate grainstone , massive to poorly bedded , intraclastic

III carbonate mudstone , festoon crossbedding

IV carbonate mudstone , rhythmic bedding

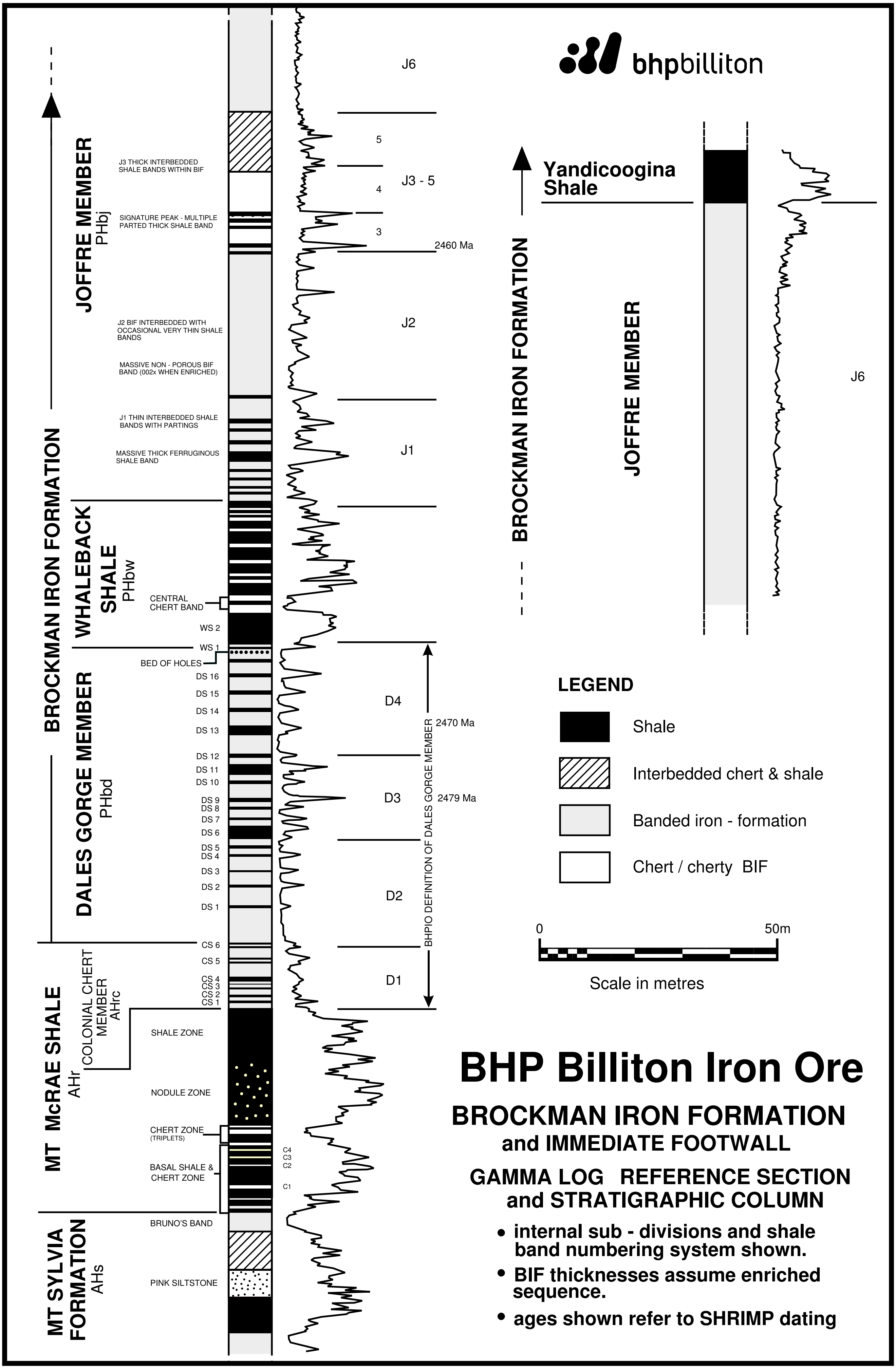
V basal conglomerate , dirty carbonate / shale matrix



D.Kepert. Oct. 99

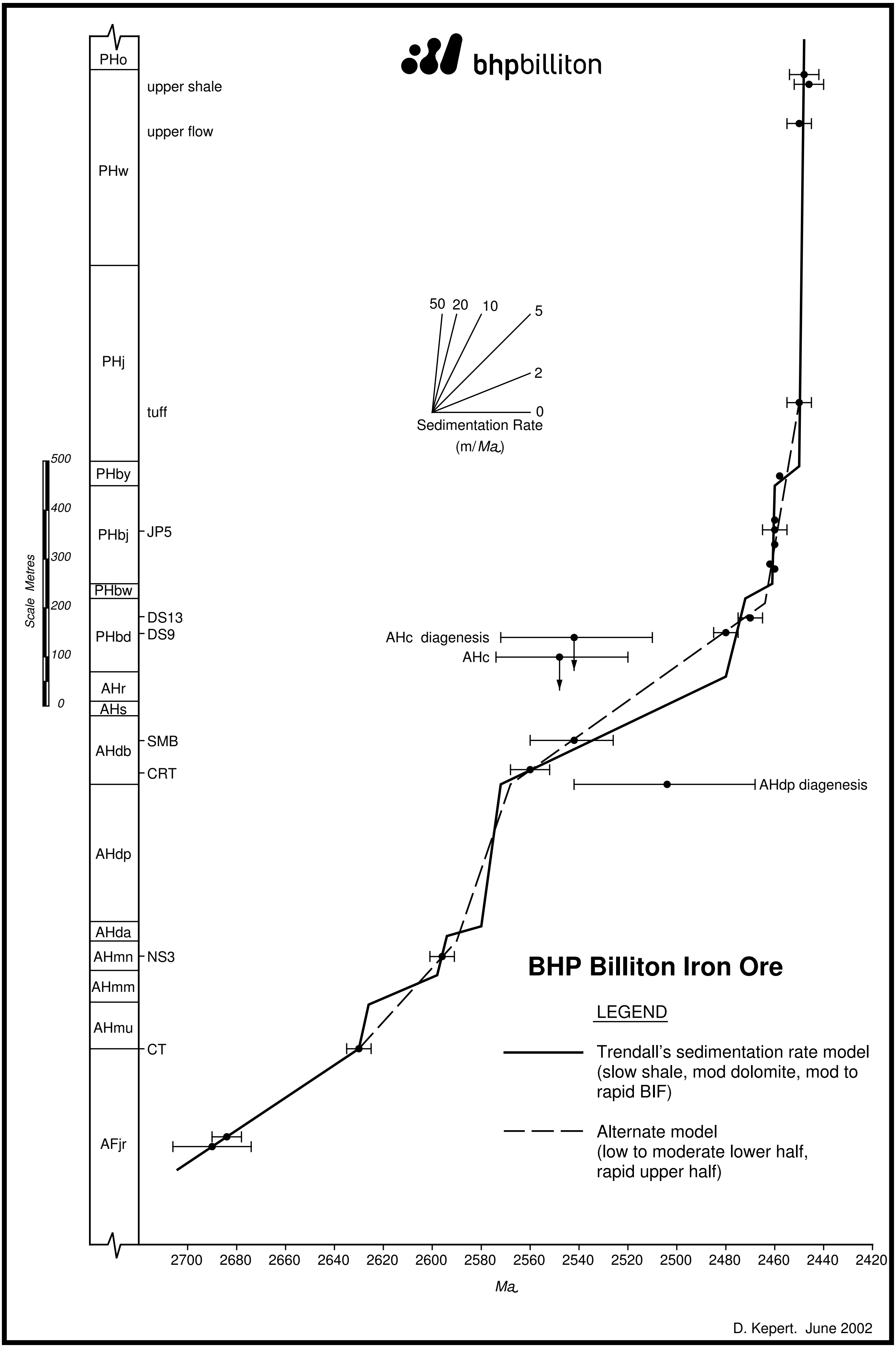
DRWG No D:\DGN\BHPIO\MAC\5355MS62.DGN DATE 26-10-99

Figure 11



DRWG No D:\DGN\BHPIO\5355MS02.DGN DATE 13-5-2002

Figure 12



DRWG No i:\cad\bhpio\pilbara\ 20934mreu01.ddgn Date 28-6-2002

Figure 13

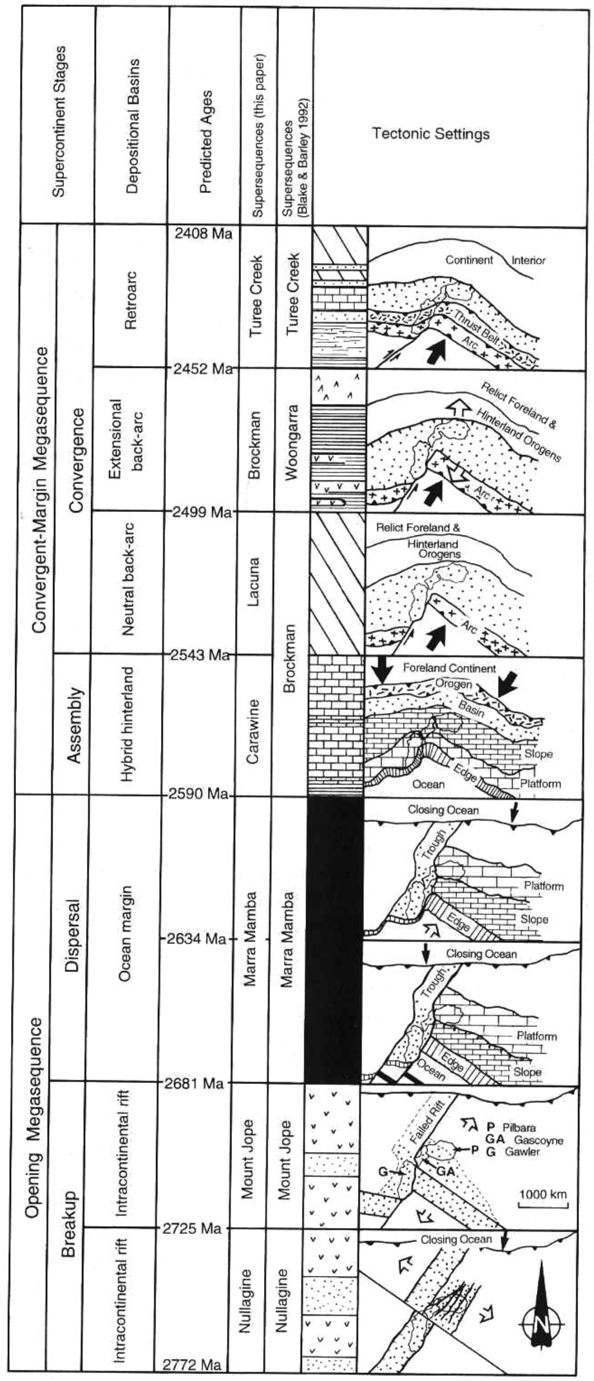


Figure 14. Sequence stratigraphic framework as defined by Krapez (1997).

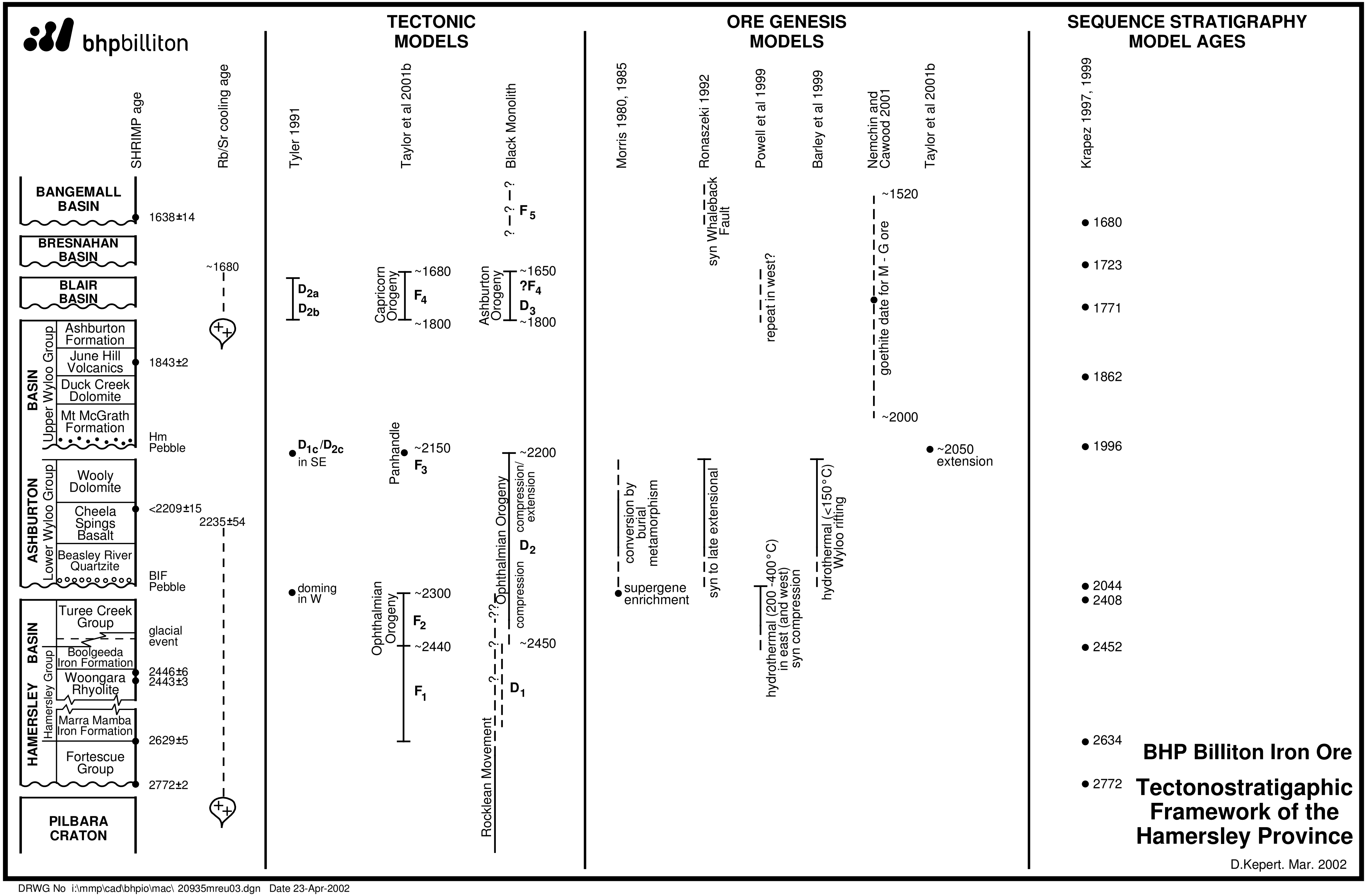

bhpbilliton
TECTONIC MODELS
ORE GENESIS MODELS
SEQUENCE STRATIGRAPHY MODEL AGES
SHRIMP age
Rb/Sr cooling age
Tyler 1991
Taylor et al 2001b
Black Monolith
Morris 1980, 1985
Ronaszeki 1992
Powell et al 1999
Barley et al 1999
Nemchin and Cawood 2001
Taylor et al 2001b
Krapez 1997, 1999
BANGEMALL BASIN
BRESNAHAN BASIN
BLAIR BASIN
ASHBURTON BASIN
Upper Wyloo Group
Ashburton Formation
June Hill Volcanics
Duck Creek Dolomite
Mt McGrath Formation
Lower Wyloo Group
Wooly Dolomite
Cheela Spings Basalt
Beasley River Quartzite
HAMERSLEY BASIN
Hamersley Group
Turee Creek Group
Boolgeeda Iron Formation
Woongara Rhyolite
Marra Mamba Iron Formation
Fortescue Group
PILBARA CRATON
1638±14
1843±2
Hm Pebble
<2209±15
BIF Pebble
glacial event
2446±6
2443±3
2629±5
2772±2
~1680
2235±54
D2a
D2b
D1c/D2c in SE
doming in W
Capricorn Orogeny
~1680
F4
~1800
Panhandle
~2150
F3
Ophthalmian Orogeny
~2300
F2
~2440
F1
? — ? — ? F5
Ashburton Orogeny
~1650
?F4
D3
~1800
~2200
Ophthalmian Orogeny
compression/ extension
D2
compression
~2450
D1
Rocklean Movement
conversion by burial metamorphism
supergene enrichment
syn Whaleback Fault
syn to late extensional
repeat in west?
hydrothermal (200 -400°C) in east (and west) syn compression
hydrothermal (<150°C) Wyloo rifting
~1520
goethite date for M - G ore
~2000
~2050 extension
1680
1723
1771
1862
1996
2044
2408
2452
2634
2772
BHP Billiton Iron Ore
Tectonostratigaphic Framework of the Hamersley Province
D.Kepert. Mar. 2002
DRWG No i:\mmp\cad\bhpio\mac\ 20935mreu03.dgn Date 23-Apr-2002

Figure 15

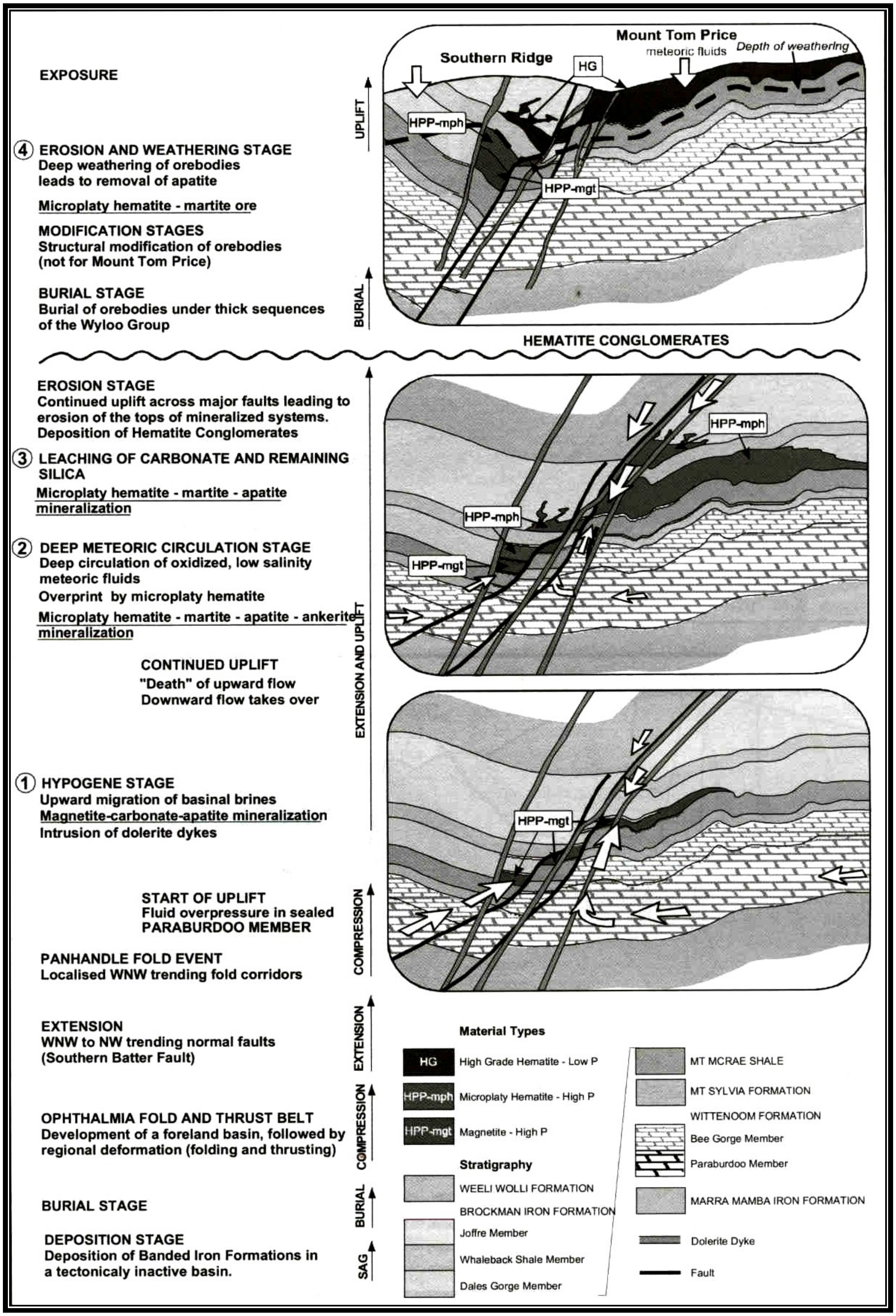
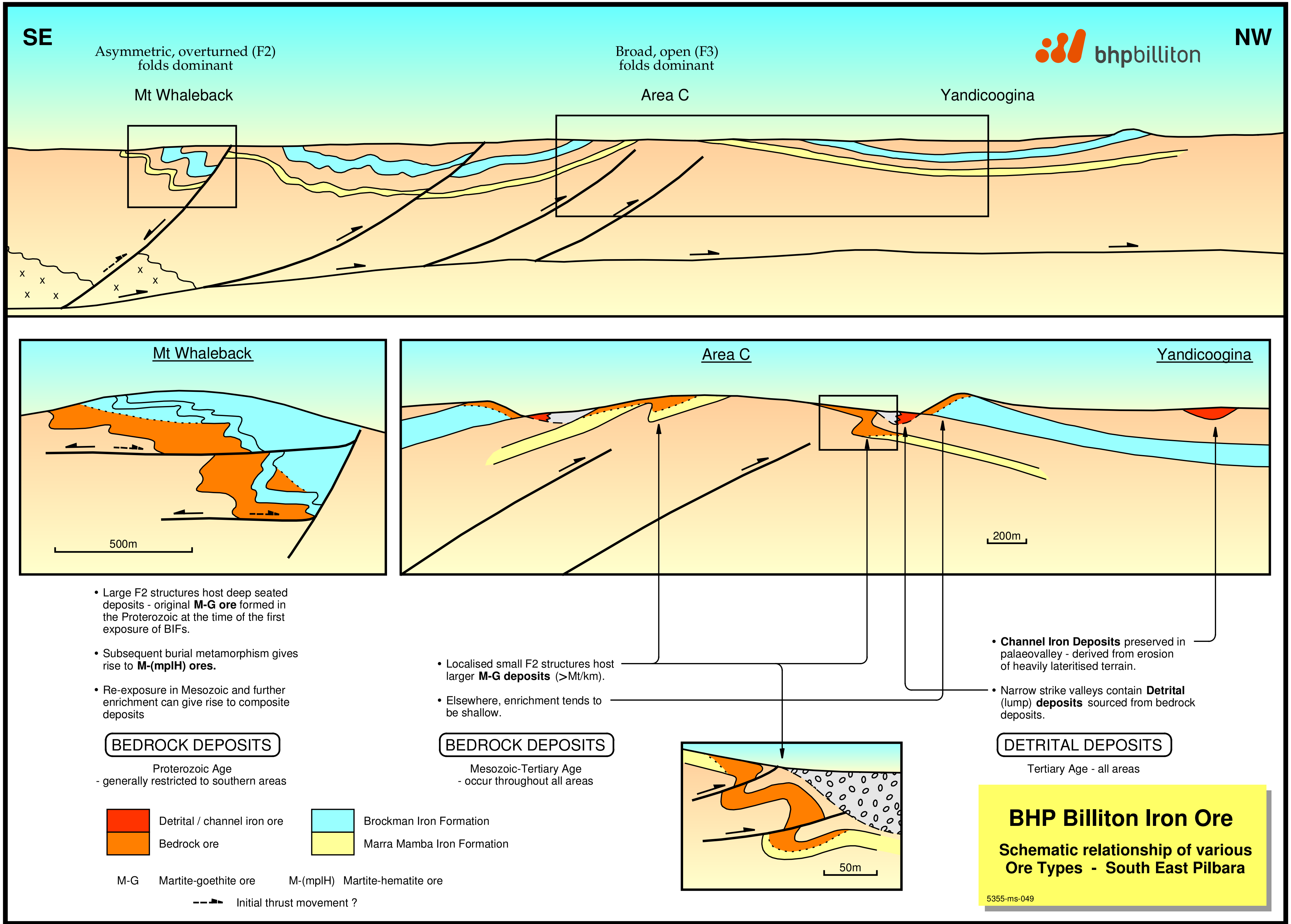


Figure 16. Genesis of the Tom Price ore body as proposed by Hamersley Iron.



FILE: d:\proj\dgn\bhpio\pilbara\5355ms49.dgn
DATE: 16-Nov-98 14:57

Figure 17

PROTEROZOIC

~2000 Ma Exposure of BIF along McGrath Trough margins
Ore formation – M-G type
~1900 Ma Burial and metamorphism of ore to (mpl H)
~1850 Ma **Erosion – Proterozoic (ore) DETRITALS** (Mt McGrath Fm)
Reburial – magnetite growth

MESOZOIC ~245 Ma

Erosion – general exposure of BIF and old ores
Extensive M-G ore formation in suitable environments
Sediments in the Fortescue valley
Maturation of Hamersley Surface 1 (HS1)

TERTIARY ~65 Ma

PALAEOCENE to EOCENE ~45 Ma — Continued maturation??? Followed by:-
Erosion – deep valleys at AHm – AHd contacts in particular

EOCENE to EARLY MIOCENE — Stripping of mainly AHm ores + AHd soil residuals resulting in red ochre detritals in silled valleys on AHda and AHmn

TERTIARY DETRITALS 1 (TD1)

↙ ↘

ORE-BEARING DETRITALS
Alluvial – fluvial, proximal
conglomeratic gravels + silt

NON-ORE DETRITALS
Alluvial, distal, red ochre silt
+ shale and ore clasts

MIDDLE MIOCENE — **Maturation of Hamersley Surface 2 (HS2)**
Deep ferricrete surface with minimal BIF – ore exposures
Extensive flats and scrub cover

MIDDLE to LATE MIOCENE ~11Ma — **Erosion** – new valleys not closely tied to geology
Gradual stripping of ferricrete
Dominantly accretionary **ooids** – no remnant BIF texture

TERTIARY DETRITALS 2 (TD2)

↙ ↘

ORE DETRITALS = CID
Alluvial gravels + fossil wood
+ G cement (infill + bog iron)

NON-ORE DETRITALS
Mottled clays from leached shale
+ dolerite, lacustrine limestones

Maturation of Hamersley Surface 3 (HS3) on remnants of HS2

PLIOCENE ~5Ma — **Erosion** – deep incision of the present surface
Stripping of **ores** and **BIF**

TERTIARY DETRITALS 3 (TD3)

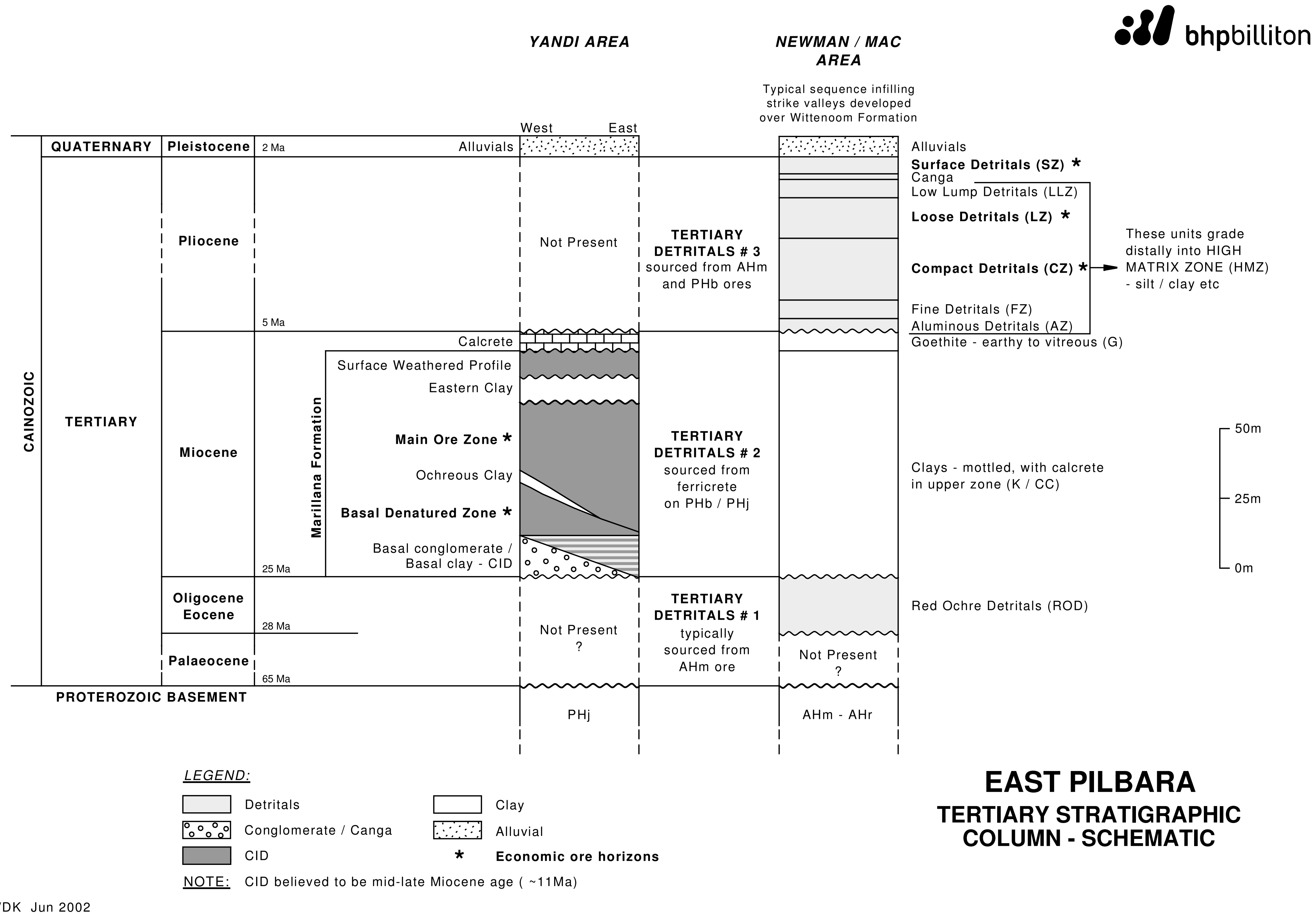
↙ ↘

ORE-BEARING DETRITALS
Colluvial – alluvial gravels
Mature M-(H) type + G^(H)
to less mature, younger M-G

BIF–BEARING - DETRITALS
BIF + M-G

RECENT — Increasing BIF detrital cover

Figure 18. Tentative timing of events leading to the formation of post Hamersley Basin detritals of the Hamersley Province (modified after Morris 1994).

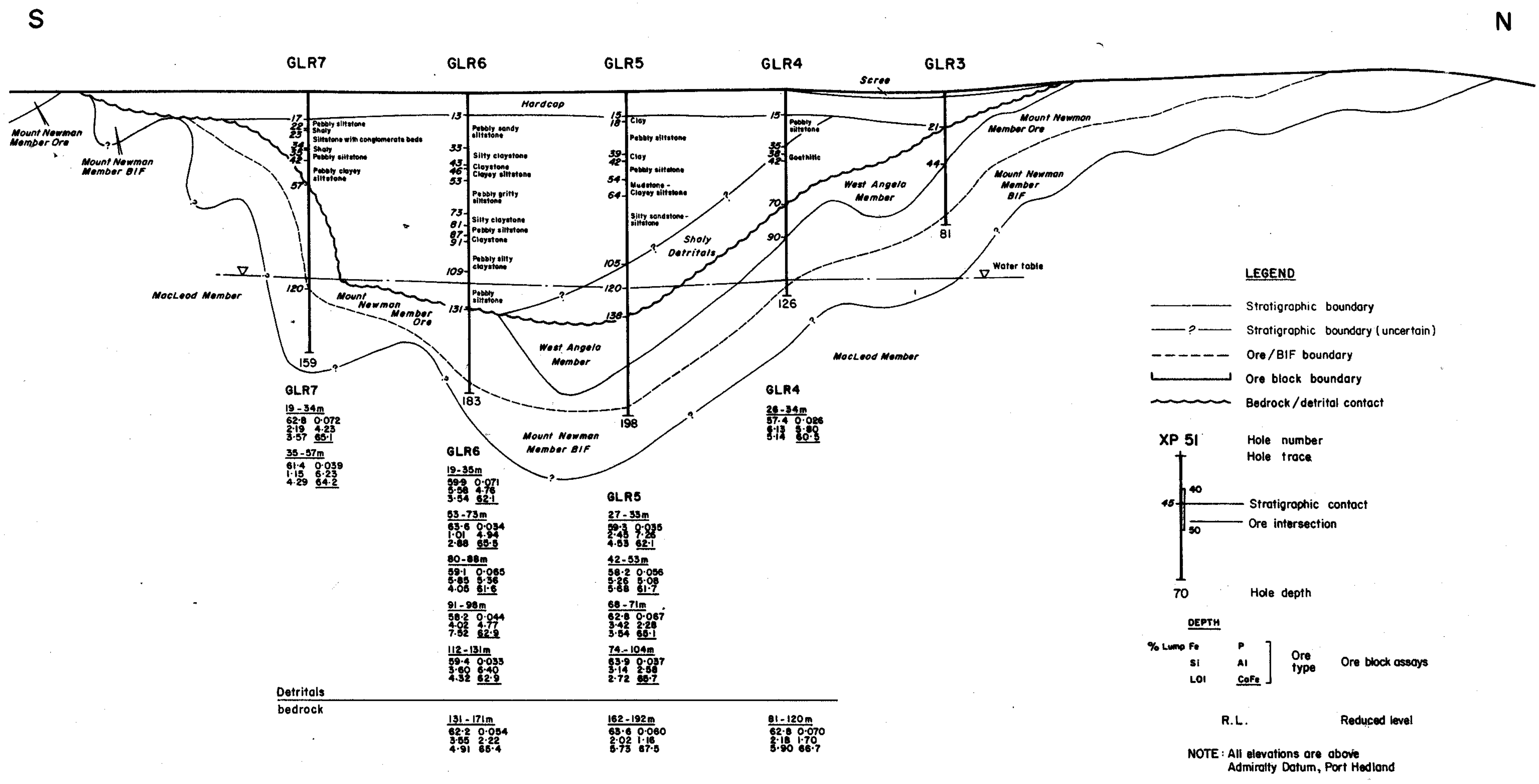


EAST PILBARA

TERTIARY STRATIGRAPHIC COLUMN - SCHEMATIC

Figure 19

FILE: i:\mmp\cad\bhpio\newman\new_log.dgn
DATE: 30-Sep-2001 12:24



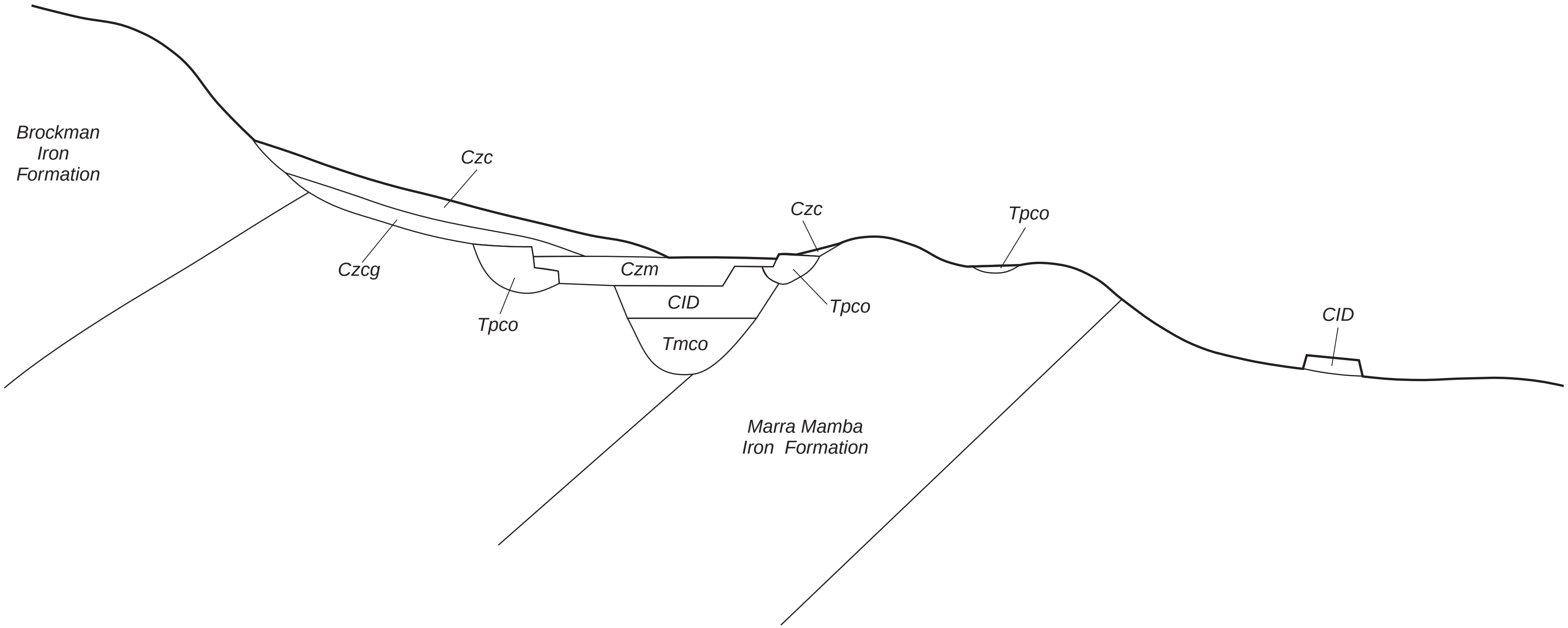
BHP Iron Ore (Goldsworthy) Pty. Ltd.

MINING AREA C
L DEPOSIT 697 500 E

RED OCHRE DETRITALS

SELECTED ASSAY COMPOSITES

Author : C.M.S.	Date : Oct 1994	FIGURE 20



NB: There is no evidence that Tmco occurs at MAC Park

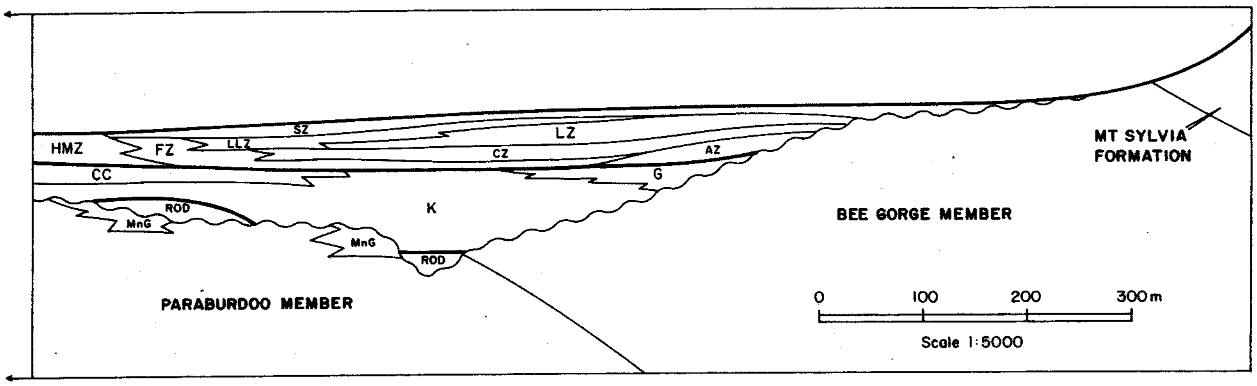
Vertical and Horizontal are not to scale

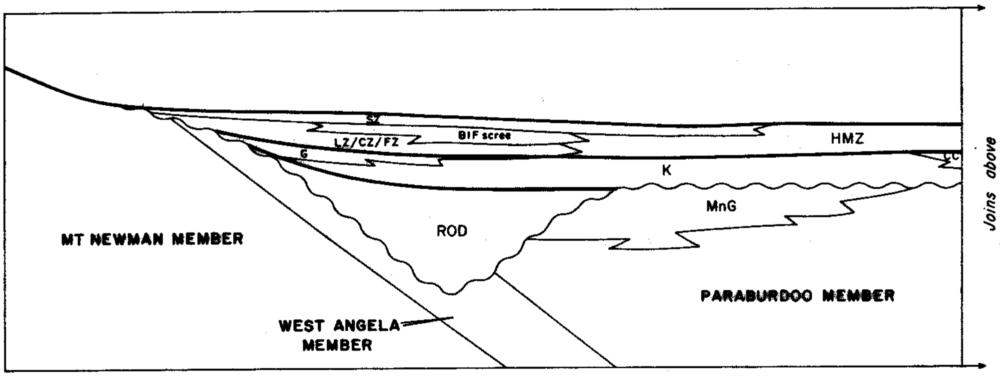
BHP Iron Ore (Goldsworthy) Pty.Ltd.

