

Lithology and proposed revisions in stratigraphic nomenclature of the Wittenoom Formation (Dolomite) and overlying formations, Hamersley Group, Western Australia

by

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Abstract

The Wittenoom Dolomite is one of the most heterolithic formations in the early Precambrian Hamersley Group and contains an abundance of well-preserved primary sedimentary features. During five field trips between 1985 and 1990, we examined the Wittenoom Dolomite at 37 field sites and in 7 diamond drillcores, and measured sections at most of them. Throughout the Hamersley Basin, we found the Wittenoom Dolomite to consist of 1) a lower unit composed of dolomite with minor chert and argillite and 2) a more heterolithic upper unit composed of argillite with subordinate thicknesses of other lithologies (mainly carbonate, chert, and BIF). We propose these two units be given formal stratigraphic status as 1) the Paraburdoo Member and 2) the Bee Gorge Member of the Wittenoom Dolomite respectively. In addition, the West Angela Member occurs sporadically at the base of the Wittenoom Dolomite, particularly in the southeastern part of the Hamersley Basin (Blockley et al., 1993). The uppermost Bee Gorge Member also contains three informal stratigraphic marker units (the Crystal-rich Tuff, Main Tuff Interval, and Spherule Marker Bed) that persist throughout most of the Hamersley Basin. Analysis of the sedimentary textures and structures of the strata of the Wittenoom Dolomite and the overlying Mount Sylvia Formation and Mount McRae Shale indicates that these three formations consist mainly of lutites with thin layers of arenite, or more rarely intraformational conglomerates, that were deposited in basinal (i.e. deeper-water) palaeoenvironments. The arenites consist mainly of carbonate and volcanoclastic detritus and were deposited mainly by low-density turbidity currents. One exception is the Main Tuff Interval, which records an exceptionally large-volume event of rapid pyroclastic turbidite sedimentation. As dolomite is dominant in only one of the three proposed members, we further propose that the name Wittenoom Formation be substituted for Wittenoom Dolomite.

KEYWORDS: Stratigraphy, nomenclature, Hamersley Basin, lithology, Wittenoom Formation, dolomite.

Introduction

The authors undertook a sedimentological study of the Wittenoom Dolomite and the overlying Mount Sylvia Formation and Mount McRae Shale of the Hamersley Group to help shed new light on depositional processes and palaeoenvironments in the Hamersley Basin.⁴ We concentrated on sedimentary rocks such as dolomite, limestone, tuff, and argillite instead of the well-known banded iron-formations or BIFs (Trendall and Blockley, 1970; Ewers and Morris, 1981). Iron-poor sedimentary rocks can be interpreted with greater certainty because

they have numerous potential Phanerozoic analogues. We chose the Wittenoom Dolomite as the focus of our study because it is the most heterogeneous formation in the Hamersley Group and contains many well-preserved sedimentary textures and structures.

We measured detailed stratigraphic sections during five field trips between 1985 and 1990. The Wittenoom Dolomite, which is restricted to the main body of the Hamersley Basin, was examined in surface exposures at 37 different sites and in core from 7 sites (Fig. 1 and Table 1). Sections were also measured in the Mount Sylvia Formation and Mount McRae Shale. These higher units are generally more poorly exposed and more highly weathered.

Field data were augmented by the study of over 1200 samples from the Hamersley Group. All samples were sawn and examined in the form of slabs. In addition, about 450 were studied in thin section, and the

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⁴ We use the phrase 'Hamersley Basin' in Trendall's (1983) sense to refer to the suite of palaeoenvironments in which the Mount Bruce Supergroup was deposited with no prior assumptions as to what types of environments they were.

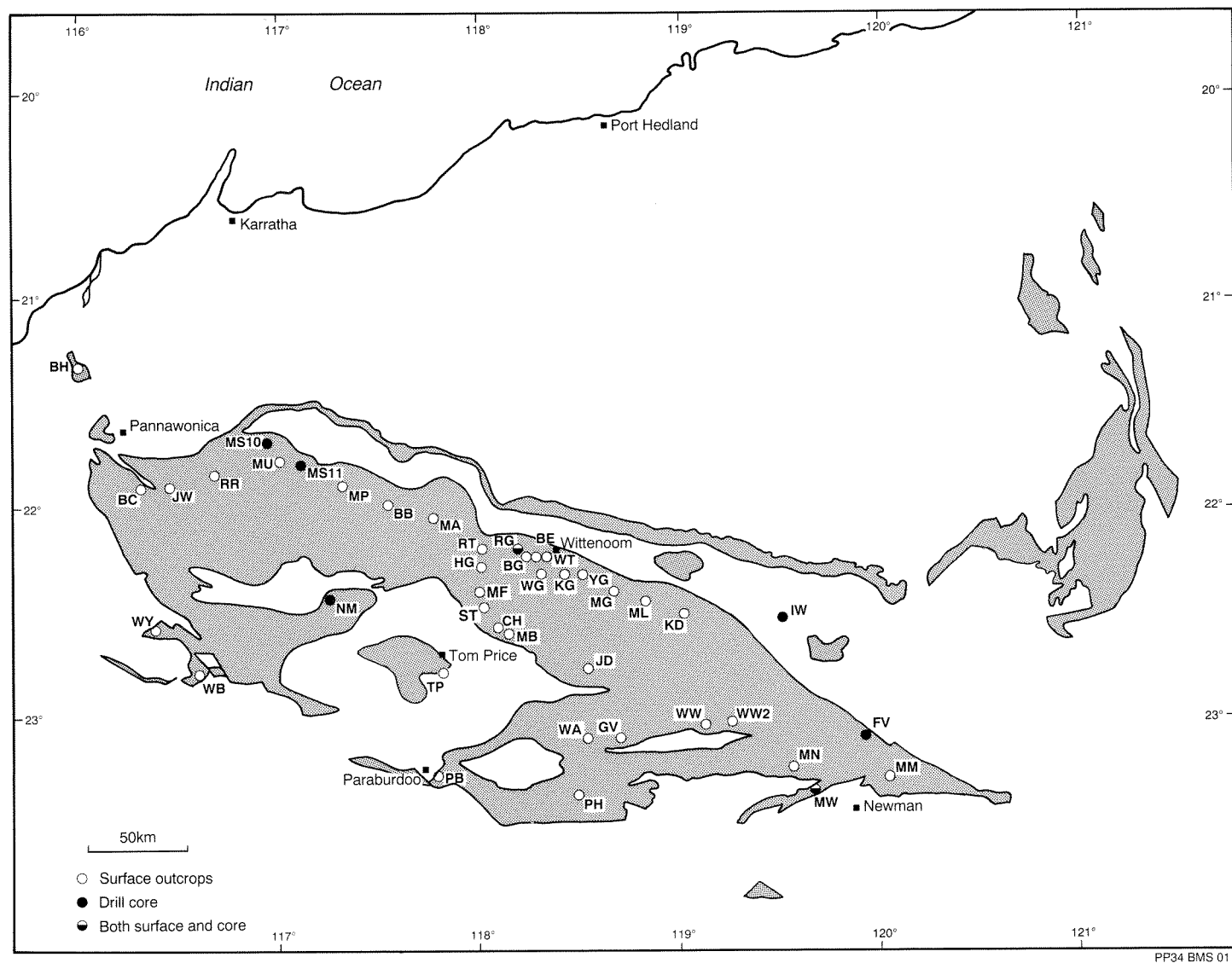


Figure 1. Geological sketch map of the Hamersley Group (after Myers and Hocking, 1988) showing the approximate locations of all study sites; their informal names and exact locations are given in Table 1.

