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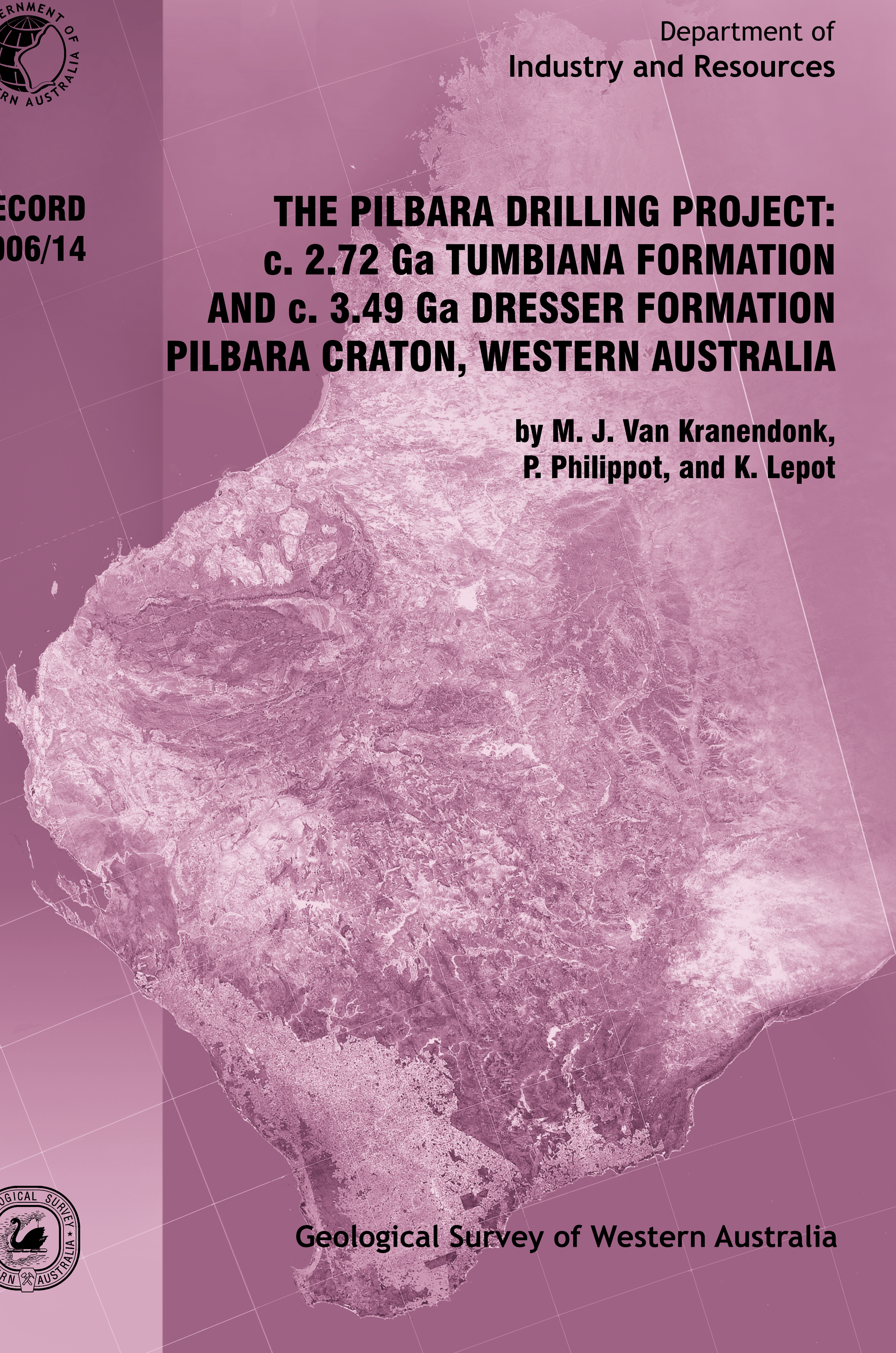

THE PILBARA DRILLING PROJECT: c. 2.72 Ga TUMBIANA FORMATION AND c. 3.49 Ga DRESSER FORMATION PILBARA CRATON, WESTERN AUSTRALIA

by M. J. Van Kranendonk,
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GEOLOGICAL SURVEY WESTERN AUSTRALIA

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The Pilbara drilling project: c. 2.72 Ga Tumbiana Formation and c. 3.49 Ga Dresser Formation, Pilbara Craton, Western Australia

by

M. J. Van Kranendonk[1], P. Philippot[2], and K. Lepot[2]

Abstract

To demonstrate the presence and type of life on early Earth, a joint scientific research project between the Institut de Physique du Globe de Paris and the Geological Survey of Western Australia drilled four diamond drillholes that intersected two distinct stromatolitic horizons in the Pilbara Craton and Hamersley Basin of Western Australia. This report presents geological logs of a diamond drillhole section (PDP1) through the c. 2.72 Ga Tumbiana Formation (Fortescue Group, Mount Bruce Supergroup, Hamersley Basin) and three parallel holes (PDP2a–c) through the c. 3.5 Ga Dresser Formation (Warrawoona Group, Pilbara Supergroup) in the southeastern part of the North Pole Dome. The four drillholes were inclined normal to bedding. All diamond drillcore was oriented.

The drilling program penetrated through the target horizons, was within budget, and provided continuous core that, except for part of PDP1, is unaffected by recent weathering. Preliminary geological and petrographic analyses provide strong evidence for the former existence of life in both target horizons.

PDP1 intersected subaerial basalts of the Maddina Formation, stromatolitic carbonates and interbedded black shale of the Meentheena Member of the Tumbiana Formation, and underlying volcaniclastic sandstones. Stromatolites are identified by domical shapes and wrinkly laminations, including black organic-rich laminae.

Drillholes at the PDP2 locality intersected overlying pillow basalts and the lowermost chert–barite unit of the Dresser Formation, which is 8 m thick, and penetrated through to hydrothermally altered footwall basalts. The chert–barite unit was found to consist of up to six discrete members. Member 1 consists of thinly bedded pyritic laminates that alternate with coarsely crystalline intrusive barite, silicified carbonate, and thin sandstone beds with clasts of felsic to intermediate volcanic rocks, barite, and hematite. Stromatolitic forms exist in pyrite laminates that formed through pyrite replacement of Fe-carbonates. Member 2 is less than 20 cm thick and consists of wavy pyrite laminates that correspond with surface outcrops of wrinkly laminated stromatolites. Member 3 is a unit of coarse conglomerate and breccia, with clasts of felsic volcanic rocks, pyritic laminates, and barite, and is cut by barite veins. This passes up to Member 4, which consists of bedded carbonates with local horizons of possible microbial laminates. A thick unit of coarsely crystalline barite is present in this member in nearby surface outcrops. Member 5 is a sandstone that unconformably overlies the other members. Member 6 consists predominantly of variably silicified, thinly bedded carbonate that is affected by brecciation and jasper alteration, and also contains a 10 cm-thick bed of felsic volcaniclastic sandstone. The stratigraphic and mineral paragenetic data from these holes confirms a felsic volcanic caldera setting of deposition.

KEYWORDS: Pilbara Craton, stratigraphic drilling, origin of life, Dresser Formation, Tumbiana Formation, stromatolites

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Introduction

A joint scientific research project — the Pilbara drilling project (PDP) — was initiated between the Institut de Physique du Globe de Paris (IPGP) and the Geological Survey of Western Australia (GSWA) in 2004. The aim of the project was to complete two diamond drillholes beneath the effects of surface weathering through two temporally and geographically distinct stromatolitic horizons in the Pilbara Craton of Western Australia to convincingly demonstrate the presence of life — and if possible, the type of life — on early Earth.

The drilling research team consisted of Dr Pascal Philippot (IPGP), Dr Martin Van Kranendonk (GSWA), Drs Purificatión López-García and David Moreira (Université Paris-Sud), and two post-graduate students of Dr Philippot at IPGP: Kevin Lepot and Yuhang Chen. Dr Philippot specializes in analysing fluids in the Earth's crust using the European Synchrotron. Drs López-García and Moreira are microbiologists whose involvement is to identify the living biotic community in the subsurface core in order to differentiate this type of organic material from other types of fossil organic material that may be observed in the core. A number of other researchers are involved in various aspects of additional research on the drillcore material.

One drillhole was completed through the c. 2.72 Ga Tumbiana Formation (Fortescue Group, Mount Bruce Supergroup, Hamersley Basin), which contains widespread and diverse stromatolites (e.g. Packer, 1990) in dolostones that are interbedded with volcaniclastic sandstones, siltstones, and black shale. The purpose of this drillhole was to obtain: fresh samples of stromatolites of unquestioned biogenicity for use in a wide range of scientific analytical tests, in order to define convincing chemical signature(s) of primary biology; and to determine the composition of Archean seawater from a shallow-marine depositional environment. These tests include carbon isotopic analyses of carbonaceous material in situ, sulfur isotopic analyses of various phases of pyrite and other sulfides (e.g. sphalerite and galena), Laser Raman spectroscopy and organic geochemistry of carbonaceous material, nanoSIMS, and fluid-inclusion analyses using the European Synchrotron.

Successful techniques from study of the first drillhole will be applied to the search for fossil life signatures in the much older and much more highly altered rocks of the second drilling target — a section through Earth's oldest putative fossil stromatolite-bearing metasedimentary rocks of the c. 3.49 Ga Dresser Formation (Warrawoona Group, Pilbara Supergroup) in the North Pole Dome. The purpose of drilling through this target was to: confirm the presence of life in these ancient rocks; constrain the environment(s) of deposition and geological setting(s) of the metasedimentary rocks; and determine the compositions and roles of fluids, including possible seawater and hydrothermal fluids, that were preserved during the development and alteration of this formation and underlying and overlying metabasaltic units.

This Record presents geological logs based on hand-sample and thin-section analyses of the diamond drillcore material obtained from drillholes PDP1 and PDP2a–c. The drilling program is deemed a success because it penetrated through the target horizons, within budget, providing continuous core that, except for part of PDP1, is unaffected by recent weathering. It was also successful because preliminary geological and petrographic evidence indicates strong evidence for the existence of life in both target horizons. The results of more-detailed scientific analyses will be presented in published papers in scientific journals.