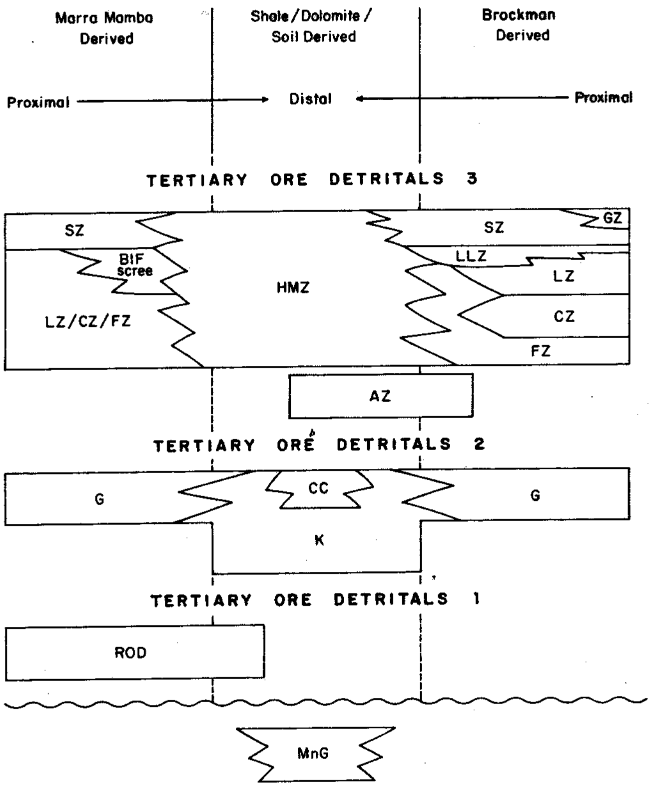
MAC PARK
TR3156H

SCHEMATIC SECTION THROUGH CAINOZOIC SEDIMENTS

Author: D.K.	Date Nov '96	FIGURE 21







TOD 3

SZ Surface Scree - goethitic hematite and/or BIF etc in brown soil matrix

GZ Surface Canga - goethite/calcareous cemented SZ (not shown on section)

LLZ Low Lump Scree - goethitic hematite/hematite with some BIF/chert in red-brown soil matrix

LZ Loose Scree - hematite and maghemite in brown-red soil matrix, typically > 40% lump

CZ Compact Scree - nodular maghemite and hematite in red soil matrix, typically > 40% lump

FZ Fine Scree - fine 2 to 5mm nodular maghemite and hematite in red soil matrix

HMZ High Matrix Scree - orangey red-brown soil with < 15% lump

AZ Aluminous Scree - shaly, goethitic and gibbsitic scree in shaly matrix

TOD 2

G Goethite - earthy to vitreous goethite, hardcap, pisolitic (CID equivalent) in places

K Clay - mottled clays, typically with goethite and limonite pods near top

CC Calcrete - calcrete, dolcrete, secondary silcrete

TOD 1

ROD Red Ochre Detritals - hematite and goethitic hematite in hematite matrix, shaly in part

MnG Manganiferous Goethite - hardcap developed on dolomite

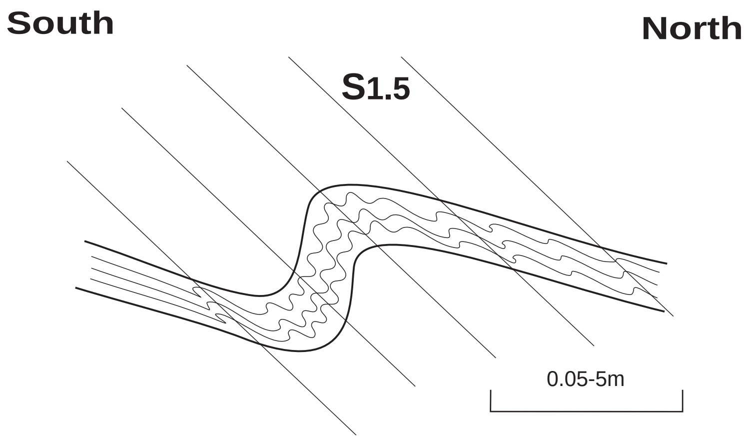
COMPOSITE SCHEMATIC CROSS SECTION OF DRILLHOLES BETWEEN 706 600 AND 707 400 E, AND 707 800 E

BHP Iron Ore (Goldsworthy) Pty. Ltd.

MINING AREA C

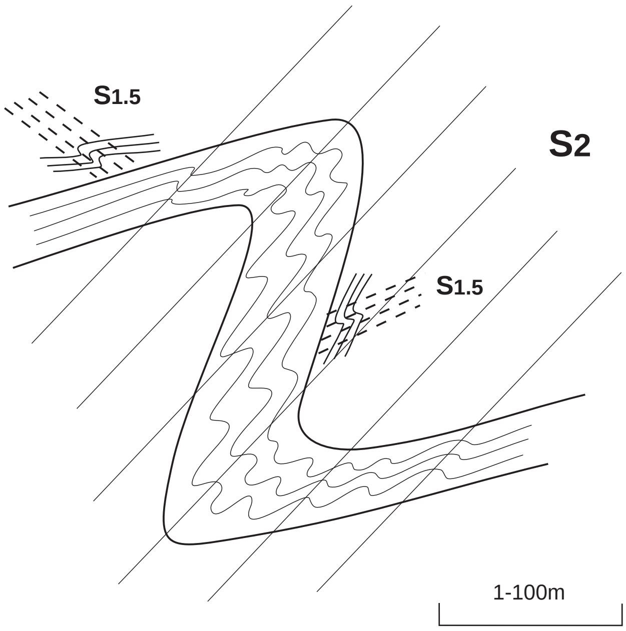
COMPOSITE SECTION ACROSS C RANGE / A DEPOSIT VALLEY

Author: DK	Date: Nov. 1994	FIGURE 22



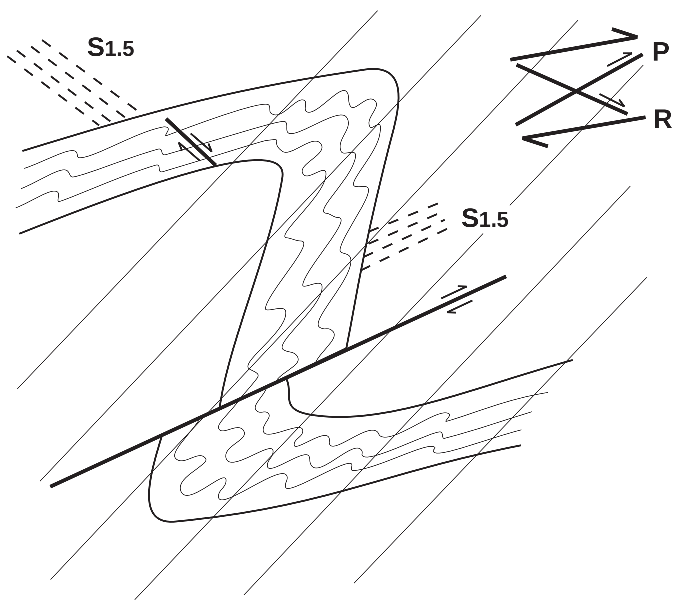
D1.5

- small to medium scale folding
- pronounced S1.5 cleavage
- moderate increase in bedding surface and stratigraphic thickness



D2

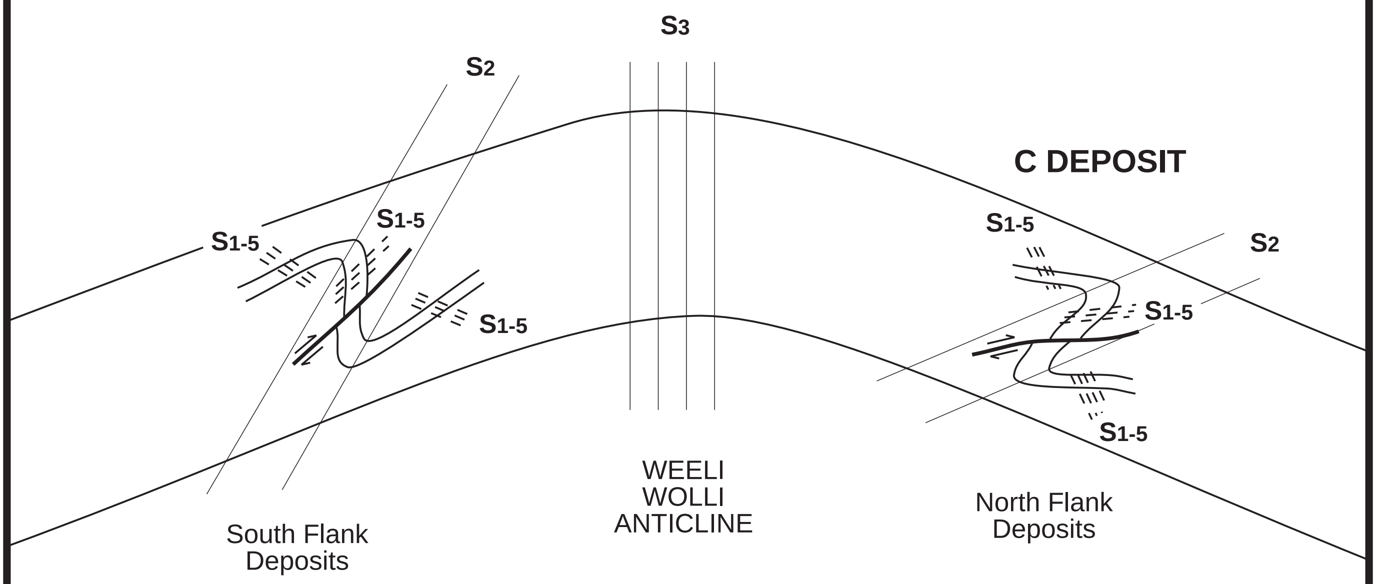
- small to large scale folding
- pronounced S2 cleavage
- partial destruction of S1.5 on flat limbs
- sub-parallel overprinting of S1.5 on steep limbs
- marked increase in bedding surface and stratigraphic thickness, especially on steep limb with addition of F2 and F1.5 crenulations



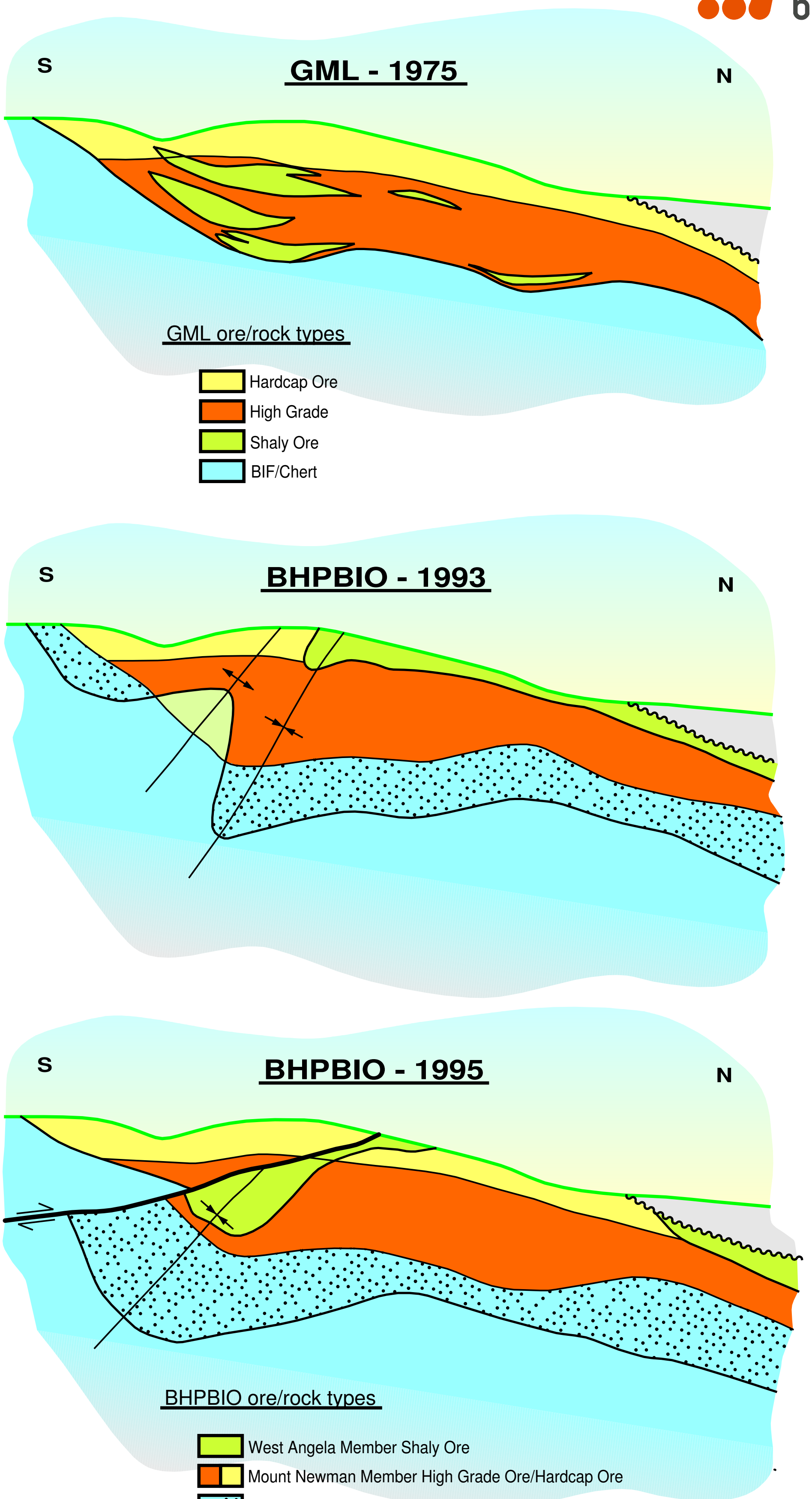
- development of thrusts (P and R shears) during folding, both apparently along S1.5 (N.B. Sense of movement etc is not consistent with folded D1.5 faulting)

D3

- small to large scale gentle warping
- moderate S3 cleavage
- limited increase in bedding surface and stratigraphic thickness



BHP Iron Ore (Goldsworthy) Pty. Ltd.		
MAC		
SCHEMATIC STRUCTURAL EVOLUTION OF C DEPOSIT		
Compiled: D.K.	Date: JUNE 1996	FIGURE 23



BHP Billiton Iron Ore

AREA C

Evolution of Stratigraphic and Structural Understanding 1975 to 1995
C Deposit Section 701200 mE

20935mreu01.dgn

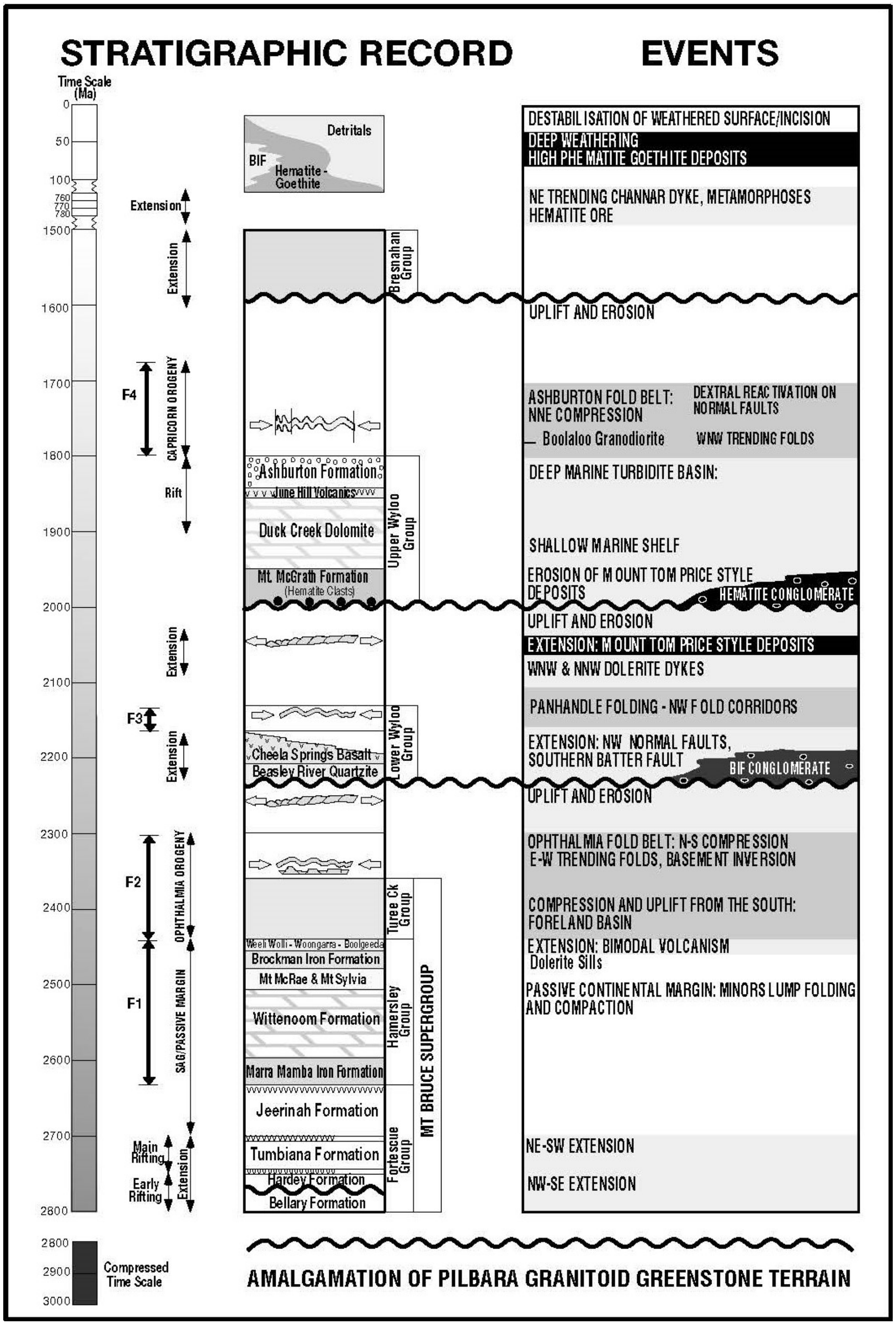
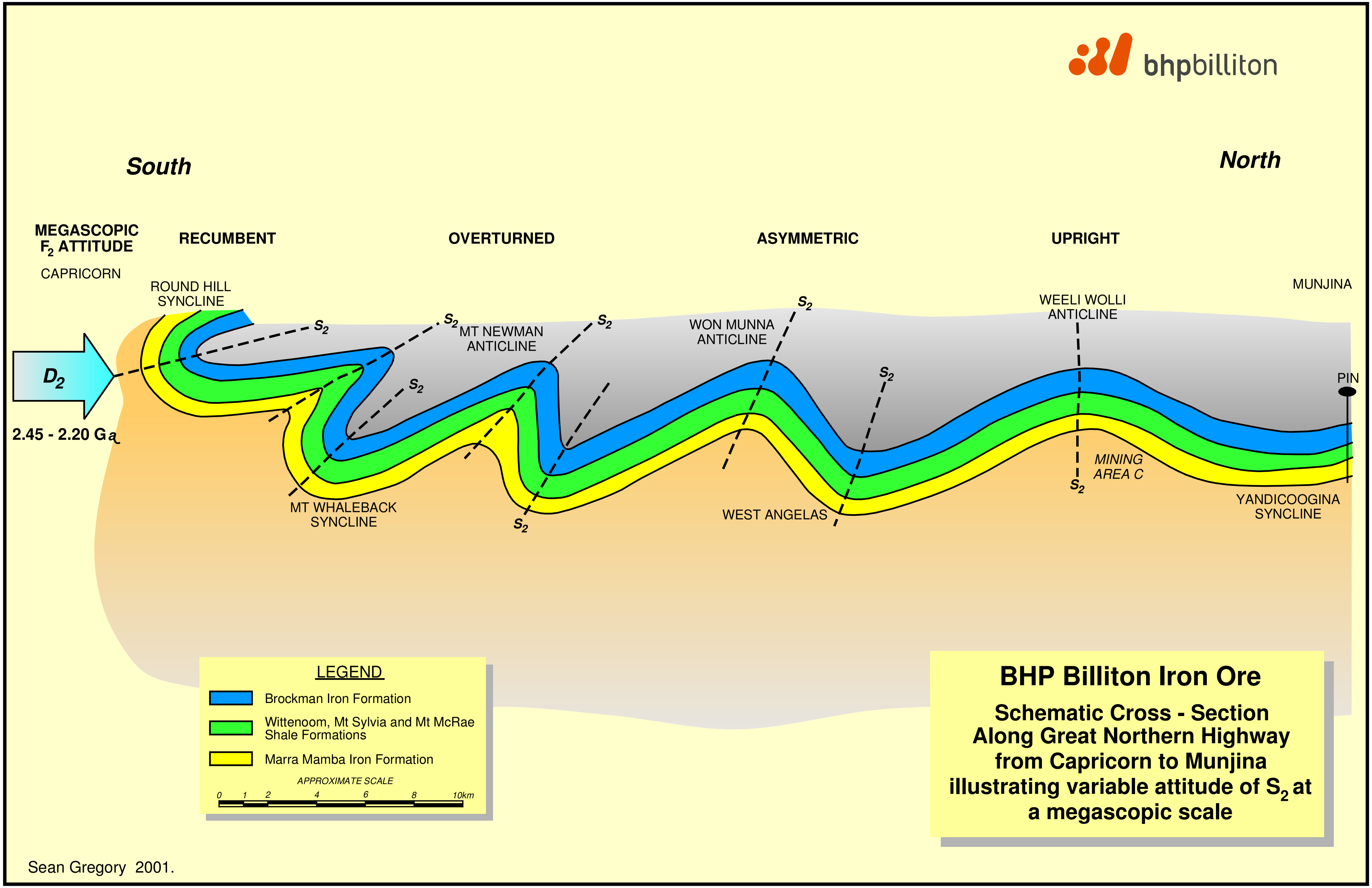
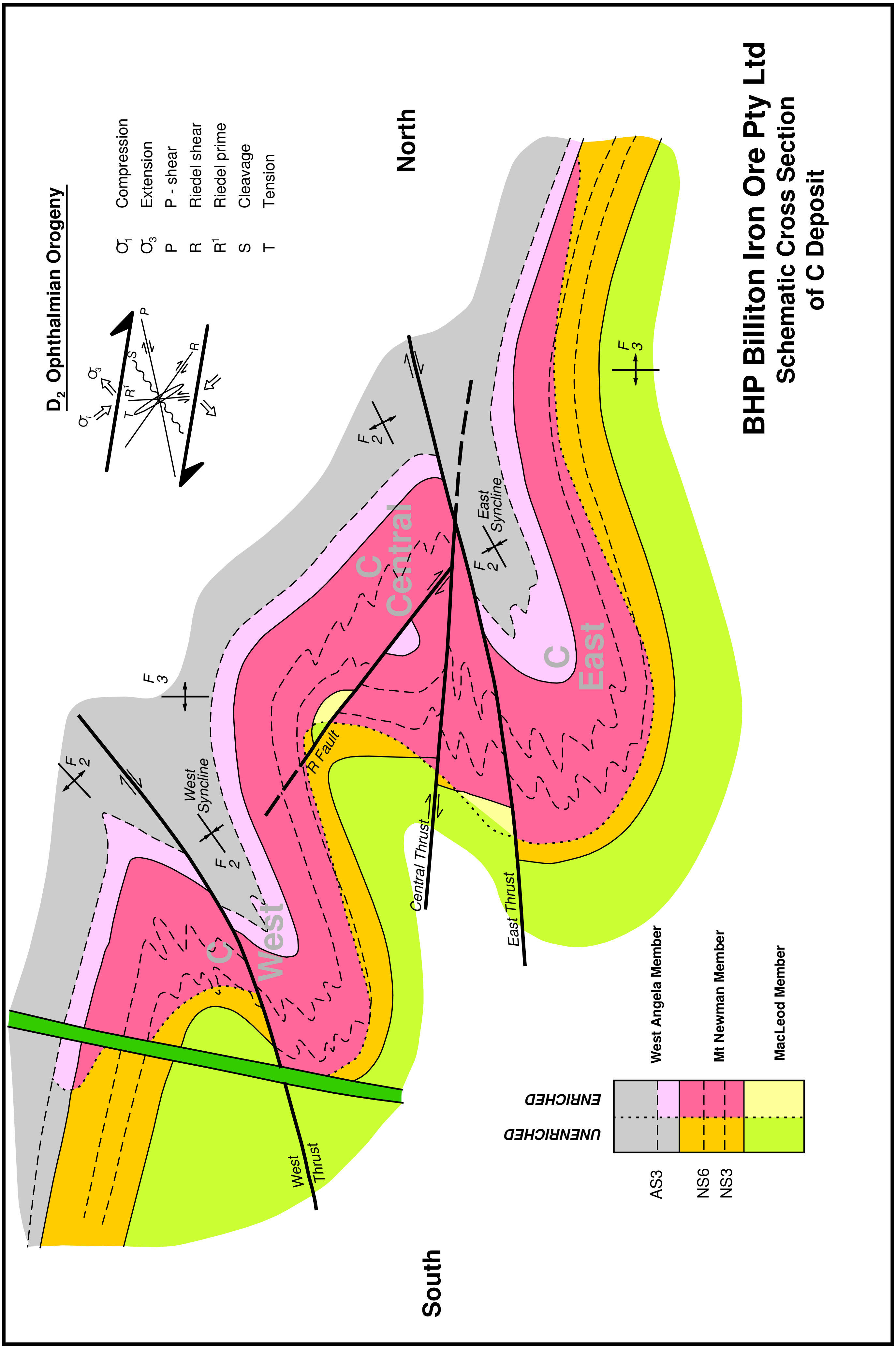


Figure 25. Hamersley Iron's tectonostratigraphic framework (from Taylor *et al* 2001b)



DWRG No i:\dgn\bhpio\mac\
21175mmp01.dgn Date 11-08-2001

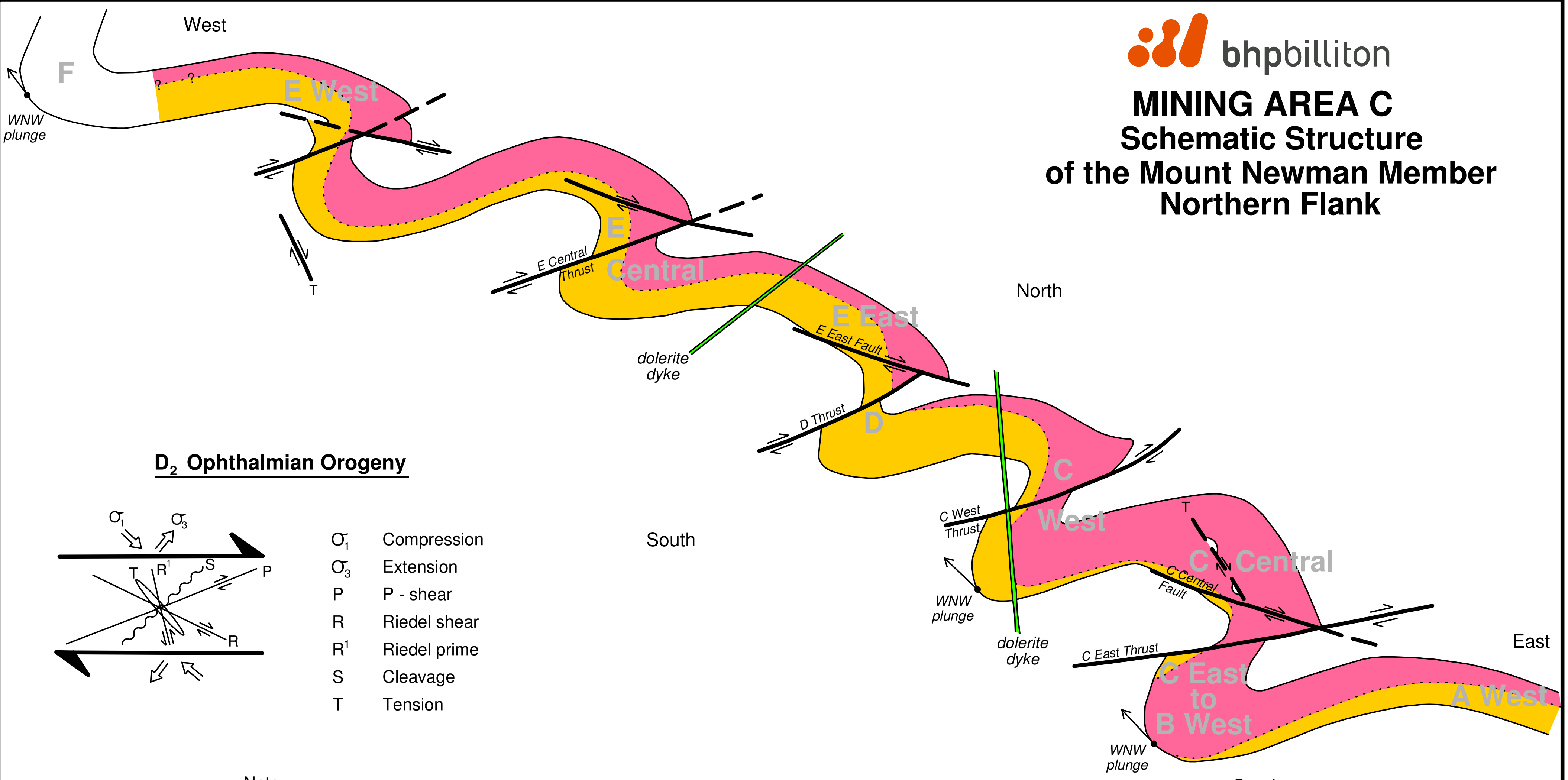
Figure 26



DRWG No D:\DGN\BHPIO\MAC\5348ms28.dgn DATE 06-Nov-2001

Figure 27

MINING AREA C
Schematic Structure of the Mount Newman Member Northern Flank



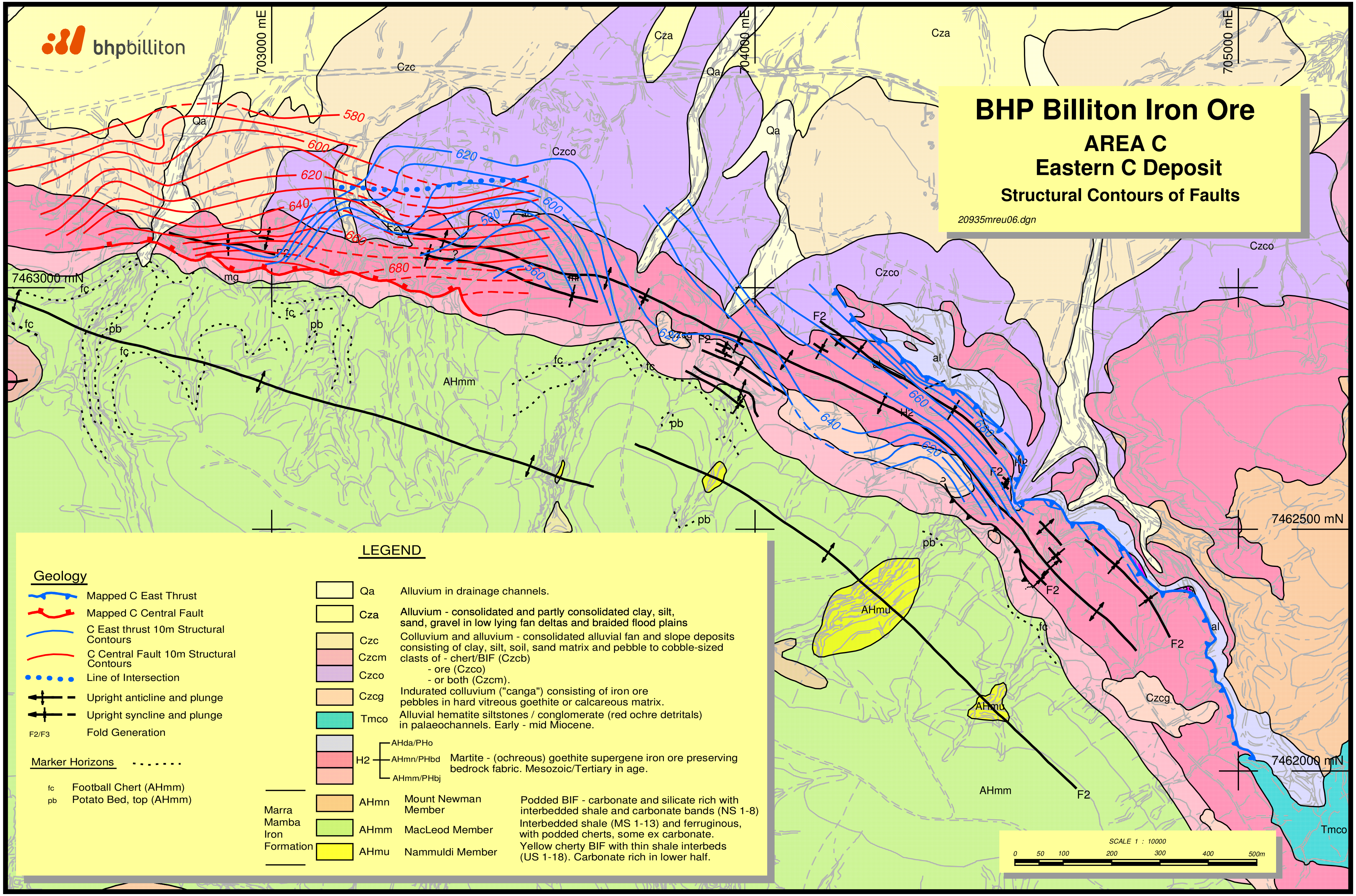
Note :-

- Only major folds and fault shown.
- All structures shown produce by the Ophthalmian Orogeny.
- Mount Newman Member mineralisation boundary highly schematic.
- Near surface, and West Angela and MacLeod Members mineralisation not shown.
- F Deposit structure and mineralisation insuffícently known.

Feb 01
D.Kepert.

DWRG No i:\dgn\bhpio\mac\5348ms32.dgn Date 12-02-2001

Figure 28



DRWG No. i:\mmp\cad\bhpio\mac\ 20935mreu06.dgn Date 4-9-2002

Figure 29

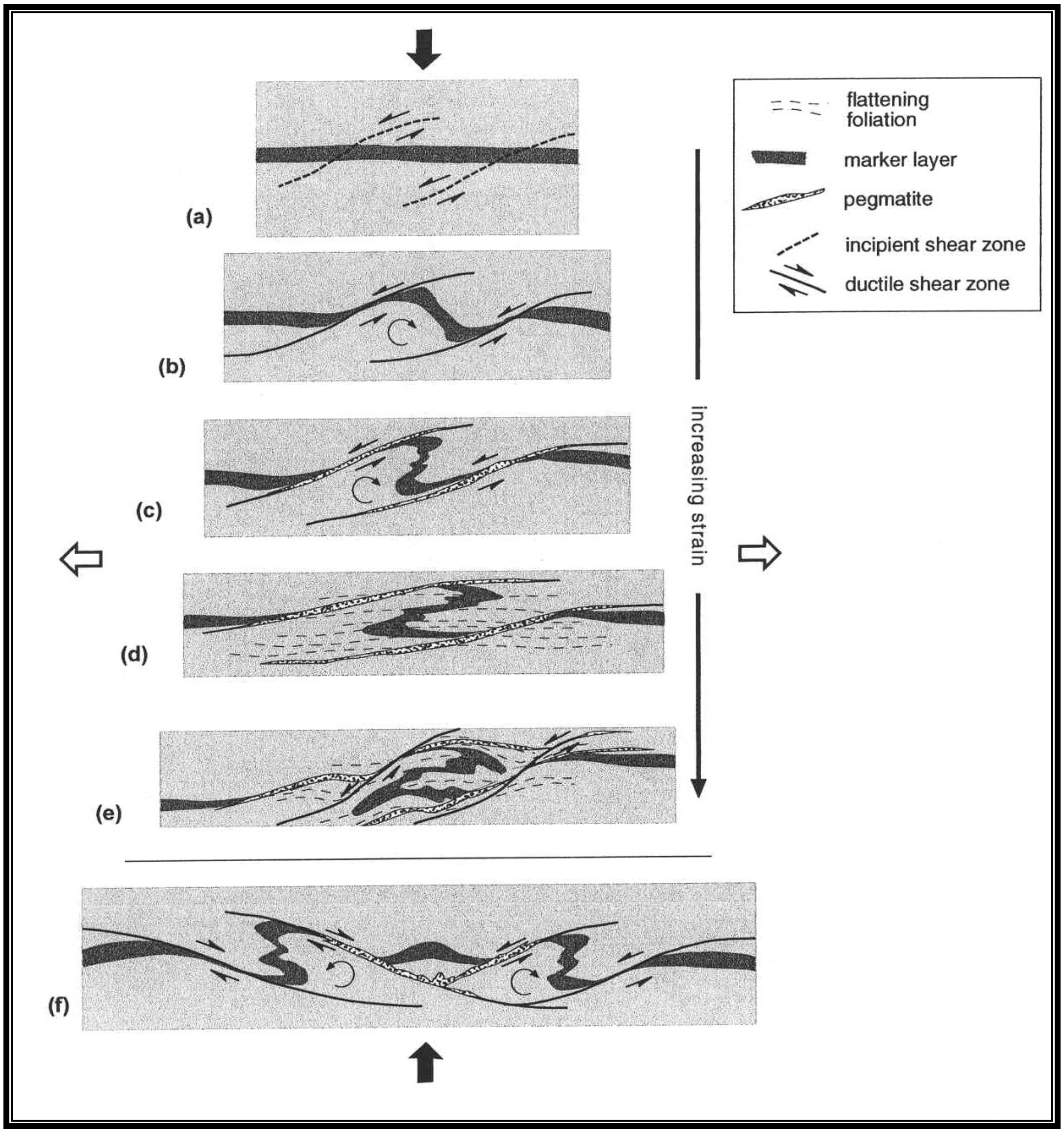


Figure 30. A model to for the development of tight, subhorizontal folds between adjacent extensional shears, (a) to (e) are isovolumetric, (f) shows development of conjugate sets (solid arrows – compression, open arrows – extension, LB Harris *pers comm* 2002).

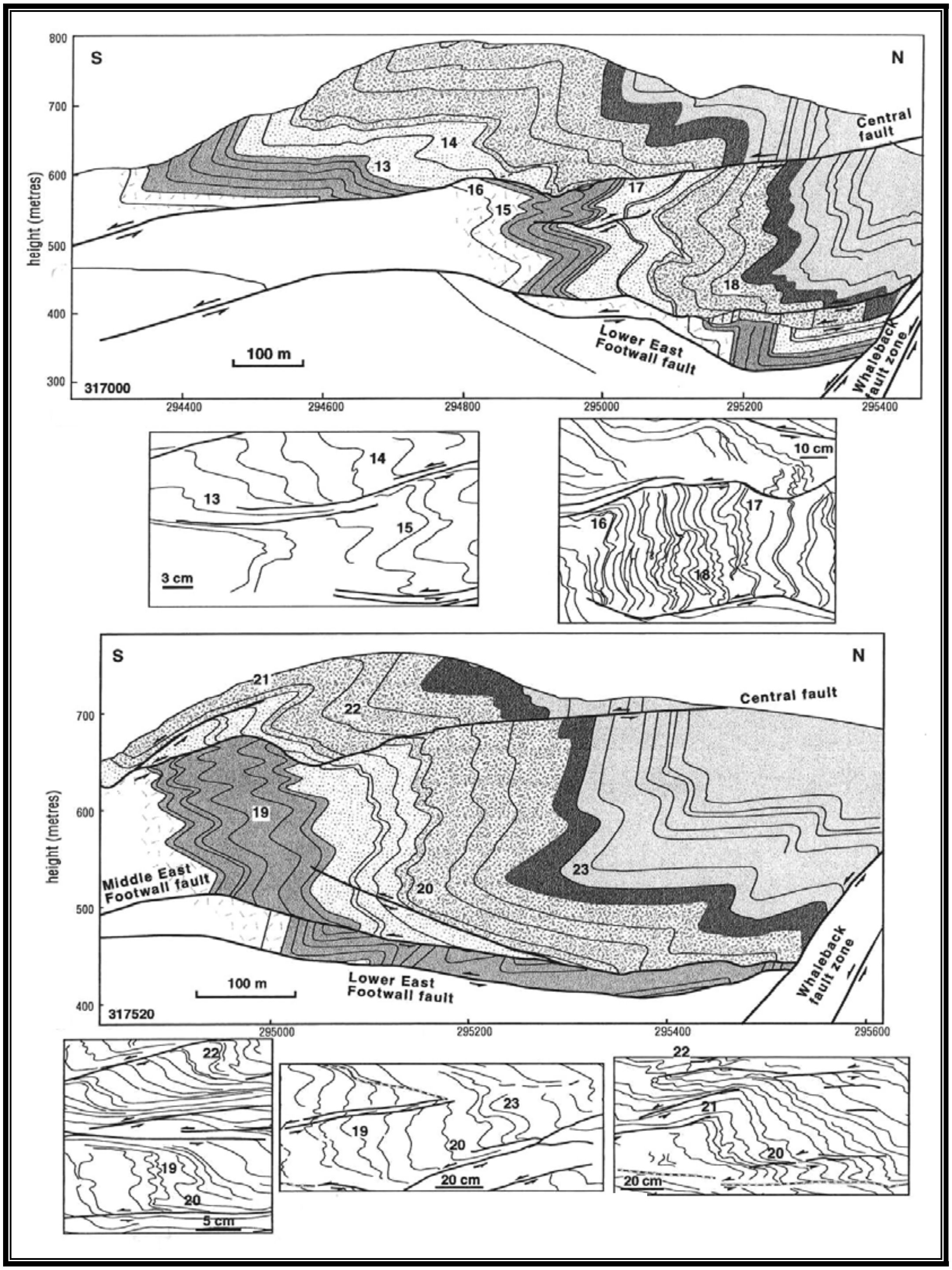


Figure 31. Similarities of fold styles between Mt Whaleback and possible extensional related folding in high grade gneisses on the south coast of Western Australia. Numbers on adjacent sketches link similar fault / fold geometries. Note the large (~500 to 2000 fold) difference in scale between the gneisses and Mt Whaleback (LB Harris *pers comm* 2002).

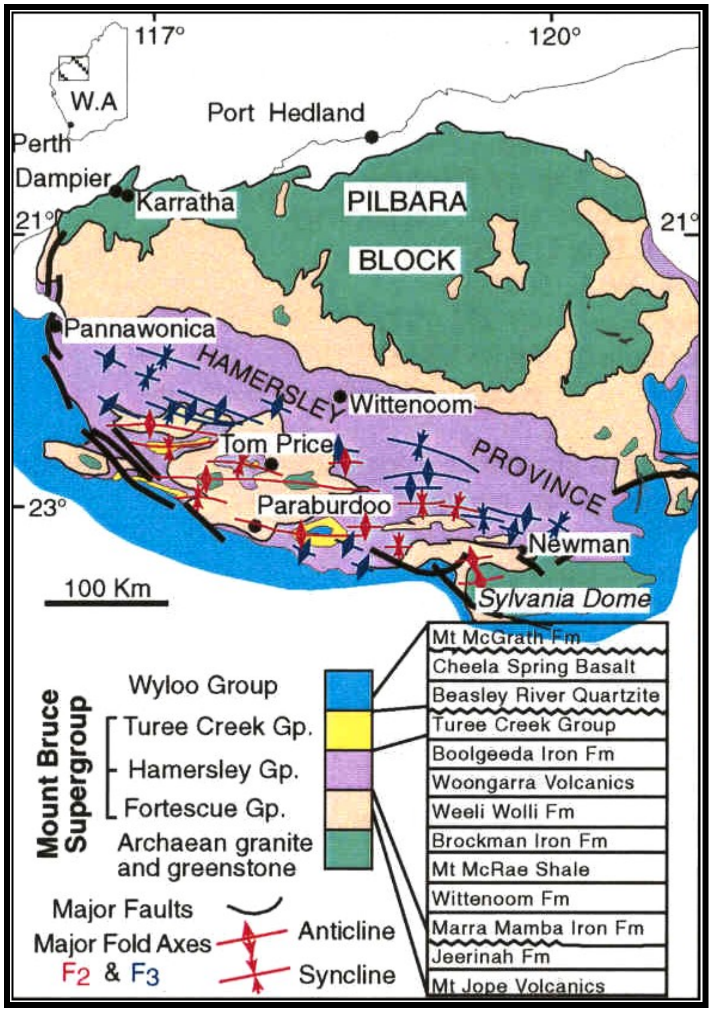


Figure 32. Regional distribution and orientation of D_2 and D_3 folds as categorised by Powell (eg in Martin *et al* 1998b), although his classifications remain doubtful being at odds with much of the work by BHPIO, HI and Hollingsworth, for example.