Table 1. Names, abbreviations, and locations of study sites indicating stratigraphic units examined.

Site name	Abbreviation	1	2	Lat. (S)		Long. (E)		W	P	B	S	M	Map sheet no. and grid location
Bacon Bore	BB	X		21°	58'	117°	36'			X			2454–619702
Bee Gorge	BG	X		22°	14'	118°	15'			X	X		2553–293414
Bee Gorge east	BE	X		22°	13'	118°	17'		X	X			2553–317422
Bilanoo Hill	BH	X		21°	16'	116°	9'			X			2155–127477
Bungaroo Creek	BC	X		21°	53'	116°	24'			X	X		2154–382805
Conical Hill	CH	X		22°	35'	118°	5'		X	X	X		2552–120029
The Governor	GV	X		23°	3'	118°	49'			V			2651–867483
Hammersley Gorge	HG	X		22°	15'	117°	59'			X	X		2453–017384
Illianna Well (FVG–1)	IW		X	22°	33'	119°	30'	X	X	?			2752–570031
Jimmawurrada Creek	JW	X		21°	54'	116°	32'		X	X			2254–523785
Juna Downs	JD	X		22°	52'	118°	33'			V			2652–657165
Kalamina Gorge	KG	X		22°	18'	118°	27'			V			2553–515324
Koodaideri	KD	X		22°	30'	119°	1'			X			2652–057104
McCameys Monster	MM	X		23°	23'	120°	5'			X	X	X	2951–019113
Millstream 10	MS10		X	21°	42'	117°	1'		X	X			2354–017003
Millstream 11 and 11A	MS11		X	21°	49'	117°	10'			X			2354–172874
Mount Bruce	MB	X		22°	36'	118°	9'				X	X	2552–174000
Mount Frederick	MF	X		22°	23'	117°	58'			V			2453–007264
Mount Lockyer	ML	X		22°	26'	118°	50'			X	X		2653–880182
Mount Margaret	MA	X		21°	56'	117°	45'			V			2454–774739
Mount Newman	MN	X		23°	17'	119°	34'		X				2851–630236
Mount Pyrtton	MP	X		21°	52'	117°	23'			X	X	X	2354–397818
Mount Stevenson	ST	X		22°	29'	118°	1'			V			2553–036116
Mount Ulric	MU	X		21°	50'	117°	12'			V			2354–203852
Mount Whaleback (MD–1, D233, D234–1, and D261)	MW	X	X	23°	22'	119°	42'			X	X	X	2851–760133
Munjina Gorge	MG	X		22°	25'	118°	42'			V			2653–745212
Nammuldi (DDH–275)	NM		X	22°	27'	117°	16'		X	X			2353–369199
Paraburdoo	PB	X		23°	15'	117°	42'	X	X	X	X	X	2451–716286
Pathetic Hill	PH	X		23°	21'	118°	45'			V			2651–805177
Range Gorge (WRL–1)	RG	X	X	22°	12'	118°	13'	X	X				2553–247453
Rio Tinto Gorge	RT	X		22°	12'	118°	1'			X	X		2553–048457
Robe River	RR	X		21°	53'	116°	43'			V			2254–699819
Tom Price	TP	X		22°	45'	117°	45'		X	X	X	X	2452–782852
Weeli Wolli Creek	WW	X		23°	3'	119°	10'		X	X	X		2751–220484
Weeli Wolli Creek 2	WW2	X		22°	59'	119°	11'			V			2752–225557
West Angelas	WA	X		23°	6'	118°	43'			V			2651–743432
Western Mining (FVD–1A)	FV		X	23°	7'	119°	58'		X	?			2851–038404
Wittenoom rubbish tip	WT	X		22°	15'	118°	19'			X			2553–354394
Wittenoom Gorge	WG	X		22°	19'	118°	20'			X		X	2553–365336
Wyloo Dome rockhole	WY	X		22°	34'	116°	25'	?	X	X	X		2152–395041
Wyloo/3 corner bore	WB	X		22°	48'	116°	35'		X	X	X		2252–566795
Yampire Gorge	YG	X		22°	19'	118°	31'			X			2653–565307

Key: 1 = surface exposures, 2 = core, W = West Angela Member, P = Paraburdoo Member, B = Bee Gorge Member, S = Mount Sylvia Formation, and M = Mount McRae Shale.

Note: a V entered in Bee Gorge Member column indicates only Main Tuff Interval was examined at that site.

compositions of selected minerals and samples were determined through staining and X-ray diffraction.

Many of the sedimentological data produced in the course of these investigations are being disseminated elsewhere as both abstracts (Simonson, 1987a, 1988a, b, 1989, 1991, 1992b; Simonson and Goode, 1988; Hassler, 1990a, b, 1991b, 1992; Hassler and Simonson, 1991; Simonson et al., 1991) and papers (Simonson and Goode, 1989; Simonson, 1990, 1992a; Hassler 1991a, in press; Simonson et al., in press). The aim of this paper is to propose several revisions in the stratigraphic nomenclature of the Wittenoom Dolomite. To document the need for the proposed revisions, measured stratigraphic sections of the Wittenoom Dolomite and the overlying Mount Sylvia Formation and Mount McRae Shale are presented,

accompanied by brief lithological descriptions. Because these three stratigraphic units have so much in common lithologically, all three are described in this paper, even though revisions are proposed only for the stratigraphic nomenclature of the Wittenoom Dolomite.

New stratigraphic nomenclature for the Wittenoom Dolomite

Trendall and Blockley (1970, p. 85) noted that the Wittenoom Dolomite consists of two distinct stratigraphic parts: a lower part composed of dolomite with minor chert and argillite, and a more heterolithic upper part composed of argillite with subordinate thicknesses of other

lithologies (mainly carbonate, chert, and BIF). In addition, Blockley et al. (1993) recently proposed the establishment of a basal West Angela Member within the Wittenoom Dolomite. Based on the data summarized in Figure 2, we propose that the remainder of the Wittenoom Dolomite be divided into two parts: a medial Paraburdoo Member and an uppermost Bee Gorge Member. As dolomite is dominant in only one of these three members, we further propose that the name Wittenoom Formation be substituted for Wittenoom Dolomite.

The contact between the Paraburdoo and Bee Gorge Members was placed at the transition from continuous dolomite beds with argillite partings (below), to predominantly argillite with or without thin intercalations of other rock types (Fig. 2). While there is no basinwide marker bed right at this contact, it is normally sharp and readily recognized in the field. The precise stratigraphic level of this transition may vary slightly as the dolomites of the Wittenoom Formation have been dissolved in the subsurface in some areas, e.g. the TP site (Simonson and Hassler, 1991). Nevertheless, we believe this lithologic transition approximates a time-stratigraphic boundary because the upward transition from carbonate to argillite dominance occurs 10 to 20 m beneath a very persistent marker bed in the Bee Gorge Member (the Crystal-rich Tuff described below) in sections measured in various parts of the Hamersley Basin (Fig. 2).

Proposed stratigraphic subdivisions

Paraburdoo Member

Type section

The type section for the Paraburdoo Member is defined as a series of exposures a few kilometres southwest of the town of Paraburdoo along the southern edge of the Hamersley Basin (latitude 23° 15' S, longitude 117° 42' E). These exposures consist of north-facing slopes and cliffs just to the east of the gravel road which reaches the top of a site known locally as Radio Hill. No single cliff contains a full section of the Paraburdoo Member, but a composite section through nearly all of the strata in the Paraburdoo Member (Fig. 2) was constructed using local marker beds to correlate from one cliff to the next.