General geology

The Pilbara Craton of Western Australia (Fig. 1) comprises a 3.65 – 2.83 Ga basement terrane of metamorphosed granites and greenstones, and the unconformably overlying Mount Bruce Supergroup of the Hamersley Basin, which was deposited between c. 2.78 and 2.45 Ga. The basement rocks are divided into three distinct lithotectonic terranes and two intervening clastic sedimentary basins (Van Kranendonk et al., 2002). The locus of the current drilling project is the East Pilbara Terrane, which is the oldest terrane in the craton and forms its core. The greenstones were deposited in four demonstrably autochthonous groups from >3.52 to 3.17 Ga that together comprise the Pilbara Supergroup (Van Kranendonk et al., 2004, in prep.). At the base of the supracrustal succession is the Warrawoona Group, which is a succession of dominantly metavolcanic rocks and less common metasedimentary rocks deposited from >3.52 to 3.43 Ga. The Warrawoona Group is unconformably to conformably overlain by the successively younger Kelly, Sulphur Springs, and Soanesville Groups, the c. 3.02 – 2.93 Ga De Grey Supergroup, and the Fortescue and Hamersley Groups of the Mount Bruce Supergroup (Hickman, 1983; Van Kranendonk et al., 2004, in prep.). The Pilbara Supergroup was intruded by granitic rocks ranging in age from 3.50 to 2.83 Ma and in composition from tonalite to syenogranite (Van Kranendonk et al., 2002, 2004, in prep.).

The c. 3.49 Ga Dresser Formation consists of metasedimentary and interbedded metamorphosed mafic volcanic rocks, and is located in the lower part of the Warrawoona Group (Fig. 1: Van Kranendonk and Morant, 1998; Van Kranendonk, 2000; Van Kranendonk et al., in prep.). The main surface exposures of the lowermost bedded metasedimentary unit in the Dresser Formation consist dominantly of layered grey, white, and red chert, with variable amounts of barite in bedding-parallel sets of weakly radiating crystal splays and in crosscutting veins. This horizon also contains diamictite with barite clasts, rippled sandstone, massive volcaniclastic sandstone, minor carbonate, and beds that contain a variety of stratiform, domical, and coniform stromatolites (Walter et al., 1980; Walter, 1983; Buick and Dunlop, 1990; Nijman et al., 1998; Van Kranendonk, 2000, 2006). Putative microfossils defined by filaments of kerogenous material have been described from underlying silica(–barite) veins (Ueno et al., 2001a,b, 2004) that represent fossilized hydrothermal fluid pathways active during deposition of the Dresser Formation (Nijman et al., 1998; Van Kranendonk, 2006).

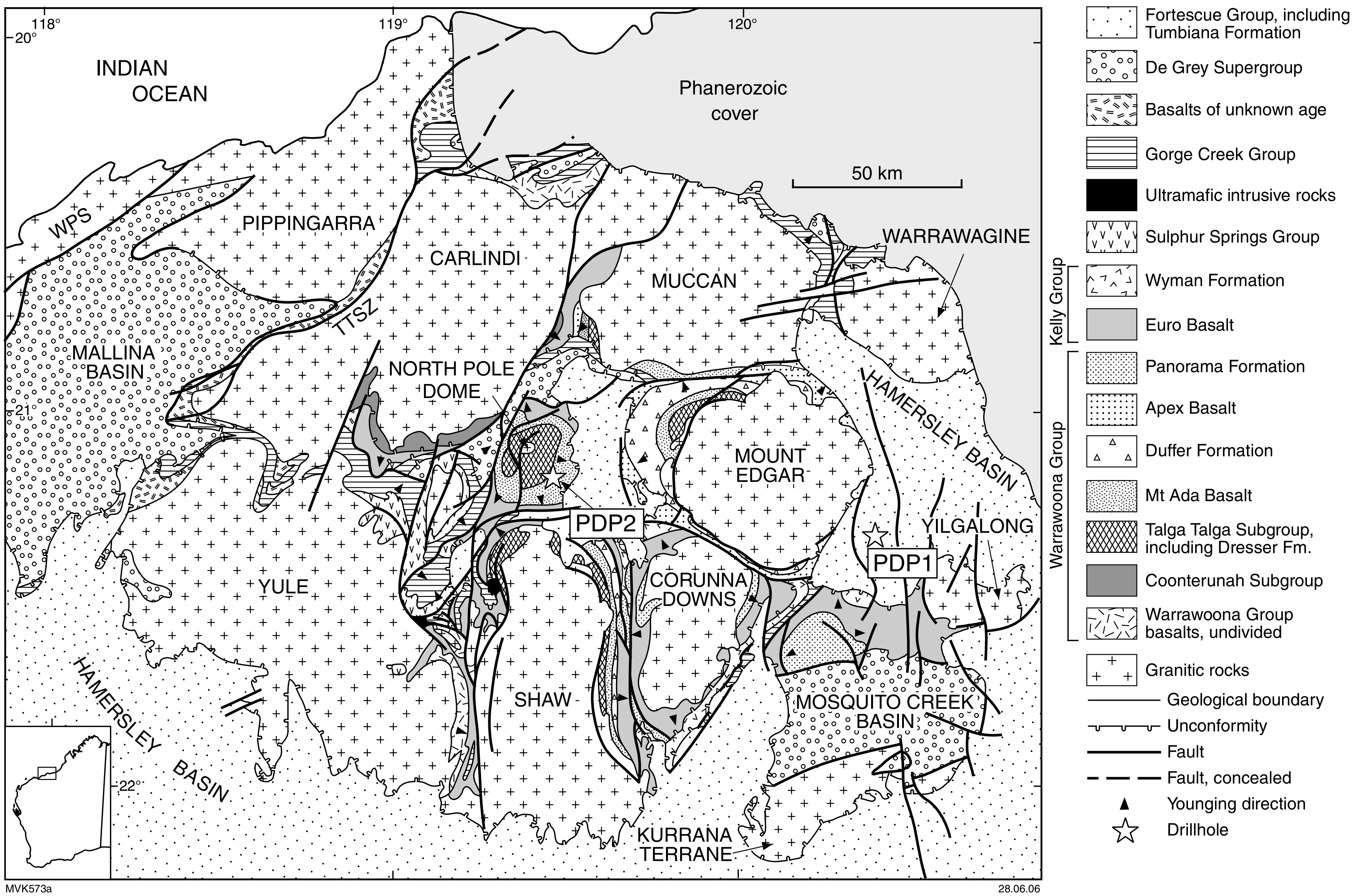

Figure 1. General geology of the Pilbara Craton, showing the basement granite–greenstone rocks and the overlying Mount Bruce Supergroup of the Hamersley Basin. Location of drillholes shown. WPS = West Pilbara Superterrane; TTSZ = Tabba Tabba Shear Zone (after Van Kranendonk et al., 2002)

The Mount Bruce Supergroup is divided into the basal Fortescue Group (2.78 – 2.63 Ga), the conformably overlying, dominantly sedimentary rocks of the Hamersley Group (2.63 – 2.45 Ga), and the unconformably overlying clastic sedimentary rocks of the undated Turee Creek Group (e.g. Blake et al., 2004; Trendall et al., 2004). The Fortescue Group is composed of alternating low-grade volcanic and sedimentary rocks, including the sedimentary Tumbiana Formation, which lies conformably above the dominantly basaltic Kylena Formation and conformably beneath the basaltic Maddina Formation (Fig. 2). The Tumbiana Formation includes a lower member of commonly lapilli-bearing volcaniclastic rocks (Mingah Member), and overlying stromatolitic dolostones of the Meentheena Member, which contain abundant and diverse stromatolites (Walter, 1983; Packer, 1990), rare microfossils (Schopf and Walter, 1983), and $\delta^{13}C$ values of kerogen in the range –40 to –60‰, which is indicative of methanotropy (Packer, 1990).

Methods

Drillsites of the PDP and the Archean Biosphere Project (a separate scientific drilling project in the Pilbara by researchers from the United States of America) were cleared for access by the Njamal Heritage Survey team under the auspices of Tony Farnham of the Yamatji Marla Barna Baba Maaja Aboriginal Corporation in July 2004. Craig Pincott (deceased, formerly of the Department of Industry and Resources, Karratha office) led the parties to the drillsites in June 2004.

A licence to take water from the site areas was granted by the Department of Environment on 14 July 2004. Ground disturbance approvals were obtained from the Environment Branch of the Department of Industry and Resources, from the Conservation and Land Management office in Karratha for the PDP1 site, and from the owners of Hillside Station for the PDP2 site, prior to bulldozing of tracks. Mr Bill Edwards of Nullagine cleared the access tracks and constructed the drillpads. Tracks were rehabilitated by Mr Edwards in September 2004.

A signed memorandum of understanding between Claude Jaupart, Director of IPGP, and Dr Tim Griffin, Director of GSWA, outlined the roles and responsibilities of the two organizations and the details for the operational procedures in the Archean drilling project. This agreement will remain in place for two years from 3 June 2004, and then for a further two years if no further action is taken. The agreement stipulates that the research members associated with IPGP will have sole access to the half-core splits for one year after arrival of the cores in France (to October 2005), after which time splits of the half-core that are retained in the GSWA core library (i.e. 25% splits of the whole core) will, subject to approval of the PDP, be available for sampling and scientific investigation.