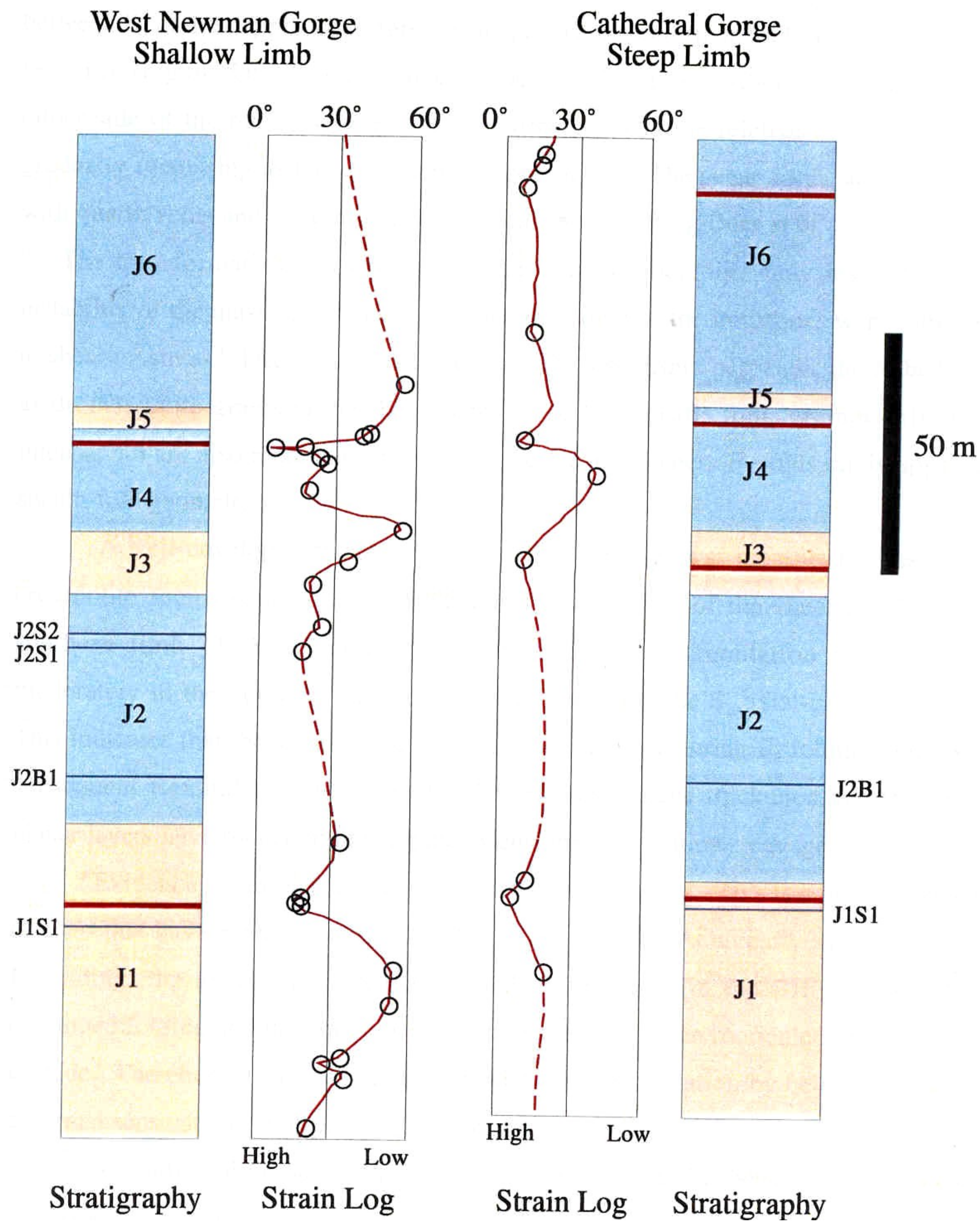
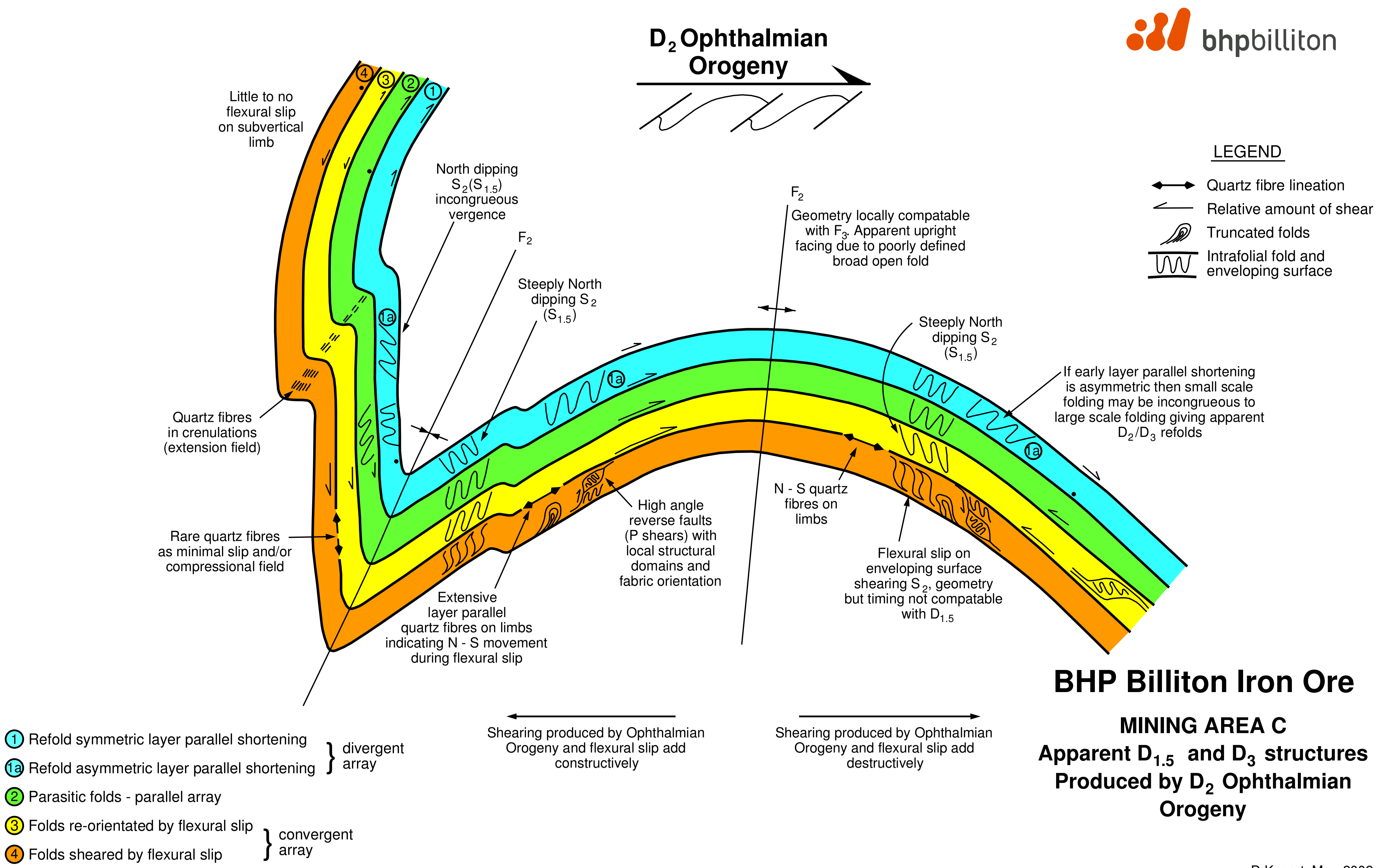


Figure 33. Apparent stratigraphic correlation of strain developed during the Ophthalmian Orogeny in the Joffre Member across the Mt Newman Anticline as measured by the relative angle between bedding (S_0) and axial plane (S_2) (from Gregory 1998).



BHP Billiton Iron Ore

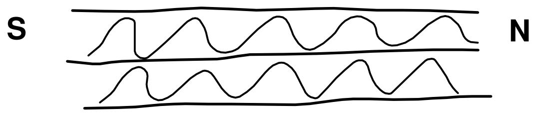
MINING AREA C
Apparent $D_{1.5}$ and D_3 structures Produced by D_2 Ophthalmian Orogeny

D.Kepert. Mar. 2002

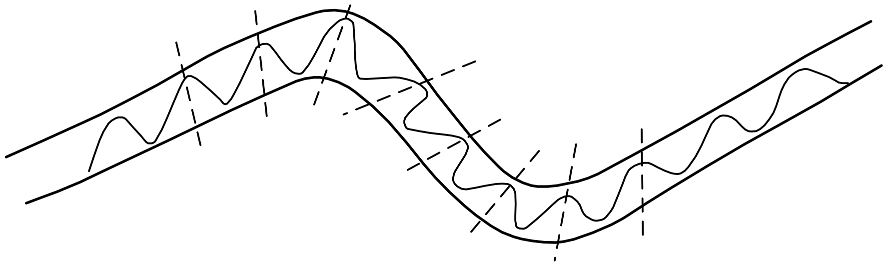
DRWG No i:\mmp\cad\bhpio\mac\ 20935mreu04.dgn Date 29-Apr-2002

Figure 34

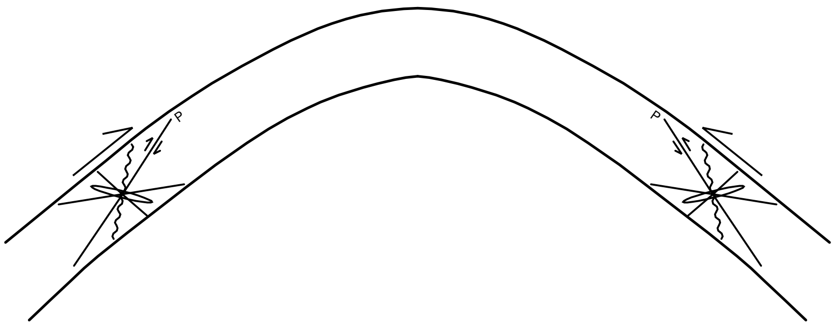
1. **Small scale layer parallel shortening → disharmonic symmetric to asymmetric folding.**



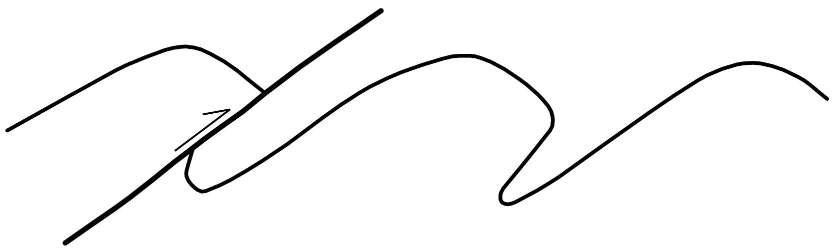
2. **Large scale folding → divergent fanning arrays.**



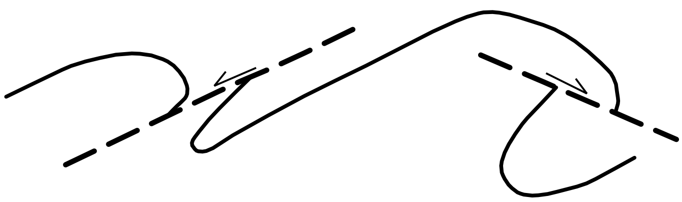
3. **Flexural slip → convergent fanning arrays**



4. **Overstrain → thrusting.**



5. **Relaxation → normal faulting parallel to existing fabric.**



BHP Billiton Iron Ore

MINING AREA C
A Model for the Development of D_2

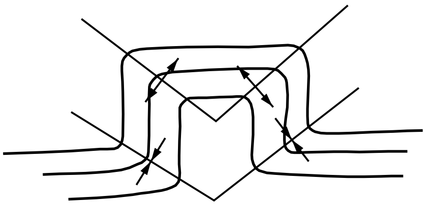
D.Kepert. Mar. 2002

DRWG No i:\mmp\cad\bhpio\mac\ 20935mreu02.dgn Date 23-Apr-2002

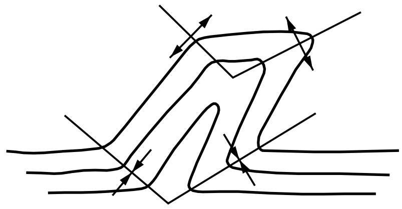
Figure 35

bhpbilliton

Box Folds

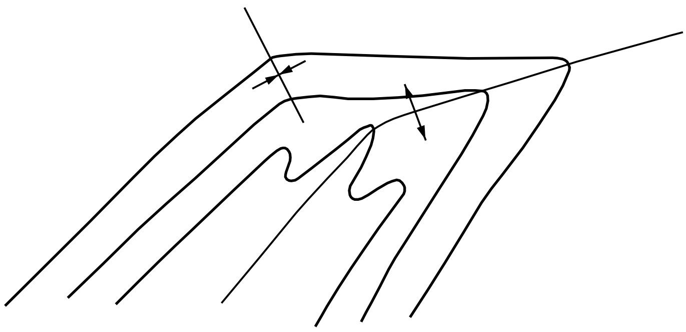


Symmetric

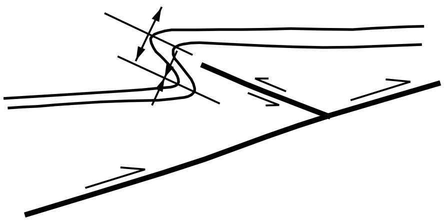


Asymmetric

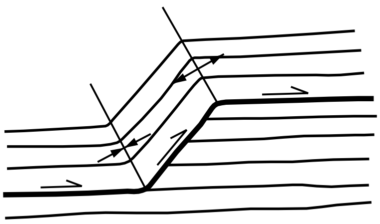
Axial Collapse



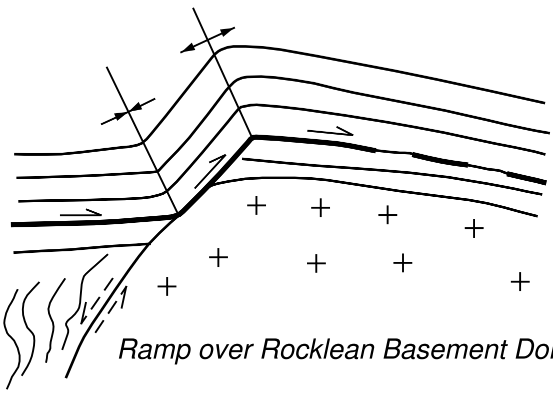
Back Thrusts



Fault Bend Folds



Ramp in Stratigraphy



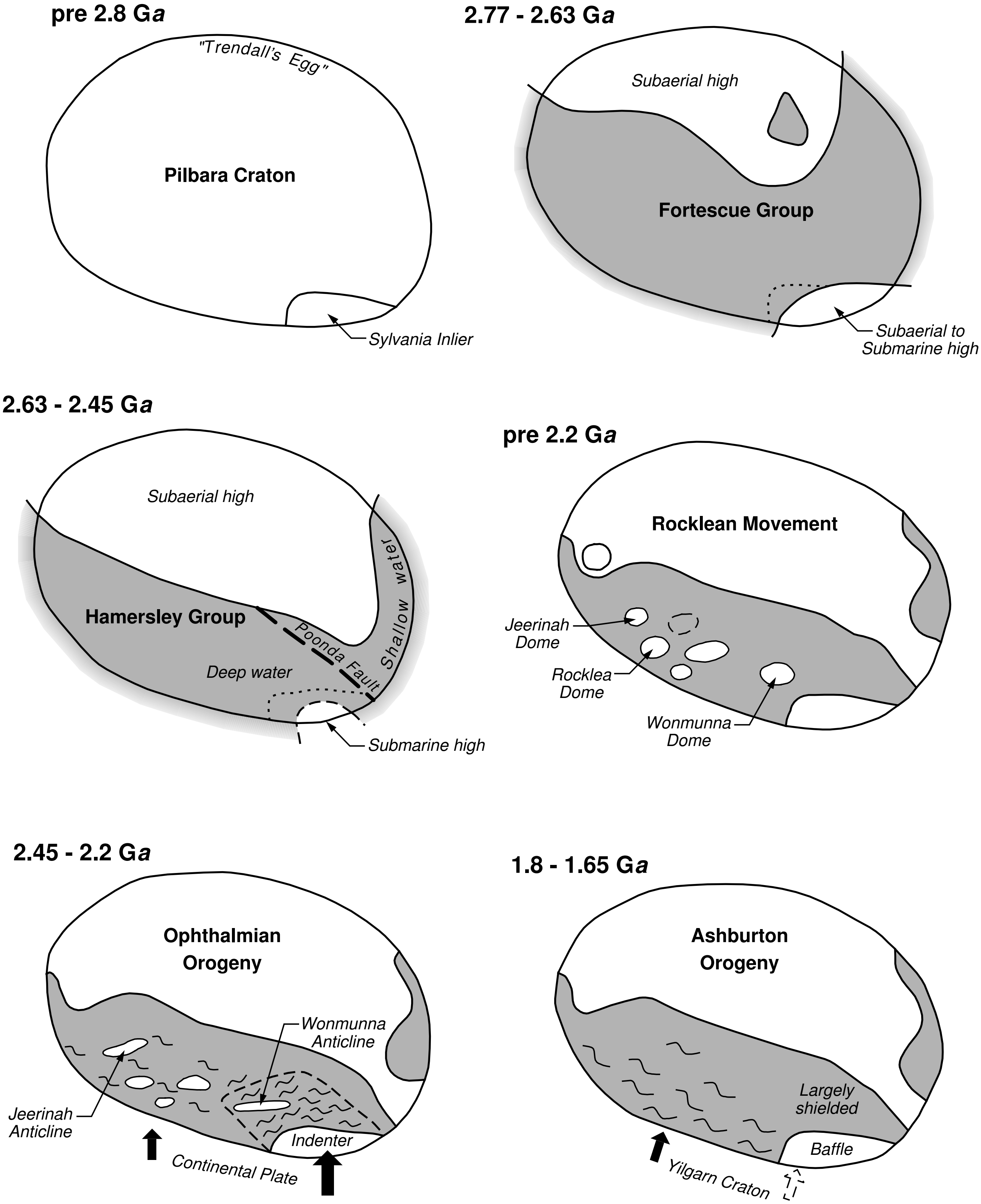
Ramp over Rocklean Basement Dome

BHP Billiton Iron Ore

Alternate Methods of Producing Large Scale South Facing Folds ("$F_{1.5}$") During D_2

D. Kepert. August 2002

Figure 36



BHP Billiton Iron Ore

Schematic Cartoon of the Tectonic Influence of the Sylvania Inlier

D. Kepert. June 2002

DRWG No i:\cad\bhpio\pilbara\ 20934mreu02.ddgn Date 28-6-2002

Figure 37

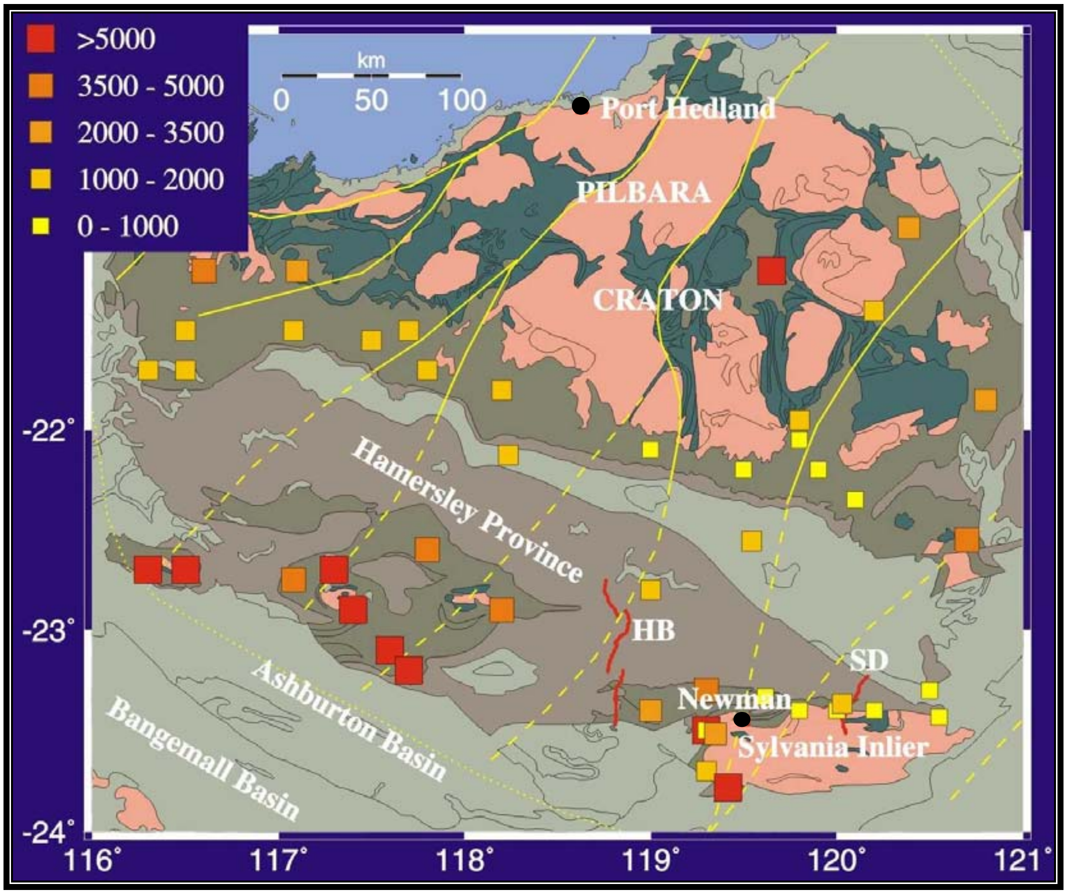


Figure 38. Variation in the stratigraphic thickness of the Fortescue Group. Note the relative thickness in the Hamersley Province compared with that onlapping the exposed Pilbara Craton marking a down warping of the southern part of the Craton. The major change in thickness occurs across the Fortescue valley and the eastern Sylvania Inlier coinciding with the probable syn sedimentary growth Poonda and Fortescue River Faults. Thicker accumulations are also evident in the Oakover sub-Basin along the eastern margin marking the progressive downwarping of the Oakover Syncline by the Rocklean Movement. Yellow lines mark GSWA interpreted domain boundaries of the Pilbara Craton, red lines the MERIWA 282 deep seismic profiles (HB – Hamersley Basin line, SD – Sylvania dome line), pink – granites, dark green – greenstone belts, olive green – Fortescue Group, grey - Hamersley Group, pale grey green – younger sediments (modified after Hackney 2001).

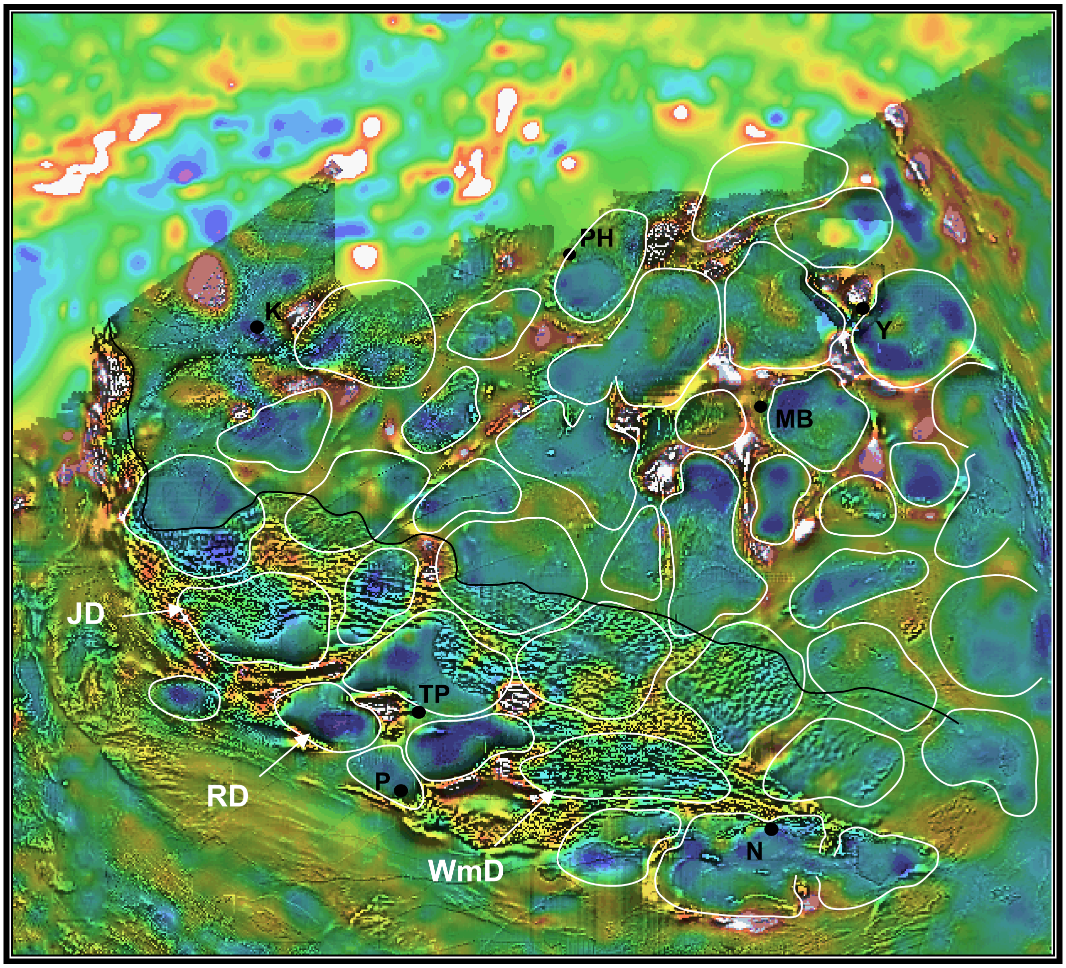
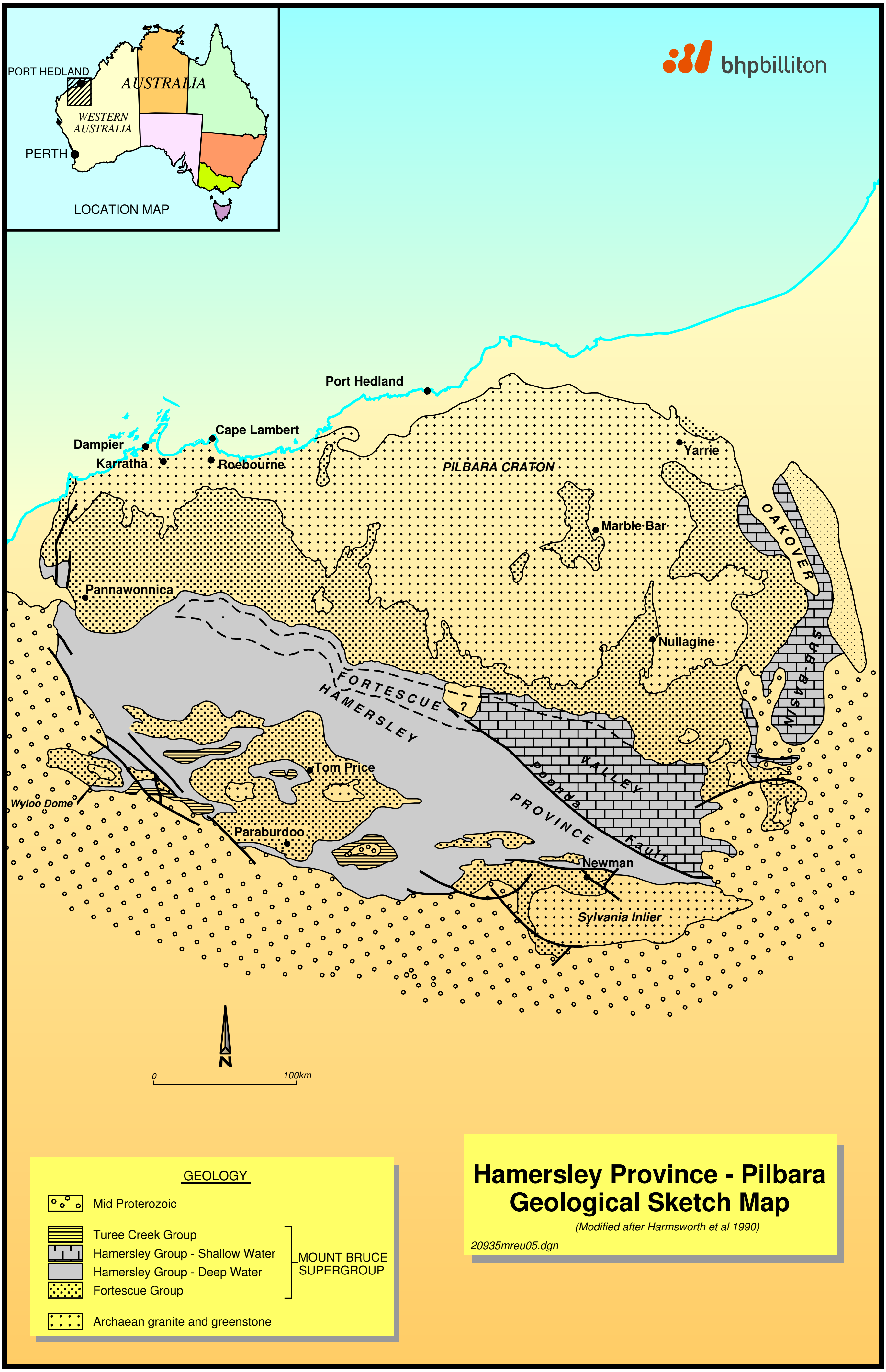


Figure 39. Grey scale first vertical derivative of airborne magnetics draped over pseudo colour regional ground gravity with regional removed showing the well defined granitic domes (magnetically relatively quiet, gravity lows) wrapped by greenstones (magnetically and gravitationally variable depending on composition but typically highs) of the exposed Pilbara Craton in the north. To the south of the black line marking the edge of the Hamersley Group, the magnetic signature of the greenstones is masked by the overlying Hamersley Group, but with the underlying granite domes still readily apparent in the gravity data. Note that on both the Jeerinah and Wonmunna Domes (JD, WmD) the anticlinal axis developed in the overlying Mt Bruce Supergroup (as defined by the magnetically quiet Fortescue Group) is offset to the south of the centre of the domes. A similar but less obvious southward offset is also apparent on the Rocklea Dome (RD). This skewing of the fold may be due to the Mt Bruce Supergroup ramping over the granite basement highs producing fault bend folds which may have a resulting south facing or "$F_{1.5}$" geometry (also see Figure 34). Magnetic data is not available over much of the Indian Ocean to the north. Localities labelled in black are Karratha (K), Marble Bar (MB), Newman (N), Paraburdoo (Pb), Port Hedland (PH), Tom Price (TP) and Yarrie (Y).



Hamersley Province - Pilbara Geological Sketch Map

(Modified after Harmsworth et al 1990)

20935mreu05.dgn

DRWG No i:\mmp\cad\bhpio\general\ 20935mreu05.dgn Date 2-Sep-2002

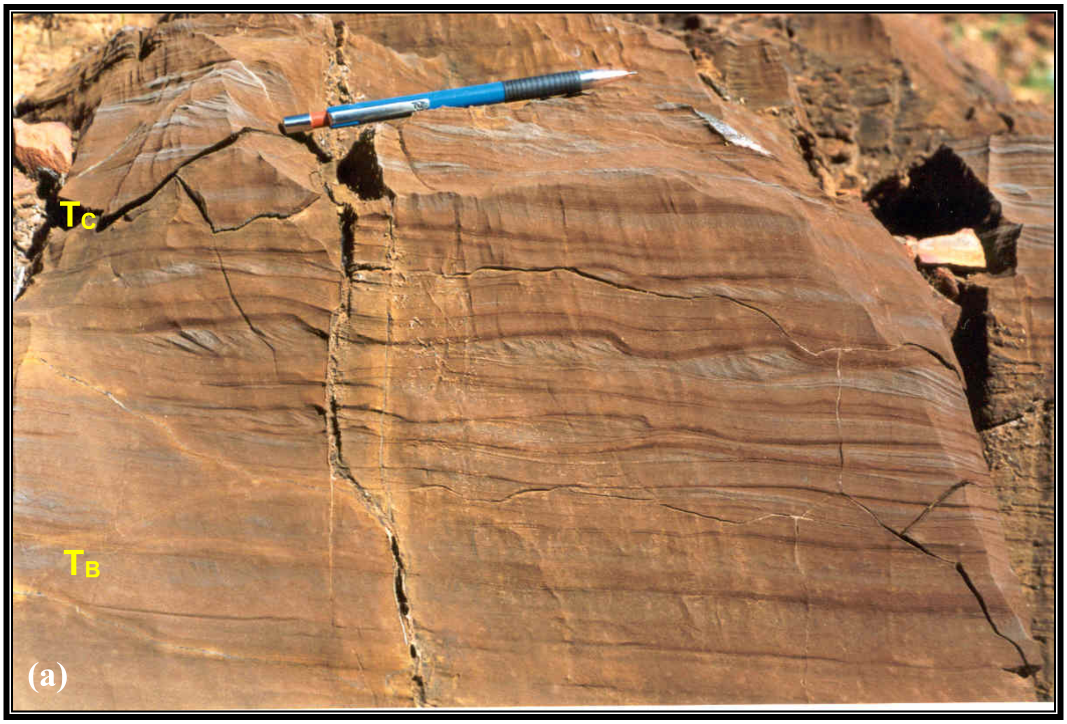
Figure 40

Photo 1. *Home away from home*. Packsaddle Camp from the air, August 1996, pre new ablution block, recreation room and camp managers house.

Photo 2. Steep southeast dipping / younging pillow basalts, Jeerinah Formation, Big Creek (looking southeast, geopick for scale).

Photo 3. D_1 rods in the lower Nammuldi Member with inset showing their extreme long axis, North Alligator (looking northeast, geopicks for scale).

Photo 4. 2 to 3 m thick carbonate turbidite unit (arrowed), Nammuldi Member, Southern Flank (looking east).



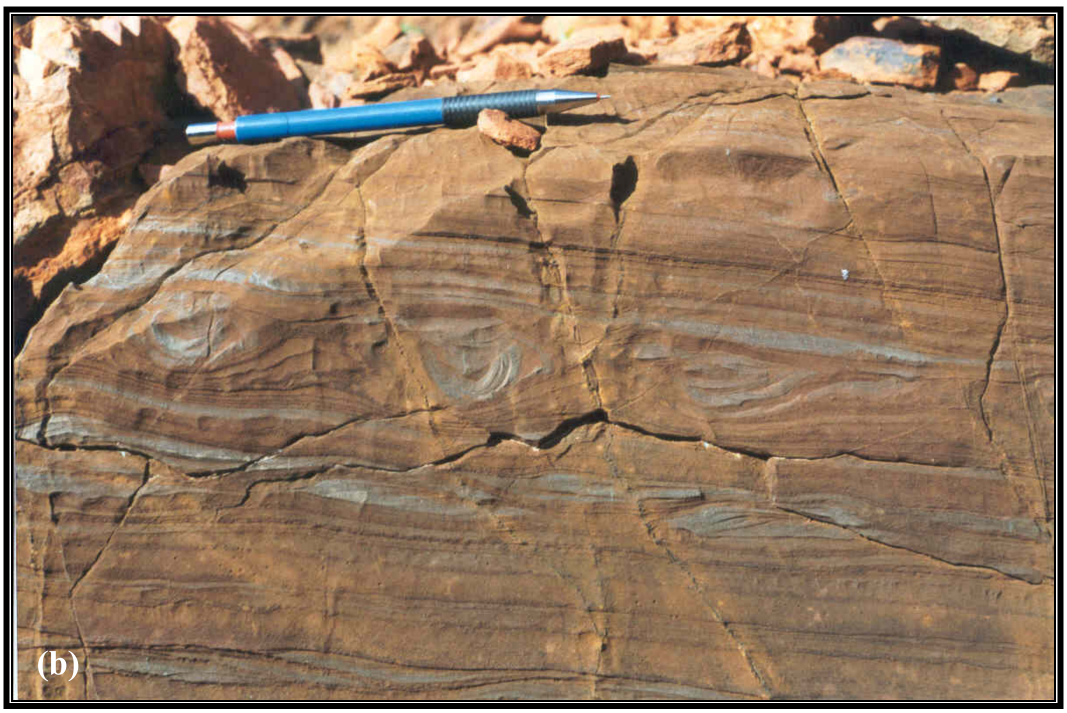


Photo 5. (a) Well developed ripple beds (T_C) indicating a source to the north overlying planar bedded carbonate (T_B), (b) same ripple bed along strike but penecontemporaneous deformation has produced loaded ripples and convolute bedding, upper part of the Nammuldi Member carbonate turbidite (looking east, pencils for scale).

Photo 6. Penecontemporaneous deformation and dewatering producing relatively large scale loading and convolute bedding structures truncated by subsequent sedimentation, T_B unit, Nammuldi Member carbonate turbidite (looking east, pencil for scale).

Photo 7. Well developed cleavage in riebeckite rich mesobands, Dun crocidolite horizon, upper Nammuldi Member, Boundary Ridge.

Photo 8. Bedding surface pavement of the Potato Bed, MacLeod Member, west end of South East Corner (looking south, geopick for scale).

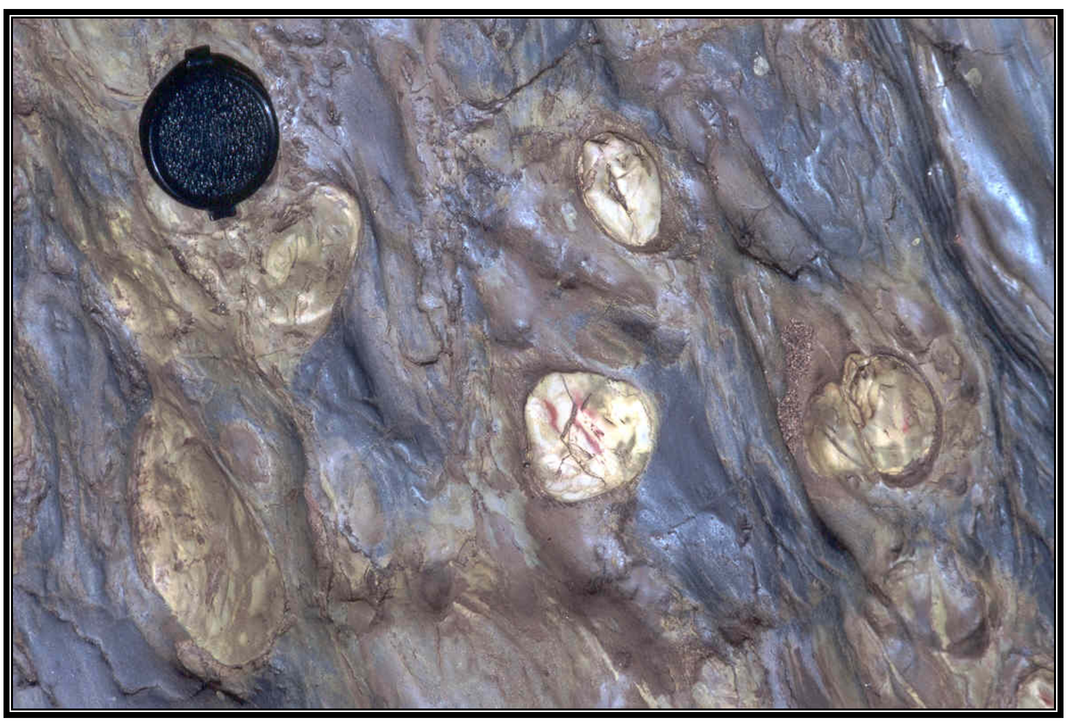


Photo 9. Water polished cross section of the Potato Bed comprising near spherical chert pods wrapped by a BIF matrix, MacLeod Member, Wonmunna Gorge (lens cap for scale).