Type areas

Exposures of the Paraburdoo Member as extensive as those near the town of Paraburdoo are rare. Exposures of the overlying Bee Gorge Member, which contains a much higher percentage of argillite, are more widespread. The break in slope at the base of many hills in the Hamersley Range nearly coincides with the contact between the Paraburdoo and Bee Gorge Members, e.g. along the Hamersley front. Good exposures of the Paraburdoo Member nevertheless occur in various parts of the Hamersley Basin, including 1) the upper reaches of Weeli Wolli Creek in the east, 2) along Jimmawurrada

Creek and its tributaries in the northwest, and 3) in and around an unnamed creek along the northern edge of the Wyloo Dome in the southwest (see Fig. 1 and Table 1 for precise locations). In addition, several cores through the Paraburdoo Member are in permanent repositories. Two that contain almost the entire thickness of the Paraburdoo Member are WRL-1 (equivalent to section RG), and DDH-275 (equivalent to section NM). These cores are stored at the CRA Exploration Pty Ltd depot in Karratha except for the Marra Mamba section and a few metres of the Wittenoom Dolomite from DDH-275 which remain at the CSIRO Exploration Geoscience Laboratory, Floreat Park, Western Australia.

General description

The Paraburdoo Member consists of dolomite with minor amounts of chert and argillite and almost always displays even, tabular bedding. Most layers of dolomite are a few centimetres to decimetres thick, and none are thicker than about 1 metre. Argillite layers are thinner on average, occurring mostly in the form of sub-millimetre partings to thin beds up to a few centimetres thick separating the dolomite layers. While argillite is present in minor amounts throughout the Paraburdoo Member, chert is restricted to specific horizons up to 2 m thick that generally contain scattered nodules of grey to black chert. All layers tend to be laterally persistent, but while excellent local marker beds abound, we were unable to correlate any from one section area of the Paraburdoo Member to another.

The exact thickness of the Paraburdoo Member is unknown, but it is at least 260 m at the type section near Paraburdoo. A thickness of over 420 m was transected in the WRL-1 core, but this could be an overestimate given the presence of breccias (Fig. 2) and the lack of marker beds to detect structural duplications.

Bee Gorge Member

Type section

The type section for the proposed Bee Gorge Member is defined as the exposures along the eastern slope of Bee Gorge near its mouth (latitude 22° 14' S, longitude 118° 15' E). This site was chosen because it is close to the type area (Wittenoom townsite) of the formation as a whole (MacLeod, 1966), it is readily accessible, and it has the thickest of any of the measured sections of the uppermost member of the Wittenoom Formation. Exposures of the strata in the Bee Gorge Member are discontinuous, but complete sections can be readily measured owing to the abundance of resistant marker beds (see below).

Type areas

After the type section, the best exposures of the Bee Gorge Member examined in this study are the Mount Pyrton, Hamersley Gorge, Wittenoom Gorge, Mount Lockyer, and Conical Hill sites (Figs 1 and 2). The only drillcore from the Bee Gorge Member in a permanent

repository are incomplete Millstream cores 10 and 11 from the northwestern part of the study area. They are stored in the Geological Survey of Western Australia's core library in Dianella and transect part of the lower Bee Gorge Member (Barnett, 1981, fig. 3).

General description

Thinly laminated, fissile, graphitic (in core) argillite is the main lithology in the Bee Gorge Member. Subordinate thicknesses of carbonate, chert, volcanoclastics, and iron formation are also present, generally occurring as resistant marker beds of lutite, i.e. sediments that originally consisted of muds of various compositions. However, a large minority of these non-argillite layers display clastic textures and current structures (and are described below). The single thickest section of coarser clastic sediment in the Bee Gorge Member is the Main Tuff Interval (defined below), which reaches 16.4 m. The thickness of individual layers of pure carbonate does not exceed 4.2 m, and the thickest layers of pure chert and iron formation are even thinner. The measured thickness of the Bee Gorge Member ranges from a maximum of 227 m at the type locality to a minimum of 111 m in the Tom Price section.

Informal stratigraphic units

In addition to the formal stratigraphic subdivisions proposed above, three marker horizons within the Bee Gorge Member were found to be distinctive and persistent enough to be given informal stratigraphic names. These informal markers, which are indicated on the measured sections (Fig. 2), are listed in ascending stratigraphic order:

1. Crystal-rich Tuff

The Crystal-rich Tuff is one of a variable number of thin, graded beds of medium sand-size and finer volcanoclastic sediment. This particular bed is distinguished by its high content of crystal debris. It rarely exceeds 10 cm in thickness, yet it was recognized at almost every site where the appropriate part of the Bee Gorge Member is exposed. Zircons separated from the Crystal-rich Tuff have been dated at 2603 ± 7 Ma (Hassler, 1991a).

2. Main Tuff Interval

The Main Tuff Interval is a highly distinctive 4.2 to 16.4 m thick sequence of pyroclastic turbidites that has been studied in detail by Hassler (1991a, in press). It contains some of the thickest beds and coarsest sediments in the Wittenoom Formation (and possibly in the entire Hamersley Group) and persists throughout the main body of the Hamersley Basin, with the possible exception of the southwestern region.

3. Spherule Marker Bed

The Spherule Marker Bed is an individual turbidite that consists of a mixture of carbonate and silicate detritus. At about 1 m, it is one of the thickest non-volcanoclastic turbidites in the Wittenoom Formation, and is the only one that contains sand-sized spherules of earlier silicate melt

that Simonson (1992a) ascribes to a major bolide impact (see below). The Spherule Marker Bed was recognized throughout most, but not all, of the main body of the Hamersley Basin.

Lithological constituents of the Wittenoom Formation, the Mount Sylvia Formation, and the Mount McRae Shale

Even though they differ radically in their relative proportions, the major lithological constituents of all three members of the Wittenoom Formation are very similar. Likewise, the Mount Sylvia Formation and the Mount McRae Shale have the same lithological constituents as the Bee Gorge Member, albeit in somewhat different proportions. Summary descriptions of these constituents condensed from the more comprehensive accounts in Simonson and Hassler (1991) form the remainder of this paper. They are presented with the aim of facilitating stratigraphic correlations both in the field and in core. The sedimentological and palaeogeographical significance of these data are discussed elsewhere (Simonson and Goode, 1989; Hassler, 1991a, in press; Simonson, 1992, and Simonson et al., in press).
















Carbonates

Carbonate rocks are dominant in the Paraburdoo Member, virtually all of which consists of dolomite. In contrast, carbonates are greatly subordinate to argillite in the overlying Bee Gorge Member, Mount Sylvia Formation, and Mount McRae Shale. The carbonates in these higher, argillite-dominated units also show a wider spread of composition; they range from dolomite to calcite to ferroan carbonate. Because of this stratigraphic variability, the descriptions of the carbonates which follow are grouped according to stratigraphic units, even though they show many similarities.











The Paraburdoo Member of the Wittenoom Formation has one of the highest carbonate contents of any unit in the Hamersley Group, rivalled only by the Carawine Dolomite (Trendall and Blockley, 1970; Goode, 1981). The Paraburdoo Member consists almost entirely of dolomite layers a few centimetres to decimetres thick separated by thin intercalations of argillite. Chert is the only other rock type present. Depositional structures are preserved inside many of the dolomite layers, but their degree of preservation varies greatly. Some dolomites are uniformly coarsely crystalline and sugary and show only faint layering, whereas others show a range of crystal sizes which, together with disseminated impurities, give definition to a number of primary features.