Subsurface rock samples were obtained by diamond drilling of four drillholes through two distinct stratigraphic horizons at two localities in the eastern part of the Pilbara Craton (Fig. 1). The drillhole locations were sited in order to obtain the best chance of intersecting the target horizons below surface weathering, but at shallow depths to minimize costs. Drillhole PDP1 was drilled from a surface location 165 m to the southeast of gently southeast-dipping outcrops of the c. 2.72 Ga Tumbiana Formation, on the northern edge of the Meentheena Centrocline, just north of the Nullagine River, towards the eastern margin of the Pilbara Craton. This site was chosen due to an excellent array of large and diverse stromatolites visible in nearby outcrops, and ease of access from nearby tracks. PDP1 was drilled with NQ2 core (47.6 mm diameter) from the surface to a depth of 104 m* (Table 1) and intersected rocks of the Maddina

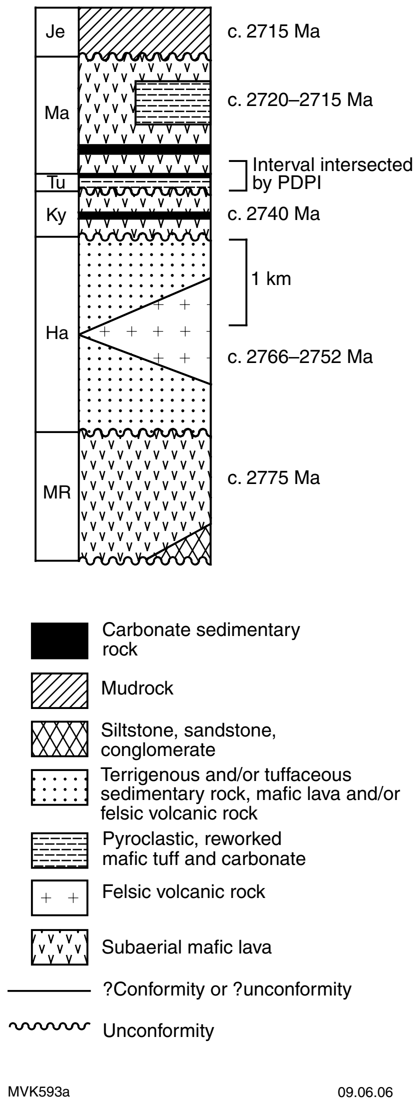

Figure 2. Simplified stratigraphic section of the Fortescue Group of the Mount Bruce Supergroup, including the Tumbiana Formation, which was the target of drillhole PDP1. Ha = Hardey Formation; Je = Jeerinah Formation; Ky = Kylena Formation; Ma = Maddina Formation; MR = Mount Roe Basalt; Tu = Tumbiana Formation

* All depths quoted are measured depths from the surface (as opposed to true vertical depths), unless otherwise specified.

and Tumbiana Formations of the Fortescue Group. Three drillholes (Table 1) were completed through the c. 3.49 Ga Dresser Formation, from drill collars located across strike at a locality in the southeastern part of the North Pole Dome. This site was chosen due to the relative continuity of bedding along strike, the presence of 'bedded' barite and wrinkly laminates (probable stromatolites) in surface outcrops, and company reports of a range of minerals and sulfate–sulfide ore textures.

All three holes at the PDP2 site were drilled towards 330°, at a plunge of 50° (Table 1). PDP2a was located 91.1 m south-southeast of surface outcrops of the Dresser Formation and used the larger HQ core (75.7 mm diameter). This hole intersected 50.6 m of weathered and altered pillow basalt and was abandoned. PDP2b was located 130.7 m away from surface outcrops of the Dresser Formation, and was drilled by Reverse Circulation (RC) Hammer to a depth of 84.0 m, which represents the level at which metasedimentary rocks were first intersected, and which was below the maximum depth of surficial weathering. This hole was drilled to a total depth of 109.6 m. PDP2c was located 8.0 m farther away from surface outcrops of the metasedimentary horizon and drilled by RC Hammer to a depth of 69.3 m, which was below the level of surficial weathering but still in the overlying pillow basalt. At this level, diamond drilling using NQ2 core (47.6 mm diameter) was commenced, and continued through the metasedimentary horizon into the underlying metabasalts to a total depth of 114.6 m (Table 1).

Drilling was undertaken by Mount Magnet Drilling using a multipurpose (RC and diamond) Hydco SD1000 drill rig. The rig was set up at PDP1 (Meentheena Centrocline) on 10 August 2004, but drilling of the hole was not commenced until 17 August 2004. It was completed by 18 August 2004, and the rig was moved to the site of PDP2 (North Pole Dome) on 19 August. Diamond drilling at PDP2a commenced on 20 August and was completed by the afternoon when the hole was abandoned due to the deep level of surface weathering. The rig was moved to PDP2b on 21 August, and drilling using RC Hammer was completed to a depth of 84.0 m. The rig was then moved to PDP2c and the top of this hole was drilled using RC Hammer to a depth of 69.3 m, also on 21 August. PDP2c was completed using diamond drilling the following day (22 August). Hole PDP2b was completed on 23 August. All diamond drillcore was oriented during drilling. Local water from either the Nullagine River (PDP1) or a local borehole (PDP2) was used during drilling, with samples of water collected at periodic intervals for microbiological analysis. No drilling mud or diesel was put down the hole during drilling to avoid undue contamination by foreign organic material, although a small amount of grease was required at rod connections and in the core barrel.

Lithological logs of the drillcore were made in the field, and photographs of core in the core trays were taken using a digital camera. Although samples were identified for microbiological studies, sampling was delayed until the core was in Perth due to a broken portable diamond saw. Drillcore was packed into galvanized steel core trays and transported by truck to Port Hedland and from there to the

Table 1. Drillhole data for the PDP project

Drillhole number	*Direction (plunge→azimuth)*	*Surface location (in GDA coordinates) Grid zone*	*Easting*	*Northing*	*Surface location Latitude*	*Longitude*	*Interval drilled with HQ core (m)*	*Interval drilled by RC Hammer (m)*	*Interval drilled with NQ core (m)*	*True vertical depth at end of hole (m)*
PDP1	75°→323°	51K	231288	7641810	21°18'15"S	120°24'40"E	–	–	0 – 104.0	100.4
PDP2a	50°→330°	50K	752229	7656300	21°10'33"S	119°25'50"E	0 – 50.6	–	–	38.8
PDP2b	50°→330°	50K	752249	7656267	21°10'34"S	119°25'50.9"E	–	0 – 84.0	84.0 – 109.6	84.0
PDP2c	50°→330°	50K	752253	7656259	21°10'34.4"S	119°25'51"E	–	0 – 69.3	69.3 – 114.6	87.8

GSWA Core Library in Carlisle, Perth. Selected samples of one-quarter core were collected for microbiology using a diamond saw and distilled water. Samples thus collected were placed into containers filled with distilled water and then shipped to France. The remaining drillcore was sawn in half at the Perth Core Library, using standard techniques. The split core was then photographed and divided. One half of the core was shipped back to IPGP in France for scientific analysis, and the other half remains at the Perth Core Library, where it is under embargo for further viewing until September 2008.

Polished and doubly polished thin sections were made of texturally interesting and stratigraphically significant features in drillholes PDP1, PDP2b, and PDP2c, with PDP2c having the most extensive suite of sections. Digital photographs were taken of the whole core in drilltrays immediately after core recovery, and again in more detail after the core was cut longitudinally in half.

Petrographic analyses of thin sections were made using a petrographic microscope, including reflected light microscopy for ore-mineral identification, by the senior author while visiting a professor at IPGP in July 2005. Detailed identification of some minerals were confirmed using transmission electron microscopy and electron dispersive spectrography by K. Lepot.

Drillcore from PDP2c was analysed using hyperspectral mineralogical logging (the HyLogging System) developed by CSIRO. This method involves very high resolution digital imaging of the core and spectroscopic determination of mineralogy using automated interpretation software — The Spectral Geologist (TSG)™. Results are presented below and in Appendix 1; further details of this technique can be obtained from the senior author.

Results

PDP1: Tumbiana Formation, Meentheena Centrocline

Surface geology at the drillsite

The Tumbiana Formation is composed of two members: the lower Mingah Member of dominantly volcaniclastic sandstones, and the overlying Meentheena Member of dominantly stromatolitic dolostones (e.g. Thorne and Trendall, 2001). Surface outcrops of the Tumbiana Formation in hills to the northwest of drillhole PDP1 display abundant and diverse stromatolites, ranging in size from a metre to centimetre scale (Fig. 3). These overlie a thick section (up to hundreds of metres) of volcaniclastic sandstone and accretionary lapilli beds (Mingah Member), which in turn overlie thick subaerial basalt flows of the Kylena Formation. The Tumbiana Formation is overlain by thick, commonly vesicular subaerial basalt flows of the Maddina Formation.

Geology of the drillcore

The top of drillhole PDP1 intersected generally fresh, low-grade metabasalt of the Maddina Formation from the surface to a depth of 42.72 m (Fig. 4). The rocks vary from very fine grained, massive to finely vesicular basalt, to coarsely vesicular basalt and basalt with large gas cavities (Fig. 5a), to coarser grained doleritic basalt with or without small, sparsely distributed vesicles. Rubbly zones at 7.7 – 8.3 m and 18.1 m, as seen in nearby surface outcrops, are interpreted to represent subaerial basalt flow tops. Metabasalts are devitrified and generally affected by deuteric alteration. At the bottom of the metabasalt section the rocks are recrystallized to a coarser grained assemblage of chlorite porphyroblasts and rutile (40.28 – 42.67 m). The lower contact of the metabasalt is a 5 cm-thick zone (42.67 – 42.72 m) of eutaxitic breccia and peperite that lies directly on the Tumbiana Formation (Fig. 5b).

The top of the Tumbiana Formation in the drillhole consists of a 9 cm-thickness of stromatolitic limestone (42.72 – 42.81 m). This overlies a thin bed of sandstone to pebbly sandstone with angular quartz pebbles up to 1 cm in diameter in a matrix of accretionary lapilli. Below this (42.89 – 44.60 m) are interbedded black shale (locally pyritic) and volcaniclastic sandstone, underlain by a 1 mm-thick bed of white quartz sandstone. Below this lies wrinkly laminated, fine-grained sedimentary rock (44.64 – 44.68 m), pyritic black shale (44.68 – 46.3 m), wrinkly laminated carbonate with hints of microbial mats (46.3 – 46.9 m), and 1 cm of thinly bedded sandstone and shale (46.9 – 47.0 m). A large stromatolite at this level caps microbially laminated carbonate to a depth of 47.8 m, which grades downwards into shale. Below the zone of rubbly, brown, altered core (48.5 – 63.3 m) is volcaniclastic sandstone with ripples, and shale (63.3 – 65.6 m). Underlying microbialite carbonate (65.6 – 67.4 m: Fig. 5c) overlies 6 cm of quartz pebble bearing conglomerate, which is the lowest unit intersected in the drillhole that is derived from weathering of basement rocks. Underlying this level is a finely interbedded mixture of microbialite, tuffaceous sandstone, rippled carbonate sandstones, sandstone, shale, and accretionary lapilli tuff. Stromatolites are well developed between 76.2 and 78.7 m, with black, organic-rich material at 78.7 – 79.3 m. Domical stromatolites reach a maximum of 20 cm in height at 76.2 – 78.3 m. The lower part of the hole, from 89.6 to 104.0 m, is monotonous volcaniclastic sandstone and shale, with beds of accretionary lapilli (Fig. 5d). Drilling was stopped at this depth.