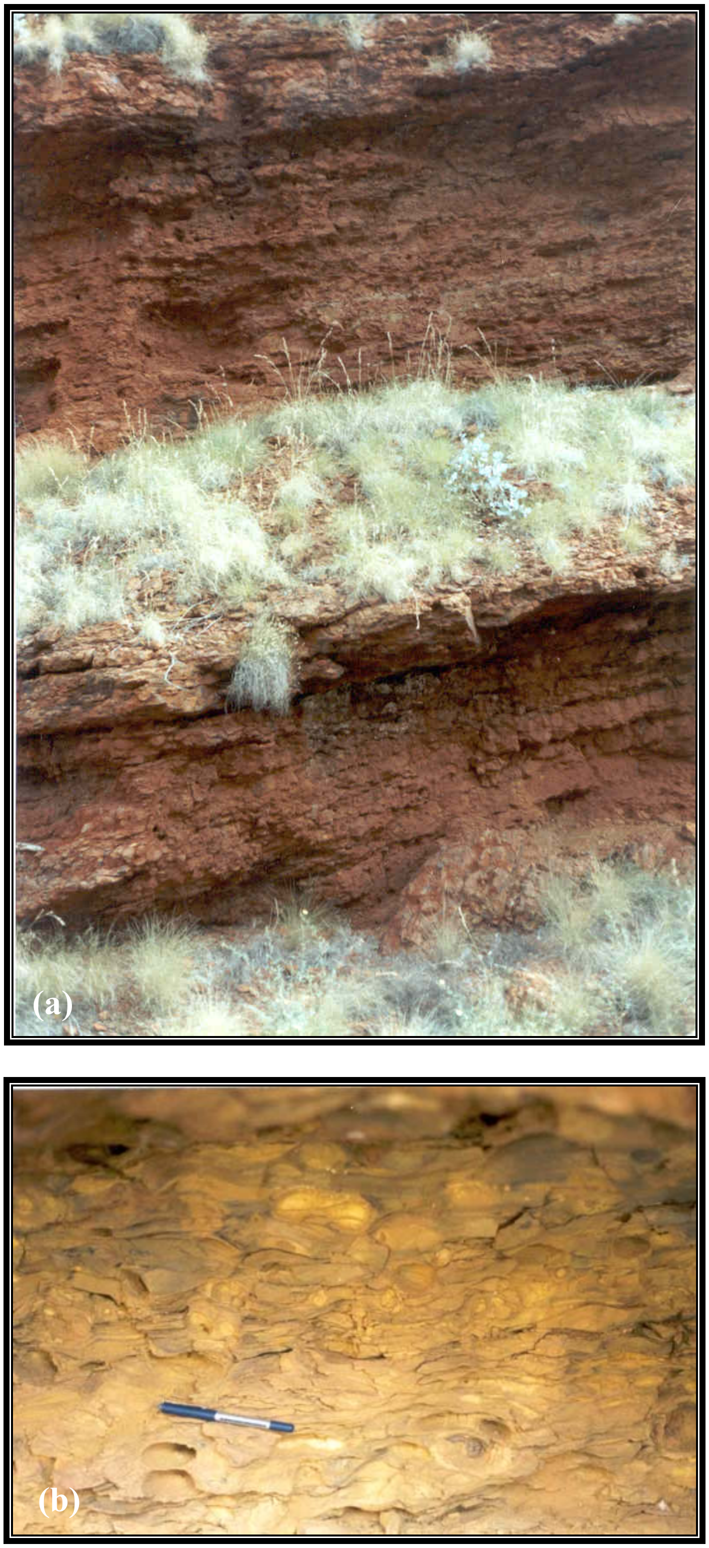


Photo 10. (a) Characteristic dimpled look of the upper two thirds of the Potato Bed in cliff section, (b) close up of under hang exposure showing limonitic cores and a limonitised cherty BIF matrix (pen for scale), Southern Flank, MacLeod Member standard section (looking west).

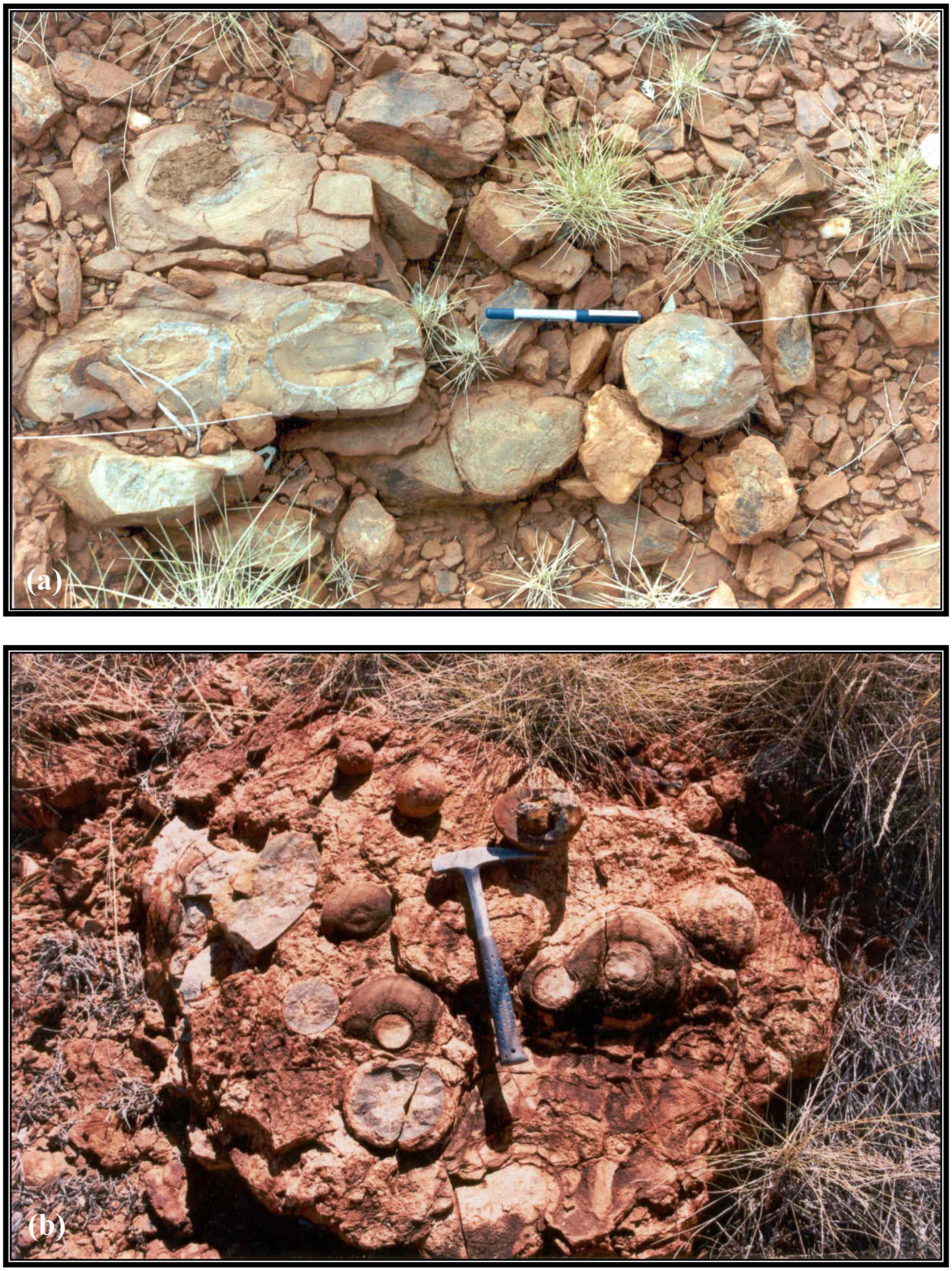


Photo 11. Bedding surfaces of Football Chert, note zoned structure of pods, septarian quartz veins and rough sandpaper surface after carbonate in (b), Southern Flank, (a) MacLeod Member standard section (looking south, pen for scale), (b) Boundary Ridge (geopick for scale).

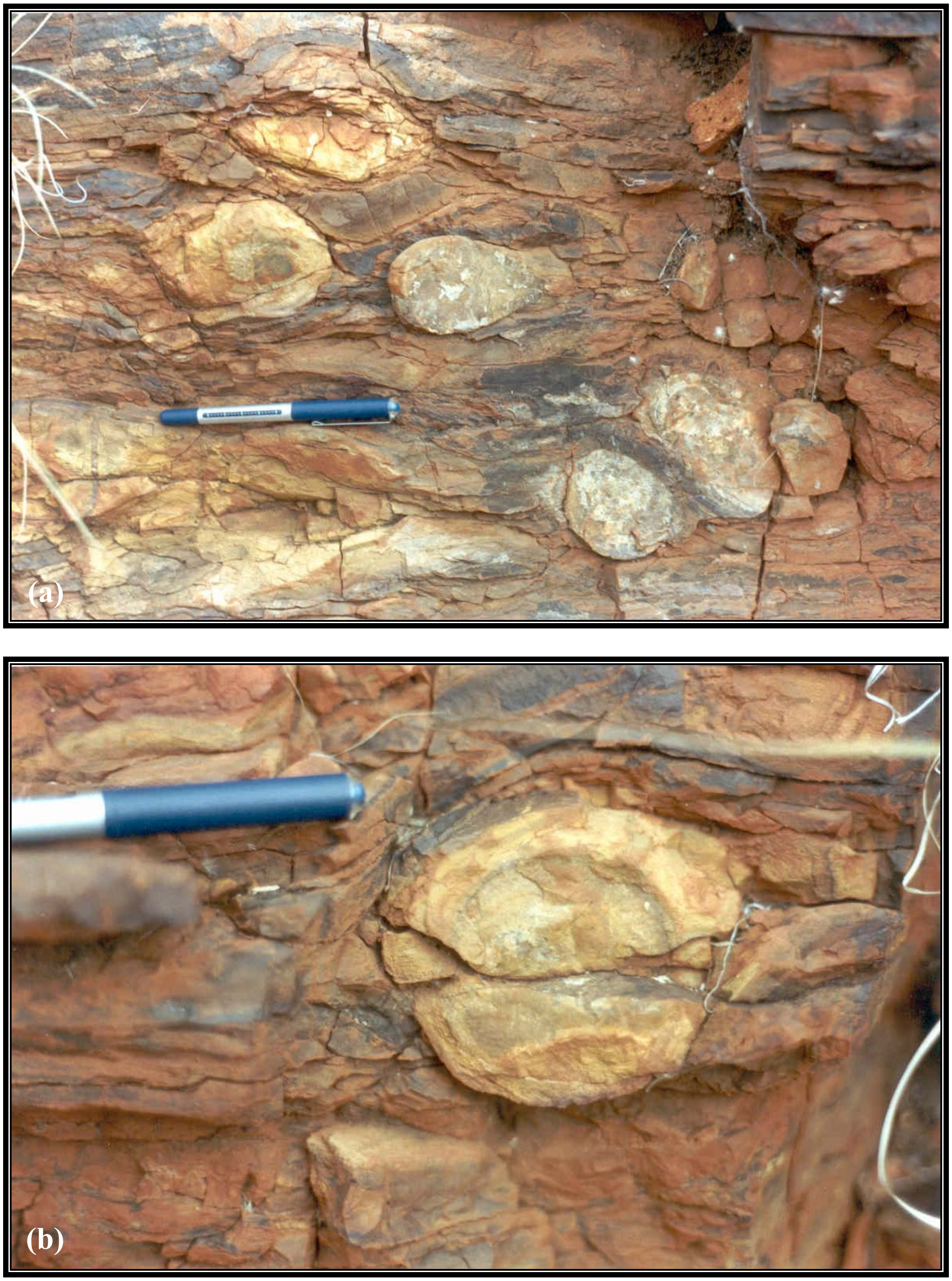


Photo 12. (a) Youngman Pods comprising yellow, limonitic chert pods in a darker slightly shaly cherty BIF matrix, note the similarities to the Potato Bed (Photos 8 to 10) with which they may be confused, (b) close up showing original bedding partly wrapping but also penetrating the outer margin of the pod, bedding in the centre of the pod has been destroyed, Southern Flank, MacLeod Member standard section (looking south, pen for scale).

Photo 13. Bedding surface of Sullivan Pods with well developed septarian quartz veins and internal voids identical to the 7 to 8 m thick Potato Bed (Photo 11), Southern Flank, hill directly west of the MacLeod Member standard section (looking north, pen for scale).

Photo 14. Characteristic planar to irregularly D_1 podded Mount Newman Member BIF, Wonmunna Gorge (looking west, MCB and DH for scale).

Photo 15. Fresh crocidolite seams, Vivash Riebeckite Zone, Mount Newman Member BIF, Blackwood Creek Gorge (pencil for scale).

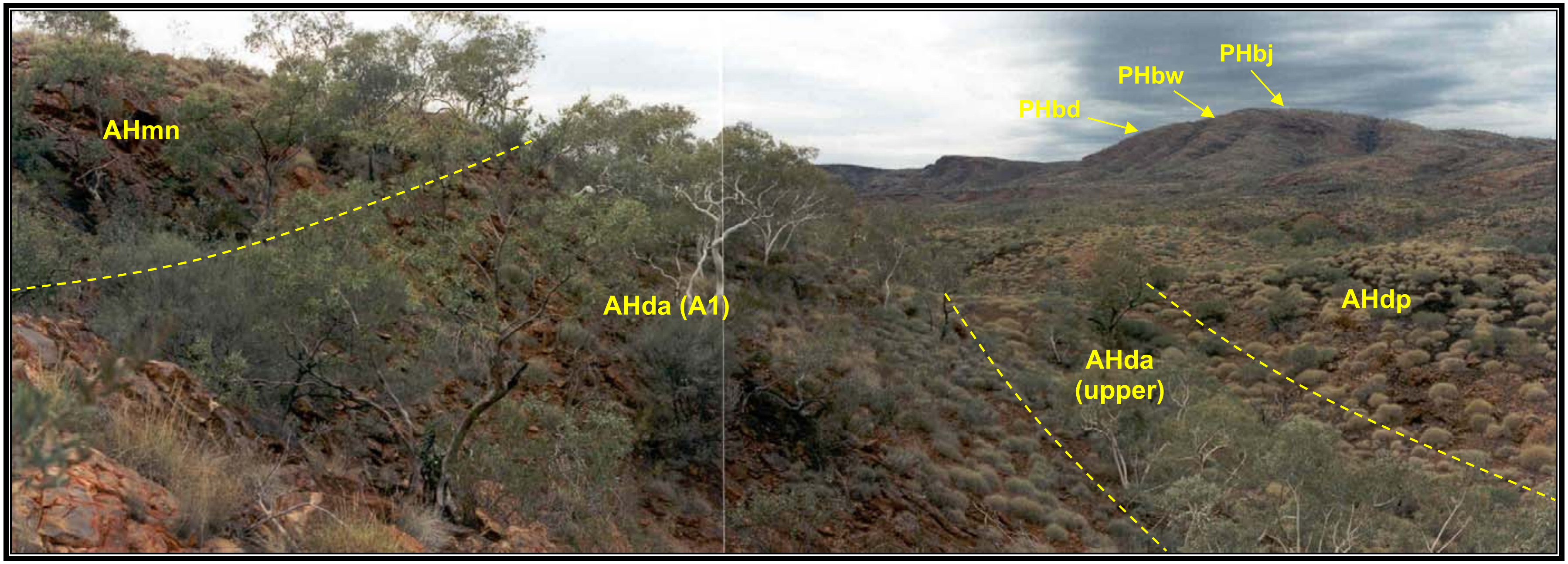


Photo 16. Panorama of south dipping strata from upper Mount Newman Member BIF to Joffre Member BIF, note the highly thinned (<5 m) upper two thirds of the West Angela Member between cropping out A1 cherty BIF (dip slope) and Paraburdoo Member dolomite (with manganiferous hardcap). Alternatively, the basal part of the dolomite may be the "unaltered" dolomitic facies of the West Angela Member best developed / preserved in the western Hamersley Province, western South Alligator to Balgara (looking east).

Photo 17. Well banded upper Paraburdoo Member dolomite with two zones of thin, interbedded chert (ch), The Governor (looking west).

Photo 18. Diagenetic breccia, Paraburdoo Member, Death Valley (geopick for scale).

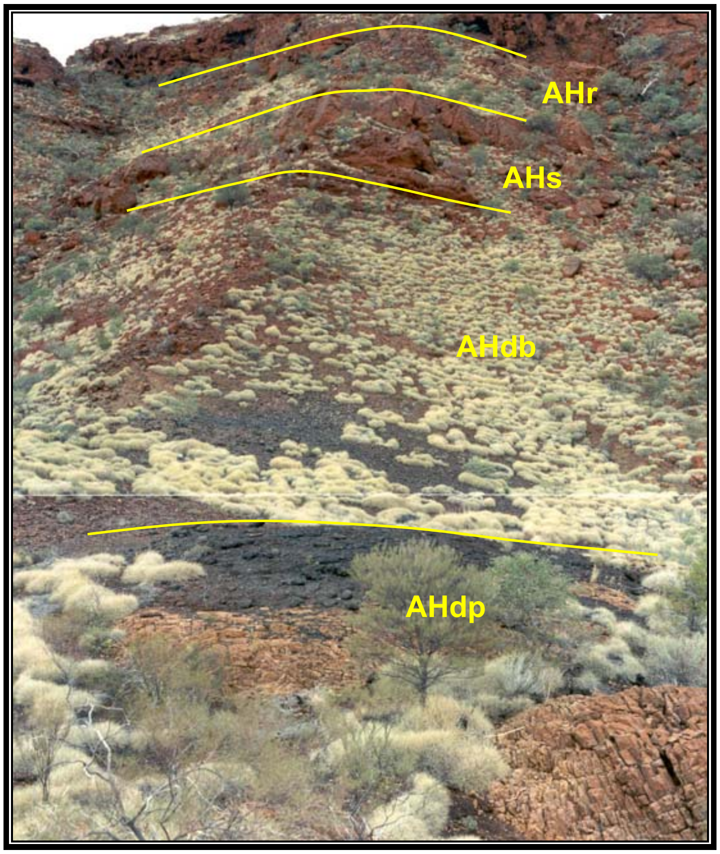


Photo 19. Severely thinned sequence from poorly exposed Bee Gorge Member to Mt McRae Shale, note the manganiferous hardcap developed on the Paraburdoo Member, Death Valley.

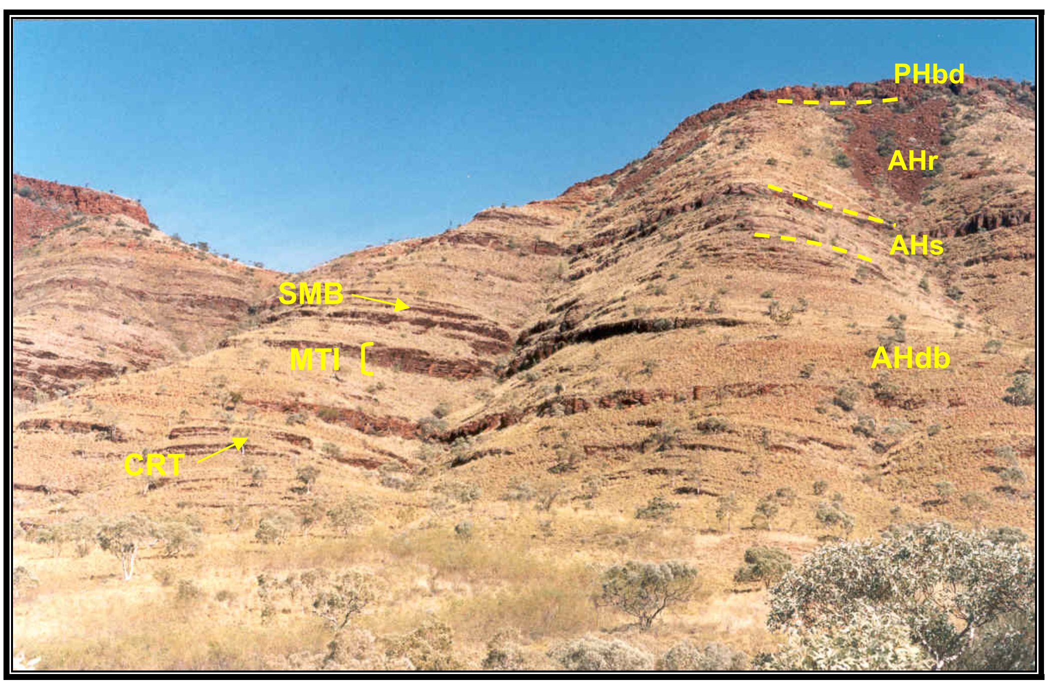


Photo 20. Well exposed Bee Gorge Member showing various marker beds (see Photos 21 to 24), the Paraburdoo Bee Gorge Member contact occurs just east of the photo at the base of the hill, west end Fork South (looking south, approximate height of hill 220 m).

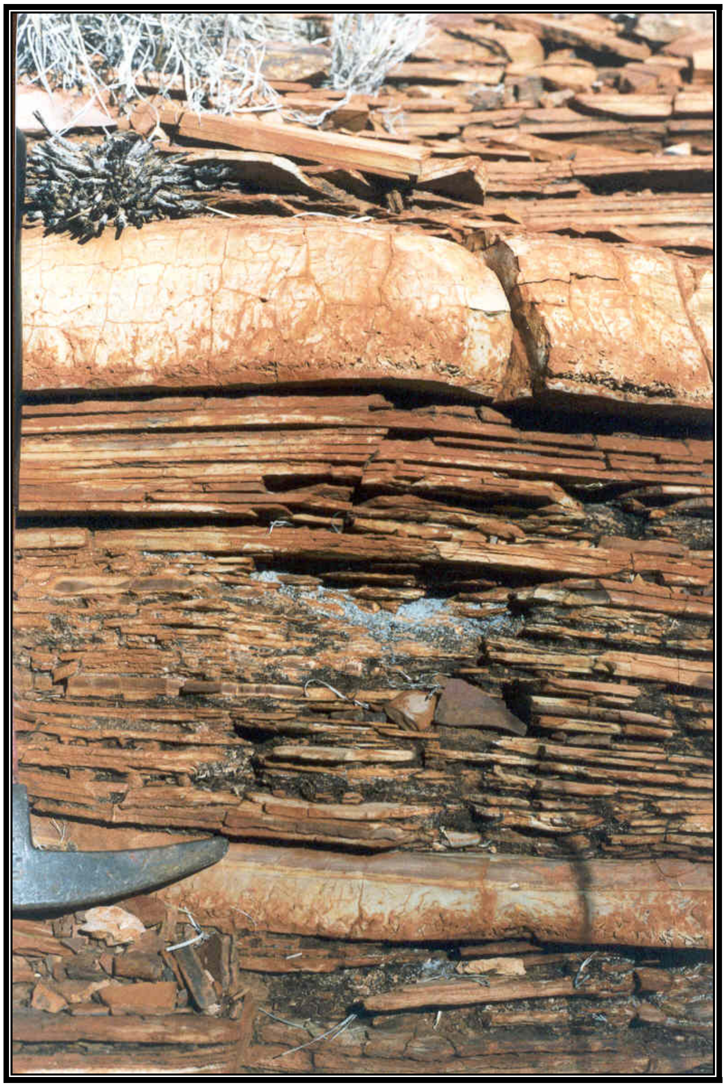


Photo 21. Crystal Rich Tuff and genetically associated lower tuff bed. Note the characteristic accumulation of crystals at the base of both the beds, Bee Gorge Member, Fork South (geopick for scale).

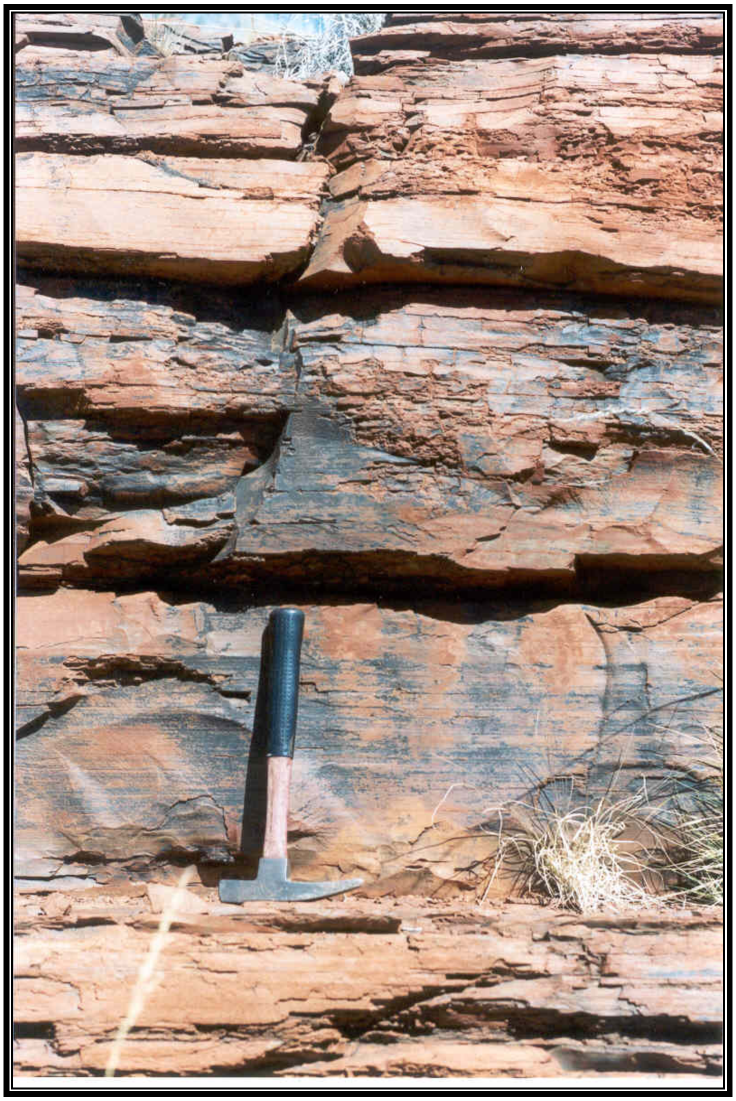


Photo 22. Part of the Main Tuff Interval, due to its blocky nature it commonly forms a prominent cliff several metres high in the middle of the Member. Note the characteristic brittle fracture pattern developed toward the top of the photo, Bee Gorge Member, Fork South (geopick for scale).

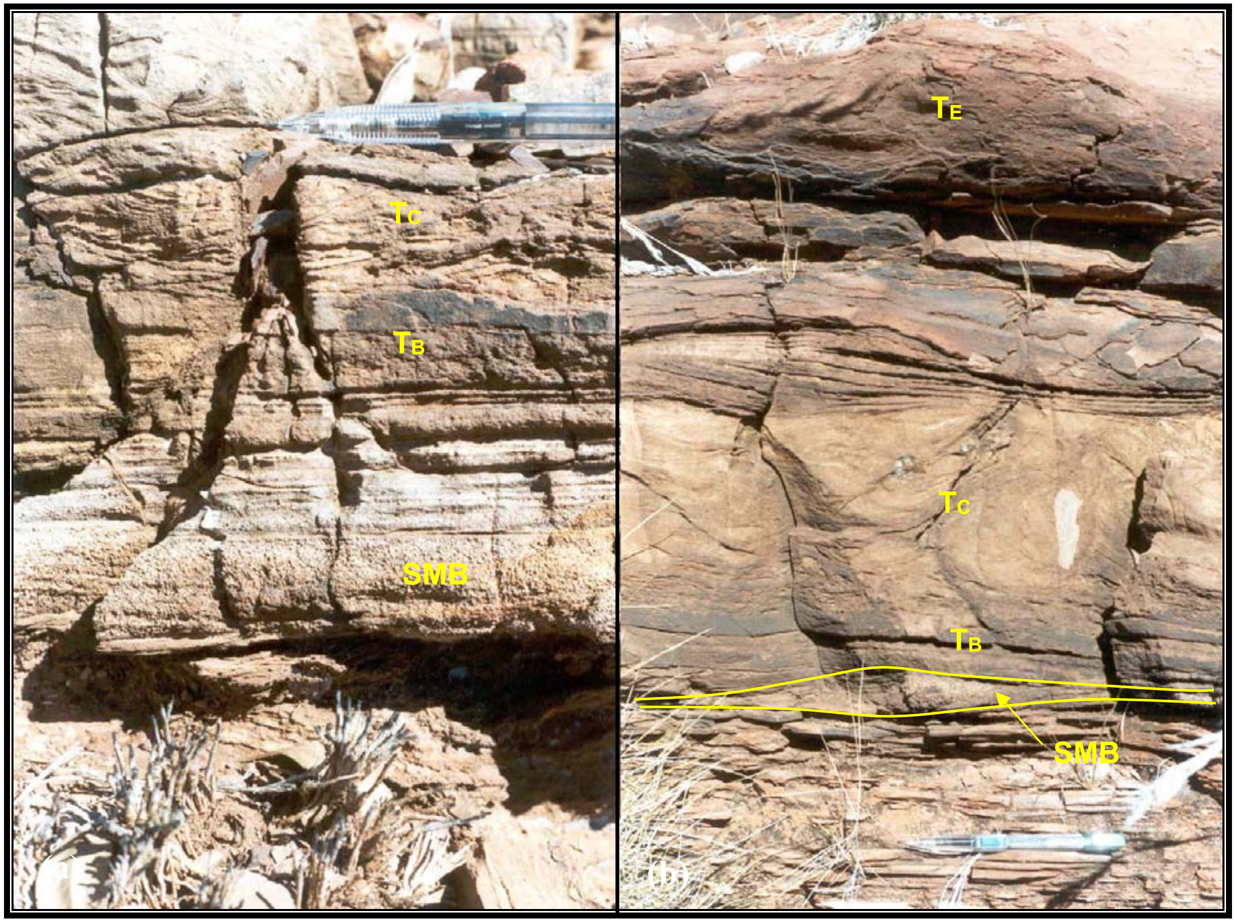


Photo 23. Spherulite Marker Bed (SMB) overlying shale and overlain by carbonate turbidite, note the difference in thicknesses of the carbonate compared with Photo 24a, (a) SMB showing a gradational upper contact with overlying carbonates indicating a genetic link, (b) lens of the SMB defining a long wavelength, southeast propagating ripple. Labels as per Photo 24, Bee Gorge Member, Fork South (looking south, pencils for scale).

Photo 24. Well developed Bouma Sequence in carbonate turbidite sequence above the Spherulite Marker Bed (SMB), Bee Gorge Member, (a) sequence from planar, well bedded carbonate (T_B), crossbedded (T_C), silty (T_D) to very fine carbonate mud (T_E) (looking south, geopick for scale), (b) close up of T_C showing loading and crossbedding partly disturbed by convolute bedding produced during compaction and dewatering (lens cap for scale).

Photo 25. Cross bedded (or faulted?) shales, Bee Gorge Member, southeast end of Governor Range (looking north northwest, geopick for scale).

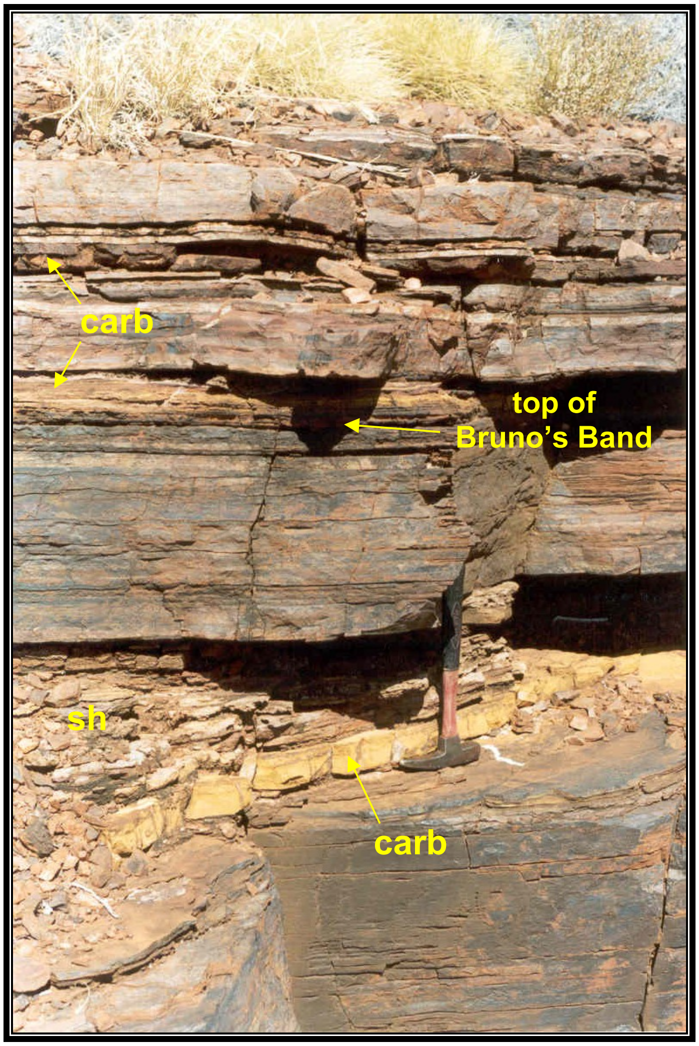


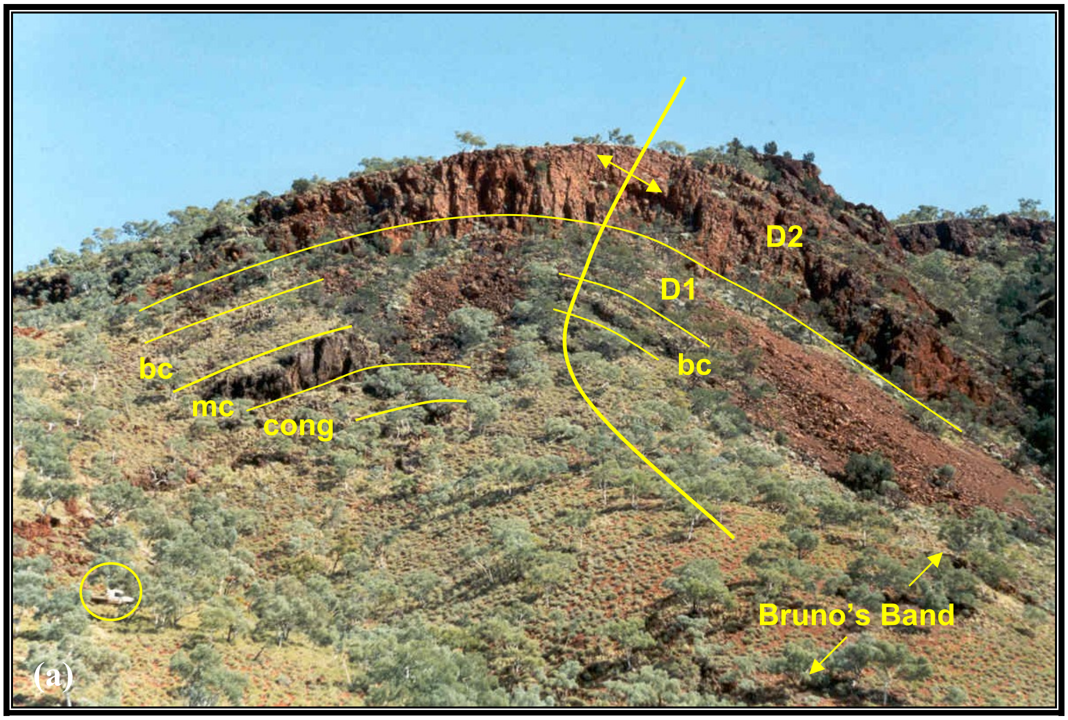
Photo 26. Top of Bruno's Band with thin yellow carbonate beds (carb) and overlying laminated chert, Eric's Point (geopick for scale). See Figure 9 for measured section.

Photo 27. (a) Partly silicified carbonates (arrows) interbedded with shale, note the two massive chert beds above the upper most carbonate bed that may be completely silicified carbonate, (b) close up of silicification process showing remnant carbonate core in massive chert bed, carbonate – massive chert facies, Mt Sylvia Formation, Eric's Point (geopicks for scale).

Photo 28. Welded ignimbrite between SB2 and Bruno's Band (SB3) sampled for age dating. Unfortunately it contained no zircons, Mt Sylvia Formation, Weeli Wolli Springs (geopick for scale).

Photo 29. Irregularly silicification of shales in the basal carbonate – massive chert facies of Mt McRae Shale producing chert lenses and nodules, similar but less well developed chert nodules also occur in the corresponding facies at the top of the Mt Sylvia Formation, Eric's Point (geopick for scale).

Photo 30. Well exposed weathered anoxic facies (nodule zone), Mt McRae Shale, 30 cm thick blocky chert on the sky line is about 5 m beneath the base of D1, Werriba Anticline (looking east).



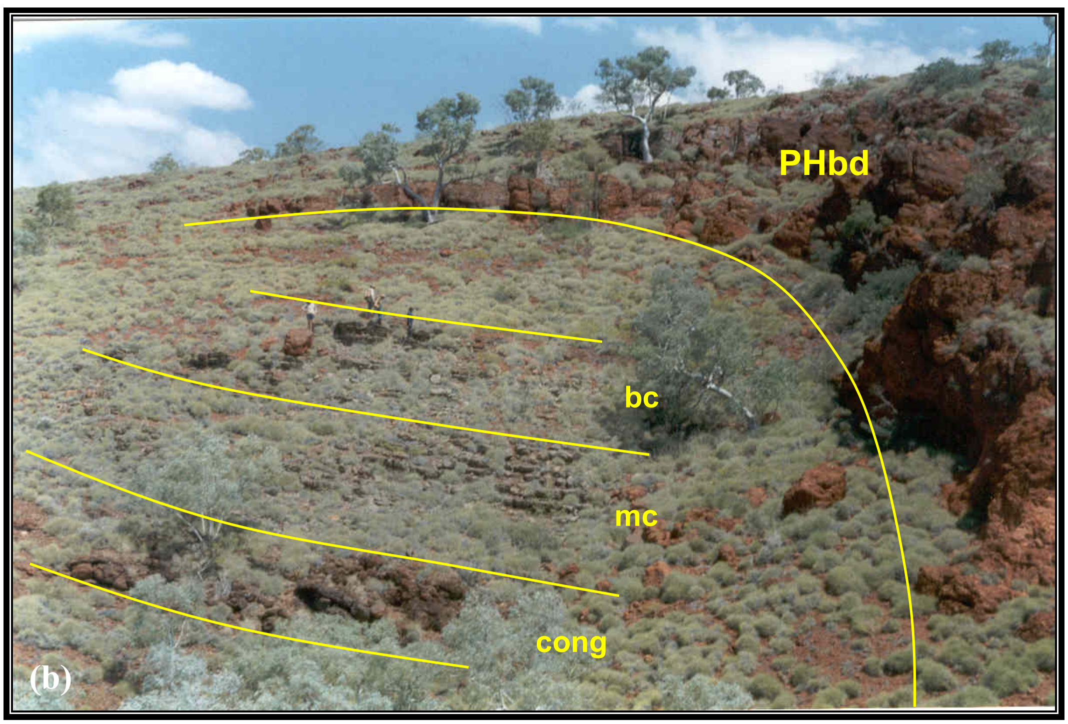


Photo 31. Mt McRae carbonate turbidite showing basal conglomerate (cong), massive carbonate (mc) and bedded carbonate (bc) preserved in the core of a macroscopic D_2 anticlines, (a) MAN Hill between P1 and P2 orebodies, Packsaddle Range (looking west, circled vehicle for scale – lower left), (b) International Hill between P5 and P6, note that the conformable south dipping limb of the preserved carbonates trends directly into flat lying Dales Gorge Member defining the axis of the D_2 fold, indicating that dissolution of the carbonate is syn D_2 (looking southwest, geos for scale).

Photo 32. (a) Basal conglomerate facies of Mt McRae carbonate turbidite comprising a dark brown shale / carbonate matrix with characteristic white chert clasts, overlain by massive carbonate facies, International Hill (MCB, ACD and DP for scale), (b) close up of the basal conglomerate with a large pink shale clast containing numerous pea to golf ball sized goethitised pyrite nodules consistent with the clasts being sourced from eroded Mt McRae Shale up slope, MAN Hill.

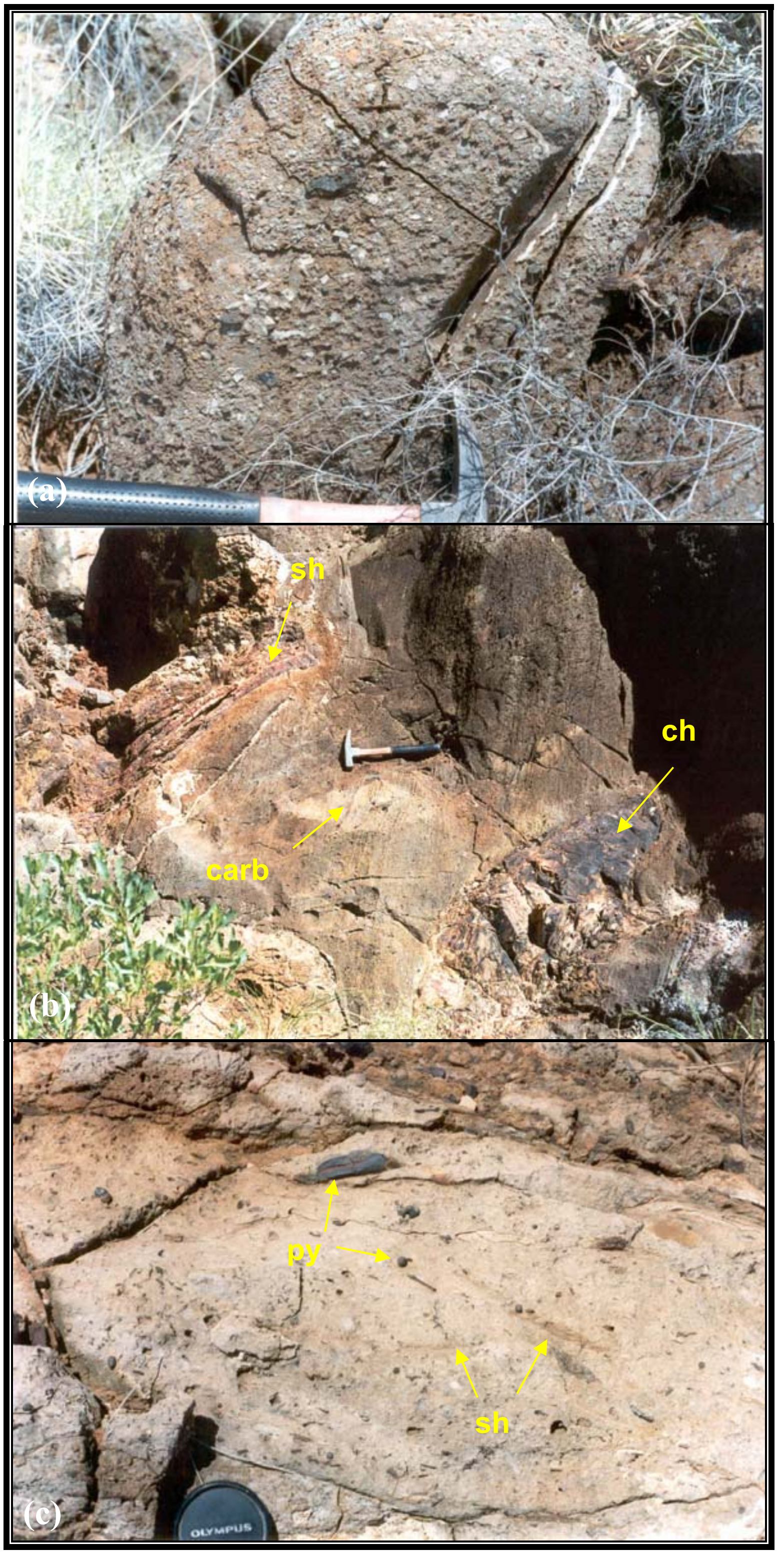


Photo 33. Massive carbonate facies of Mt McRae carbonate turbidite showing the variation in size and lithology of the clasts, (a) typical intraclastic tabular carbonate clasts, note the upward fining sequence (towards upper left), International Hill, (b) boulder size shale (sh), chert (ch) and carbonate (carb) clasts with only rare smaller clasts, MAN Hill (geopicks for scale), (c) goethitised pyrite nodules (py) and shale clasts derived from the anoxic zone of the Mt McRae Shale, Governor Range (lens cap for scale).