Most of the dolomites in the Paraburdoo Member with well-preserved primary features display thin continuous laminations that are generally one to several millimetres thick. The laminations consist of alternating light and dark rock that consist respectively of nearly pure carbonate contrasting with carbonate rich in carbonaceous and/or

LITHOLOGICAL SYMBOLS IN STRATIGRAPHIC COLUMNS

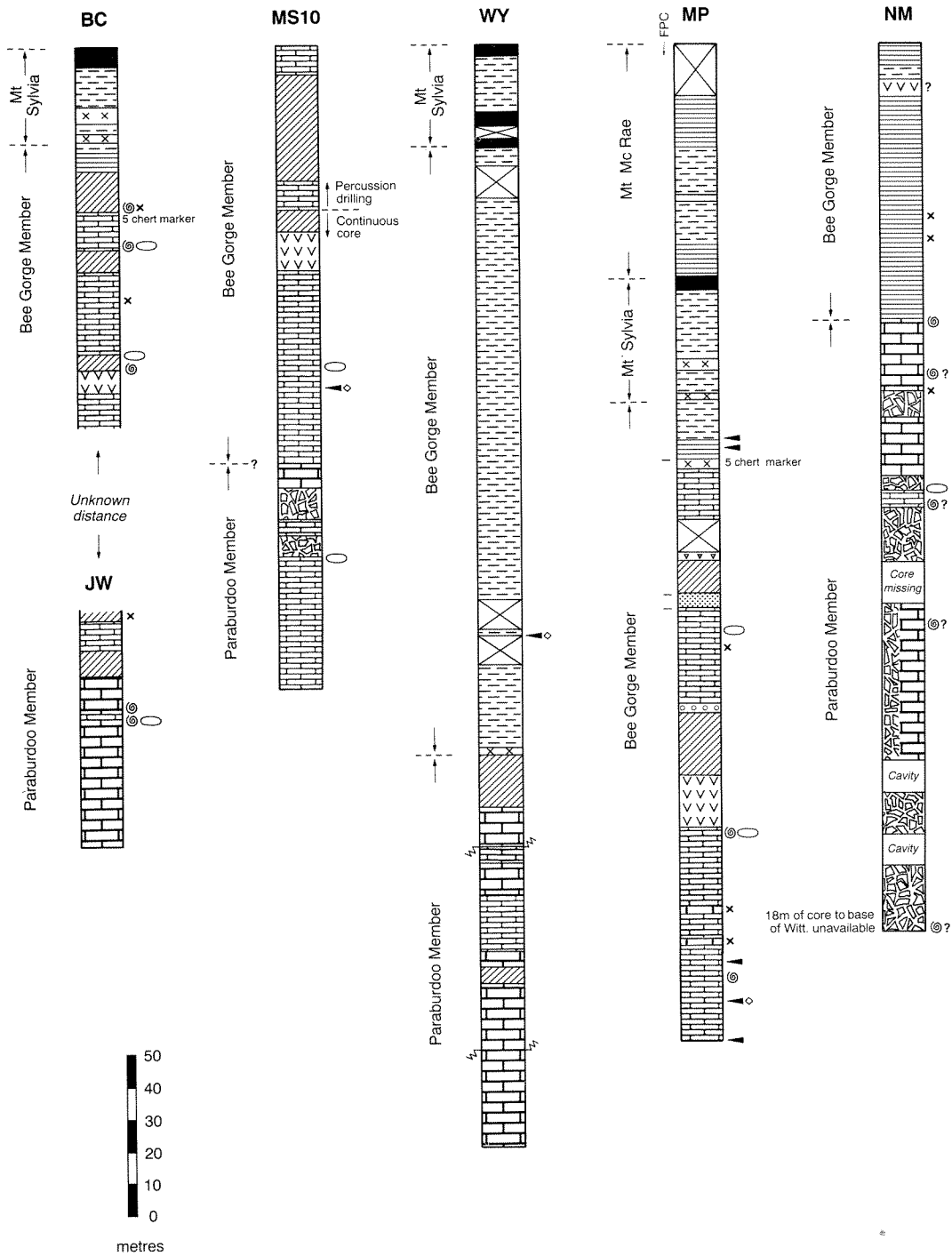
	Pure carbonate (usually dolomite) with argillaceous partings and negligible chert
	Cherty or silicified carbonate (usually dolomite)
	Brecciated carbonate of sedimentary clasts in a coarsely sparry matrix (N.B. such zones exist but were avoided in surface exposures, so symbol only appears in core sections)
	Thinly interbedded argillite and dolomite, limestone and/or ferroan carbonate lutite with negligible chert; argillite usually dominant
	Argillite with thin interbeds of chert lutite and negligible carbonate
	Argillite with thin interbeds of both chert and carbonate lutite
	Argillite with thin interbeds of ferruginous chert arenite and negligible carbonate
	Argillite with thin interbeds of clastic dolomite, limestone and/or ferroan carbonate with or without thin chert interbeds
	Pure argillite
	Volcanics of the Main Tuff Interval (N.B. see Hassler, 1991, and in press for information on internal features; none are depicted on these sections)
	'Volcanic siltstone' of the Mount McRae Shale
	Bedded chert with minor argillite
	Highly ferruginous chert and banded iron-formation
	Covered interval
	Spherule-bearing turbidite (Spherule Marker Bed)

LITHOGRAPHIC SYMBOLS NEXT TO STRATIGRAPHIC COLUMNS

	Argillite-hosted concretions of limestone, dolomite, and/or ferroan carbonates
	Argillite-hosted chert concretions
	Roll-up or related soft-sediment deformation structure in carbonate
	Ripple cross-lamination, mostly of the climbing current variety
	Thin layer of tuff
	Crystal-rich Tuff marker layer
	Isolated carbonate layer with coarse clastic features
	Carbonate arenite containing oolites
	Prominent cherty marker bed in either carbonate or argillite
	Section line interrupted; unknown amount of section missing

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Figure 2. Measured sections of the Wittenoom Formation, the Mount Sylvia Formation, and/or the Mount McRae Shale. The sections are keyed to Figure 1 and Table 1 by the abbreviation(s) above the columns. Columns BG/BE and CH/MB are both composites of sections from two closely spaced sites, whereas the rest of the columns represent sections measured at single sites. The symbols to the right of each column indicate the stratigraphic locations of specific sedimentary features explained in legend, whilst tic marks to the left of some columns indicate the locations of beds of flat-pebble conglomerate (FPC). Diagrammatic versions of these same sections also appear in Figure 3A of Simonson et al. (in press).