PDP2a, 2b, and 2c: Dresser Formation, North Pole Dome

Surface geology at the drillsite

The Dresser Formation, near the top of the Talga Talga Subgroup of the Warrawoona Group, consists of up to five bedded chert horizons interbedded with pillow basalt and dolerite within the lower part of the Warrawoona Group (Fig. 1: Nijman et al., 1998; Van Kranendonk and Morant, 1998; Van Kranendonk, 2000). The thickest, lowermost chert includes: layered grey, white, blue, black, and red chert; barite, in both concordant layers and discordant veins; felsic volcaniclastic rocks; bedded carbonate; diamictite; finely laminated rocks, interpreted as probable stromatolites; and sandstone (Walter et al.,

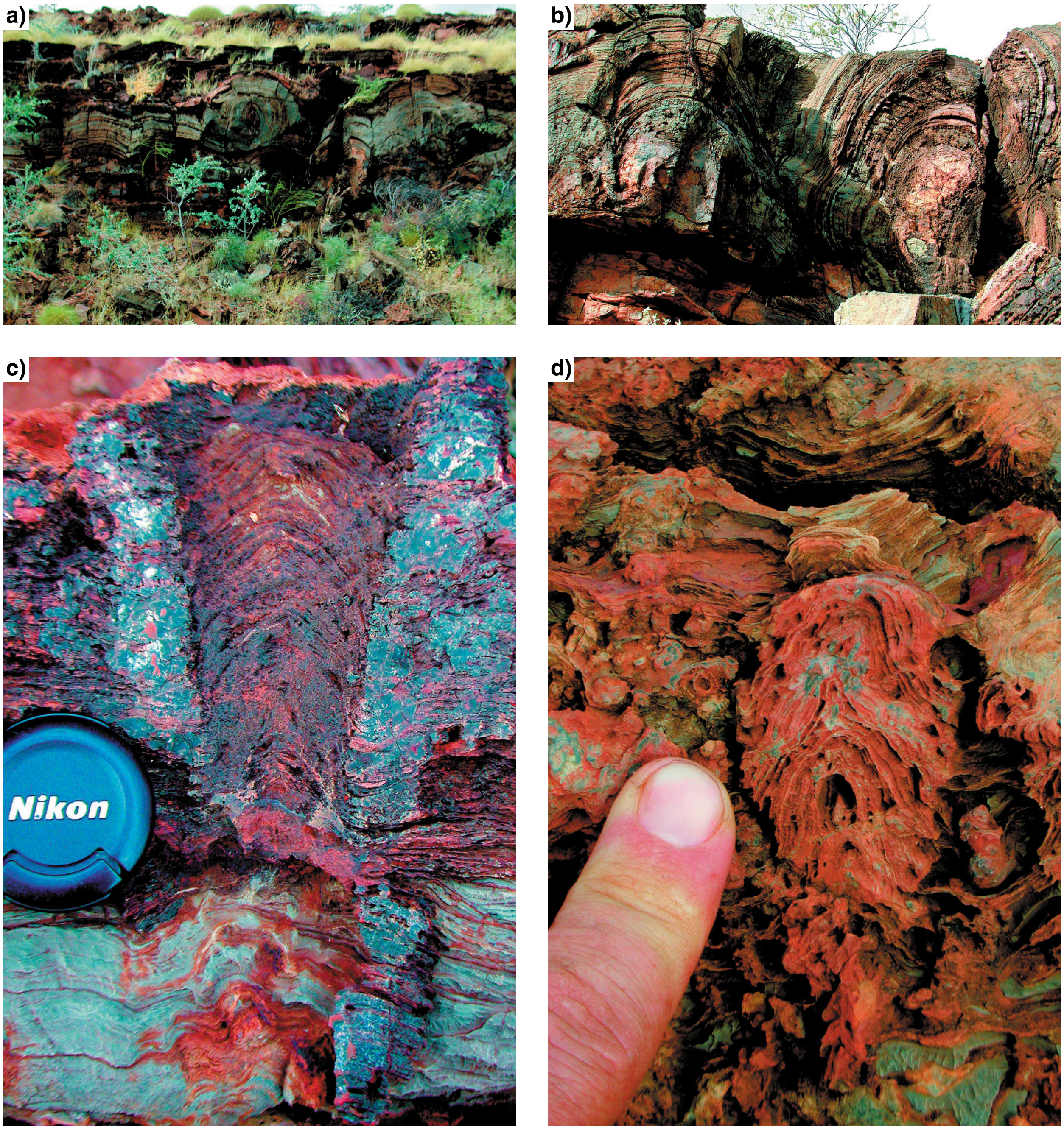

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Figure 3. Outcrop photos of Meentheena Member stromatolites near the site of PDP1: a) long-distance view of the Meentheena Member with metre-scale domical stromatolites (height of cliff is about 4 m); b) close-up view of metre-scale stromatolites; c) mesoscale columnar stromatolite (lens cap is 2 cm in diameter); d) small-scale columnar stromatolite from on top of a large-scale stromatolite, showing a well-developed axial zone

1980; Buick and Dunlop, 1990; Nijman et al., 1998; Van Kranendonk, 2000, 2006; Van Kranendonk and Pirajno, 2004). The bedded deposits are fed by veins of hydrothermal silica(–barite–Fe-oxides) that formed within active growth faults (Nijman et al., 1998; Van Kranendonk, 2006). Syngenetic galena in barite in the formation is dated at 3.49 Ga (Thorpe et al., 1992).

Surface outcrops at the drillsite locality indicate that the lowermost chert–barite unit of the Dresser Formation varies between 6 and 12 m thick across tens of metres of strike length (Fig. 6). Exposures continue for kilometres along strike on either side of the drillsite, but were not mapped in detail. However, several small cross-faults offset the unit along strike to the west and affect the thickness of the stratigraphy, suggesting that they are growth faults, as observed elsewhere in the formation (e.g. Nijman et al., 1998). Underlying the chert–barite unit is carbonate-altered, pale-green weathering komatiitic basalt that is transected by numerous veins of grey to black silica and