Photo 34. Bedded carbonate of Mt McRae carbonate turbidite, (a) alternating carbonate and dirty (shaly) carbonate beds, MAN Hill, (b) upward fining, coarse to fine grain sized carbonate sands, note the bedding parallel stylolite surfaces (arrowed), International Hill (geopicks for scale).

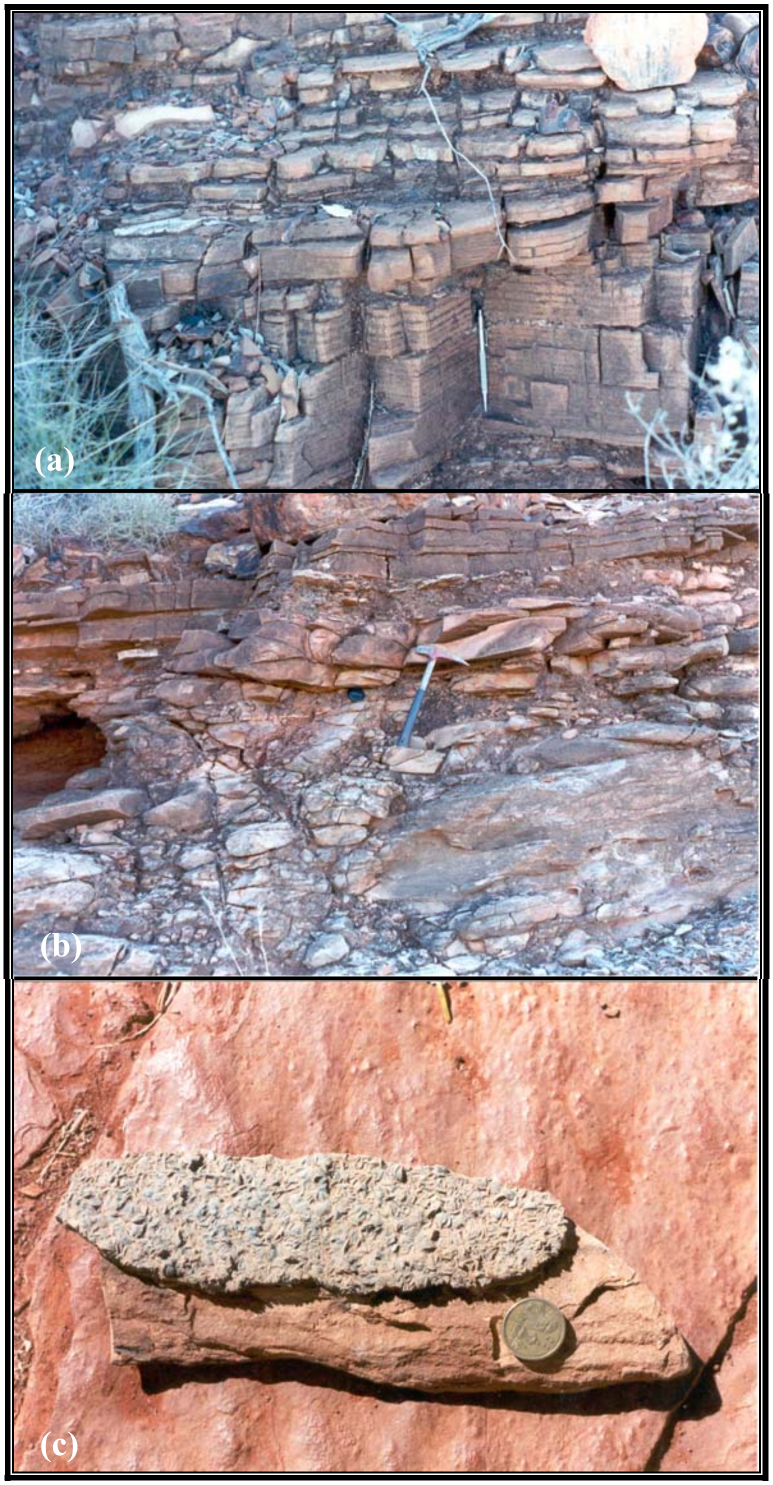


Photo 35. Additional sedimentary features in the Mt McRae carbonate turbidite from Balgara, (a) Well developed rhythmite carbonate (pencil for scale), (b) festoon style crossbedding with overlying rhythmite (geopick for scale), (c) float with lozenge shaped gypsum crystals of unknown origin on a bedding surface (coin for scale).

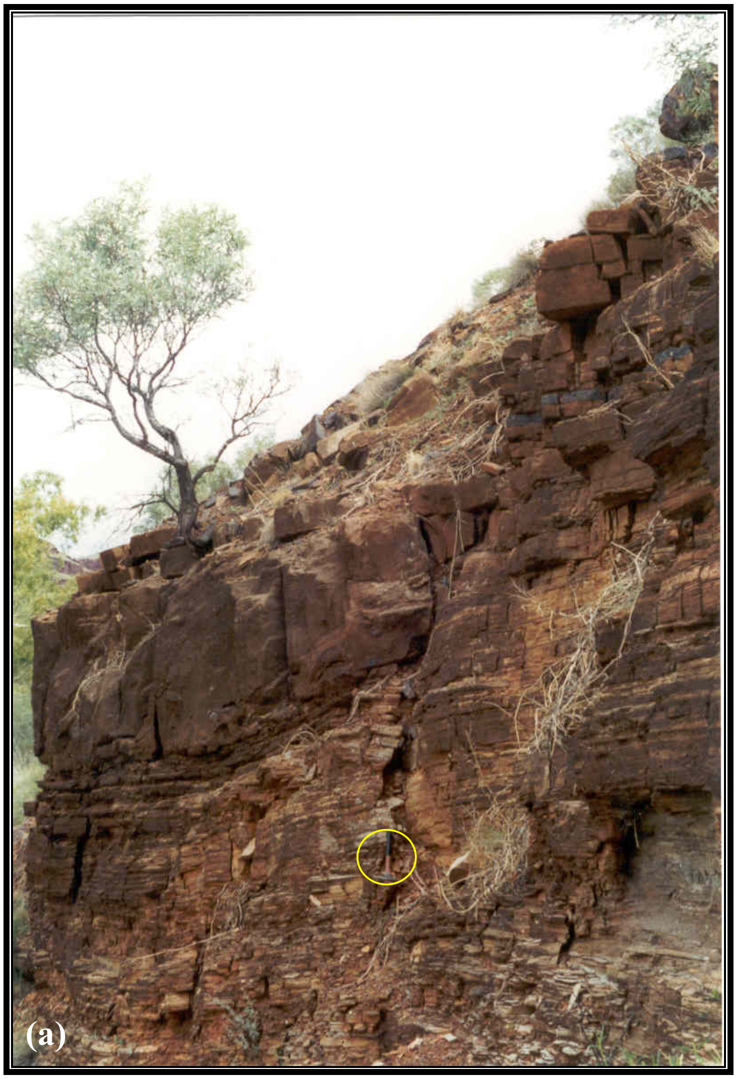


Photo 36. (a) Intraclastic carbonate channel cut into well bedded carbonate (looking west, circled geopick for scale), (b) close up of the massive channel fill showing numerous tabular carbonate intraclasts (lens cap for scale), upper Mt McRae Shale, Wittenoom Gorge.

Photo 37. Concentric rings developed on a bedding surface resulting from shrinkage by dehydration of underlying macules (compare with Photo 50), Dales Gorge Member BIF, tributary of Munjina Gorge (foot for scale, photo curtesy of Alec Trendall).

Photo 38. Trendall's Bed of Holes between CS6 shale doublet, Dales Gorge Member, Turee Creek (ruler for scale, photo curtesy of John Blockley).

Photo 39. Bedding plane of the false bed of holes at the base of DB0, Dales Gorge Member, Fort Hill (pen for scale).

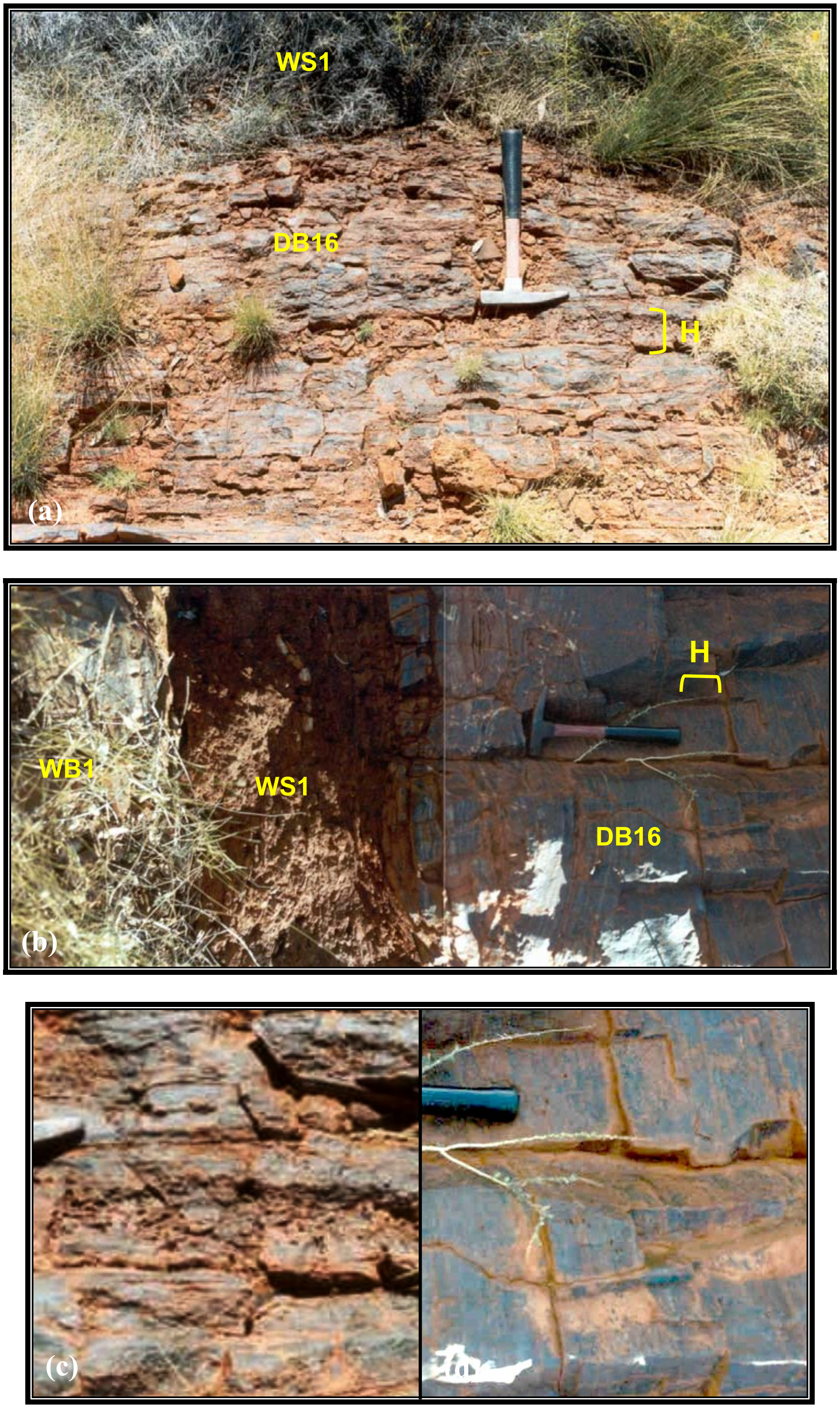


Photo 40. Huleatt's Bed of Holes (H) at the top of the Dales Gorge Member, note the adjacent more diffuse beds of holes, (a, c) M – G mineralisation (OB21, looking north), (b, d) unmineralised BIF, note the white chert mesobands at the top of DB16 (OB23, looking west at overturned sequence, up is to the right, younging to the left, geopicks for scale).

Photo 41. Basal planar and upper crossbedded carbonate turbidite in DS1, Dales Gorge Member, Wittenoom Gorge (lens cap for scale).

Photo 42. Dales Gorge Member S macroband (inferred as DS2 by Blake) comprising basal interbedded chert and black stilpnomelane rich shale and upper poorly bedded carbonate bearing beds (MCB and MP for scale). Inset shows an upper graded carbonate turbiditic grainstone (arrow on main photo, lens cap for scale), Fortescue Falls.

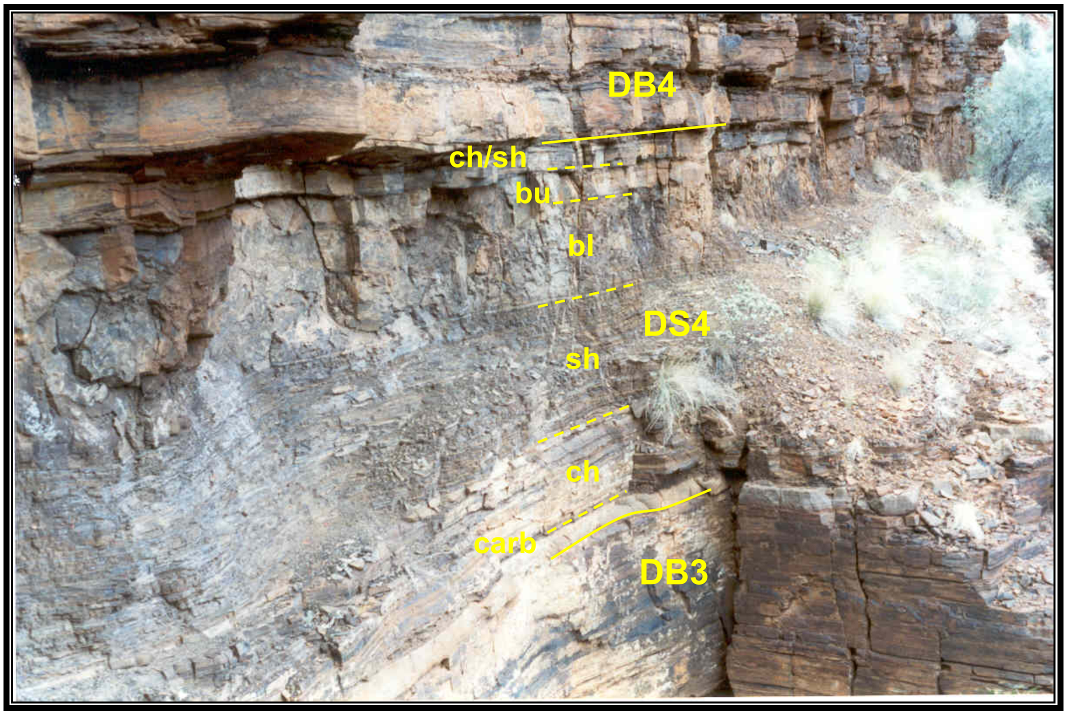


Photo 43. DS4, comprising a basal turbiditic carbonate bed (carb), cherts (ch), well bedded shales (sh), bolide derived unit subdivided into a lower massive coarse grained unit (bl) and upper fine grained unit (bu), and an upper interbedded chert / shale, Dales Gorge Member, Mine Pool, Wittenoom Gorge.

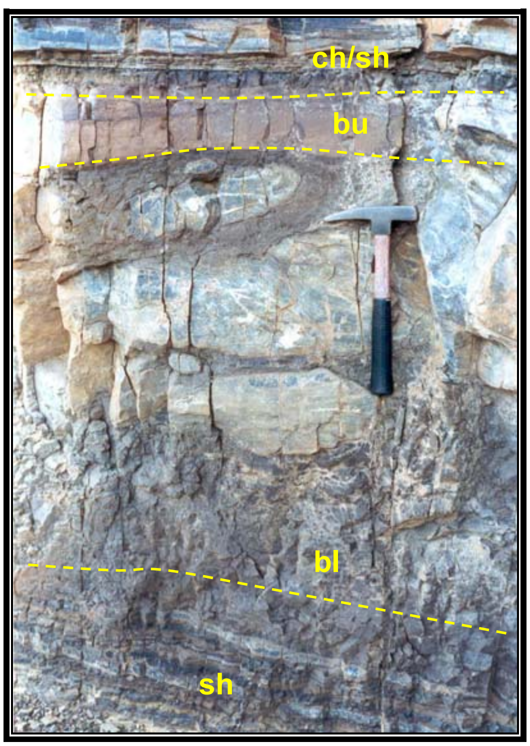


Photo 44. DS4 bolide derived unit with chert boulders toward the top of the lower massive unit, labels as per previous photo, Dales Gorge Member, Mine Pool, Wittenoom Gorge (geopick for scale).

Photo 45. Upright boulder in DS4 bolide derived layer piercing overlying strata due to later compaction, Dales Gorge Member, Mine Pool, Wittenoom Gorge (geopick for scale).

Photo 46. Clasts from DS4 bolide derived layer, (a) syn erosional deformation of clast margins (enlargement of Photo 44), (b) partly, irregularly silicified carbonate clasts with domal structures possibly after stromatolitic mounds, relict carbonate is pale grey with a distinct dark brown weathering patina, Dales Gorge Member, Mine Pool, Wittenoom Gorge (geopick for scale).

Photo 47. Bedding surface of the Central Chert of the Mt Whaleback Shale Member showing characteristic wavy to hummocky bedding. This feature has traditionally been ascribed to fold interferences between various deformation, however its frequency and degree of development does not vary with orientation or intensity of deformation(s) and therefore, is an original sedimentary (eg loading) to diagenetic feature, Werriba Anticline (looking north, circled geopick for scale).

Photo 48. Radiating structures (~ 5 cm diameter) developed in a single 2 to 3 cm thick bed of J2 BIF produced by a non photosynthetic ocean floor algal mats, Joffre Member, Mt Meharry.

Photo 49. J4 marker chert showing characteristic white brown microbanding, OB24 (pen for scale).

Photo 50. Cowpat Pods formed by the dehydration and compression of a ?hydrous silica gel rich layer during diagenesis, upper J6, Joffre Member, Mindy (geopick for scale).

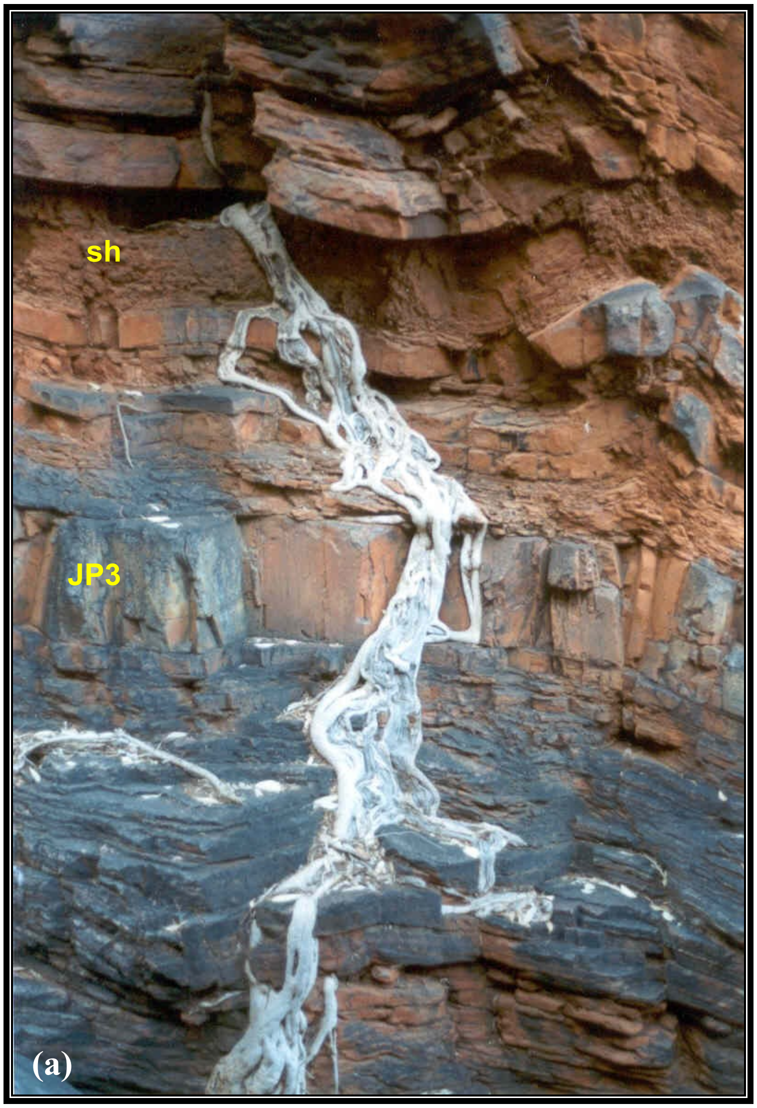


Photo 51. JP3 porcelanite, note the characteristic blocky fracture and overlying shale (sh) and (b) upper contact with voids after phenocrysts, upper J2, Joffre Member, south west Lambs Creek.

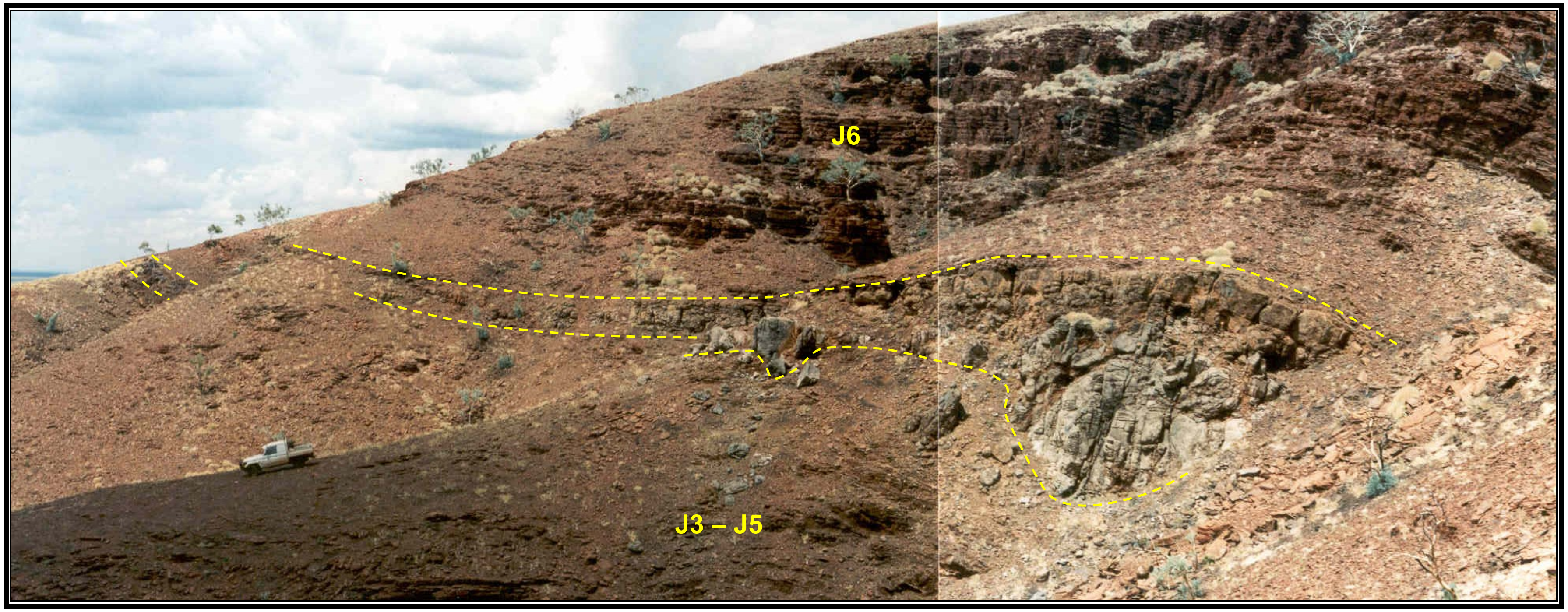


Photo 52. Panorama of the upper Mindy Debris Flow showing basal megaclasts over 10 m across, the planar upper contact with overlying J6 BIF and the Fortescue valley in the background (vehicle for scale).

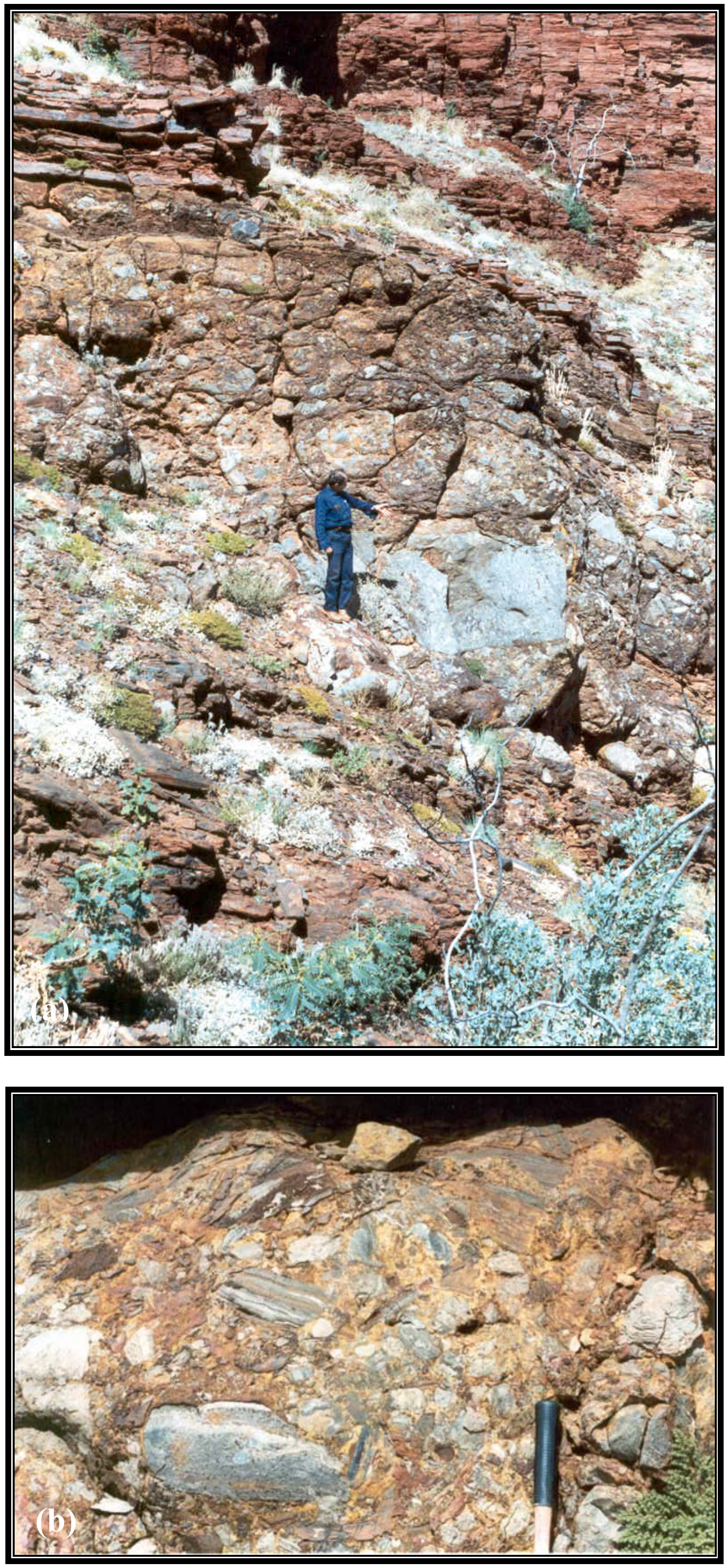


Photo 53. (a) Upper Mindy Debris Flow with a basal megaclast and conformable lower and upper BIF contacts (JF for scale) and (b) typical size and lithological variation in clasts (geopick for scale).

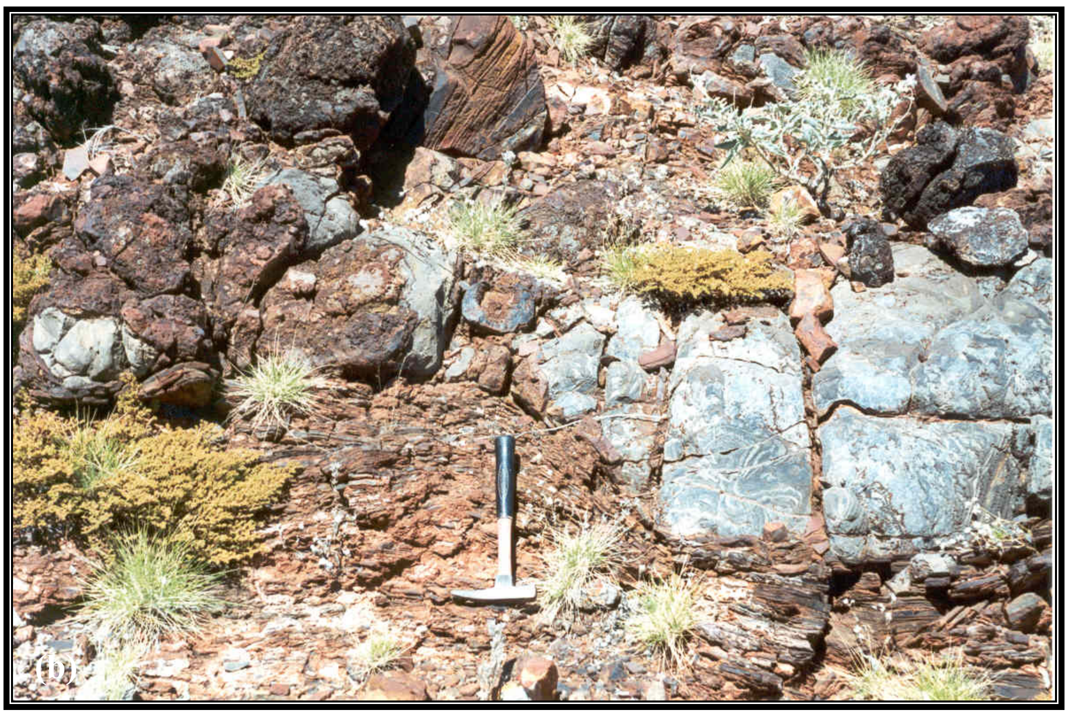


Photo 54. Basal contact of the upper Mindy Debris Flow showing simple downward drag and local truncation of bedding. A lack of significant disruption to the bedding (eg convolution or highly variable thicknesses) indicates that the BIF substrate was already moderately lithified immediately after its deposition and not a thick, soft hydrous colloidal gel as per most genetic models for BIF and chert sedimentation (geopick for scale).

Photo 55. Upper planar contact of the upper Mindy Debris Flow (geopick for scale).

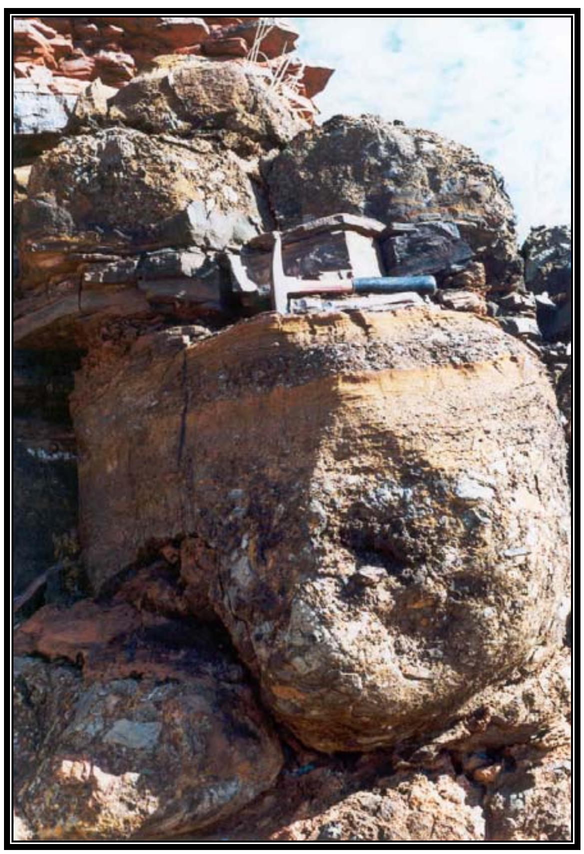
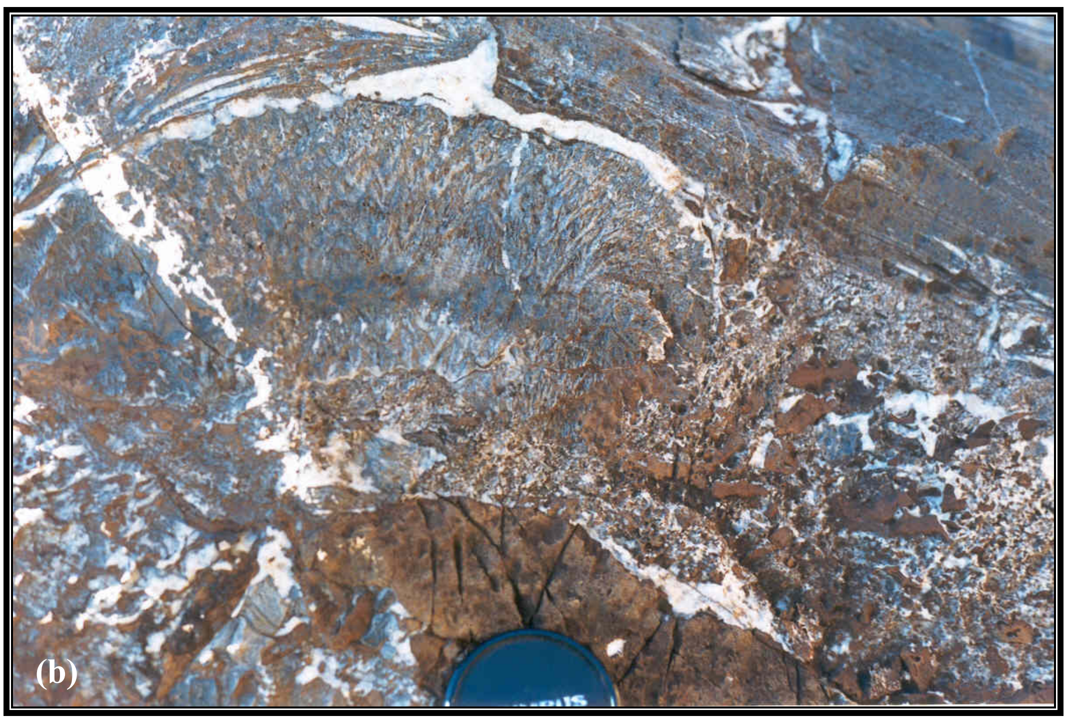


Photo 56. Cyclic normal graded beds with a BIF interbed indicating a period of cessation in high energy activity, top of the upper Mindy Debris Flow (geopick for scale).


OLYMPUS
(a)


(b)

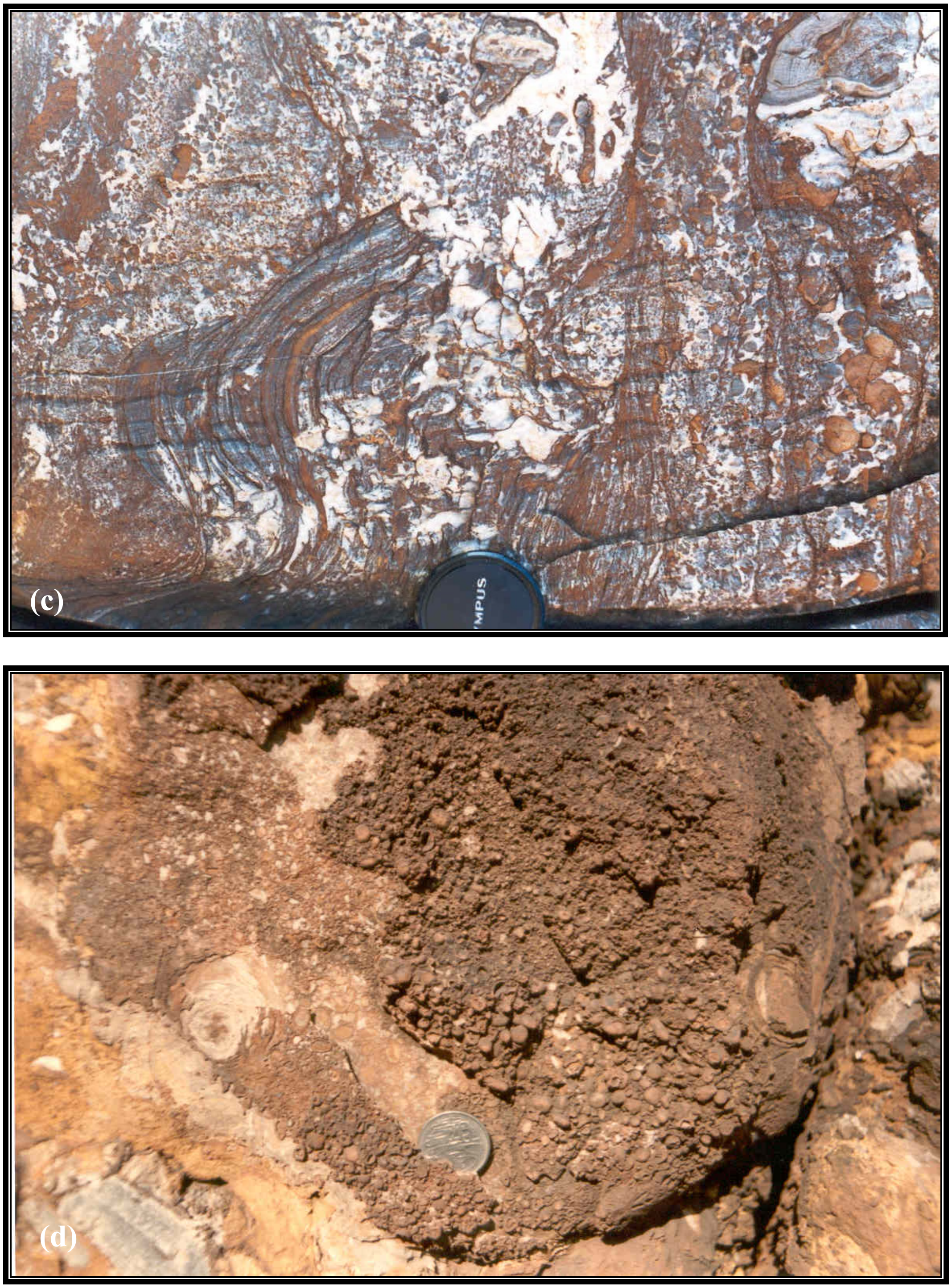


Photo 57. Shallow water textures in carbonate clasts, (a) stromatolite, (b) bottom nucleating radiating crystals (after aragonite) indicative of a hypersaline environment, (c) disrupted algal mats (possibly stromatolitic) and multiple upward fining granule beds (up is to the left) indicating a high energy environment, (d) carbonate ooids indicating wave near shore wave action, upper Mindy Debris Flow (lens caps and coin for scale).

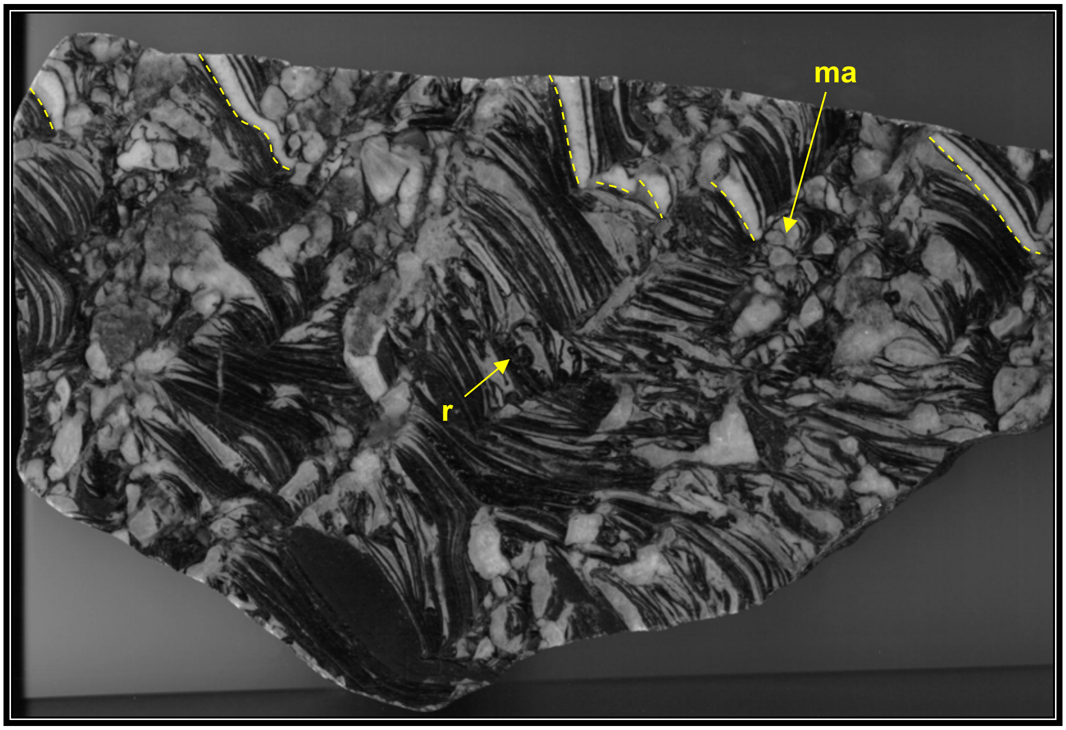


Photo 58. Disrupted finely banded biogenic carbonate clast cut perpendicular to bedding. Of note are fenestral like voids between the darker biogenic lamellae filled with calcspar, displacive precipitates after mosaic anhydrite diagnostic of a shallow hypersaline environment (ma), roll up structures produced by curling of microbial mats (r) and a characteristic thick twinned calcite layer (dashed) toward the top of the clast giving a degree of measure of the post depositional disruption, upper Mindy Debris Flow (~30 cm across).

Photo 59. Trilobite Chert, the 'spines' are sinuous D_1 rods, Yandicoogina Shale Member, Box Canyon (looking southwest, geopick for scale).

Photo 60. Woongarra Rhyolite showing (a) rhythmic compositional banding (safety glasses for scale) and (b) well developed vertical columna jointing 20 to 30 cm in diameter, 1 km downstream of Eagle Rock Falls.