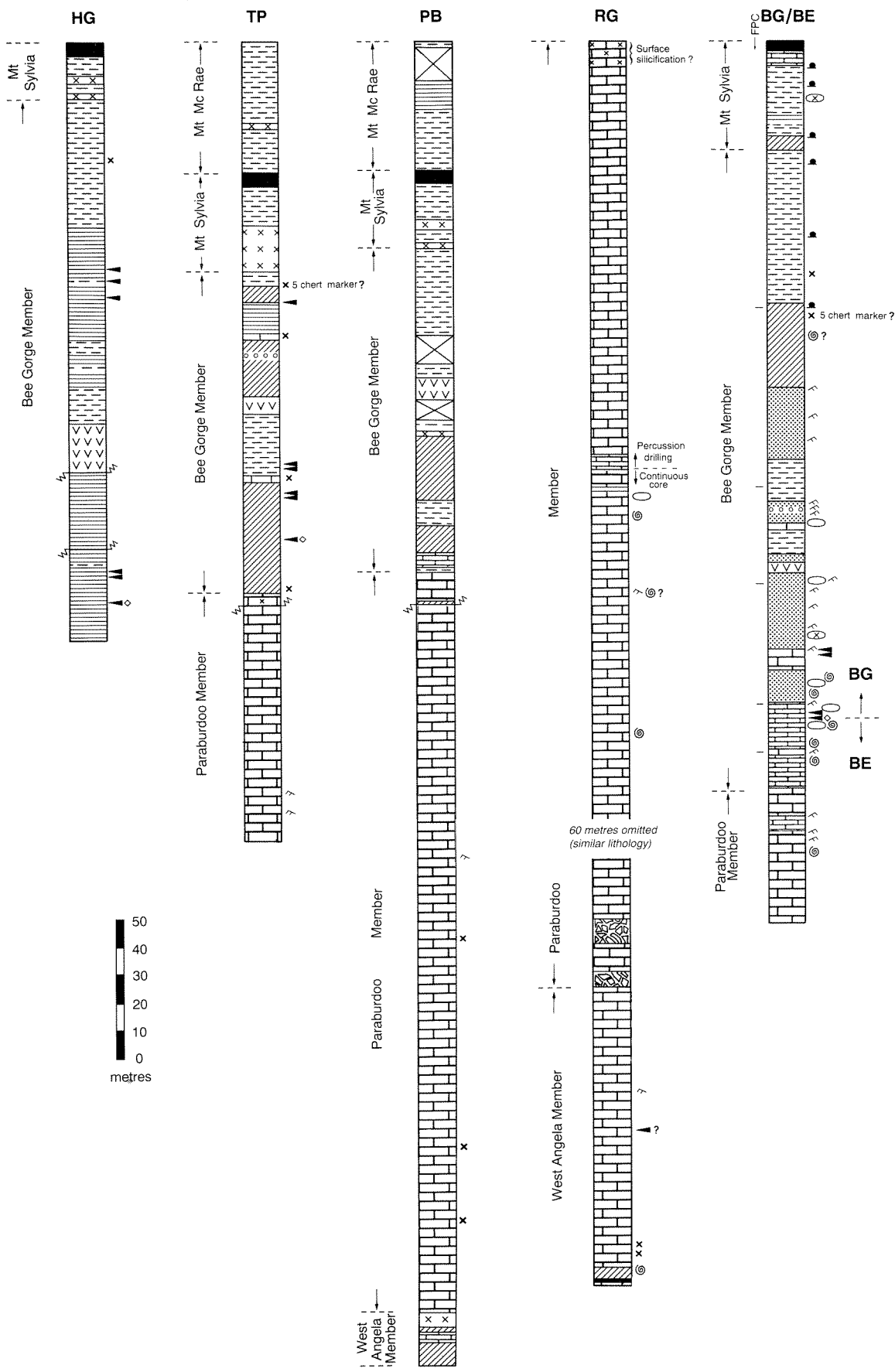
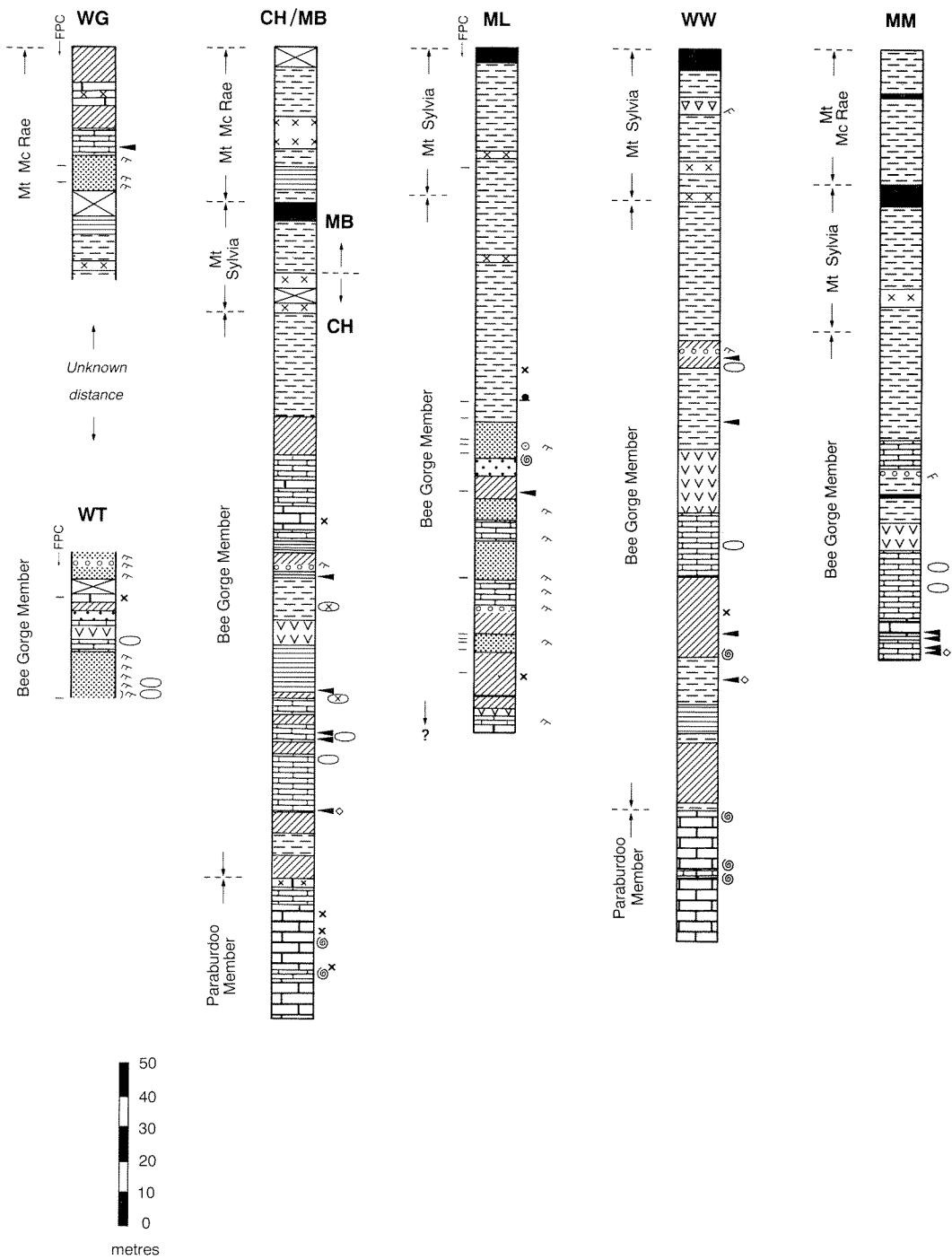


Figure 2. (continued)



argillaceous material. Although they are laterally persistent, these laminations are typically 'lumpy', pinching and swelling on a small scale (Simonson et al., in press, fig. 21). Based on the thin and continuous nature of these laminations, and the absence of any current structures or coarse clastic textures, we believe they originated as carbonate mud.

In addition to thin laminations, small but distinctive soft-sediment folds referred to as roll-up structures are a volumetrically minor but widespread (Fig. 2) component of these dolomite layers. The geometry of these folds (especially the laminations that are rolled up in spirals—Simonson et al., in press, figs 24, 25) indicates some of the thin laminations were stabilized by the presence of cohesive microbial mats (Simonson, 1988b). Corresponding structures occur in the carbonates of the Transvaal Supergroup (Beukes, 1987; Klein et al., 1987) and have been interpreted similarly.