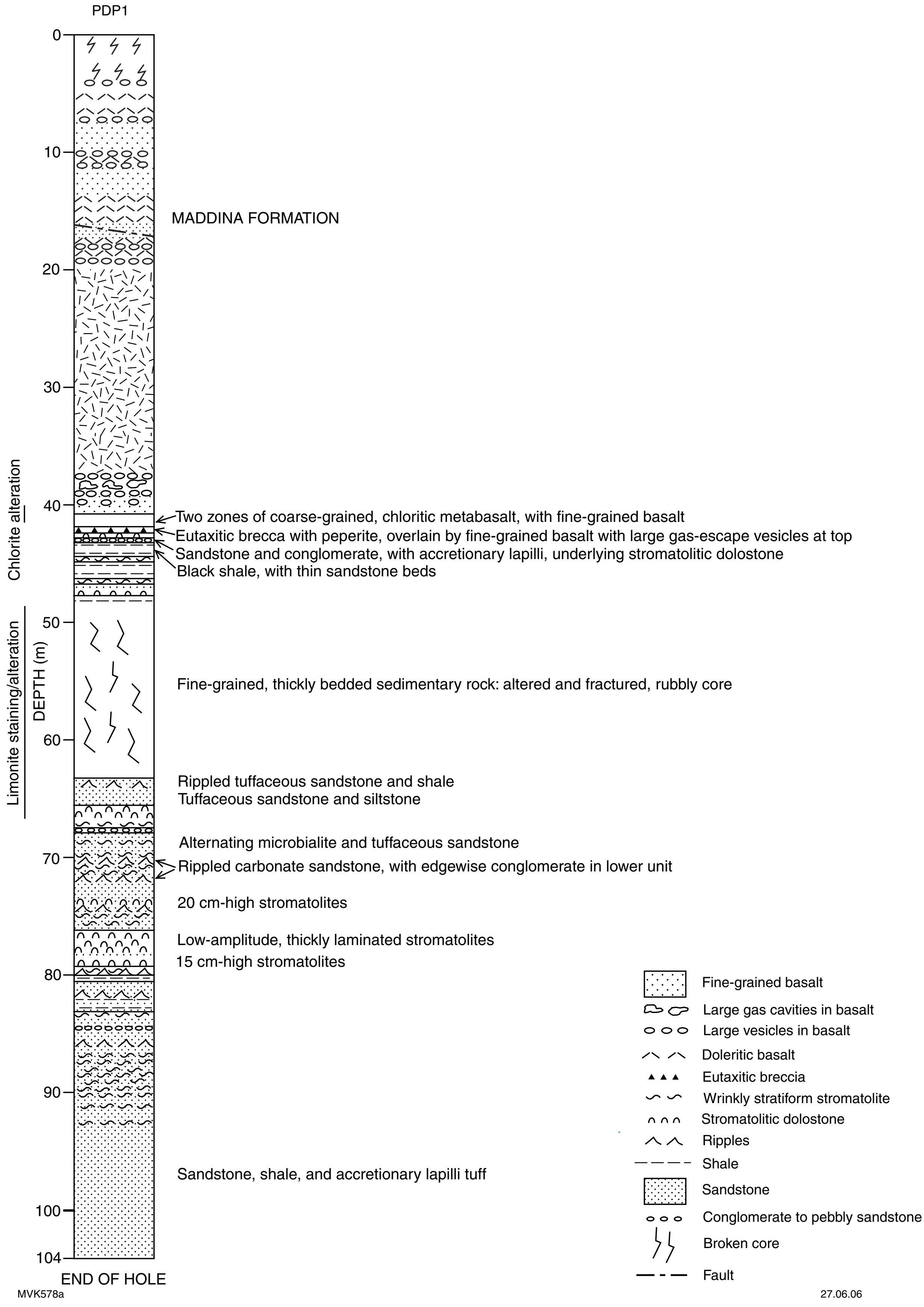

Figure 4. Section of drillhole PDP1 through the Maddina and Tumbiana Formations

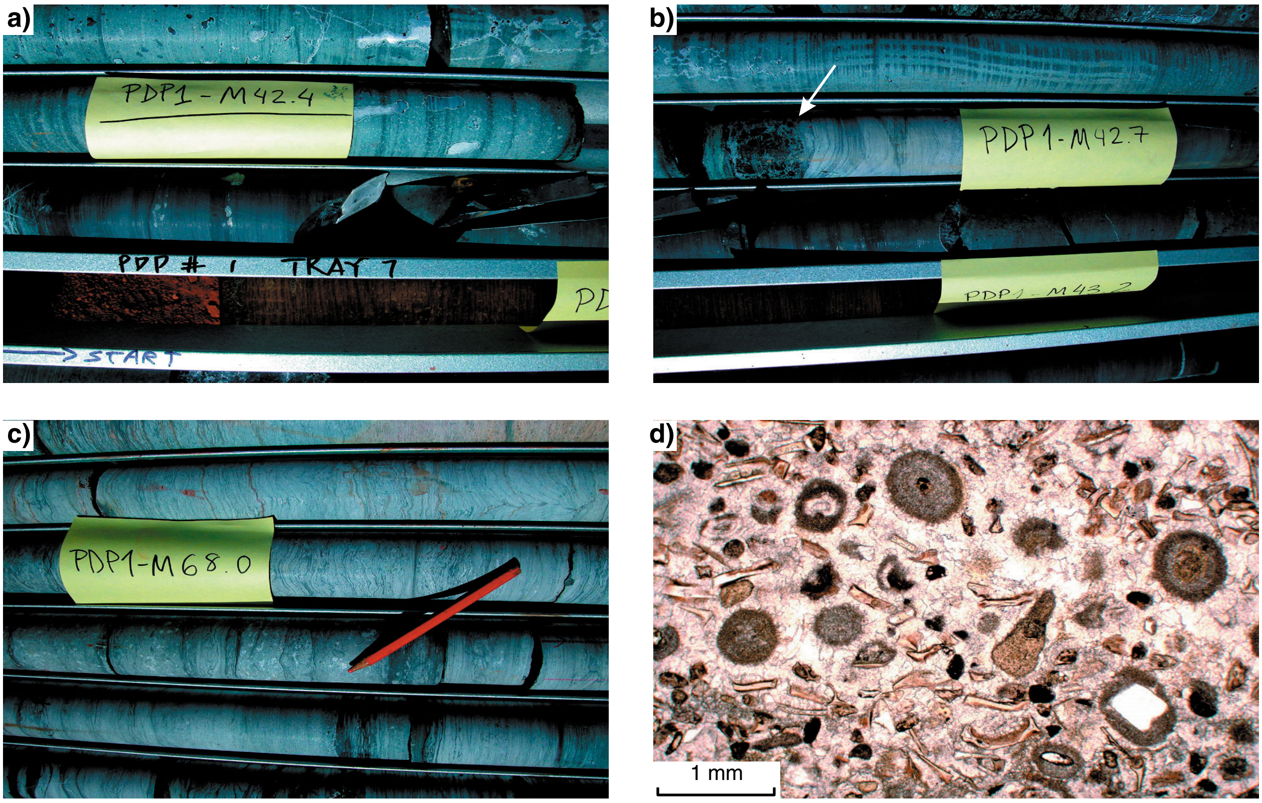

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Figure 5. Samples of Maddina and Tumbiana Formations from PDP1: a) vesicular basalt of the Maddina Formation; b) eutaxitic breccia (arrow) at the base of the Maddina Formation, on the Tumbiana Formation; c) stromatolitic carbonate of the Meentheena Member, Tumbiana Formation; d) thin-section view of volcaniclastic sandstone, showing cuspate volcanic glass shards and accretionary lapilli. Bottom of core is to right in a)–c)

veins of silica–barite. Overlying the chert–barite unit are well-preserved, dark-green weathering, chlorite–carbonate altered pillow basalts that contain amygdales, varioles, and abundant interpillow hyaloclastite breccia. A significant observation is that not a single vein of silica(–barite) cuts the overlying basalts.

Bedded sedimentary rocks of the lowermost chert–barite unit of the Dresser Formation can be divided into six members, in ascending order (Fig. 6). Member 1 has a locally exposed basal contact with underlying basalts and includes a 2 cm-thick unit of angular sandstone to flat pebble conglomerate with clasts of metabasalt up to 1 cm long. Elsewhere, the lower contact of Member 1 is intruded either by black silica veins or by black silica and coarse crystalline barite veins. The remainder of Member 1 consists of coarsely crystalline stratiform barite that is interbedded with greenish grey, silicified, fine-grained sedimentary rock and millimetre-thick layers of wrinkly laminate.

Member 2 conformably overlies Member 1 and consists of 30–40 cm of black-weathering wrinkly laminate containing abundant, low-amplitude domical shapes that are interpreted as probable stratiform stromatolites (Fig. 7a,b).

Member 3 overlies Member 2 with a locally down-cutting erosional basal contact, and consists of an approximately 150 cm-thick, creamy white-weathering conglomerate and sandstone. This member contains clasts, up to 2 cm in size, of wrinkly laminates and chert, but shows no internal bedding. It is locally cut by discordant chert and barite veins at the base, and by sets of 20–30 cm-thick coarsely crystalline barite veins oriented parallel to bedding towards the top. A 10 cm bed of white-weathering, fine- to medium-grained sandstone is at the top of the member. This bed can only be tentatively identified as a felsic volcaniclastic rock due to significant weathering.

The bottom part of Member 4 (Fig. 7c) is composed of 10 cm-thick layers of brown carbonate and metre-thick layers of coarsely crystalline stratiform barite (crystals up to 30 cm long). Wrinkly laminates lie towards the top of the thick barite units. The top part of this member is composed of a 70–160 cm-thick unit of centimetre-layered brown, grey, white, and black chert, with very thin wrinkly laminates at the base, and one broadly domical, low-amplitude stromatolite (30 cm wide by 5 cm high) in the middle. At the easternmost outcrops, the transition from wrinkly laminate and barite to overlying layered chert is marked by a 10 cm-thick unit of rip-up conglomerate with clasts of wrinkly laminates up to 1 cm long.

Member 5 disconformably to unconformably overlies Member 4 (Figs 6 and 7d) and consists dominantly of fairly homogeneous, greenish grey, medium-grained

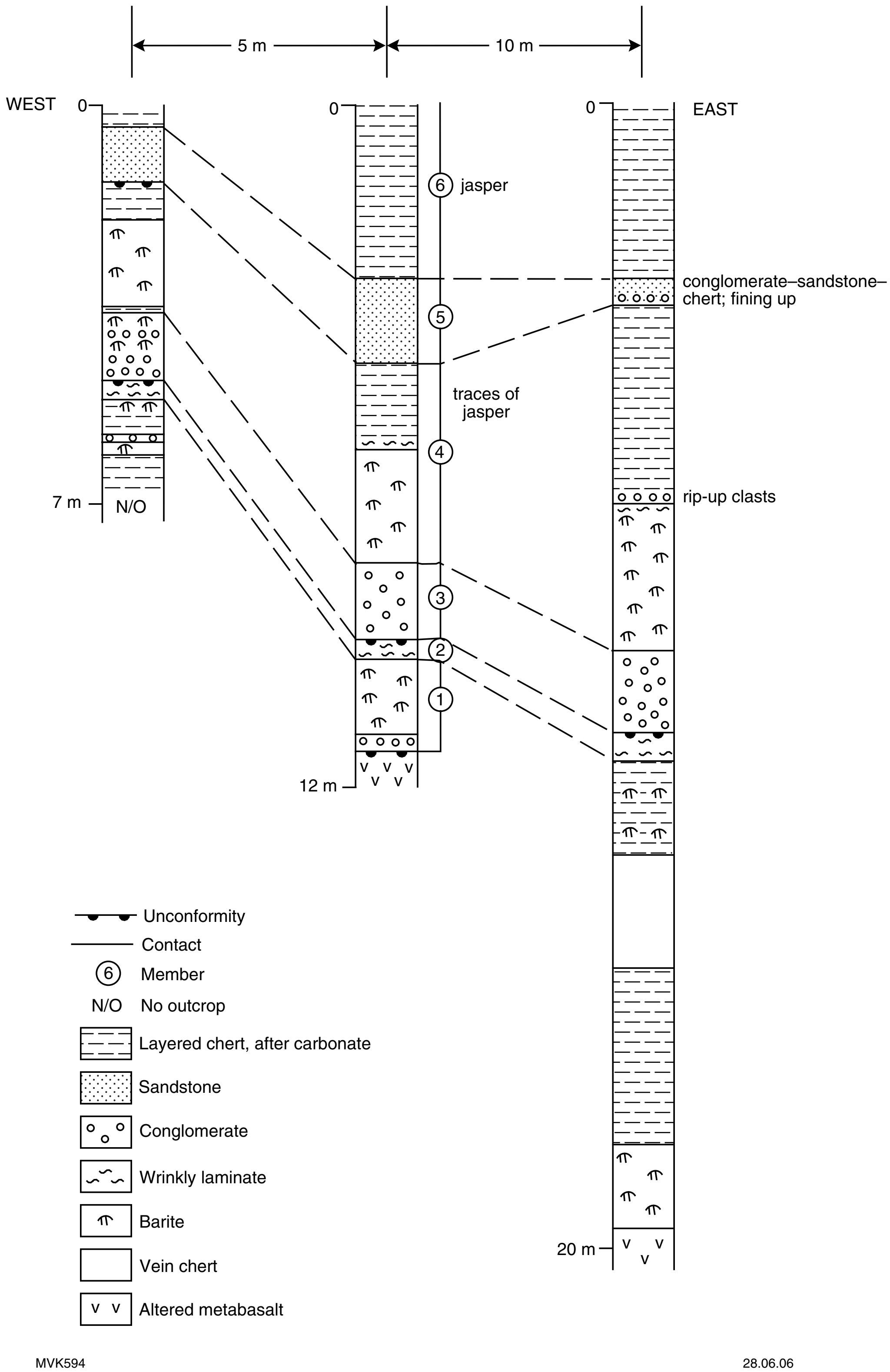


Figure 6. Outcrop stratigraphic sections through the Dresser Formation near the site of PDP2. Circled numbers on the right side of the middle section represent stratigraphic members discussed in the text, and are extended to adjacent sections by dashed lines. Datum of 0 m is the top of the lowermost Dresser Formation chert–barite unit