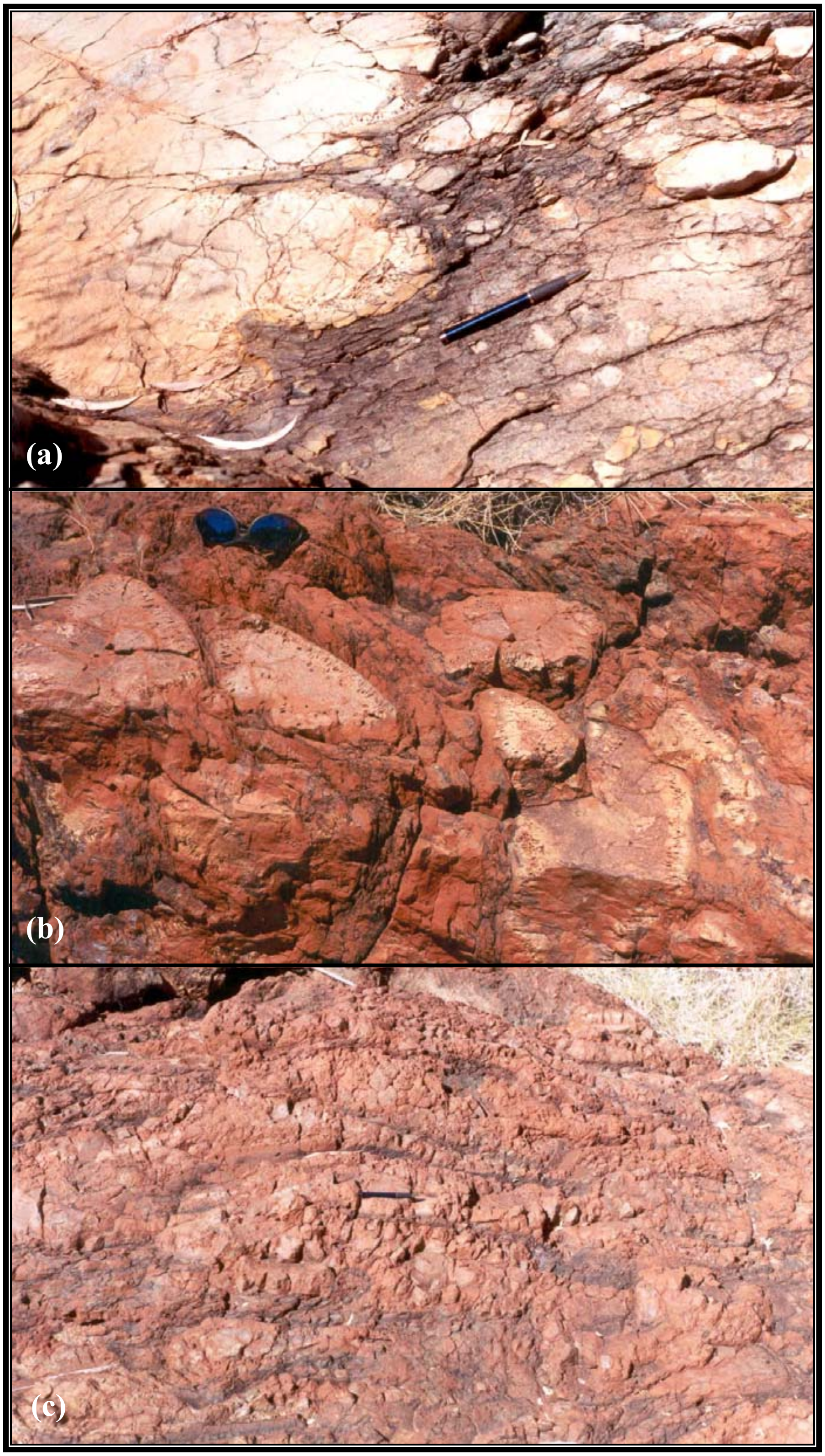


Photo 61. Hyaloclastic breccia developed in "Weeli Wolli" dolerite, (a) pillow sculptured contact between massive dolerite (right) and the breccia (pen for scale), (b) well developed pillows with chilled margins and elongate radiating vesicles (apparent in all outcrops, safety glasses for scale), (c) flow banded, highly elongate pillows (pen for scale), upper Weeli Wolli Formation, 2 km downstream of Eagle Rock Falls

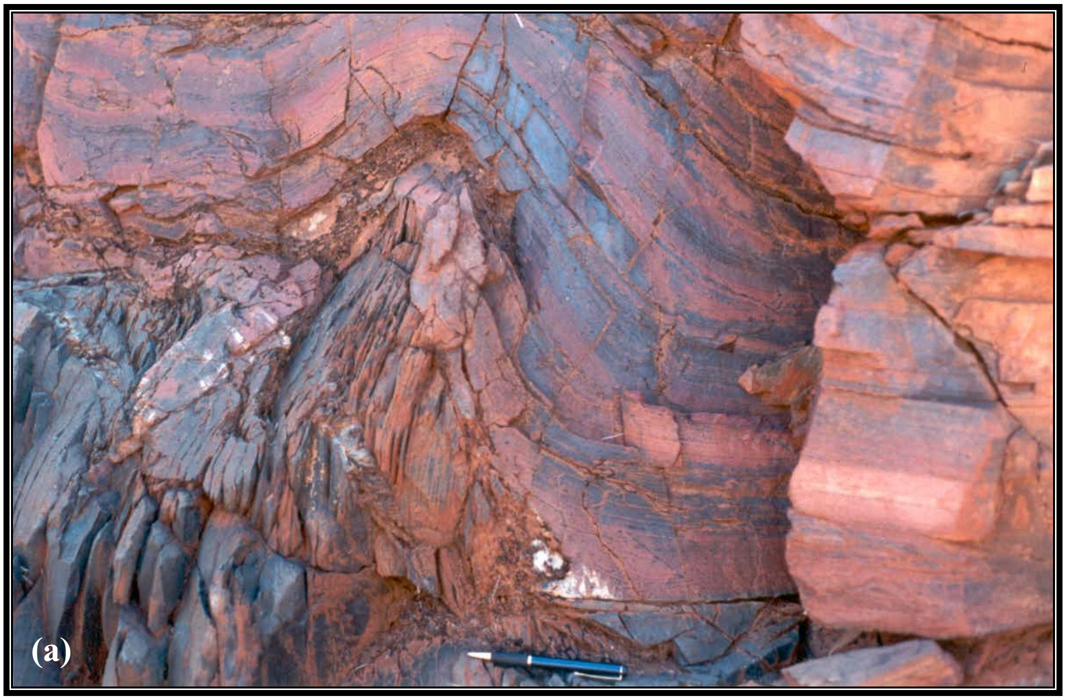
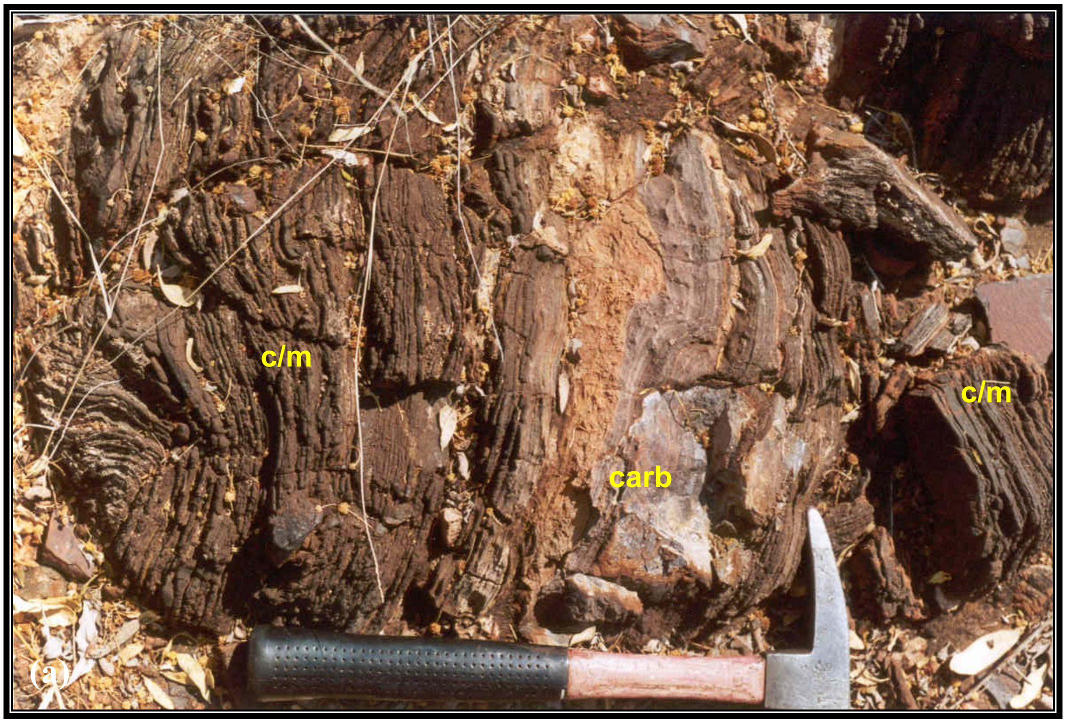


Photo 62. Contact between dolerite sill and BIF of the Weeli Wolli Formation showing (a) upward intruding apophyses truncating bedding in the BIF and (b) several small scale rafts or xenoliths (arrowed) of BIF incorporated in to the top of the sill. There is no evidence of marginal pillows as indicated by Barley *et al* (1997) with the entire outcrop showing a non-vesicular chilled margin with perpendicular micro columna jointing, 2 km downstream of Eagle Rock Falls (looking northwest, pen for scale).



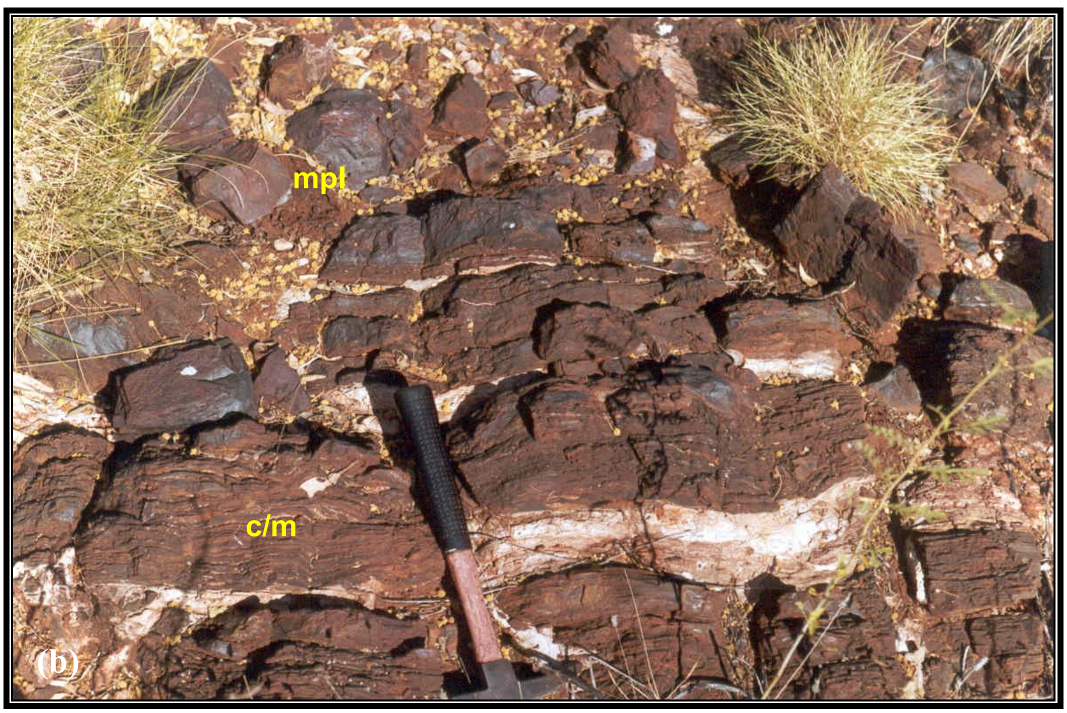


Photo 63. Iron – carbonate mineralisation developed in the Dales Gorge Member at OB28, lithologies in outcrop include complete carbonate replacement (carb), finely banded carbonate and martite (c/m) and M-(mpl H) (mpl). White carbonate in (b) is secondary calcrete (geopicks for scale).

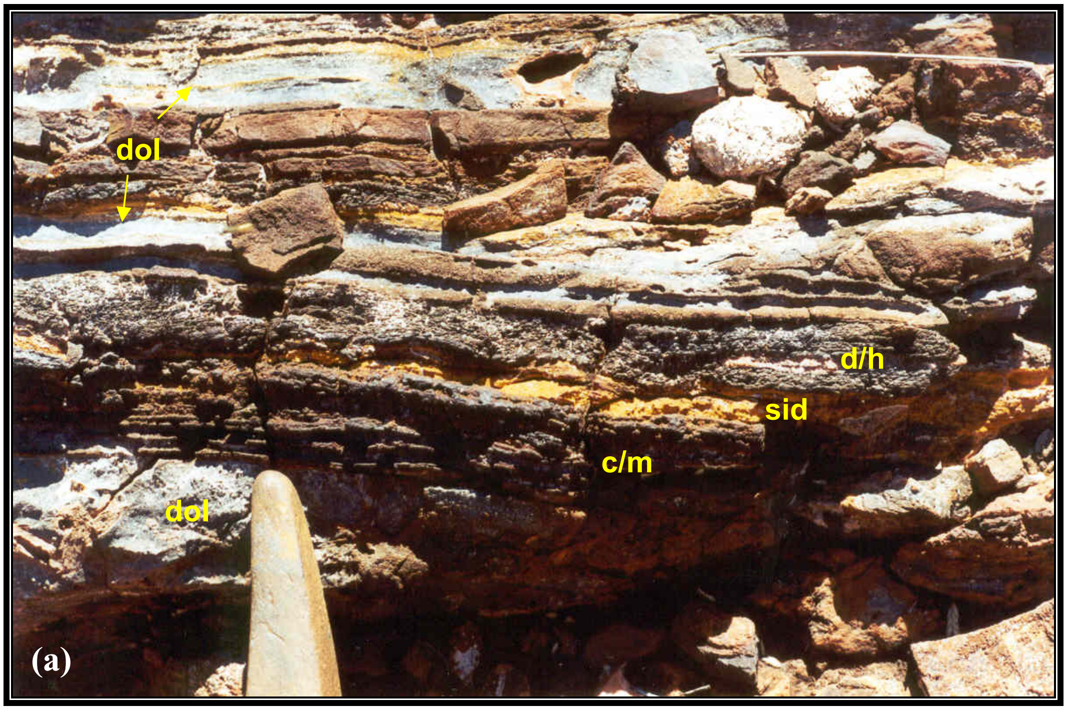


Photo 64. Iron – carbonate mineralisation developed in the Joffre Member at Werriba Anticline, lithologies include grey crystalline dolomite (dol), dolomite with disseminated specular hematite (d/h), yellow siderite (sid), finely banded carbonate and martite (c/m) and possible M-(mpl H) (mpl?) (tip of geopick for scale).

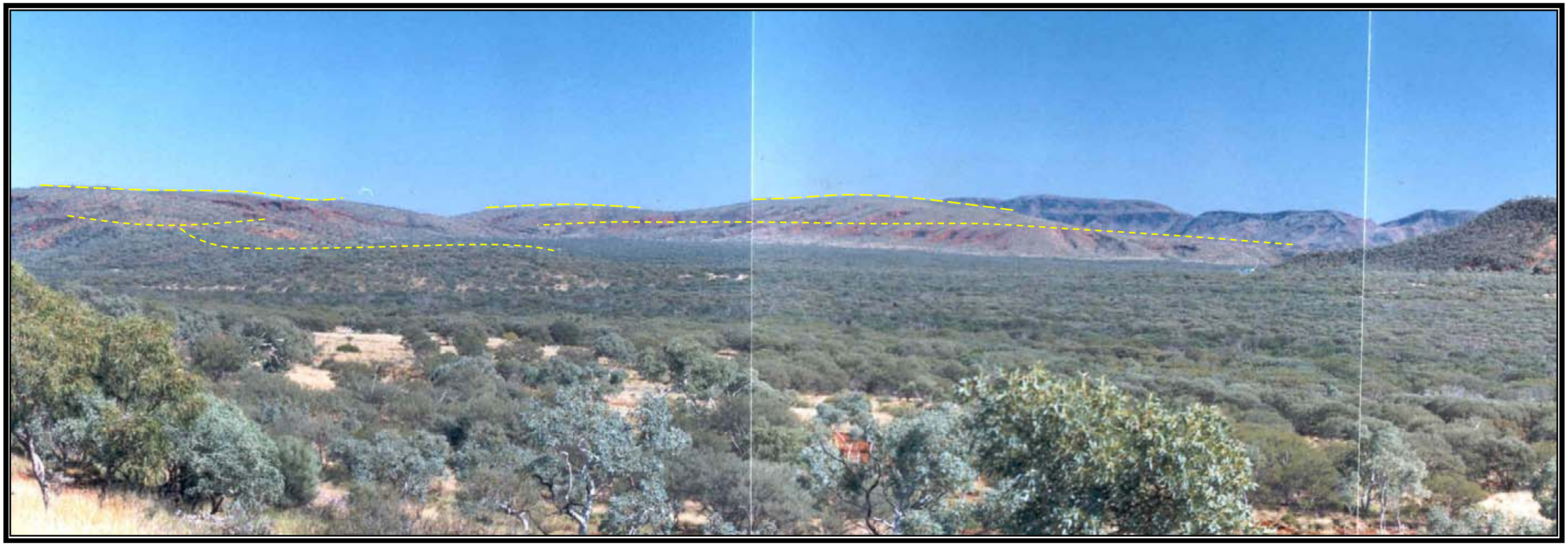


Photo 65. Landforms showing two levels of terracing developed on the Marra Mamba Iron Formation possibly corresponding to different Tertiary cycles, from Jaws Extended looking west northwest across Jaws with Mt Meharry in the background.

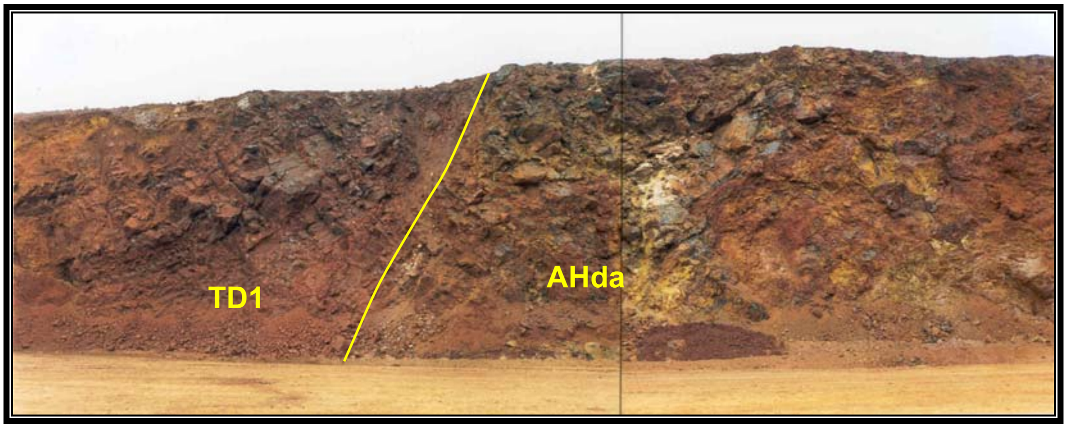


Photo 66. Well bedded hematite siltstone (TD1) draped on to West Angela Member, steepening of bedding toward the contact is interpreted as being due to dewatering and compaction, OB29 (bench height 6 m).

Photo 67. Typical outcrop appearance chaotic poorly sorted alluvial coarse conglomerate facies of the Miocene conglomerate, Southern Flank (pen for scale). Note the difference in appearance of the conglomerate between hardcapped exposures here less altered cliff sections in some of the subsequent photos.

Photo 68. Fluvial Miocene conglomerate with interbedded silty overbank deposits. Note the scouring of the silt layers (arrowed), Poxy Leg Gully, Southern Flank (30 cm ruler for scale).

Photo 69. 1 m RC drill samples showing a large range in colour corresponding to conglomeratic (darker reds to purples) to more silty and shaly facies (pinks to browns), top of hole arrowed, GLR0006, L Deposit, Southern Flank.

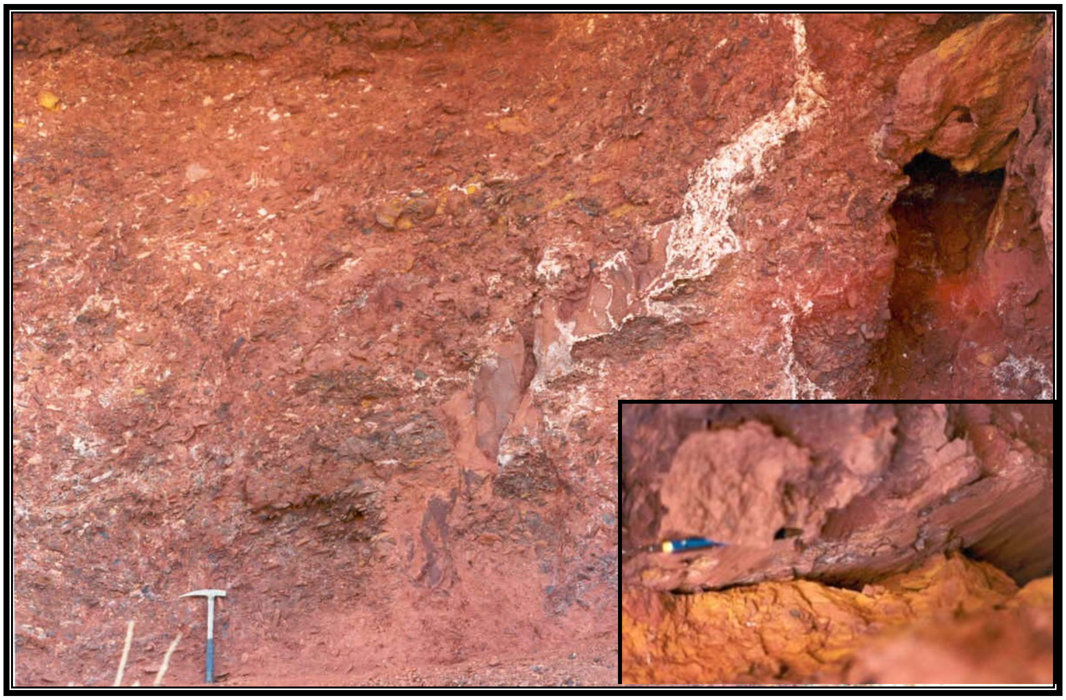


Photo 70. Irregular clastic dykes derived from interbedded silts injected into Miocene conglomerate (TD1) during compaction and dewatering. Note the well developed marginal slickensides indicating forceful intrusion / injection (inset, pencil for scale), Poxy Leg Gully, Southern Flank (geopick for scale).

Photo 71. Moderate to steeply dipping Miocene conglomerate on the southern margin of the confined east / west palaeovalley, Southern Flank (looking east, 30 cm ruler for scale).

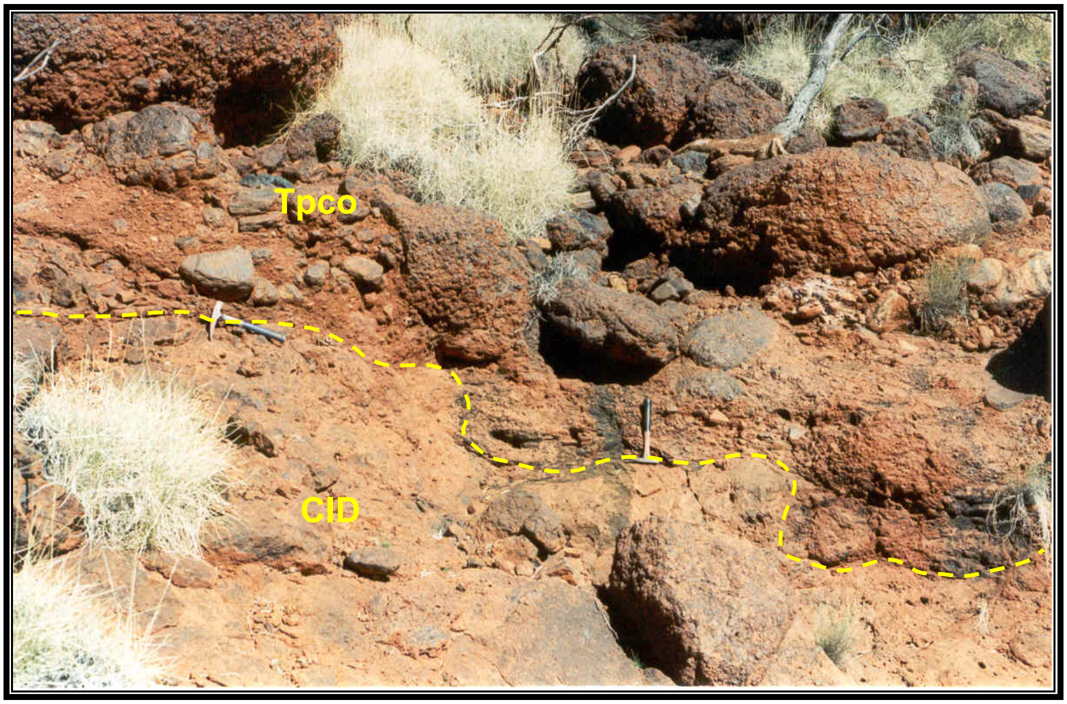


Photo 72. ?Pliocene conglomerate (Tpco) overlying CID on an irregular, erosional unconformity surface, Death Valley (geopicks on unconformity for scale).

Photo 73. (a) Recent slips on Mt Meharry (WA's highest point - 1250 m) with basal Joffre Member detaching and sliding on Mt Whaleback Shale Member, (b) close up showing part of the failed block ramping up over *in situ* BIF suggesting catastrophic failure rather than gradual creep (arrowed).

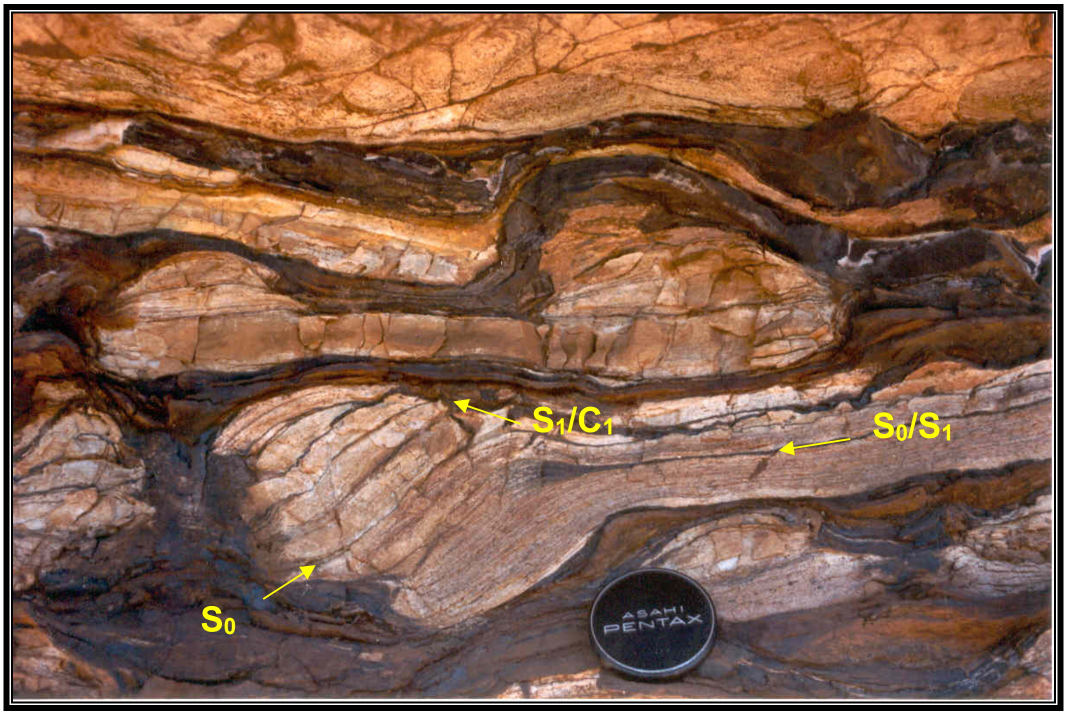


Photo 74. "Boney – O" D_1 boudinage of chert mesobands directly beneath NS5 producing locally divergent S_0 and S_1. Note the oxide microband (S_0/S_1 arrow) produced by compression / dissolution of chert with finely disseminated oxide, Mount Newman Member BIF, B Deposit (looking west, lens cap for scale).

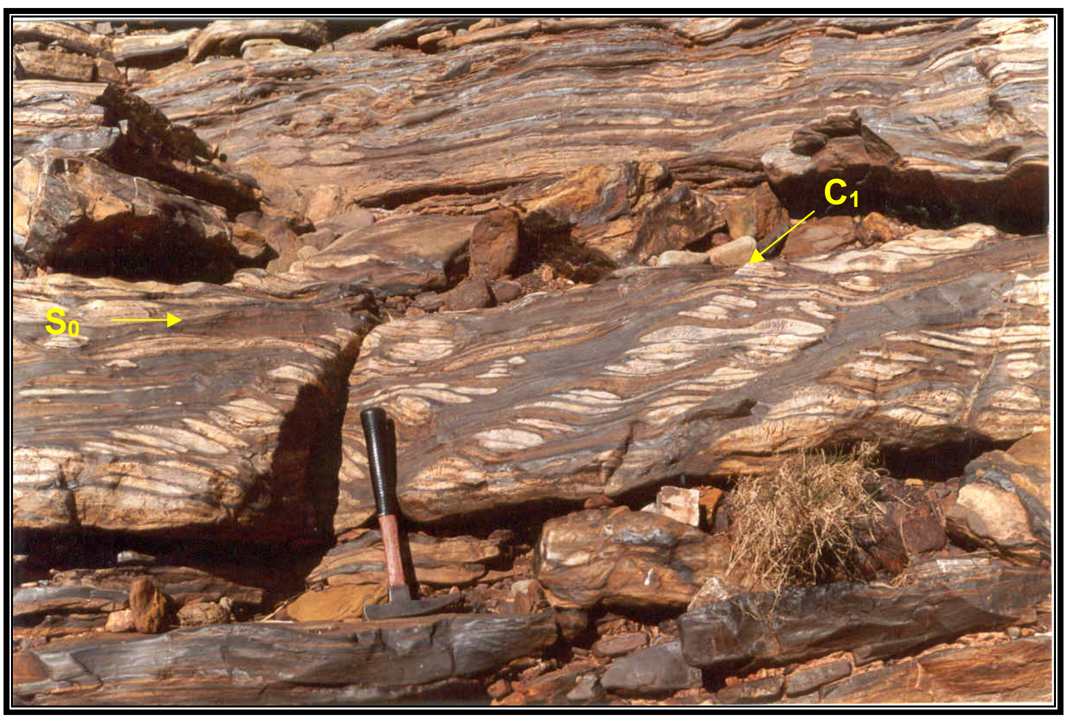
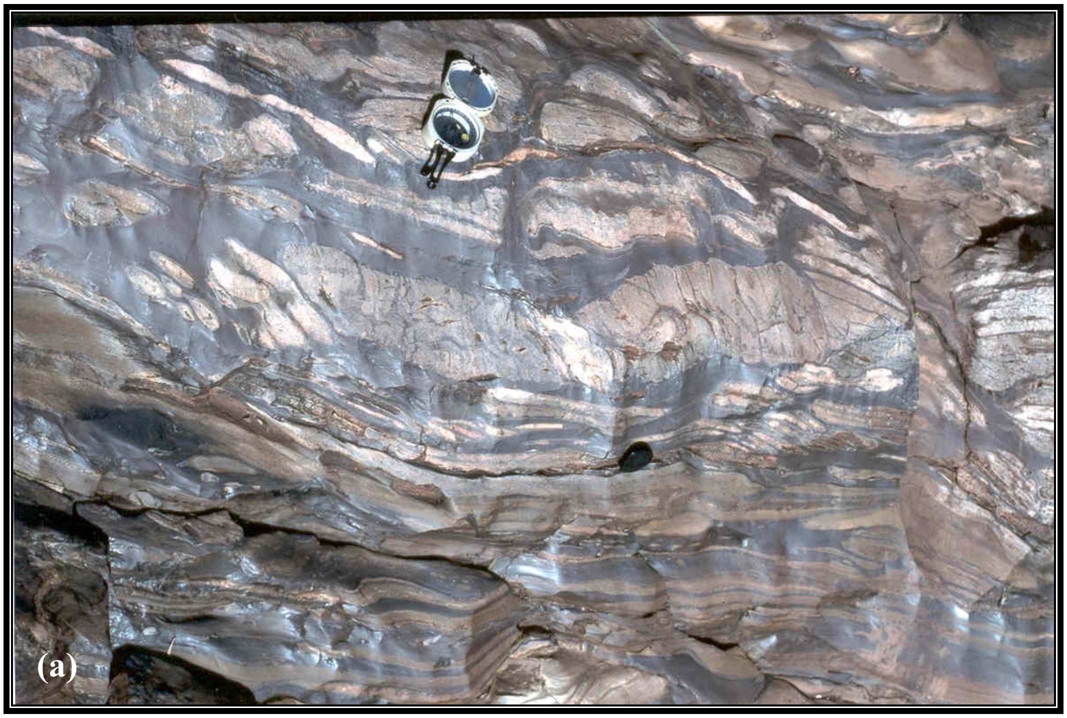


Photo 75. Well developed stacked pods oblique to bedding produced by D_1 extensional shears and 20 to 30 % volume loss. Note that the in-pod banding is subparallel to adjacent bedding, Mount Newman Member BIF, Wonmunna Gorge (looking south, geopick for scale).



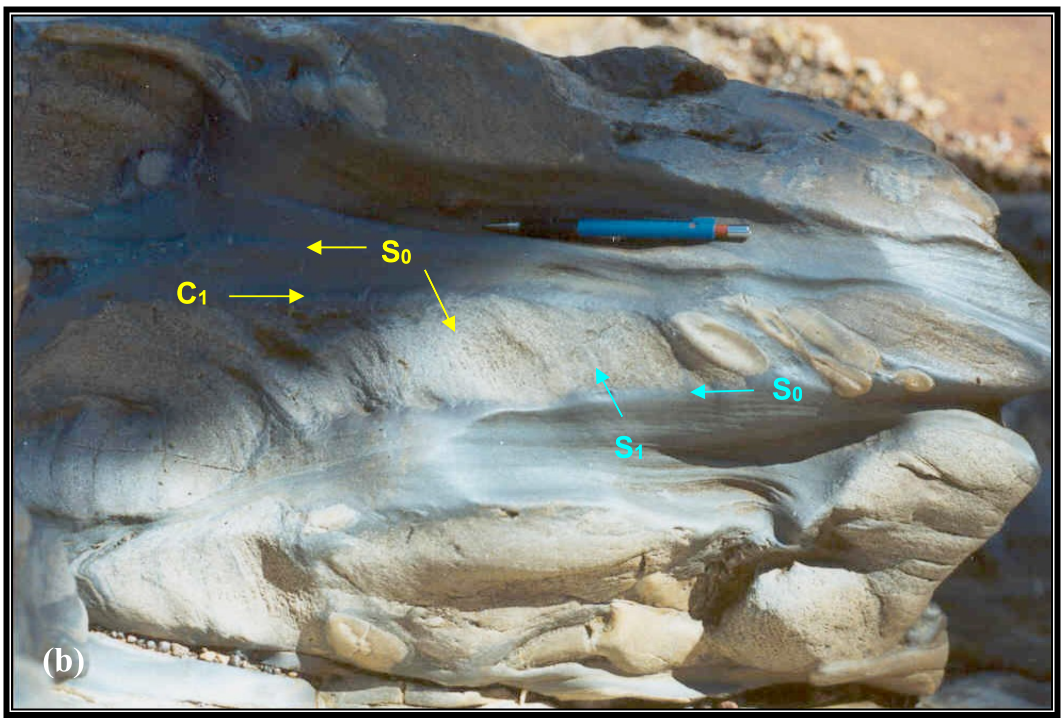


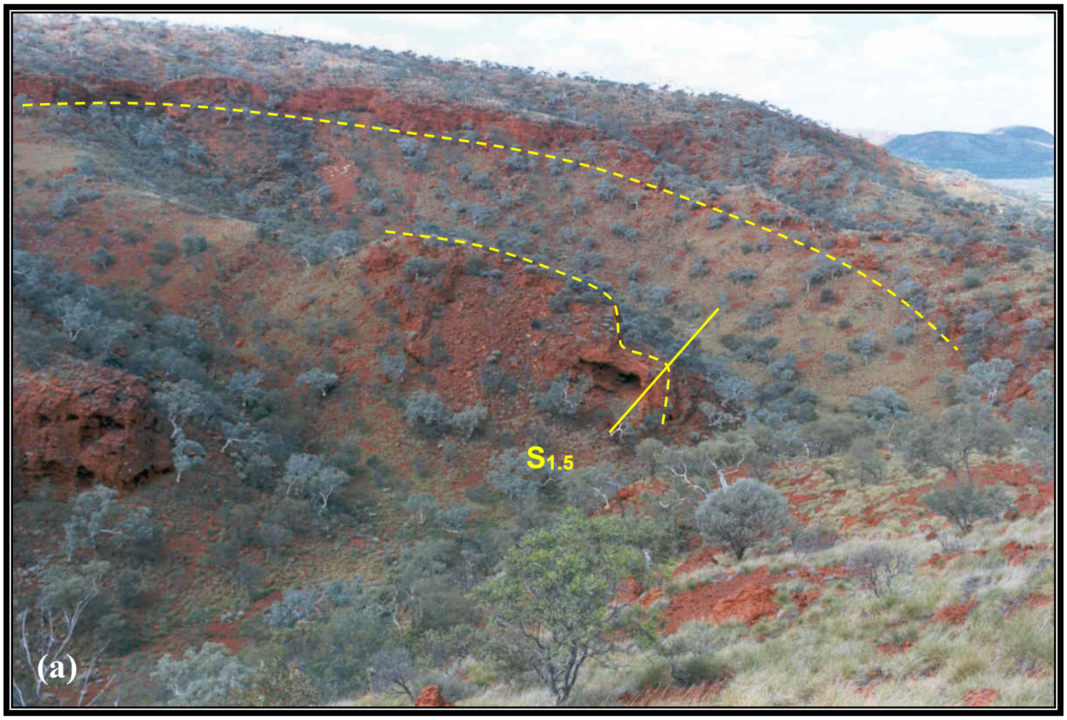
Photo 76. Stacked pods developed subparallel to bedding where the in-pod banding forms a high angle to the enveloping bedding, in (a) the total thickness of the strata in the pod is about 71 cm compared with about 8 cm between the bounding chert beds along strike from the pod indicating a volume loss of nearly 90 %. Such pods may have developed as an end case from extensional stacked pods such as in Photo 75, whereby continuing dissolution of silica results in near total collapse of the affected layer and subsequent rotation toward bedding of any remaining pods (as per the yellow labels in (b)). Alternatively, the in-pod banding might be a locally refracted S_1 with the long axis of the pod being bedding (blue labels in (b)). Whilst unlikely, it does resolve the problem of extreme local variation in bed thicknesses, Mount Newman Member BIF, Wonmunna Gorge (Brunton and pencil for scale, looking south).

Photo 77. D_1 modification of Potato Bed producing elongate and coalesced pods, MacLeod Member, Jaws Extended? (looking northeast, geopick for scale).

Photo 78. Southwest trending D_1 carbonate rod developed by partial dissolution of a continuous carbonate bed, Mt Sylvia Formation, Eric's Point (looking south southwest, geopick for scale).

Photo 79. Sinuous D_1 chert rods in ("snakes") in J6 BIF, Joffre Member, Snake Gorge, Packsaddle Range (looking southeast).

Photo 80. Perpendicular cross section of a Nammuldi Member Rod asymmetrically wrapped by bedding and with orthogonal quartz filled tension gashes rotated with respect to bedding, North Alligator (looking northeast, lens cap for scale).



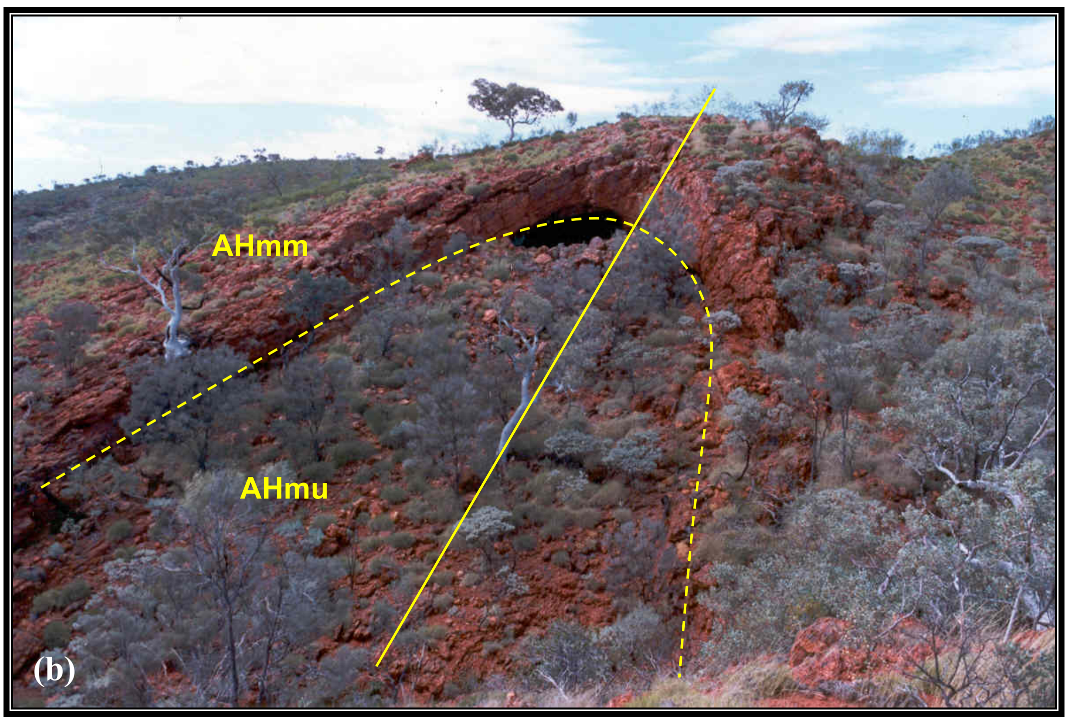


Photo 81. South facing folds previously interpreted as $D_{1.5}$ folds, (a) very broad and open fold with minor mesoscopic folding implying a south facing, however given the openness and the lack of visible limbs, the overall geometry is open to debate as it may be a weak box like kink on the southern part of a D_2 fold closure (eg Photo 89), Nammuldi Member, South Alligator (looking east), (b) close south facing fold on the north limb of the Alligator Anticline which is compatible with a weakly convergent D_2 array as seen elsewhere, MacLeod to Nammuldi Members, North Alligator (looking east).