Dolomite layers with well-preserved thin laminations form a continuum with others that contain darker bodies or clots with diffuse margins. Such textures are referred to as pseudo-arenites by Simonson and Hassler (1991) because they appear to be the diagenetically degraded products of the thin carbonaceous laminations. Other thin dolomite layers are massive internally and have a graded appearance due to subtle changes in colour and/or the presence of small, probably intraclastic carbonaceous flakes in their basal parts.

Thin layers of carbonate arenite are also present among the dolomites of the Paraburdoo Member, but are quite rare. These layers show detrital textures consisting of sand-sized peloids or intraclasts and/or structures such as ripple cross-lamination. Most are believed to be turbidites because they are very similar to the arenites of the Bee Gorge Member (see below), but one occurrence of possible hummocky cross-stratification was observed at the TP site (Simonson and Hassler, 1991).

Rare layers rich in ferroan carbonate also occur in the Paraburdoo Member, most notably in the basal part stratigraphically close to the more ferruginous West Angela Member (Blockley et al., 1993). In surface exposures, ferroan carbonates can be readily differentiated from dolomite layers because they develop a thick weathering rind with a distinct golden, orange, or yellow colour. In contrast, a paper-thin, buff-coloured weathering rind develops on the dolomites. Limestones weather a neutral grey, but no limestones were positively identified in the Paraburdoo Member. In fresh drillcore, the carbonate varieties are not as easily differentiated because they all appear uniformly grey.

Like the Paraburdoo Member, the carbonates in the Bee Gorge Member are dominated by thinly laminated layers of dolomite lutite. Unlike the Paraburdoo Member, however, carbonates are much less voluminous than argillite. In addition, appreciable thicknesses of limestone and ferroan carbonate are present in the Bee Gorge Member, and a significant minority of carbonate layers are arenites or flat-pebble conglomerates rather than lutites. The carbonate arenites display features typical of turbidites such as great lateral persistence, normal grading, and

partial (particularly t_b – t_c) Bouma sequences. Changes in grain size and palaeocurrent measurements on the climbing ripple cross-laminations that are commonly present in these turbidites indicate they were dispersed south and west across the Hamersley Basin (Simonson et al., in press). Limestones and coarse clastic carbonates are thickest and most abundant in the north-central part of the Hamersley Basin. Ferroan carbonates are most abundant in the stratigraphically higher parts of the Bee Gorge Member.

Carbonates are least abundant in the Mount Sylvia Formation and Mount McRae Shale. Those which are present tend to be rich in ferroan carbonate and lacking in evidence of a coarse clastic origin. The Mount McRae Shale, however, contains one carbonate package (10.6 m thick) rich in limestone arenites at site WG. Like the turbidites of the Bee Gorge Member, these arenites display normal grading and climbing ripple cross-lamination with south- and west-directed palaeocurrents. Layers of flat-pebble conglomerate are also locally present in the Mount Sylvia Formation.

Argillite

In fresh samples from drillcore, almost all of the argillites in all of the units studied are dark grey to black, and those with little carbonate are highly fissile. Many bedding surfaces appear graphitic, attesting to a high content of carbonaceous matter. In contrast, samples from surface exposures typically have a brownish or reddish colour due to oxidation of carbonaceous material and iron-bearing minerals. Some argillites, particularly in the Mount Sylvia Formation and Mount McRae Shale, are highly bleached and altered to a powdery consistency in surface exposures. Many surface samples of argillites also differ from core samples in having veinlets and more irregular masses of calcite. Breccia textures, inclusions of exotic mineral grains, and other features indicate this calcite represents calcrete formed by relatively recent surface-weathering processes.

The most prominent X-ray peaks in Paraburdoo Member argillites are those of dolomite and quartz, with progressively smaller peaks for chlorite, muscovite (or a similar 10 angstrom clay mineral), and potassium feldspar. The same silicate minerals were also detected in HCl-insoluble residues from associated carbonate layers, although their relative abundances vary somewhat. In contrast, the quartz and chlorite peaks were higher than the carbonate peaks in argillites of the Bee Gorge Member, and calcite and an iron-bearing ankeritic phase were detected in some rocks instead of, or in addition to, dolomite. Mineralogically, Mount Sylvia Formation argillites are very similar to those of the Bee Gorge Member, but those of the Mount McRae Shale differ in that muscovite, rather than chlorite, is the dominant sheet silicate. Kaolinite was detected only in samples of the bleached, powdery argillite, where it is generally the dominant sheet silicate. In contrast, disseminated sulfides are widespread in many samples from drillcore but rare in surface samples.

Stratigraphically, the abundance of carbonate and argillite varies antipathetically. The carbonate-poor Bee Gorge Member contains sequences of virtually uninterrupted argillite tens of metres thick, whereas no package of argillite thicker than about a metre was observed in the carbonate-rich Paraburdoo Member. The ratio of argillite to carbonate is even higher in the Mount Sylvia Formation and Mount McRae Shale, although these units tend to be more altered and less well exposed than the Bee Gorge Member.

Primary and secondary features are present in many of the argillites, although they are not as diverse or informative as those of the carbonates. By far the most abundant primary features in the argillites are very thin laminations that reflect subtle differences in the composition and grain size of the constituent minerals. In general, these laminations are monotonously even and nondescript, but some are rhythmic in nature.

Although rare, two types of exceptionally thick argillite beds occur in the Bee Gorge Member and overlying units. One type comprises massive layers up to 30 cm thick that lack fissility. Some of these layers contain liquefaction structures and possible intraformational pebbles, suggesting they originated via soft-sediment disruption. The other type of thick argillite beds comprises layers up to several centimetres thick that are greener on weathered surfaces and less fissile than normal argillite. These layers resemble the fine volcanoclastic strata of the Main Tuff Interval (described below) and may represent times when fine-grained volcanoclastic material was being added to the normal hemipelagic muds as they were deposited.

Concretions and nodules are the commonest types of secondary features in the argillites of the Paraburdoo and Bee Gorge Members. Carbonate concretions are widespread (Fig. 2), range up to 75 cm long by 15 cm thick, and consist of calcite, dolomite, or ferroan phases. Internally, they can be massive or concentrically layered, but most are thinly laminated. Many display lumpy lamination, and some contain roll-up and related soft-sediment deformation structures (described above). Chert nodules, which occur in argillite but are rare, are described in the next section. Finally, spheroidal nodules of coarsely crystalline pyrite pseudomorphed by hematite were observed in weathered argillites of the Mount McRae Shale in a few localities. These nodules, known as 'Devil's golf balls', are several centimetres in diameter.

Chert and iron-formation

Nodules (discontinuous masses) and beds (continuous layers) of chert are both present in all of the units we studied. They generally form two discrete populations, although the distinction becomes blurred in the case of a few continuous chert bands with widely spaced gaps. Chert is relatively rare in the Paraburdoo Member and consists almost exclusively of carbonate-hosted nodules. The Bee Gorge Member and overlying units contain a greater abundance of both bedded and nodular chert. Thus, as with argillite and carbonate, the ratio of chert to carbonate increases upsection in the units we studied.

Most nodular chert occurs in carbonate host beds. Chert nodules are usually black (presumably from carbonaceous inclusions) and vary in shape from spheroids and flattened ovoids to more complicated forms with rounded protuberances. The nodules are rarely thicker than 10 cm and tend to be highly elongated parallel to bedding. Carbonate layers rich in chert nodules range up to 2 m in thickness and form excellent local marker beds. Chert nodules hosted by argillite are rare and tend to be more widely spaced and regular (ellipsoidal) in shape than those in carbonate.