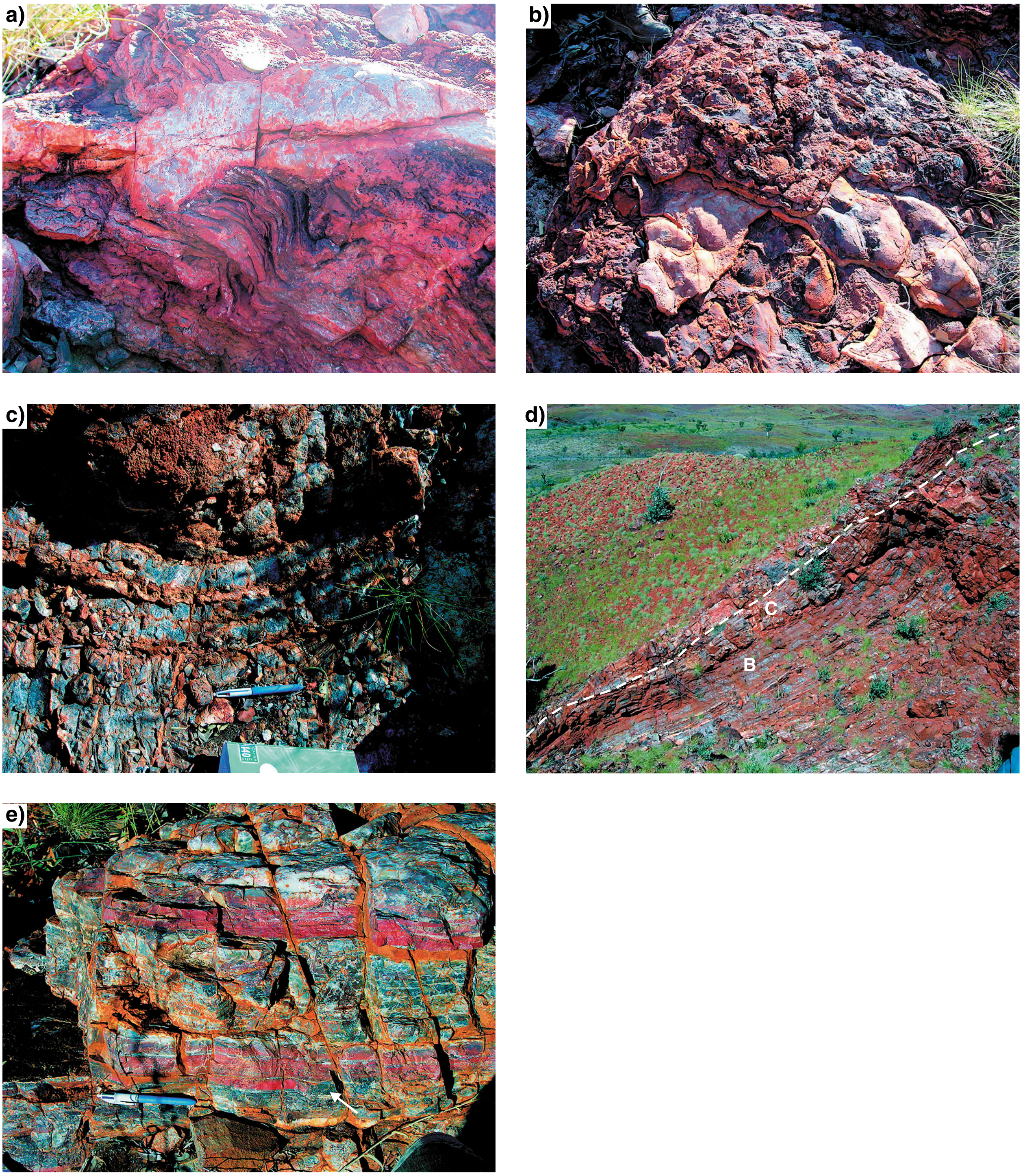


Figure 7. Outcrop photos of the lowermost chert–barite unit of the Dresser Formation near the site of PDP2: a) cross-sectional view of wrinkly laminate of Member 2, interpreted to be stratiform stromatolite, cut by a light-grey silica vein; b) plan view of wrinkly laminate of Member 2. Note the domical forms interpreted to be stromatolites. Light-coloured, smooth surface is a subhorizontal vein of silica parallel to bedding; c) coarsely crystalline barite interlayered with thin wrinkly laminate, from Member 4; d) view looking south of a cross section through the upper part of the Dresser Formation, showing the angular unconformity (dashed line) between Member 4 (lower part of photograph) and Members 5 and 6 (metre-thick, light-coloured unit above dashed line). B = barite; C = chert. Rubbly area in upper part of photograph is proximal colluvium developed on overlying pillowed metabasalt; e) jaspilitic chert of Member 6. Note the discontinuous nature of the jasper bands in the lower part of the photograph (arrow), suggesting a replacement origin for the jasper

sandstone with only faint traces of bedding. At the easternmost outcrops, the member consists of a 50 cm-thick, fining-upwards sequence of conglomerate–sandstone–chert.

Member 6 conformably overlies Member 5; it is up to 7 m thick and composed of centimetre-layered grey, white, and red chert (Fig. 7e).

Variations in stratigraphic thickness of the formation across strike in outcrop are due to thickness variations of the upper carbonate (Member 6), the middle carbonate (Member 4), and the amount of chert and barite in the lower part of the section. Note that the sections outline three upward-fining sequences of local conglomerate and sandstone-layered chert (i.e. Members 1 and 2, Members 3 and 4, and Members 5 and 6), with barite–chert veining restricted to below Member 5 (Fig. 6).

Geology of the drillcore

RC cuttings from drillholes PDP2a, 2b, and 2c consist of variably weathered and altered, pillowed metabasalt, but these were neither sampled nor studied. Bedded sedimentary rocks of the Dresser Formation are between 8.5 and 9.0 m thick in drillhole sections PDP2b and PDP2c (Figs 8 and 9). Neither of these cores contain all six of the members identified in outcrop: Member 3 is missing in PDP2b and Member 4 is missing in both PDP2b and PDP2c. The downcutting unconformity at the base of Member 5–6 is interpreted to be the cause of the loss of Member 4 in both drillholes and the significant thinning of Member 3 in PDP2b, whereas the loss of Member 5 in PDP2b is interpreted to be the result of a lateral facies change. Units identified from the PDP2c drillcore are described below, from stratigraphic base to top.

North Star Basalt

The underlying basaltic rocks are herein correlated with the North Star Basalt. They consist of carbonate-altered komatiitic basalt with relict pyroxene spinifex texture that is now completely replaced by carbonate – white mica – pyrite and with leucoxene that developed as an alteration product of igneous ilmenite. Paragonite (Na-rich mica) has been identified over a 1 m interval by Hyperspectral analysis of the core. Vesicles are filled by an early phase of carbonate and a subsequent phase of microquartz and carbonate that was introduced by crosscutting veins. These veins locally consist of two distinct phases: 1) an early phase of black chert composed of abundant carbonaceous material and minor pyrite, with a remarkable pseudoclastic texture of rounded clasts of variable size in a slightly paler matrix; and 2) a later phase of white microquartz with radiating fibrous quartz texture and with zones of carbonate rhombs or scattered carbonate rhombs in the microquartz.

Dresser Formation

Member 1

Member 1 consists of 255–530 cm of dominantly coarse crystalline barite, with centimetre-thick beds of finely laminated pyrite(–sphalerite), and variable amounts and thicknesses of zoned grey to white chert veins up to 260 cm thick. Carbonate is present in this member, as well as minor amounts of sandstone, as described below. Barite forms a variety of shapes and styles of crystal fans. Most are weakly upward-radiating crystal sets, generally 5–15 cm thick, interlayered with finely laminated pyrite(–sphalerite) (Fig. 10a). Whereas most crystal splays are coarse from the base to the top, some splays grade from coarse crystals at the base to finer crystals towards the top. Barite crystal splays are demonstrably intrusive into the sulfide laminates, and locally into carbonate (Fig. 10b,c). There are also downward-radiating barite crystal splays into the pyritic laminates that also clearly demonstrate the post-depositional nature of most of the barite (Fig. 10d). However, there are one or two examples where flat sulfide laminates are present atop coarse barite crystal fans (Fig. 10e), suggesting the possibility of periodic deposition of pyrite (or pyrite-replaced) laminates directly on barite crystals, as further described below, although this is not absolutely confirmed.

Barite is also in the cores of zoned silica–barite veinlets emplaced parallel to bedding in pyritic laminates, and in barite veins parallel to, or crosscutting the laminates. Characteristically, the coarser, euhedral barite crystals show well-developed growth zoning. At some levels, but not everywhere, growth zones in barite are mantled by fine-grained pyrite (Fig. 10e,f). There is no evidence, anywhere in the core, of original gypsum, as suggested by Buick and Dunlop (1990).

The pyritic laminates vary in form from flat, finely bedded laminates (Fig. 11a), to laminates affected by soft-sediment deformation (Fig. 11b), to laminates with irregular shapes pushed up (or down) by barite crystal fans (Fig. 10d,e), to laminates with columnar stromatolite-like textures (Figs 10e, 11b). There are also centimetre-thick areas of quite irregular pyrite with no obvious lamination. Whereas the shape of pyritic laminates is commonly affected by later barite crystallization, pyritic laminates that outline small columnar stromatolites are in areas unaffected by barite crystal growth, with flat bedding both above and below the columnar structures, indicating a primary origin to the columnar forms (Fig. 11b).

In flat-bedded and stromatolitic pyritic laminates, the fine-scale layering is composed of pyrite, with smaller amounts of carbonate, chert, barite, and sphalerite. In some cases, pyrite has demonstrably replaced carbonate, most importantly in the stromatolitic laminates. Chert, barite, and sphalerite are later components, as described below.