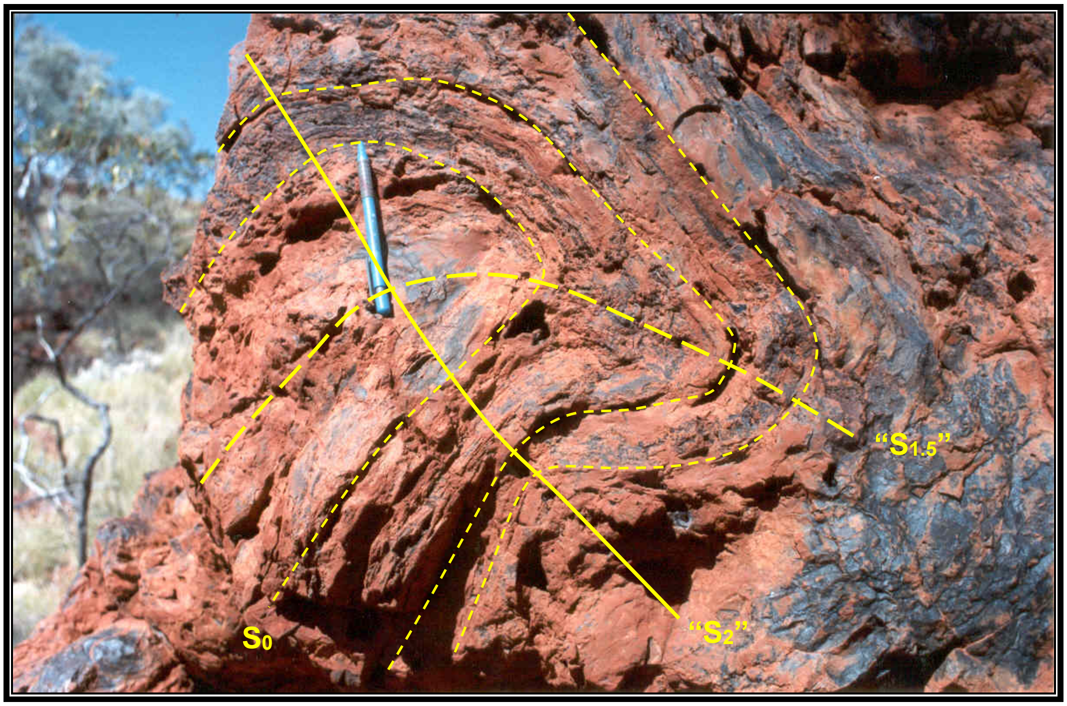
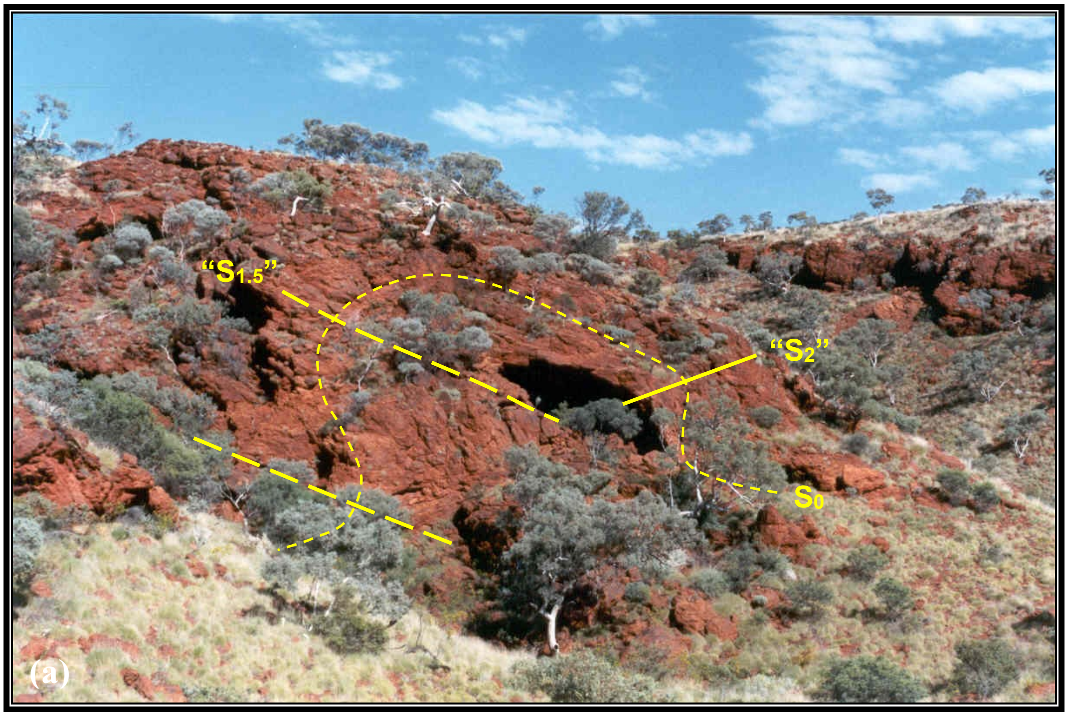


Photo 82. Refolded fold previously interpreted as $D_{1.5}$ / D_2 interference structure. Note that the "F_2" in places does not fold some of the fabrics. The same geometry is developed at C Deposit where it has been shown to be produced solely by D_2 as part of a convergent array across a D_2 anticline which has subsequently been modified by shearing produced by D_2 flexural slip (see Figure 34). Note the apparent large reorientation of the "$S_{1.5}$" (~70º) compared with some bedding surfaces (S_0) which show no to a highly variable angle of displacement, mineralised Mount Newman Member, South Alligator (looking east, pencil for scale).



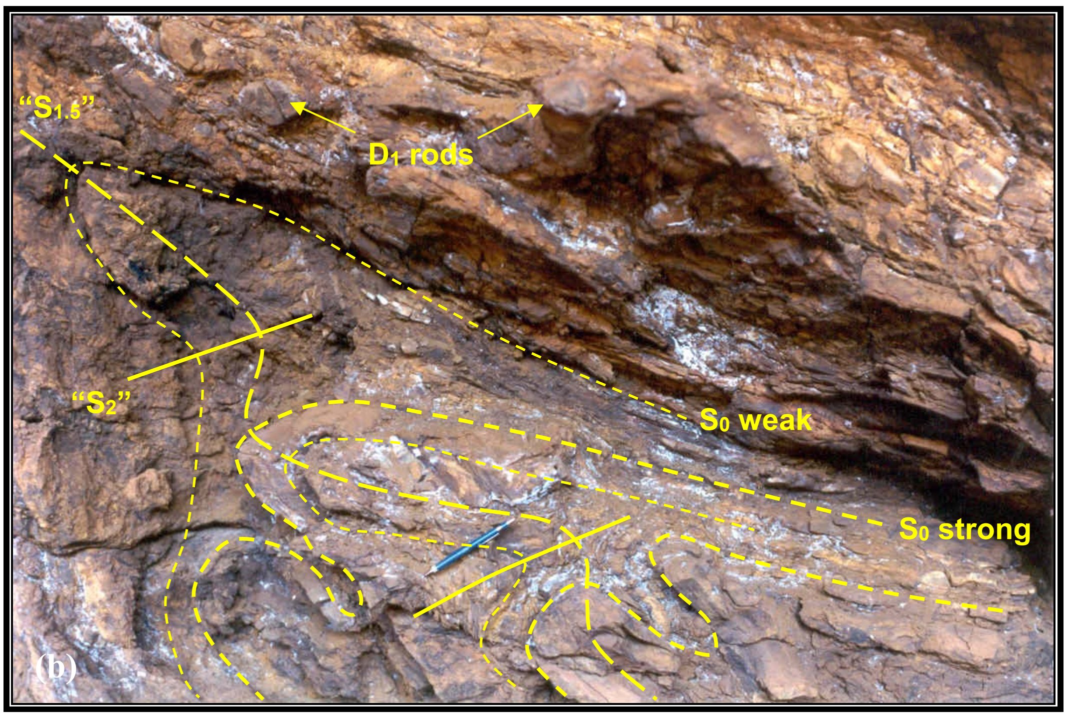


Photo 83. (a) Macroscopic fold previously interpreted as a $D_{1.5}$ / D_2 interference structure, alternatively it may have developed as a south facing (D_2) fold on the north limb of the regional Alligator Anticline as part of a convergent array. The weaker north facing fold is then a coeval poorly developed conjugate fold defining a lopsided box fold. (b) Detail of the back of the cave in (a) showing an apparently folded axial surface however the "later folds" coincide with the multiple closure of relatively stronger and thicker beds and do not penetrate in to the surrounding strata indicating that they are due to axial collapse. Note the D_1 rods in the roof of the cave, lower Nammuldi Member, North Alligator (looking west, pencil for scale).

Photo 84. Juxtaposition of small scale, north facing D_2 intrafolial folds in J1 BIF with adjacent, well developed north dipping crenulation cleavage previously interpreted as $S_{1.5}$, but with no discernable interference. The cleavage is restricted to beds immediately above and below the folded bed. Its origin and timing remains an enigma, but a weak texture on the fracture face of the folded bed and no apparent reorientation of the cleavage immediately above the folds suggests the cleavage post dates the folding, but is only developed in a specific susceptible lithology. That is, it is not $D_{1.5}$. Joffre Member, Fork South (looking east, pencil for scale).

Photo 85. Non-cylindrical curvilinear D_2 folds developed on a bedding surface of a fallen block of Dales Gorge BIF. Larger scale folds vary from open symmetrical, through asymmetrical to overturned over very little distance (less than a wavelength). Axial traces are noticeable curved including a secondary set rotated about 30º with respect to the dominant set with the resulting anastomosing pattern identical to megascopic fold patterns developed along the Southern Flank, for example, West Newman Gorge (handle of geopick for scale).

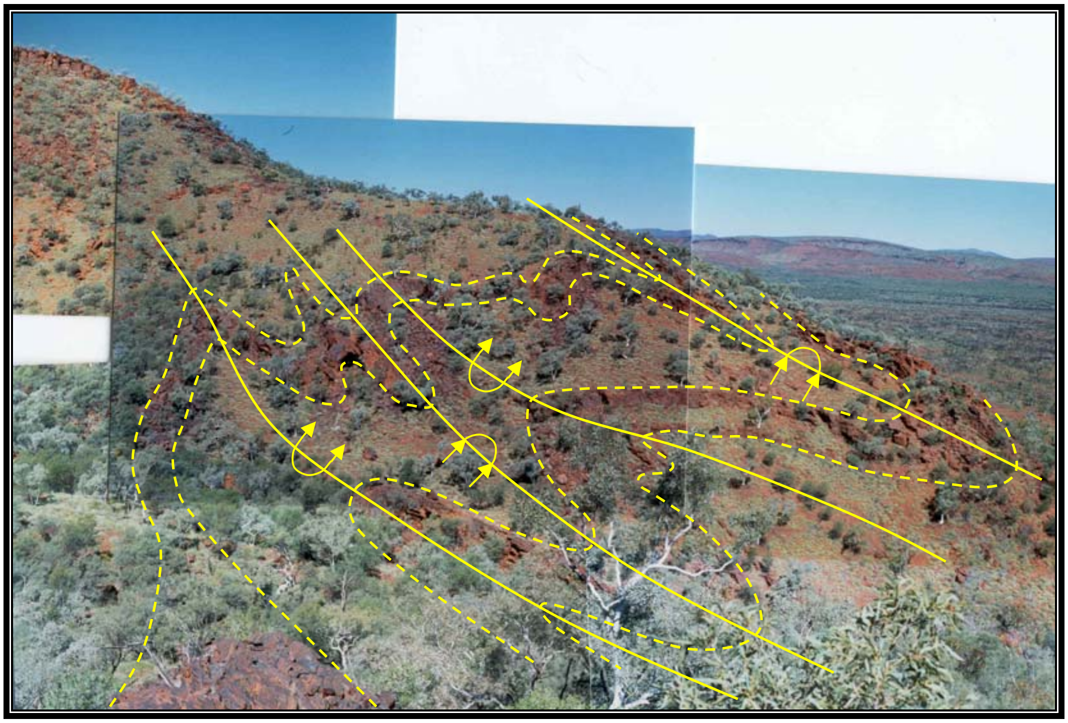


Photo 86. Overturned, southeast facing D_2 folds with fold axes trending 130 to 150º developed in the Mt Sylvia Formation. They were initially thought to be D_2 folds reorientated by D_4 but now recognised as being purely D_2 in origin. Dashed lines are top and base of Bruno's Band, top of SB2 and base of SB1, The Governor (looking south southwest).

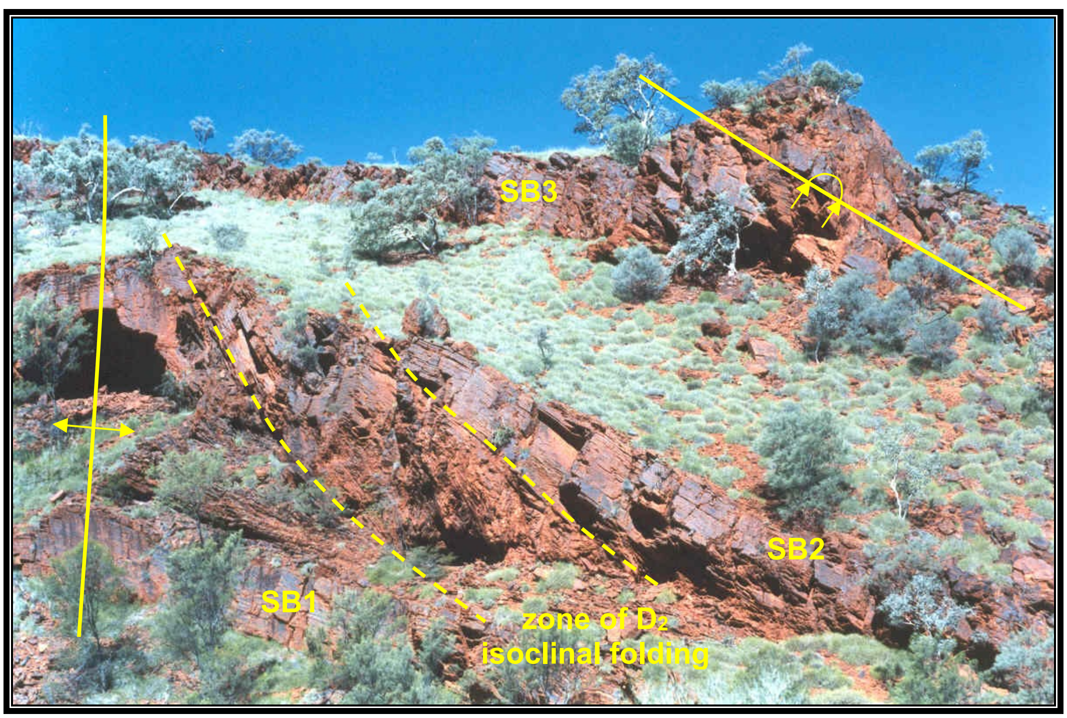


Photo 87. Isoclinal, ramp like D_2 folds producing localised stratigraphic thickening of shales between SB1 and SB2, and of SB2. The upright fold is interpreted as a D_3 fold but may be ongoing D_2 deformation, Mt Sylvia Formation, The Governor (looking west southwest).

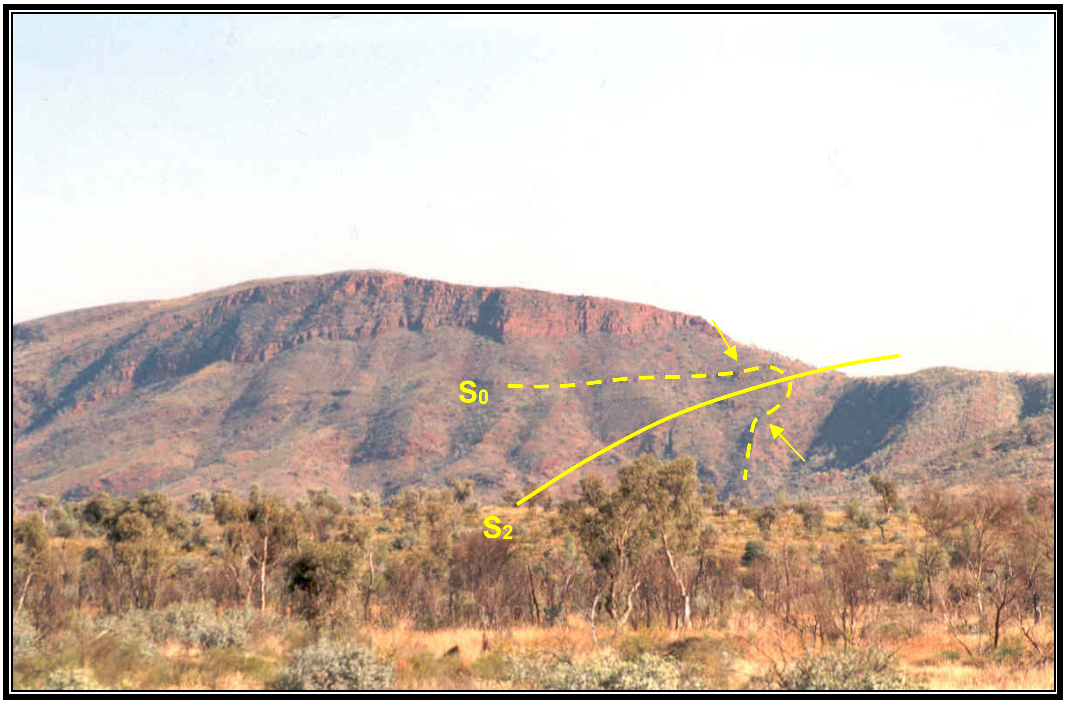


Photo 88. Mt Newman showing the D_2 Mt Newman Anticline comprising the gently south dipping limb of the eastern face and the overturned, steeply south dipping limbs best seen in Cathedral Gorge. Note that the fold closure Bruno's Band has been pinched resulting in axial collapse and a curvature of the axial surface. The subvertical open folds apparent on the gently south dipping which are best defined by the Mt McRae Shale / Dales Gorge Member contact were previously thought to be D_3 folds but are of indeterminate age (looking west).

Photo 89. Typical complex folding patterns produced during D_2 with nonparallel north facing folds and local development of conjugate south facing folds producing asymmetric box folds. This fold style is predicted for anisotropic multilayered rocks and is commonly developed at all scales throughout the Hamersley Province. The geometry is not compatible with two fold generations, Dales Gorge Member (with labelled S macrobands), West Newman Gorge (looking west).

Photo 90. Disharmonic D_2 folding producing bedding parallel detachment between relatively undeformed Mount Newman Member BIF and D_2 folded MacLeod Member along MS13 (line of small caves), Southern Flank (geopick for scale).

Photo 91. Detachment between tightly D_2 folded ?Joffre Member BIF and planar Mt Whaleback Shale Member, the detachment here may be part of a larger scale flat lying thrust, Eastern Ridge (looking east).

Photo 92. Localised small scale thrusts and space accommodating faults in AS3 with the fault surfaces ramping in and out of stratigraphy, West Angela Member, south limb of OB29 (looking northwest, geopick for scale).

Photo 93. Multiple structural repetition of a single south dipping Karijini Dolerite sill along the *en echelon* Jump Up Thrust, Juna Downs (looking northwest obliquely across Milli Milli Anticline toward north dipping Brockman Iron Formation hills).

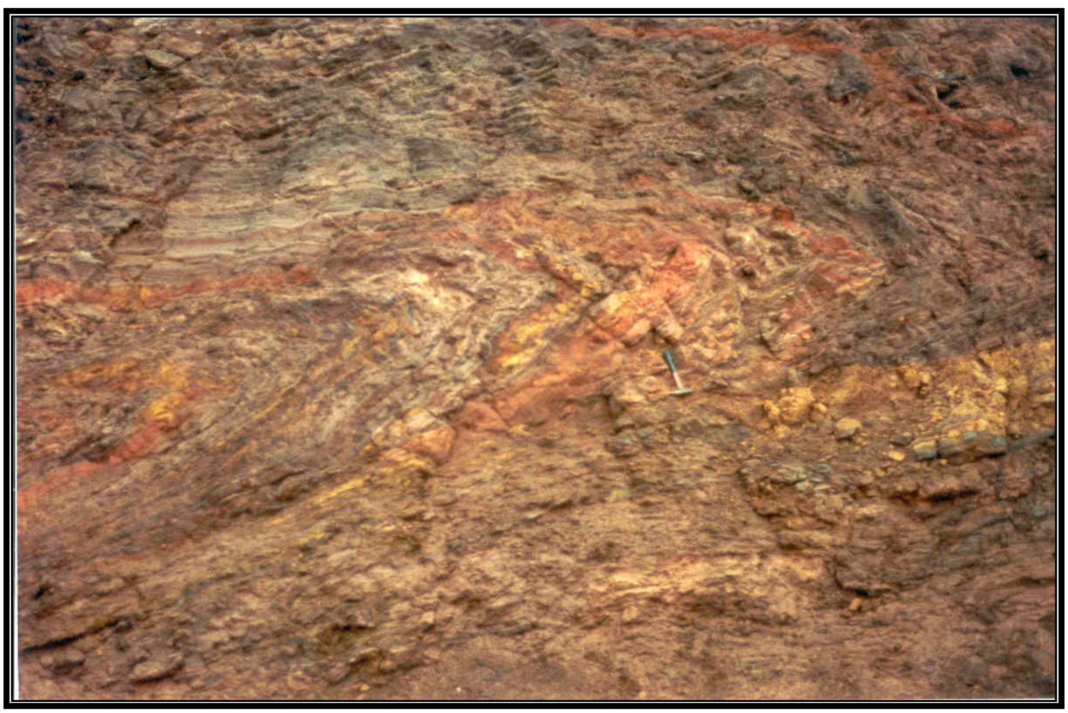


Photo 94. Bedding parallel D_2 thrust developed by over strain during recumbent folding along the overturned limb. The thrust surface varies from a single surface left of the geopick to a thick limonitic shaly fault gauge to the right, mineralised Joffre Member, upper benches of W4 pit, Jimblebar (geopick for scale, looking west).

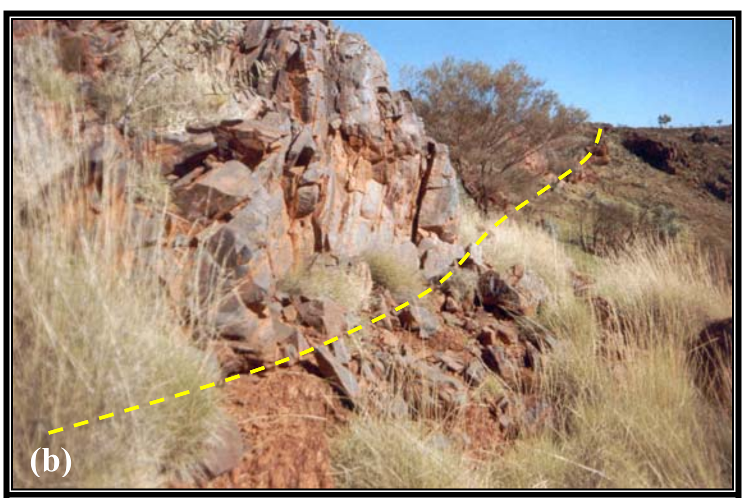


Photo 95. D_2 Neptune Thrust discordant to bedding between steeply dipping to overturned Dales Gorge Member BIF and vertical Mt Whaleback Shale Member, note the thrust parallel fabric along the pencil in (a) and drag folding in the BIF in (b). The thrust is subparallel to S_2 dipping about 30º south, western end of Eastern Ridge (both looking west).

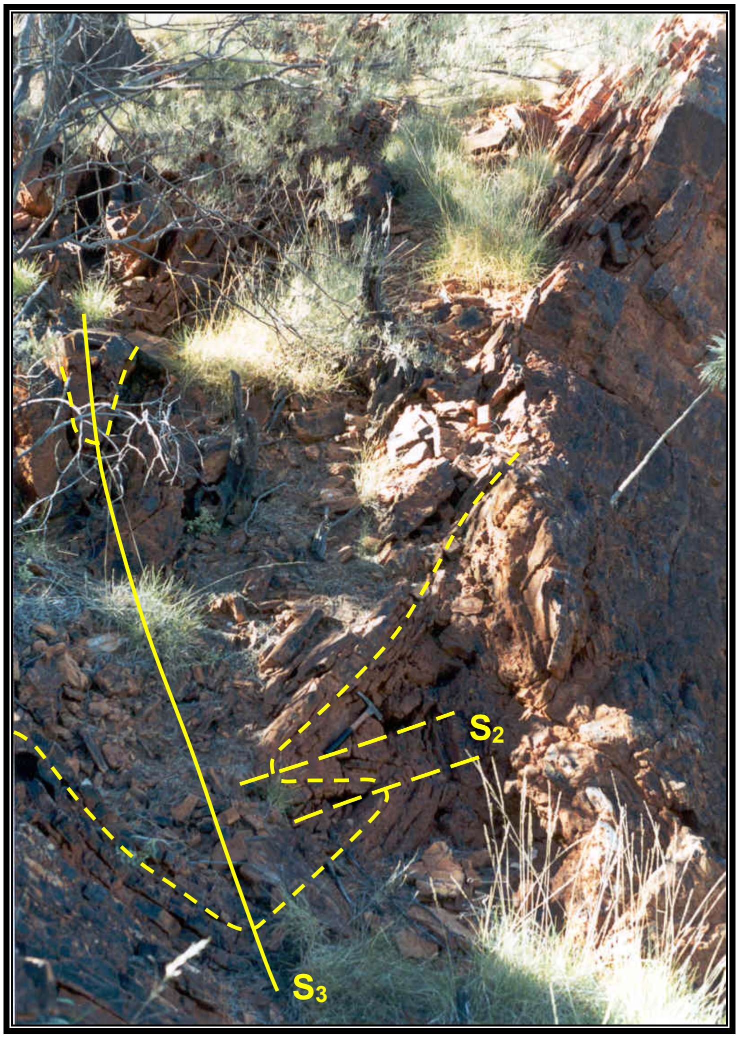


Photo 96. Small scale antithetic folding compatible with a D_2 fold being re-orientated by D_3 fold, Dales Gorge Member, The Governor (looking east, geopick for scale).

Photo 97. Megascopic west northwest trending open upright D_3 fold (or D_4?) with a macroscopic asymmetric D_2 fold on its southern limb. Alternatively the geometry may all be D_2 in origin, Mt Meharry Massif, (looking west northwest from Parallel Ridge).

Photo 98. Macroscopic asymmetric fold trending north northwest of unproven affinity but previously interpreted as either a reorientated $F_{1.5}$ or F_2, or as a F_4. The fold may have developed as a south facing D_2 fold on the north limb of Alligator Anticline (ie part of a convergent array - it is just along strike from Photo 83) and reorientated by flexural slip for example. Note the asymmetric development of the box fold, Nammuldi Member, North Alligator (looking south southeast, DAK for scale).

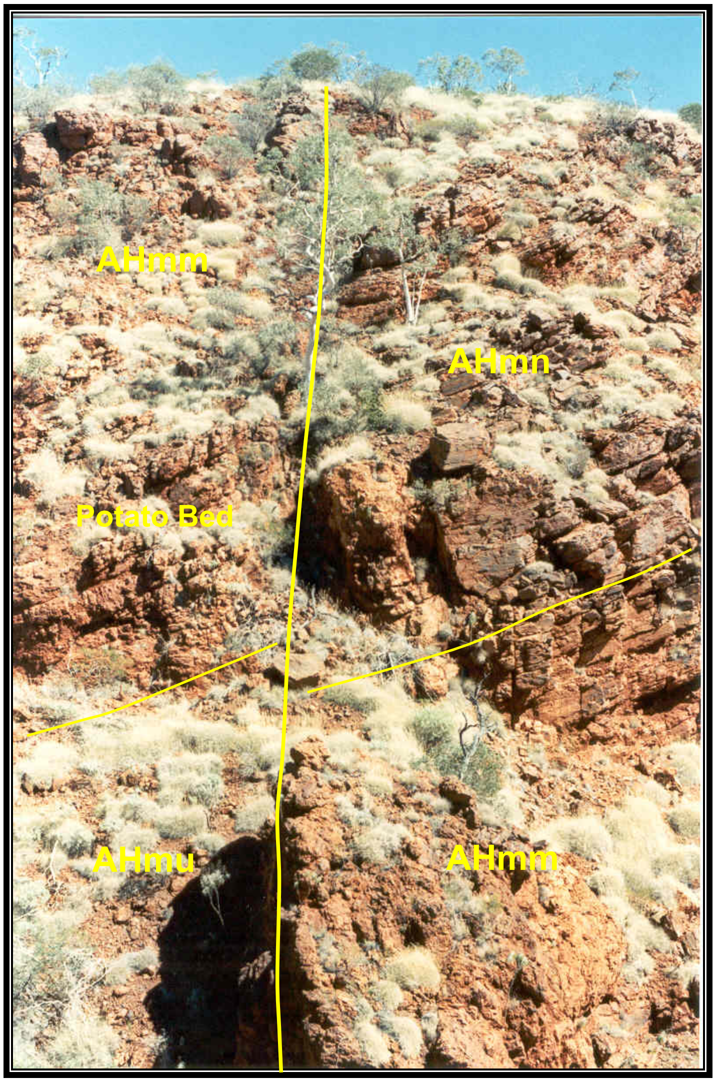


Photo 99. East / west transverse HS Fault in east dipping Marra Mamba Iron Formation, between Eterak and Big Creek. Note the similar orientation of bedding either side of the fault (looking west).

Photo 100. Breccia fault splay off Box Canyon Fault (about 5 m north), comprising BIF clasts in yellow silicified matrix, J6 BIF, Joffre Member, Weeli Wolli Springs (looking west, geopick for scale).

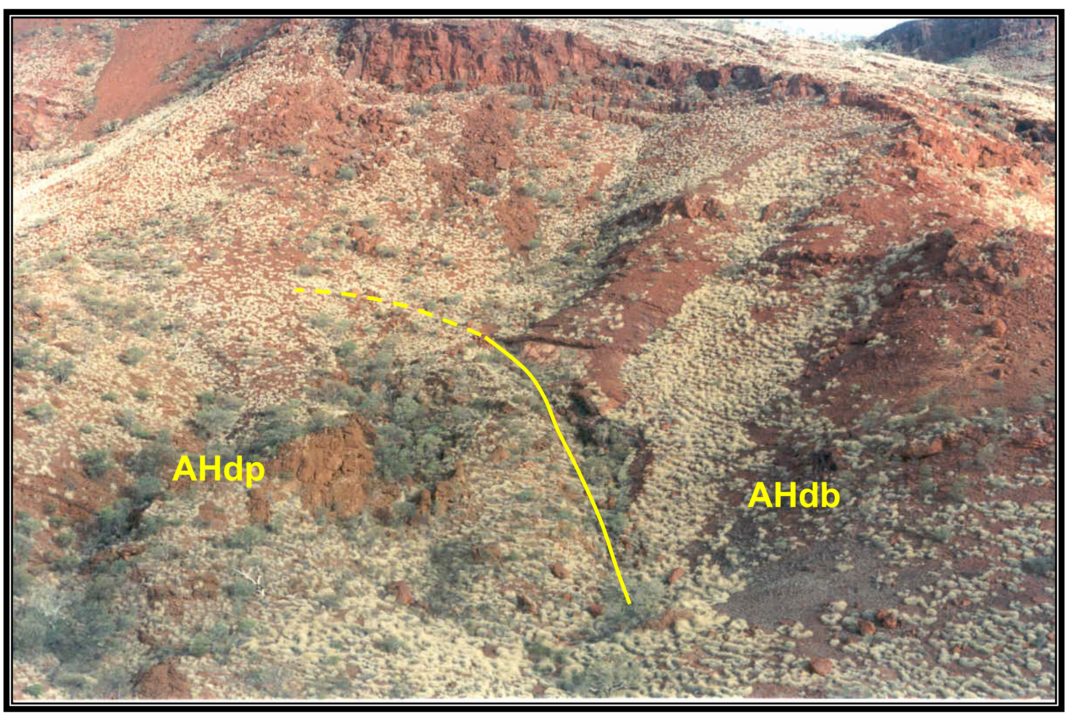


Photo 101. High angle, intraformational fault between Paraburdoo and Bee Gorge Members. There is no displacement in the overlying exposed Bruno's Band or Dales Gorge Member with the fault probably soling in to bedding in the Bee Gorge Member, Death Valley (looking south).

Photo 102. Steeply north dipping normal fault, MacLeod Member, E Deposit (looking east, MCB for scale)

Photo 103. North trending, upward propagating conjugate kinks of unknown affinity developed in finely bedded shales terminating against a chert mesoband (C1?), Mt McRae Shale, Werriba Anticline (looking north, circled geopick for scale).

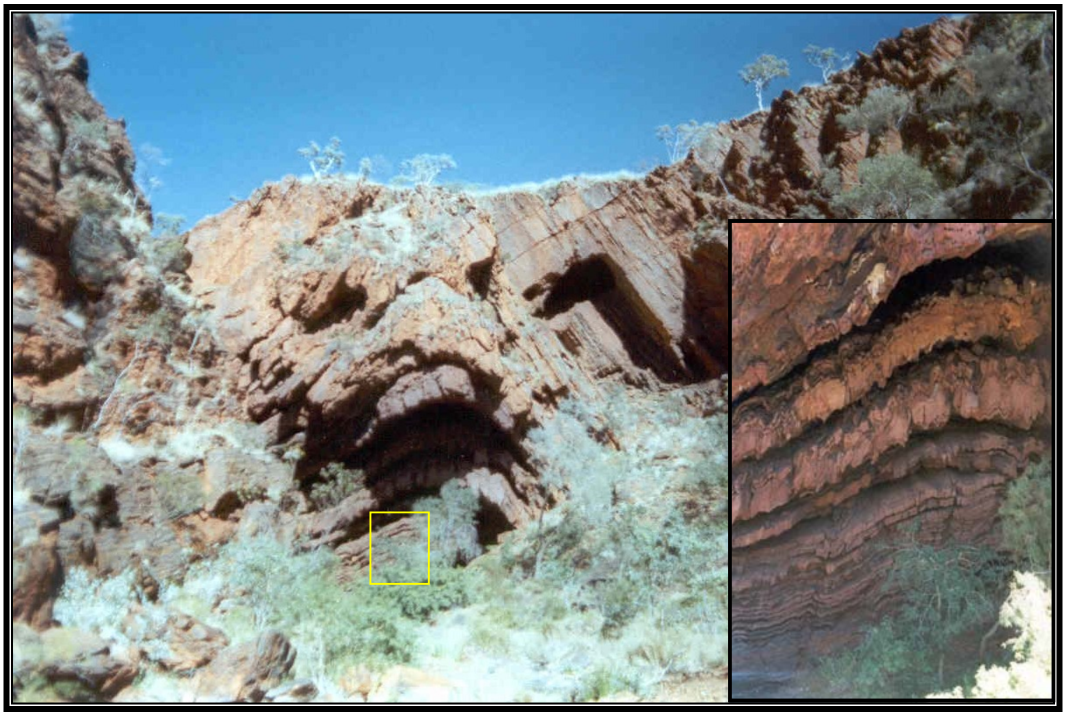


Photo 104. Upright D_2 fold in J6 BIF with convergent fanning cleavage. Inset showing layer parallel compression producing structural thickening in the closure, Joffre Member, gorge north of Box Canyon.

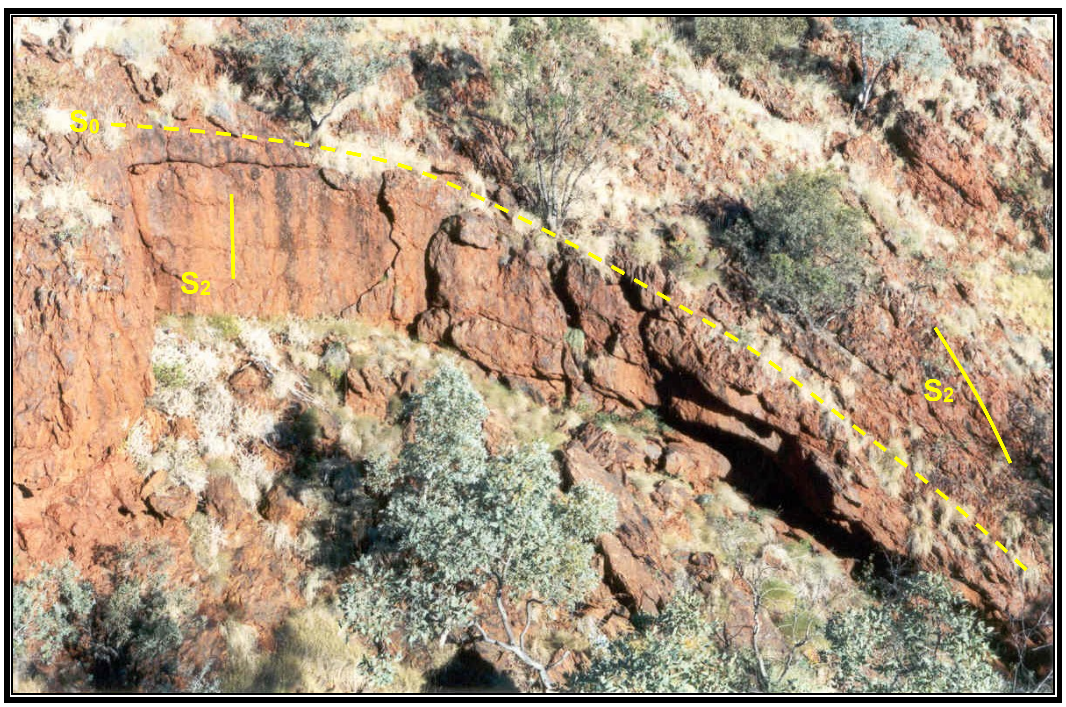


Photo 105. West face of Saper Vedere Gully showing part of an open, upright D_2 anticline. Initial layer parallel shortening followed by folding with associated flexural slip has resulted in a convergent fanning S_2 array. See Photo 106 for further detail, N1, Mount Newman Member, C Deposit.

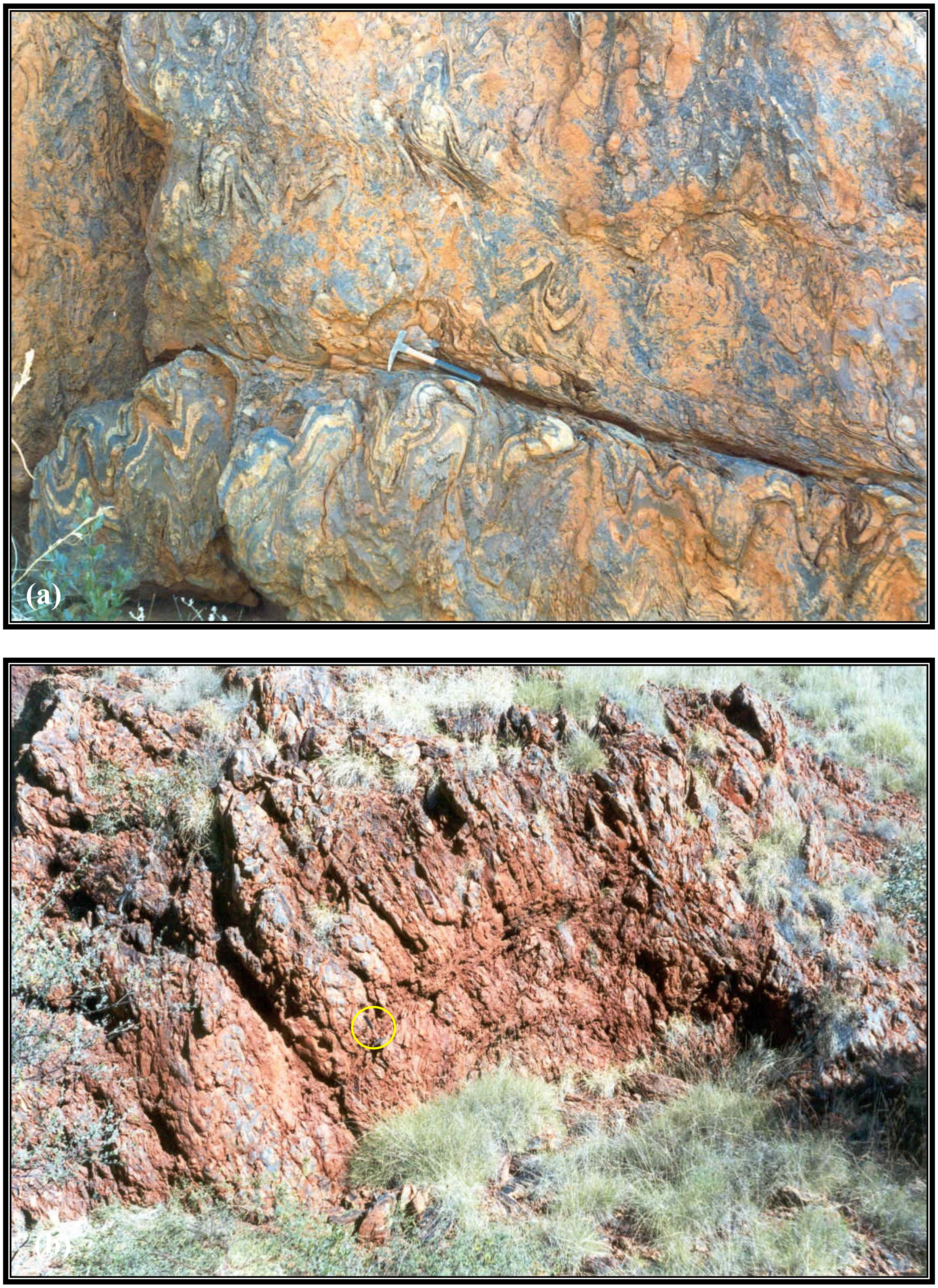


Photo 106. Layer parallel shortening defining a convergent fanning array across the upright D_2 Saper Vedere anticline in Photo 105, (a) subhorizontal S_0 enveloping surface adjacent to the anticlinal closure showing gross shortening perpendicular to S_0 with locally developed slip parallel to S_0 due to differential shortening and minor flexural slip, (b) mesoscopic parasitic fold on the north limb with S_0 subparallel to the main north dipping limb and perpendicular to the local south dipping limb (this parasitic fold and associated north dipping cleavage was previously one of the type occurrences of "$S_{1.5}$"). The overall geometry across the anticline is best modelled by initial layer parallel shortening followed by folding with associated flexural slip producing a convergent fanning array as shown in Figures 34, 33, Mount Newman Member, Saper Vedere Gully, C Deposit (looking west, geopicks for scale).