Internally, chert nodules in both carbonates and argillites show a variety of fabrics created by subtle variations in the sizes of quartz crystals and/or the abundance of fine impurities. Some nodules are massive whilst others show thin laminations, many of which are continuous with those in the adjacent carbonate. Cross-strata and flat pebbles are likewise pseudomorphed in chert nodules hosted by beds of clastic carbonate. Lastly, some nodules display faint concentric structures and/or gradational margins. All of these characteristics indicate the chert nodules formed via replacement.

Individual layers of bedded chert range from about 2 to 20 cm in thickness. Many occur in bundles of closely spaced layers separated by argillaceous partings that have aggregate thicknesses of 25 to 150 cm. Such bundles typically form excellent marker horizons by way of subtle but consistent differences in the thickness, colour, and degree of podding (described below) of the constituent chert layers. We were able to correlate some of the most distinctive bundles for long distances. For example, one bundle near the top of the Bee Gorge Member informally designated the 'five chert marker' (Fig. 2), is present in both the BC and MP sections, which are 100 km apart. It also appears to be present in the BG and TP sections another 80 to 100 km farther to the east and south respectively (Figs 1 and 2).

Most bedded cherts display thin laminations and lack visible clastic textures, indicating they originated as fine (mud-sized) sediment. In contrast to the chert nodules, we interpret these chert beds as largely primary siliceous lutites for two reasons: nowhere did we observe any chert beds passing laterally into sediment of a different composition, and the chert beds contain some features we did not observe in rocks of any other composition. The best example of the latter is small, irregular pockets of microbreccia like those described from cherty iron-formation by Trendall and Blockley (1970, fig. 45). These microbreccias differ from the flat-pebble conglomerates of the carbonates in three ways: they have a matrix of fine-grained chert rather than sand, their upper and lower contacts both transgress bedding, and the platy 'clasts' are all derived from local layers (usually a single one). Consequently, we concur with Trendall and Blockley (1970) that they formed *in situ* through soft-sediment disruption. In addition, the thin laminations in the bedded cherts are thicker than those of the argillites, and although they pinch and swell in places, they do so on longer wavelengths than the lumpy lamination of the carbonate lutites.

Some chert beds display thickened portions similar to the chert nodules described above and with the same characteristics as the chert pods of Trendall and Blockley (1970). In contrast to the bulk of the silica in the bedded cherts, which we believe is primary, we interpret these pods as secondary concretions enriched in silica during diagenesis by analogy with concretions of other compositions in other types of host strata (Simonson, 1987b, p. 509).

Thin, laterally discontinuous chert layers with coarser clastic textures also occur at two distinct stratigraphic levels in the Bee Gorge Member at several sites (Fig. 2; see Simonson and Goode, 1989, fig. 3 for more detail). These layers have higher contents of iron-bearing minerals than most of the cherts, giving them greenish and reddish colours. The clastic chert beds at the lower stratigraphic level are coarse arenites to fine, flat-pebble conglomerates. They consist of tabular intraclasts up to 14 mm long, and some are normally graded. The clastic chert beds at the higher stratigraphic level are finer arenites with more equidimensional grains, including some chert oolites. We interpret these clastic chert layers as distal storm deposits, and they are very similar to cherty beds in granular iron-formations such as those of the Nabberu Basin in Western Australia, or the North American iron ranges (Simonson and Goode, 1989).

Iron-bearing minerals are also disseminated in some of the chert lutites, particularly those in the Mount Sylvia Formation and Mount McRae Shale, and layers of true BIF (especially jaspilite) are present locally in the Bee Gorge Member and overlying units (Fig. 2). The thickest and most prominent of the BIFs is informally known as Bruno's Band, which is located at the top of the Mount Sylvia Formation (Trendall and Blockley, 1970, p. 86). This marker bed ranges from 3.6 to 6.7 m in thickness and is present throughout the Hamersley Basin (Fig. 2). The Mount Sylvia Formation also contains two thinner layers of ferruginous chert that are almost as pervasive as Bruno's Band (Fig. 2). These two layers are commonly referred to as BIFs but do not contain enough iron to qualify for that name. These three ferruginous marker beds form a triplet whose proportional spacing is remarkably consistent throughout the Hamersley Basin. BIFs and ferruginous chert lutites both display thin laminations and podding comparable with those of BIFs elsewhere in the Hamersley Group (Trendall and Blockley, 1970; Ewers and Morris, 1981; McConchie, 1984).

Volcaniclastics

By far the most significant accumulation of volcaniclastic sediments in the units we studied is the Main Tuff Interval (MTI) of the Bee Gorge Member. The MTI is a 4.2 to 16.4 metre-thick sequence of pyroclastic turbidites that has a preserved volume of 200 km³. In outcrop, the MTI stands out from the surrounding argillite and chert as a conspicuous ledge which weathers to a distinctive grey-green to olive colour with an orange-red surface stain. Coarser grained portions of this unit, which are often replaced by carbonate, weather to a yellow-brown colour. In general, finer grained and thinner

sections are better preserved than coarse-grained, thick-bedded sections. In core, the MTI ranges from light to dark grey in colour and portions replaced by carbonate may show a crystalline texture.

The MTI is composed of altered pyroclastic material, detrital crystals, and intrabasinal rip-up clasts. Pyroclastic material includes coarse sand- to silt-sized, blocky to oblong vitric grains and coarse sand-sized accretionary and armoured lapilli; all of these have been pervasively altered to a mixture of chlorite, clay minerals, and carbonate. Fine to very fine sand-sized feldspar and quartz crystals are a minor but persistent component of the MTI. Intrabasinal rip-up clasts consist largely of argillite, with minor amounts of chert and carbonate (including concretions), and range from sand to megaclast size. Of these clast types, only accretionary lapilli and sand-sized or larger rip-up clasts are visible to the naked eye.

Three types of turbidite depositional sequences have been recognized in the MTI, based on patterns of sedimentary structures, grain-size trends, and the presence of erosional surfaces. In each measured section, the MTI consists of 14 to 28 of these depositional sequences. The sequence types are as follows:

1. *Thick graded-bed sequences* (45–545 cm thick) consisting of one, or very rarely two, decimetre- to metre-scale beds capped by one to eight centimetre-scale beds. Each sequence base is commonly an irregular erosional surface, and the thick beds in several sequences contain argillite boulders and megaclasts (Hassler, 1990b). Pyroclasts in the thick basal bed are normally graded, as are any intraclasts that are present. Granule-sized intraclasts also occur at the same level as fine sand-sized pyroclasts, indicating density grading. The overlying thin beds are finer grained than the basal thick bed, and the uppermost thin bed is the finest of all. Most thin beds are normally graded, but rare layers with ripple cross-lamination are also present. In heavily weathered sections, only the top of the thick bed and the lowest of the overlying thin beds are exposed.
2. *Thin normally graded-bed sequences* (4–28 cm thick) consisting of one to three 2–10 cm-thick normally graded beds, overlain by one to fourteen thinner normally graded beds, each less than 2 cm thick. Grain size decreases upwards through individual sequences, and some sequences also show double grading as described by Fiske and Matsuda (1964), but bedding thicknesses show no regular patterns. Planar laminations and rare ripple cross-laminations are present within the upper thin graded beds in places. Some sequences are capped by a single layer 5–11 cm thick that is very fine grained.
3. *Complex Bouma sequences* (5–29 cm thick), which include the components of classical Bouma sequences (Bouma, 1962) but commonly show repetitions of t_b , t_b , and t_c intervals within a single depositional sequence. Sequences with multiple t_b and t_c intervals are most common; sequences showing the full range of t_a – t_c intervals are rare.