Thin carbonate and sandstone beds are locally preserved. A centimetre-thick bed of carbonate and overlying sandstone is preserved in PDP2c at 96.5 m (Figs 10b and 11c). Here, the carbonate is green in colour and has been partly replaced by pyrite, prior to being cut by barite crystals. These barite crystals cut right through to almost the very top of the carbonate bed, where they are capped by a thin (<0.1 mm), irregular, slightly darker layer of carbonaceous material that may represent an organic biofilm (see description of better-preserved films in Member 6, below). The crystals, as is typical for most of the coarse barite crystals in thin section, have a coarse

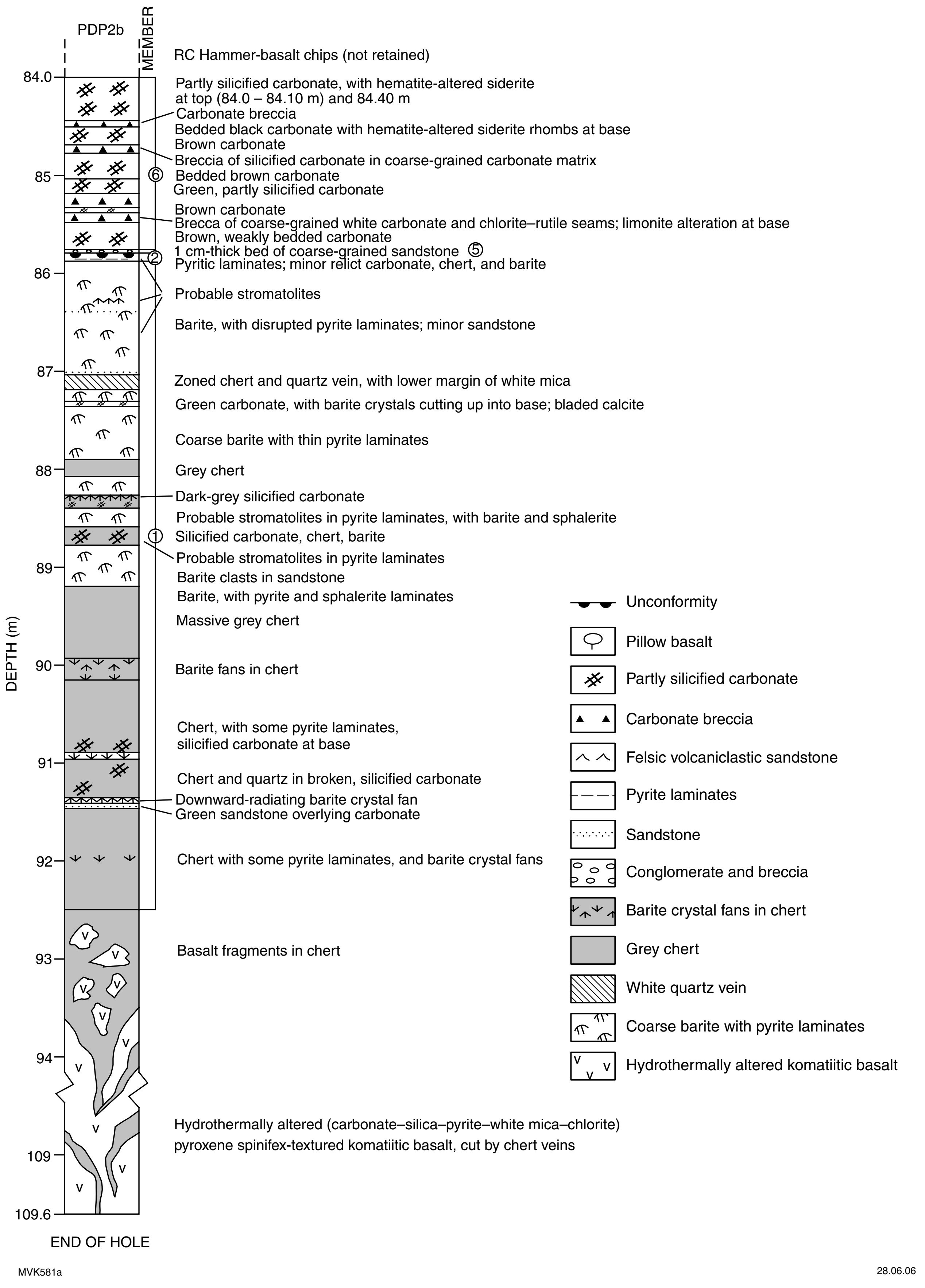


Figure 8. Lithological log of diamond drillcore from PDP2b

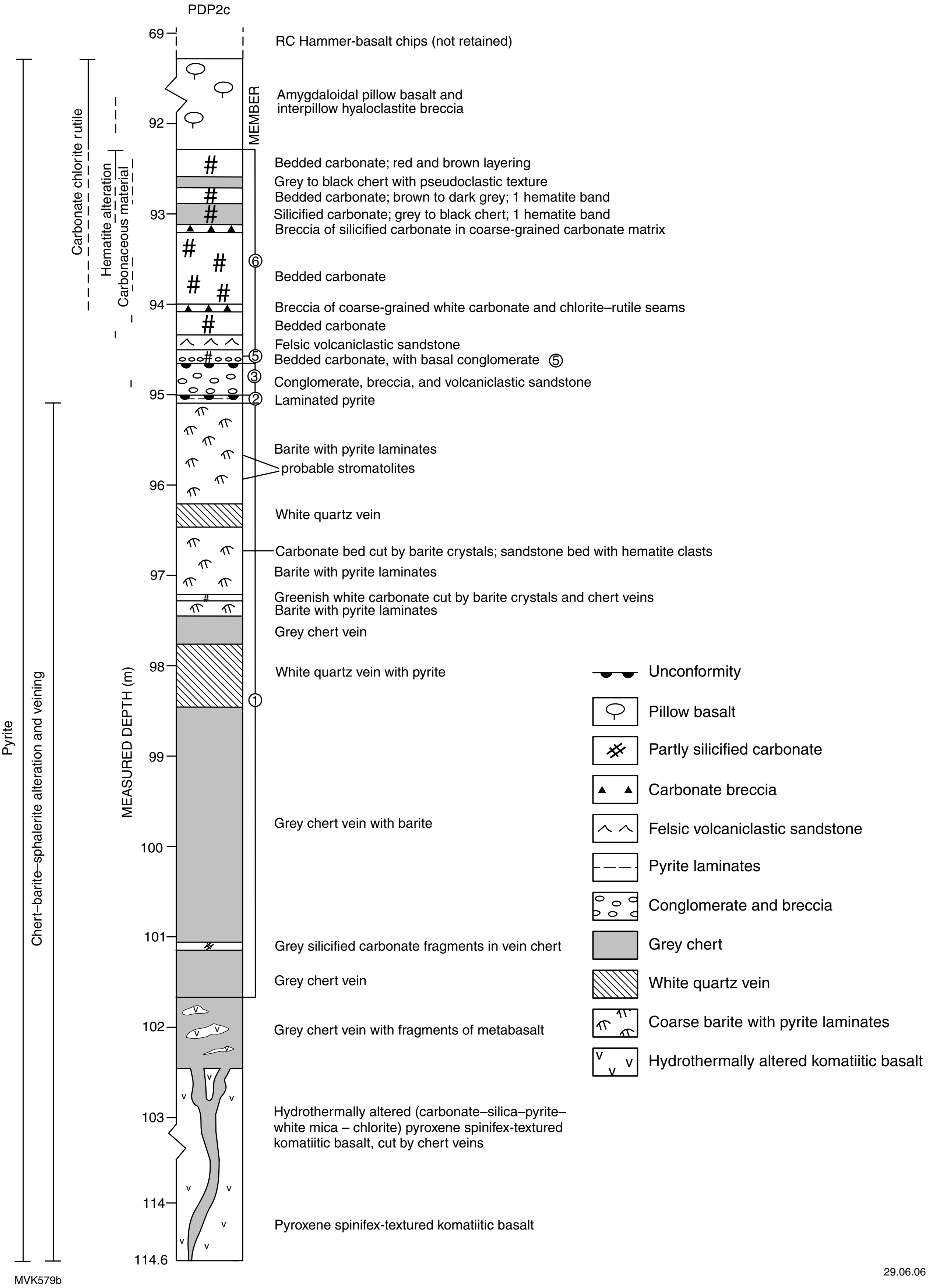


Figure 9. Lithological log of diamond drillcore from PDP2c

crystalline core and a mantle of fine-grained intergrowth of microquartz and barite. This mantle represents the crystallized fluid medium in which the barite crystals grew and which partly resorbed the barite crystals themselves. This marginal zone to the barite crystals continues around the crystal tops where they cut up into the carbonate, without any sign of erosion by the overlying sediment. This indicates that the crystals did not penetrate through the top of the sediment, but crystallized within the carbonate sediment. However, it is clear from the fact that the overlying sandstone thins over the tops of the barite crystals and thickens over the troughs between crystals, that the barite crystals distorted the topography of the seafloor. Therefore, the barite crystals grew below the seabed, prior to lithification of the sediments (Fig. 11c).

The sandstone overlying the carbonate–pyrite–barite association described above contains sand grains that are dominantly composed of very fine grained carbonate rimmed by pyrite. One of the carbonate grains contains a core of microquartz, indicating at least local carbonate replacement of original material, followed by the pyrite replacement. Also present are very fine grained detrital hematite grains, which probably derived from the eroded cores of altered Fe-rich carbonate rhombs, as described below (see also Member 6).

Sandstone was also intersected at 88.8 m in PDP2b. Here, well-rounded clasts, 1–3 mm in size, of barite, carbonate-altered barite, intermediate to felsic volcanic rock, laminated pyrite, hematite, and hematite-altered coarse-crystalline carbonate lie in a matrix of replacive microquartz. This sandstone bed is overlain by further intervals of laminated pyrite and barite crystal fans. This relationship is important because it shows that: 1) there were repeated episodes of barite-rich fluids entering, crystallizing, and being eroded in the system during sediment accumulation; 2) periods of barite crystallization (and locally, erosion) alternated with periods of pyrite replacement of carbonate and possibly of pyrite deposition (laminates); 3) sandstones were being deposited with material sourced from mixed provenance (i.e. distal felsic volcanic clasts and proximal carbonate and barite clasts); and 4) barite was a primary mineral phase during sediment accumulation, and was not formed by later barite replacement of gypsum, as previously suggested (Groves et al., 1981; Buick and Dunlop, 1990). The volcanic clasts are composed of feldspar–porphyritic varieties, with intermediate to felsic compositions that contrast with the underlying basalts. This is important, as it marks the onset of felsic volcanism in this system, whose eruptive products are more proximal and voluminous higher up in the section.