Photo 107. Ophthalmian Orogeny high strain zone of intensely intrafolial folded and sheared, steeply south dipping overturned J6 BIF, S_2 here is subvertical compared with more normal 40º south dips in low strain Dales Gorge Member 200 m to the south, Joffre Member, Ando's Gorge, eastern Ophthalmia Range (looking west, junior geologists KTK and AAK for scale).

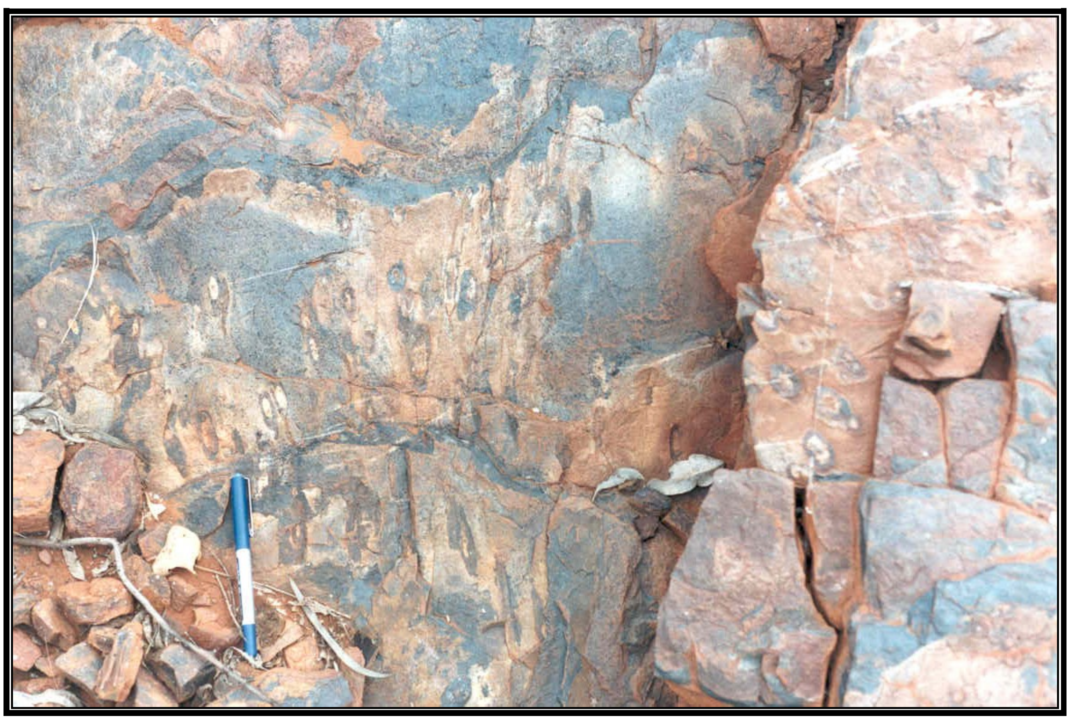
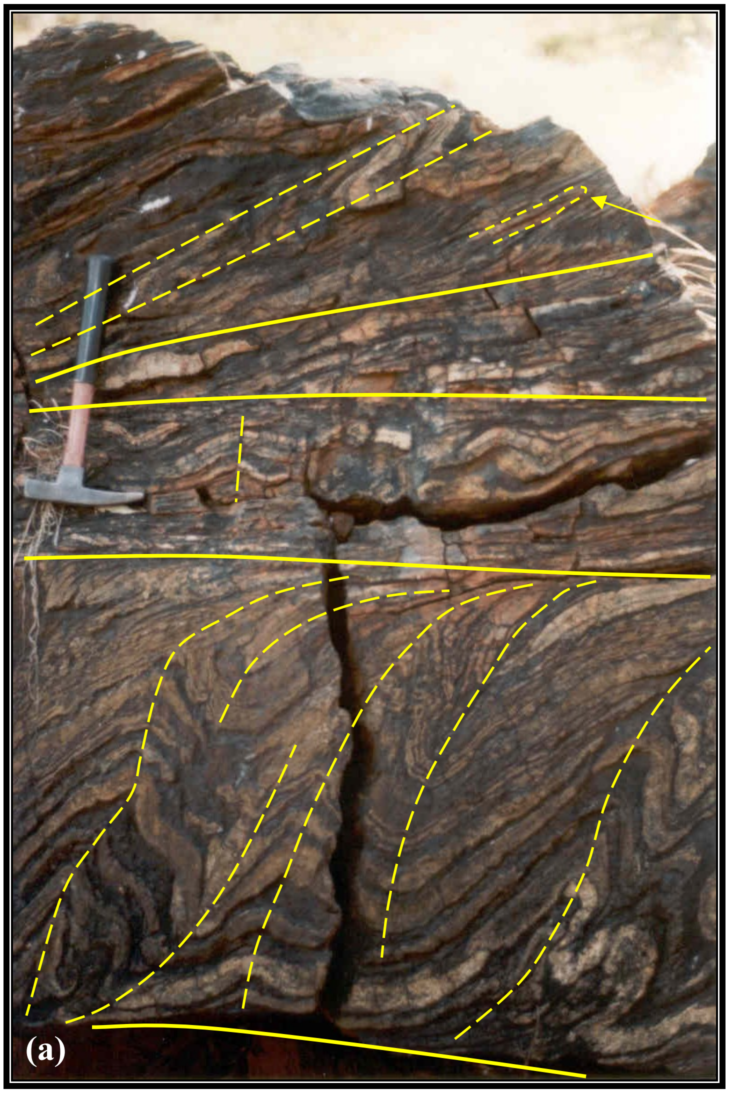


Photo 108. Overturned subhorizontal bedding surface of the false bed of holes in DB0 deformed by D_2 bedding parallel flexural slip with a strain ratio of 5:1, unfolding the less deformed holes on the bedding surface to the right results in a northeast stretching lineation parallel to D_1 boudinage, Dales Gorge Member, Fort Hill (pen for scale pointing due north).


(a)


(b)

Photo 109. Flexural slip rotating earlier D_2 intrafolial folding in Mount Newman Member BIF with the degree of rotation approximately proportional to the degree of strain, (a) subdivided into four subparallel structural domains from the base up being low to moderate (locally high) strain producing sinusoidal S_2, very low strain (to locally high strain toward the margins) with poorly developed upright folds, ?low strain but with some evidence of shearing including truncation of beds with the underlying zone and high strain zone of oblique tight to isoclinal folding. Note that the narrow intrafolial isoclinal folds such as that in the upper domain (arrowed) have historically been described as D_1 in origin, E Deposit (looking east). (b) flexural slip shears truncating earlier D_2 intrafolial folds, E Deposit (looking east). (c) similar to (a) but with thin well defined very high strain zones between some of the lower strain domains where all fabric has been dragged subparallel to the flexural slip surface, that is the bedding enveloping surface, E Deposit (looking east, geopick for scale).

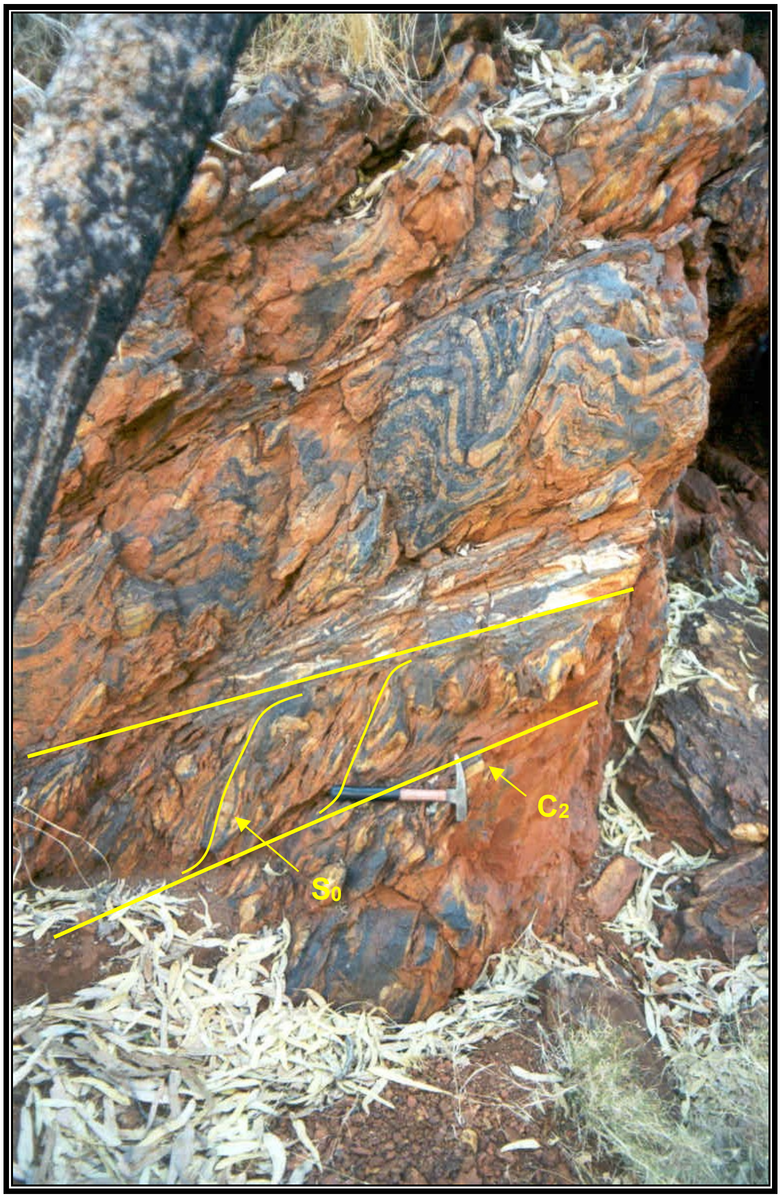


Photo 110. North over south low angle shears along S_0 enveloping surfaces producing localised sigmoidal S_0 defining a S/C like fabric. The shears were previously interpreted as being $C_{1.5}$ but their timing is not compatible with respect to S_2 and instead are produced by intense flexural slip during D_2 folding. The north dipping axial surfaces above (previously interpreted as $S_{1.5}$) are part of a S_2 convergent fanning array (see Figure 34 for structural setting), north dipping limb, Mount Newman Member BIF, Saper Vedere Gully, C Deposit (looking east, geopick for scale).

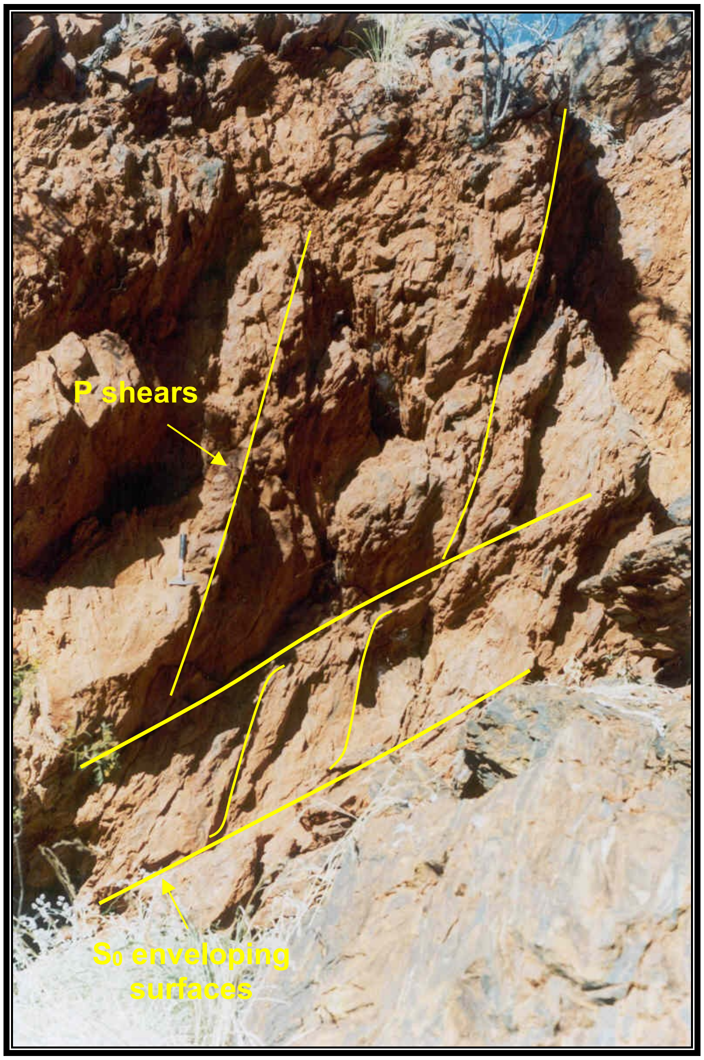


Photo 111. North dipping limb of an upright D_2 anticline with reverse, high angle P shears developed between S_0 enveloping surfaces during intense flexural slip across the fold. This fabric was previously misinterpreted to be $S_{1.5}$. Late, northing dipping normal faulting inferred at C Deposit may preferentially develop on this pre-existing fabric. Similar south dipping shears may also be developed on south dipping limbs (see Figure 34 for structural setting), north dipping limb, Saper Vedere Gully, Mount Newman Member BIF, C Deposit (looking east, geopick for scale).

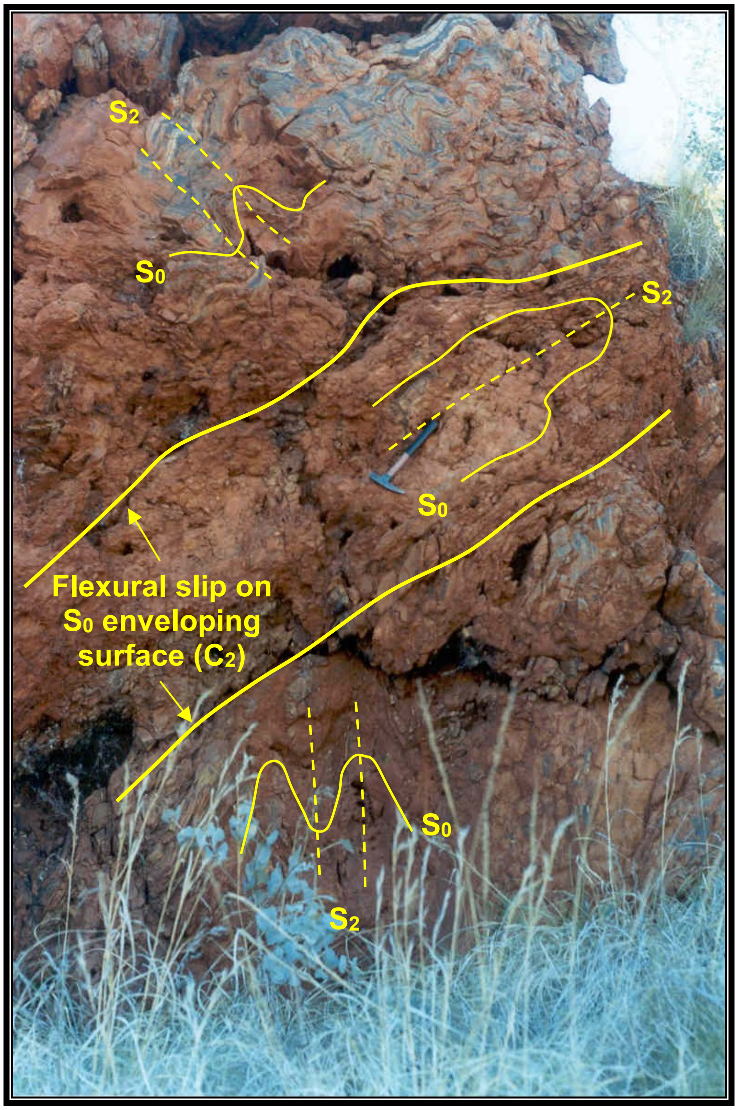


Photo 112. Widely varying S_2 in adjacent structural domains produced by strain partitioning via flexural slip and high angle P shears on the north dipping limb of an open D_2 fold. Here a remnant low strain zone of "normal" south dipping S_2 is perpendicularly juxtaposed against mesoscopic D_2 folds (parallel to geopick handle) reorientated / produced by intense flexural slip. This outcrop was previously interpreted as adjacent $F_{1.5}$ and F_2 folds with no observable interference or overprinting and even includes upright "F_3" folds in the lowermost domain, Mount Newman Member BIF, Saper Vedere Gully, C Deposit (looking east, geopick for scale). Further examples of low angle variation in S_2 in adjacent structural domains can be seen in Photo 109.

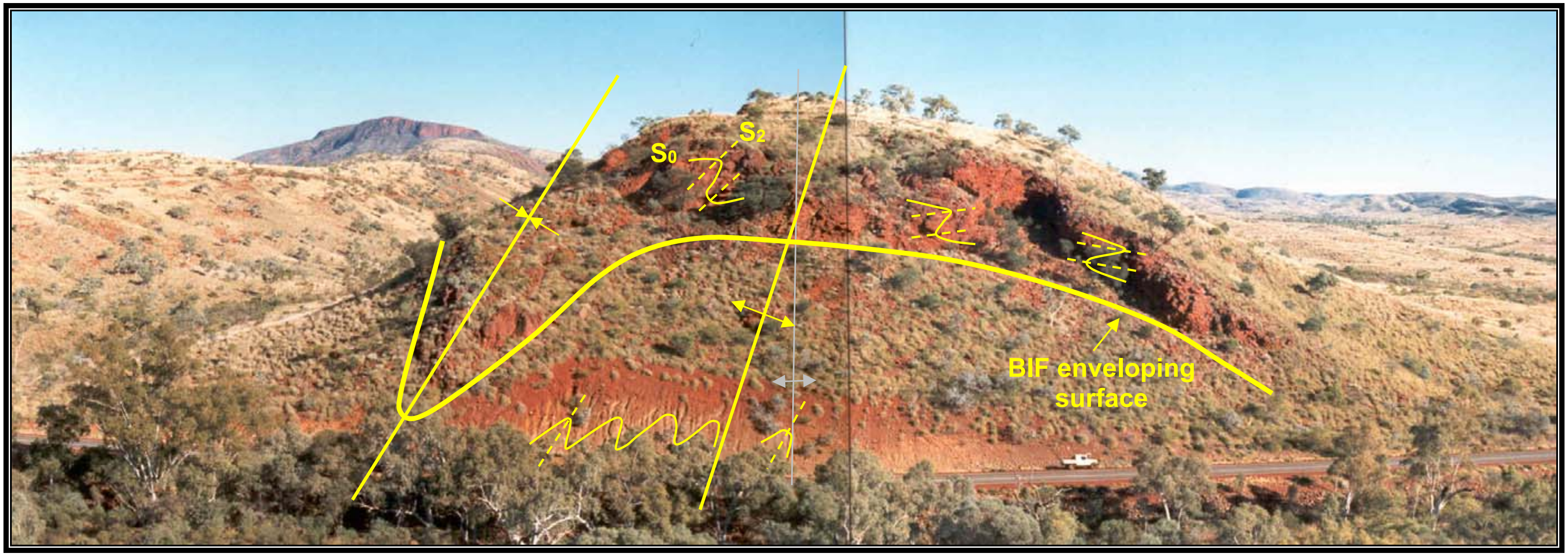


Photo 113. Apparent F_2 / F_3 refold of Weeli Wolli Formation BIF at Cathedral Gorge. The geometry of the BIF has previously been explained as being produced by refolding of tight, north facing D_2 folds by to an open upright D_3 fold (in grey). As argued here however, it is compatible with being produced by D_2 only by initial asymmetric layer parallel shortening followed by more open megascopic folding controlled by the thick stiff adjacent dolerite sills. Evidence for this includes that folding in underlying shales are not reorientated, that the shape of the enveloping surface is identical to proven D_2 folding seen elsewhere (eg Figure 34) and that Mt Newman in the background which forms the next corresponding flat D_2 limb to the south also has a similar geometry but lacking the intrafolial folds due to less rheological incompatibilities. A long flat limb from here northwards also implies the anticline is D_2 (vehicle for scale).

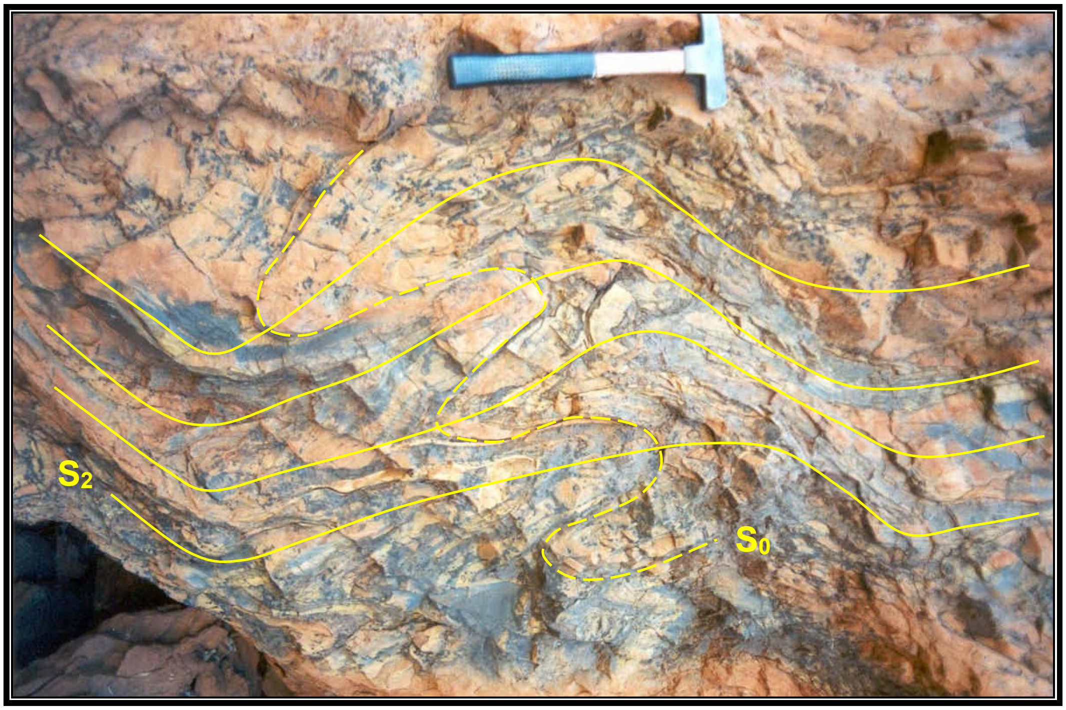


Photo 114. Weak to moderately developed shears subparallel to S_0 enveloping surface producing multiple sinusoidal S_2 surfaces. Unlike the geometry in the previous photo, the shearing here is compatible with the being late extensional crenulation cleavage rather than flexural slip. It has a similar structural setting (north dipping limb of an open D_2 anticline) and sense of movement as the north dipping extensional faults interpreted from drilling along the Northern Flank. The folding of S_2 here is unlikely to be due to D_3 folding as there is a distinct asymmetry and thinning of the north dipping limb, Saper Vedere Gully, C Deposit (looking west, geopick for scale).

APPENDICES

1 Summary of Areas Mapped

2.1 Karijini Dolerite Refernce Section, Alligator Anticline
2.2 Characterisitcs of Dolerite Dykes Suites defined by Tyler (1991)

3 Gazeteer of localities used in text

APPENDIX 1.0

Summary of Areas Mapped

Program / Area	Scale Mapped	Scale Compiled	Mappers	Comments
1994 MAC East				
Southern Flank	~1:20 000	1:20 000	SLL,CMS,ACD,NY,DH1	
Northern Flank	~1:20 000	1:20 000	SLL,CMS,ACD,NY,DH1	partly remapped at 1:5 000 in 1995 / 2000
hinge	~1:20 000	1:20 000	SLL,ACD,NY,DH1	reconn only
1995 MAC West				
Parallel Ridge	~1:20 000	~1:20 000	SLL, ACD, MCB	
Boundary Ridge	~1:20 000	~1:20 000	SLL, ACD, MCB	
North Alligator	~1:20 000	~1:20 000	DAK, SLL, ACD, MCB	
South Alligator	~1:20 000	~1:20 000	DAK, SLL, ACD, MCB	
Jaws	~1:20 000	~1:20 000	DAK, SLL, ACD, MCB	
Jaws Extended	~1:20 000	~1:20 000	SLL	
South East Corner	~1:20 000	~1:20 000	DAK, SLL, ACD, MCB	
Camp Hill	~1:20 000	~1:20 000	MCB	
A, B and C Deposits	~1:5 000	1:5 000	SLL, ACD, MCB	mostly remapped at 1:5 000 in 2000
1996 MAC Park				
Balgara	~1:20 000	~1:20 000	DAK, SLL, ACD, MCB	
West Alligator	~1:20 000	~1:20 000	DAK, MCB	
Dog Leg	~1:20 000	~1:20 000	DAK, SLL, ACD, MCB	
Eterak / Big Creek	~1:20 000	~1:20 000	DAK, SLL, ACD, MCB	
Mt Trevarton	~1:20 000	~1:20 000	DAK, ACD, MCB	Brockman mainly reconn
Death Valley	~1:20 000	~1:20 000	DAK, SLL, ACD, MCB	
1997 Packsaddle Range				
Packsaddle Hill	1:10 000	1:10 000	DAK, MCB, DP	
Iron Ore Ridge	1:10 000	1:10 000	DAK, MCB, DP	
MAN Hill	1:10 000	1:10 000	DAK, MCB, ACD, DP	
International Hill	1:10 000	1:10 000	DAK, MCB, ACD, DP	
Spring Hill	1:10 000	1:10 000	DAK, MCB, DP	
Hill 65	~1:20 000	1:20 000	DAK, MCB, DP	
Fork North	~1:20 000	1:20 000	DAK	remapped at 1:10 000 in 1998
1998 MAC Brockman				
Fork North	1:10 000	1:10 000	DAK, MCB, DH2, MP	
Fork South	1:10 000	1:10 000	DAK, MCB, DH2, MP	
Governor Range	1:10 000	1:10 000	DAK, MCB, DH2, MP	
Little Robbie	~1:20 000	1:20 000	DH2, MP	
The Governor	1:10 000	1:10 000	DAK, MP	
The Noose	1:10 000	1:10 000	MCB, MP	
Wildflower Mountain	1:10 000	1:10 000	DAK, MCB, DH2, MP	
Floodplain	~1:20 000	1:20 000	DAK, MP	
1999				
Mt Robinson	1:10 000	1:10 000	DAK, MCB, CMS	
16 Mile Hill	~1:20 000	1:20 000	CMS	
2000				
Werriba Anticline	1:10 000	1:10 000	DAK, MCB	
B, C, D and E Deposits	1:5 000	1:5 000	DAK, MCB	

MCB Mark Benbow
ACD Andrew Duncan
DH1 Danny Hampton
DH2 Dave Harris
DAK Doug Kepert
SLL Steve Lipple
DP Dave Pearcey
MP Melanie Pierini
CMS Chris Sullivan
NY Noel Youngman

APPENDIX 2.1 Karijini Dolerite Reference Section, Alligator Anticline

Unit	Approximate Thickness Host	Sill	Photo Station SLL 9/612/?	ACD 8/721/?	Description
AHmu	-		43	55	chert, silicified carbonate
AFjr	10		43		white weathering tuff
PKd_1		**135**		**55**	**fine grained dolerite, ophitic texture, feldspar laths, S3 mineral cleavage**
PKd_2			**44**		**fine grained dolerite, S_3 mineral cleavage**
$AFjs_1$	20		46		white well banded chert, tan tuff, S_2 or S_3 cleavage
PKd_3		**65**	**46**		**fine grained dolerite**
PKd_4			**44**		**fine grained dolerite, micropophyritic near base to glomeroporphyritic near top**
$AFjs_v$	?		47		felsic agglomerate, silic brown rhyolitic tuff, rare qtz filled amygdales, trace ex sulphide
PKd_5		**100**			**fine grained dolerite**
$AFjs_2$	45		48, 55-58, 61-65		brown carbonate, grey chert with red shale near base, brown chert at top (locally hornfelsed)
PKd_6		**20**	**53**		**fine grained dolerite, S_3 fracture cleavage, intense S_3 mineral cleavage near fold**
$AFjs_3$	10 60		48, 50-52, 58, 66	 59	brown silicified carbonate, basal green stip tuff, 15 cm white chert at top
PKd_7			**48, 49, 54, 60**		
$AFjs_4$	20 58		59 607/5	 57	basal brown carbonate, upper chert
PKd_8		**45**			**fine grained dolerite**
$AFjs_5$	10				no outcrop
PKd_9		**55**	**607/1**		**fine grained blue-green dolerite, S_3 fracture cleavage**
$AFjs_v$					fine, white tuff
PKd_{10}		**190**	**607/6**		**fine grained dolerite**
PKd_{11}					**fine grained dolerite**
PKd_{12}					**fine grained dolerite**
base not exposed					
Total	332	**680**			

APPENDIX 2.2

Characteristics of Dolerite Dyke Suites defined by Tyler (1991)

Suite	Orientation	Distribution	Tectonic Affiliation	Age Limits	Comments
Pd_1 (Black Range Dykes)	NNE	Yarrie to Rocklea Dome and Sylvania Inlier	feeder dykes to Mt Roe Basalt	2772	wide, laterally continuous, form mineralising structure at Sunrise Hill
Pd_2	E-W	restricted to Sylvania Inlier	syn Fortescue Group	2770 - 2630	
Pd_3	ENE	rare, restricted to SW Sylvania Inlier	syn Ophthalmian Orogeny	2450 - 2200	
Pd_4	WNW		cross cut Ophthalmian folds intrude up to Beasley River Quartzite		?also feeders to Cheela Springs Basalt
Pd_5	NW	very widespread in west Hamersleys	feeder dykes to Cheela Springs Basalt ?recrystalises ore at Brockman Syncline	<2210	?equivalent to Round Hummock Suite on Marble Bar sheet
Pd_6	E-W	rare, restricted to W Sylvania Inlier			
Pd_7	NE to NNE	sparse but from Pilbara to Bangemalls	recrystalises ore at Channar ?intrude minor faults at Jimblebar	~770	very long, apparent on airborne mag, equivalent to Mundine Well Suite on Marble Bar sheet
Murramunda Dolerite	N - S	15 x 0.5 km intrusion in E Sylvania Inlier			possibly equivalent to Davis Dolerite in Billy Goat Bore area
Pd_8	WNW	restricted to S Sylvania Inlier and Bangemalls			

APPENDIX 3.0

Gazeteer of Localities

Locality	AMG66 Zone 50		AMG66 Zone 51	
	Easting	Northing	Easting	Northing
16 Mile Hill	671,000	7,468,500		
47A (pa)	627,000	7,530,000		
A Deposit	707,000	7,463,000		
Alligator Anticline	660,000	7,449,500		
Ando's Gorge	802,000	7,418,000		
Arrowhead	735,000	7,441,000		
B Deposit	706,000	7,461,500		
Bakers	735,000	7,434,000		
Balgara	653,000	7,444,700		
Bee Gorge	629,500	7,537,000		
Bellary Dome	560,000	7,445,000		
Big Creek	615,000	7,452,000		
Big Creek Fault	621,000	7,452,000		
Billy Goat Bore (BGB5)			254,500	7,537,900
Blackwood Creek	703,000	7,460,500		
Blackwood Creek Gorge	701,000	7,461,000		
Boundary Ridge	678,000	7,451,500		
Box Canyon	723,500	7,465,000		
Box Canyon Fault	722,800	7,465,000		
Brockman Anticline	525,000	7,505,000		
C Deposit	703,000	7,463,200		
Calamina Gorge	646,000	7,525,000		
Camp Hill	672,000	7,466,000		
Cathedral Gorge	768,500	7,423,500		
Chabbledoo Range	696,000	7,457,000		
Channar	581,000	7,423,000		
Chevron Hill	730,000	7,457,000		
Circular Pool	660,600	7,513,500		
Coondewanna (Lake Robinson)	683,500	7,454,000		
Coondewanna Ridge	697,000	7,430,500		
D Deposit	698,000	7,462,300		
Dales Gorge	660,000	7,512,300		
Datsun Syncline	692,000	7,451,400		
DDH186 (pa)	594,500	7,522,500		
DDH275	536,900	7,519,900		
Deadmans Hill	746,500	7,365,500		
Death Valley	613,000	7,445,000		
Dingo Soak	637,000	7,459,000		
Dog Leg	630,500	7,461,800		
Dog Leg Fault	629,500	7,462,600		
Duck Creek Syncline	456,000	7,508,000		
E Deposit	694,000	7,462,200		
Eagle Rock Falls	764,500	7,444,400		
Eastern Ridge	783,000	7,417,500		
Eric's Point	678,500	7,470,500		
Eterak	624,000	7,456,600		
Eterak Fault	626,500	7,456,500		
F Deposit	692,000	7,461,600		
Floodplain	684,500	7,465,700		
Fly Mountain	667,000	7,472,700		
Fork North	675,000	7,461,000		
Fork South	676,000	7,456,000		

APPENDIX 3.0

Gazeteer of Localities

Locality	AMG66 Zone 50		AMG66 Zone 51	
	Easting	Northing	Easting	Northing
Fort Hill	792,500	7,418,500		
Fortescue Falls	659,500	7,513,300		
Fortescue River Fault	790,400	7,419,000		
FVG1a	757,000	7,503,100		
G Deposit	689,000	7,457,300		
Giles Point	723,500	7,428,500		
Governor Range	679,000	7,447,000		
H Deposit	686,500	7,456,700		
Hardey River Gorge	552,800	7,484,400		
Hardey Syncline	516,000	7,465,000		
Hester Siding	709,200	7,544,700		
Hill 65	670,300	7,463,900		
Homestead Gorge	767,000	7,424,000		
Hope Downs	713,400	7,460,500		
Hope Downs 3	694,500	7,427,200		
Hope Downs Gorge	710,500	7,454,000		
Hope Downs North	716,500	7,460,500		
HS Fault	622,000	7,453,900		
I Deposit	687,500	7,455,500		
Ilbianna Well (FVG1a)	757,000	7,503,100		
International Hill	706,100	7,466,100		
Iron Ore Ridge	686,000	7,463,000		
J Deposit	690,000	7,455,200		
Jaws	666,000	7,448,300		
Jaws Extended	674,500	7,445,200		
Jeerinah Anticline	509,000	7,520,000		
Jirrpalpar Range	703,500	7,462,000		
Joffre Gorge	632,000	7,525,500		
Jump Up Bore	650,400	7,465,700		
Juna Downs Homestead	652,200	7,468,300		
K Deposit	693,000	7,454,200		
Koodaideri detrital deposit	699,000	7,518,000		
L Deposit	697,000	7,455,000		
Lake Robinson (Gundawuna)	683,500	7,454,000		
Lamb Creek	700,000	7,474,000		
Little Robbie	683,700	7,449,700		
M Deposit	700,500	7,454,500		
MacLeod Standard Section	706,700	7,453,600		
MAN Hill	697,000	7,464,800		
Man-In-The-Moon Hill	646,200	7,448,200		
Middle Prong	669,500	7,459,500		
Milli Milli Anticline	670,000	7,467,500		
Milli Milli Dome	610,000	7,473,000		
Mindy Mindy	748,000	7,480,000		
Ministers North	717,000	7,474,000		
Mt Meharry	667,300	7,457,000		
Mt Newman Anticline	762,500	7,424,500		
Mt Robinson	692,900	7,451,200		
Mt Trevarton	627,700	7,455,300		
Mulga Downs	650,000	7,557,000		
N Deposit	701,500	7,456,100		

APPENDIX 3.0

Gazeteer of Localities

Locality	AMG66 Zone 50		AMG66 Zone 51	
	Easting	Northing	Easting	Northing
Nammuldi	543,000	7,521,000		
North Alligator	660,000	7,451,500		
North Alligator Fault	648,000	7,451,000		
North Pamelia Hill	730,500	7,452,500		
Northern Flank	700,000	7,463,000		
O Deposit	704,000	7,454,900		
Oakover Sub-basin			300,000	7,575,000
P Deposit	708,000	7,454,800		
P1 (C1)	695,000	7,464,200		
P2 (C2)	698,500	7,464,400		
P3 (C3)	701,000	7,465,000		
P4 (C4)	705,000	7,465,000		
P5 (C5)	707,500	7,465,000		
P6 (C6)	710,500	7,466,200		
Packsaddle Camp	674,600	7,466,400		
Packsaddle Hill	678,400	7,463,200		
Packsaddle Syncline	683,000	7,464,000		
Parallel Ridge	672,000	7,454,000		
Poonda Fault	800,000	7,440,000		
Poxy Leg Gully	710,000	7,453,500		
Prairie Downs	730,000	7,405,000		
Prairie Downs Fault	730,000	7,409,500		
Q Deposit	701,000	7,458,800		
R Deposit	708,000	7,457,700		
Range Gorge (WRL1)	624,700	7,545,300		
Rhodes Ridge	742,000	7,444,000		
Rocklea	527,600	7,462,400		
Rocklea Dome	535,000	7,475,000		
Roundtop Hill	732,200	7,462,000		
S Hill	712,000	7,433,000		
Saper Vedere Gully	700,550	7,462,550		
Silvergrass	530,000	7,533,000		
Snake Gorge	699,000	7,465,500		
South Alligator	660,000	7,447,000		
South Alligator Fault	646,000	7,447,500		
South East Corner	693,000	7,444,500		
South Parmelia Hill	726,000	7,448,000		
Southern Flank	700,000	7,454,500		
Spring Hill	720,000	7,463,700		
Sylvania Inlier	800,000	7,390,000		
The Amphitheatre	707,500	7,456,500		
The Governor	687,200	7,447,800		
The Noose	681,000	7,469,000		
Tiger Eye, A Deposit	705,600	7,462,400		
Trepekad	631,500	7,460,400		
Tubaddubudda			253,000	7,431,000
Tuckerbox Gorge	693,700	7,464,000		
Tuckerbox Hill	694,100	7,463,800		
Turee Creek	608,800	7,444,000		
Turner Syncline	565,000	7,488,000		
Waterloo Bore	744,400	7,486,100		

APPENDIX 3.0

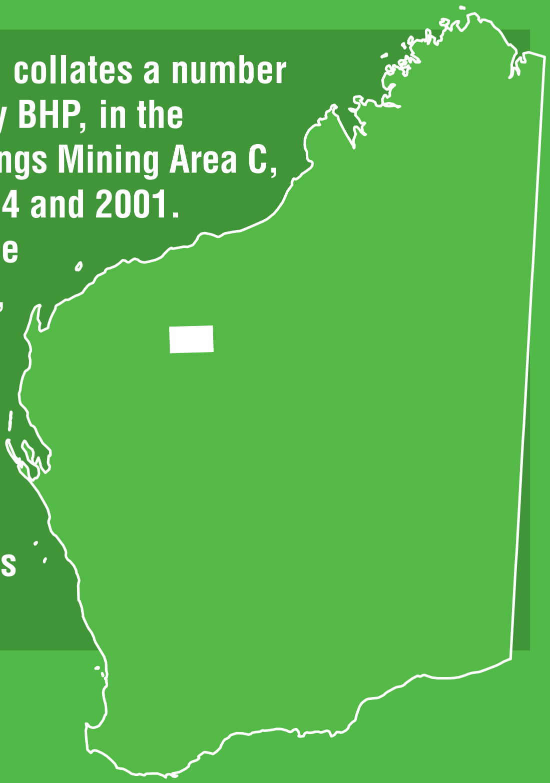
Gazeteer of Localities

Locality	AMG66 Zone 50		AMG66 Zone 51	
	Easting	Northing	Easting	Northing
Weeli Wolli Anticline	700,000	7,457,500		
Weeli Wolli Fault	726,000	7,464,500		
Weeli Wolli Springs	725,400	7,463,600		
Werriba Anticline	717,000	7,474,000		
West Alligator	647,000	7,448,000		
West Angelas	674,500	7,441,500		
West Angelas Hills	673,500	7,442,500		
Western Ridge	768,500	7,410,500		
Wildflower Mountain	674,000	7,472,000		
Wittenoom Gorge	637,500	7,531,500		
Wonmunna Anticline	705,000	7,440,000		
Wonmunna Gorge	718,700	7,444,400		
Woodie Woodie			317,000	7,605,000
Woongarra Pool	510,300	7,469,400		
WRL1	624,700	7,545,300		
Wunna Munna Flats	725,000	7,430,000		
Wyloo Dome	440,000	7,490,000		
Yampire Gorge	651,000	7,525,000		
Yandicoogina Creek Gorge	717,000	7,471,300		
Yeera Bluff	414,000	7,596,300		
Yeerabiddy Fault	701,500	7,466,200		
Yeerabiddy Syncline	708,000	7,469,000		

- it goes on forever -

- it's full of stars!

This Report, known as 'The Black Monolith', collates a number of detailed mapping programs carried out by BHP, in the Hamersley province, on their tenement holdings Mining Area C, Mudlark Well and Weeli Wolli, between 1994 and 2001. The work is a comprehensive summary of the stratigraphy of the Mount Bruce Supergroup, in this area, from the upper part of the Fortescue Group to the top of the overlying Hamersley Group. It outlines the structure of the region and main controlling factors on the tectonic evolution of the Hamersley Basin within the context of the regional ideas at the time of writing.



Further details of geological products and maps produced by the Geological Survey of Western Australia are available from:

Information Centre
Department of Mines, Industry Regulation and Safety
100 Plain Street
EAST PERTH WA 6004
Phone: (08) 9222 3459   Fax: (08) 9222 3444

www.dmp.wa.gov.au/GSWApublications

KEPERT

THE MAPPED STRATIGRAPHY AND STRUCTURE OF THE MINING AREA C REGION, HAMERSLEY PROVINCE

REPORT 185