We interpret sequence types 1 and 2 (thick graded-bed and thin normally graded-bed sequences respectively) as deposits of highly concentrated turbidity currents dominated by suspension sedimentation, as modeled by Lowe (1988). This is based on the abundance of normal and density grading, the rarity of ripple cross-lamination and planar lamination, and the presence of erosional surfaces and intrabasinal rip-up clasts in these sequences. In contrast, the combination of graded bedding and traction structures in sequence type 3 (complex Bouma sequences) suggests they represent deposition from high- and low-density turbidity currents, as described by Middleton and Hampton (1976) and Lowe (1982).

The MTI records an exceptionally large-volume pyroclastic sedimentation event during deposition of the Wittenoom Formation. A lack of non-volcanogenic interbeds indicates that the MTI accumulated rapidly on the floor of the Hamersley Basin. Palaeocurrent data indicate that the unit was derived from a source volcano located to the north, and that it had a complex depositional history (Hassler, 1991a, in press).

Beds in many MTI sections are cut by distinctive veins that typically occur in networks which traverse bedding packages up to 2.4 m thick. The veins consist of coarsely crystalline carbonate that weathers yellow-brown and contain slivers of the MTI host rock, some of which are displaced downward. Individual veins can be up to 5 mm wide and are elongated perpendicular to bedding. They are generally arcuate to sinuous in cross section and can form polygonal patterns in plan, resembling those formed by desiccation cracks. In addition to the MTI, similar vein networks were observed in a carbonate package high in the Bee Gorge Member at the CH site.

In addition to the highly concentrated volcanics of the MTI, the Bee Gorge Member contains a number of thin, isolated tuff beds. These solitary tuff beds are similar in appearance to the MTI in both cores and surface exposures, e.g. they are greener and less fissile than the ambient argillite. Individual tuff beds rarely exceed 10 cm in thickness and are still recognizable where less than a centimetre thick. Much of the detritus in these thin tuff beds is very fine grained and difficult to resolve microscopically, but where individual grains can be distinguished, they are very well sorted and range up to medium sand size. Many thin tuffs display excellent normal grading, but traction structures such as ripple cross-lamination are rarely present.

The most distinctive and widespread of the thin tuffs is the Crystal-rich Tuff. This bed is normally graded and well sorted throughout, and the clasts reach a maximum size of 0.2 mm at the base of the bed. The clasts are mainly finely crystalline aggregates (some with obvious microlitic textures) and crystalline grains. The latter consist of potassium feldspar (?after plagioclase) and lesser monocrystalline quartz, both of which display many partially to completely euhedral outlines. Such crystals are more abundant in this bed than in any of the other thin tuffs and are generally visible in hand sample; hence the name Crystal-rich Tuff. A few of the aggregate clasts appear to be vesicular, but none have the pronged shapes of felsic shards.

The Crystal-rich Tuff layer persists laterally for hundreds of kilometres and is present throughout most of the Hamersley Basin. It is close to 10 cm thick at all sites with two exceptions: it expands to 19 cm at the GV site in the southeast, and shrinks to 5 cm at the WY site in the southwest. Based on the lack of traction structures, and excellent sorting and grading, we interpret this and other thin tuff layers as direct eruptive fallout deposits. The character of the clasts indicates the volcanic eruptions responsible were probably hydroclastic rather than pyroclastic, i.e. phreatoplinian rather than plinian (Cas and Wright, 1987, p. 158–162).

In the southeastern part of the Hamersley Basin, the Mount McRae Shale contains a layer of coarser clastic material. We only observed this layer in the WW section (Fig. 2), where it is about 5.3 m thick, and in drillcore from the Mount Whaleback mine area, where it is informally known as the 'volcanic siltstone'. Samples from this layer consist of quartz, chlorite, dolomite, and possibly lesser amounts of potassium feldspar. Petrographically, they show about equal amounts of chert grains, carbonate, and sheet silicates with lesser quartz sand and silt. The carbonates and the sheet silicates both appear to be replacing original detrital grains, whereas the quartz, chert, and small numbers of feldspar grains appear to be original detritus. This layer generally appears massive and structureless, although locally it has rare ripple cross-lamination and soft-sediment deformation structures. Whether these rocks represent a separate episode of volcanism or a highly anomalous influx of siliciclastic sand is unclear because of the limited number of observations, as well as the obscuring effect of the strong tectonic foliation typical of many strata in this part of the Hamersley Basin (Tyler and Thorne, 1990).

Ewers and Morris (1981) presented persuasive geochemical arguments that the S or 'shale' macrobands of the Dales Gorge Member of the overlying Brockman Iron Formation are volcanogenic in origin. In the Bee Gorge Member, the mineralogical compositions of the thin tuff beds and ambient argillite are consistently different. Potassium feldspar and muscovite (or a similar 10 angstrom clay mineral) are abundant in the tuffs but not in the argillite, whereas chlorite is abundant in the argillite but generally undetectable in the tuffs. These differences suggests the argillites of the Bee Gorge Member (and those of the Paraburdoo Member and Mount Sylvia Formation, which are similar) are siliciclastic rather than volcanoclastic in origin. The absence of the only iron-bearing silicate mineral which is abundant in the argillites also explains why the weathered tuffs are less red.

In contrast, the argillites of the Mount McRae Shale contain more muscovite than chlorite, i.e. they are closer to the tuffs mineralogically than to the underlying argillites. This may indicate an upsection increase in the influx of fine volcanoclastic detritus into the Hamersley Basin, in keeping with Ewers and Morris' (1981) interpretation of the S bands in the overlying Brockman Iron Formation.

Silicate-melt spherules

A single turbidite just above the Main Tuff Interval of the Bee Gorge Member is known as the Spherule Marker

Bed (Fig. 2) because it contains an abundance of sand-sized spherules that do not occur at any other level in the Wittenoom Formation, the Mount Sylvia Formation, or the Mount McRae Shale. These spherules resemble silicified oolites in outcrop, but they consist almost entirely of potassium feldspar replaced in part by carbonate minerals. The vast majority of the spherules are coarse to very coarse sand size and have spheroidal to ovoid shapes, although a few are more irregular, e.g. peanut shaped. Internally, most of the spherules display acicular to lath-shaped crystals that radiate inwards from the margins, indicating they are quenched and devitrified droplets of former silicate melt.

The turbidite which hosts the spherules is 12–130 cm thick and generally displays partial (t_b – t_c) Bouma sequences. The spherules are usually restricted to discontinuous lenses 3–65 mm thick at the base of the bed. Some of these lenses are cross-stratified and many contain imbricated slabs of carbonate lutite up to 62 cm long and/or finer flat pebbles of highly ferruginous sediment. However, at site BB the spherules are restricted to thin lenses along a single horizon in the argillite underneath the base of the turbidite, indicating they were dispersed independently.

Based on these lines of evidence, we interpret these spherules as melt droplets that were originally part of a strewn field generated by a major bolide impact (Simonson, 1992a). Identical spherules and larger, more irregular silicate bodies with similar textures also occur in a 22.7 m-thick dolomite debris flow deposit (the dolomixtite) near the base of the Carawine Dolomite. Based on evidence presented in Simonson (1992a) and Simonson et al. (in press), we interpret the dolomixtite layer as a more proximal equivalent of the Spherule Marker Bed. In addition, similar spherules occur in a single layer in the S4 band of the Dales Gorge Member of the Brockman Iron Formation (LaBerge, 1966, figs 5, 6, and 7; Trendall and Blockley, 1970, fig. 44B) and may be the product of a subsequent impact.

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