Sphalerite forms zones around barite crystals, is found in barite–chert veins that cut laminated pyrite, and is precipitated between individual laminates of pyrite that have been forced apart by the invading siliceous and barite-rich fluids (Fig. 11d). Thus, sphalerite post-dates precipitation of pyrite and is clearly associated with the intrusion of barite veins.

Multispectral logging of the core has identified hydrothermal kaolinite in the large, white microquartz vein at the base of the member, consistent with the observation of extensive hydrothermal kaolinite in footwall basalts and of minor kaolinite in hydrothermal chert veins in outcrop at the Dresser Mine and farther along strike to the north (Van Kranendonk and Pirajno, 2004). Brown (2005) discussed the difference between the spectra of hydrothermal kaolinite, which has a highly ordered crystallinity, and kaolinite formed by surficial weathering processes, which has a less well ordered structure.

Mineral paragenesis

Evidence from rocks in this member indicates several pulses of fluids precipitating a common sequence of minerals. Sediment accumulation included primary deposition of carbonate. This was followed by pyrite replacement of carbonate, with or without primary pyrite precipitation, and then by crystallization of barite–chert–sphalerite (with local secondary pyrite and carbonate) from later fluids. In some cases, this sequence of events was followed by deposition of sandstone and then by the same sequence of events described above. How many times this process (with, or without all components) took place during accumulation of Member 1 is yet to be determined. However, this will probably remain enigmatic as it is not always clear how much of the pyritic laminates represent carbonate replaced by pyrite, or pyrite deposited as a primary precipitate. Nor is it clear how many of the repeated sequences of barite crystal fans capped by pyrite laminates represent either repeated pulses of pyrite deposition (or pyrite replacement of carbonate) followed by barite crystallization from later fluids, or a single, originally thicker, episode of pyrite deposition (or pyrite replacement of carbonate) that was intruded by multiple bedding-parallel veins of barite-precipitating fluids.

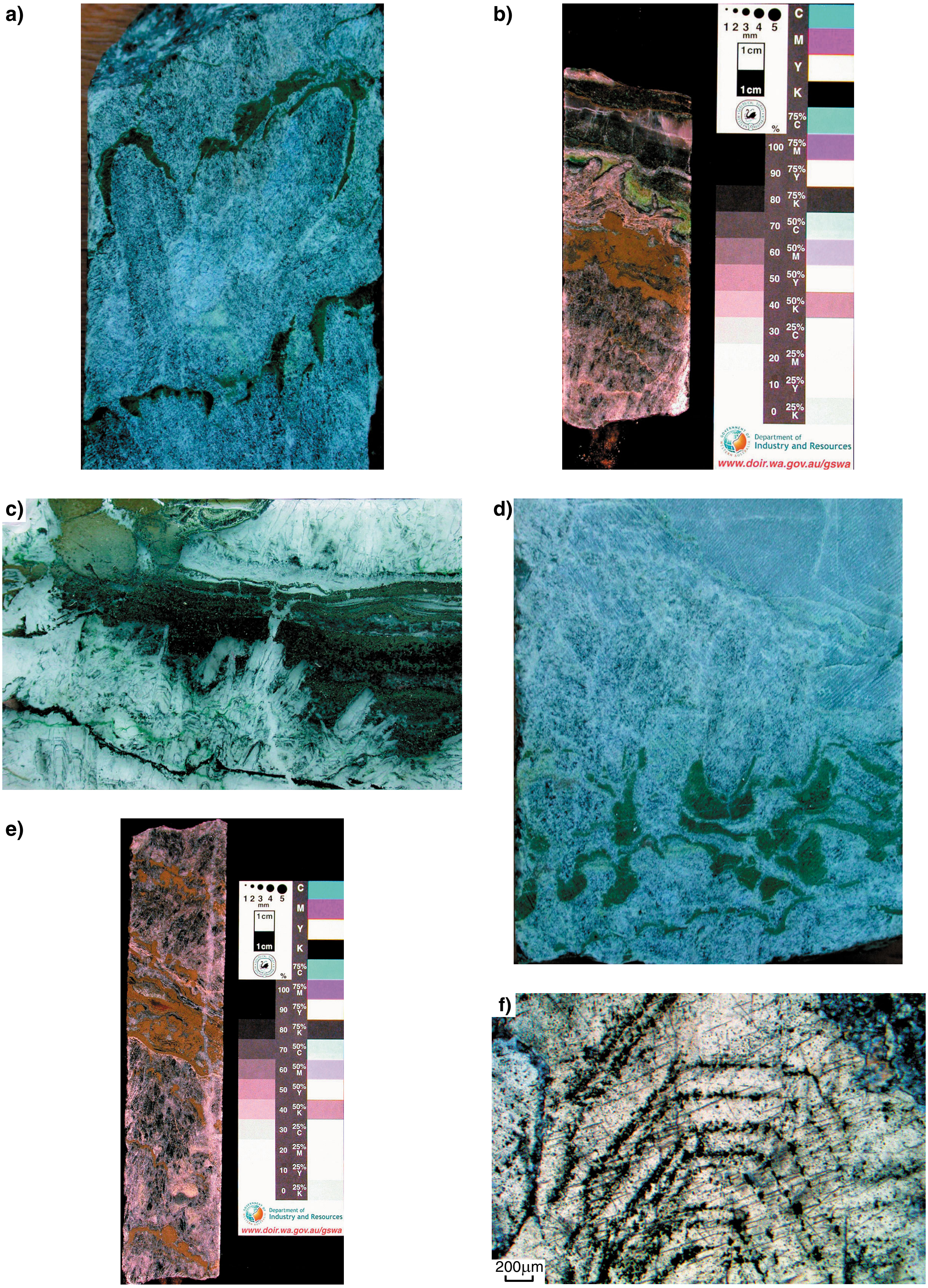
The observation of detrital hematite grains in sandstone in this member indicates early hematite alteration of siderite between the pulses of depositional–hydrothermal alteration events described above. The significance of this and related observations is discussed below.

Member 2

Member 2 consists of flat, thinly bedded pyritic laminates between 5 and 10 cm thick (Fig. 11a). It is not clear if they differ in any way from pyritic laminates in the underlying member, other than being slightly thicker and not intruded by coarse barite crystal fans. Pyritic laminates are cut by veins of microquartz with a barite–sphalerite core. These veins commonly intrude along the pyrite bedding, precipitating sphalerite along pyrite contacts. The microquartz forms a fibrous texture between the laminates, indicating growth as the pyritic strata were forced apart by high fluid pressure.

Member 3

Member 3 in PDP2c is 37 cm thick and can be divided roughly at the midway point into two subunits (Figs 11a and 12). The lower subunit consists of numerous long, thin, disrupted clasts of laminated pyrite (Fig. 13a) and fine-grained, green carbonate in a matrix of microquartz with recrystallized euhedral carbonate rhombs. At the base and top of the subunit are wedges of felsic to intermediate volcaniclastic rock. The top wedge is part of


a)
b)
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200µm
1 cm
Department of Industry and Resources
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a clast of medium- to coarse-grained volcaniclastic rock and overlying felsic ash that is overturned, as indicated by an upward-cutting erosional contact between the ash and the volcaniclastic rock, and by downward-facing graded beds in the ash unit. The volcaniclastic sandstone is composed of carbonate- and white mica-altered volcanic clasts that consist mostly of intermediate to felsic volcanic rock fragments. Most clasts are fine grained (devitrified volcanic glass), but some are plagioclase porphyritic (Fig. 13b), and others have small vesicles.

The overlying subunit contains a 2–3 cm-thick basal bed of fining-upward, coarse- to fine-grained volcaniclastic rock and welded tuff. The base of this bed is poorly sorted pebbly sandstone (Fig. 11a) with well-rounded to subangular clasts, up to 1 cm in diameter, of texturally variable felsic volcanic rock (porphyritic, vesicular, etc.) and felsic volcaniclastic rock. The clasts have been thoroughly affected by chlorite–carbonate–pyrite–white mica alteration, which has resulted in pyrite rims on clasts and alteration of feldspars to microquartz and white mica (Fig. 13c). This bed grades up into felsic volcaniclastic sandstone and welded tuff (Fig. 13d), which in turn passes up into ultra fine grained felsic volcanic ash now represented by very fine grained quartz and white mica. Veins of microquartz and carbonate–microquartz–pyrite cut this unit and are unconformably overlain by rocks of Member 5, as described below (Fig. 12).

The two subunits in this member are separated by a 1–3 mm-thick, locally isoclinally folded seam of strongly foliated chlorite–pyrite–rutile that cuts clasts in both the overlying and underlying volcaniclastic breccia beds (Figs 12 and 13e). Given the proximal nature of felsic volcanism in this unit — as represented by welded tuffs and the coarse, unsorted nature of the breccias — and the hot, ductile nature of the chlorite–pyrite–rutile seam in what is otherwise a very low grade series of rocks, this seam is interpreted to represent a slump fault or tectonic slide associated with a volcanic eruptive event and associated faulting. Further evidence for this interpretation is the fact that bedding in the immediately overlying fine-grained carbonate rocks is moderately dipping. This contrasts markedly with both underlying and overlying bedding, which is subhorizontal, and indicates deposition of the slump on an approximate 45° slope (Fig. 11a).

Figure 10. (opposite) Features of the Dresser Formation in drillcore and thin section: a) part of drillcore showing coarse barite crystals intruding and displacing pyrite laminates (from PDP2b, Member 1); b) drillcore section (from PDP2c, Member 1, 96.6 m) showing coarse barite crystals cutting up into bedded carbonate (green material); c) whole thin-section view of barite crystals cutting through pyrite–sphalerite laminates. Note growth zones outlined by pyrite in the barite crystals (from PDP2c, Member 1, 95.35 m; section is about 4 cm wide); d) drillcore section showing coarse barite crystals growing both downward (upper part of photograph) and upward (bottom part of photograph) into pyritic laminates (from PDP2b, Member 1, 86.4 m); e) part of drillcore showing alternating barite crystals and pyrite laminates (from PDP2c, Member 1); f) thin-section photomicrograph of pyrite growth zones in a barite crystal (from PDP2b, Member 1, 88.4 m). Note that stratigraphic way up (and top of core samples) is at the top of each image. Core in a), b), d), and e) is 47.6 mm wide

Member 5

The basal contact of Member 5 in PDP2c is an unconformity on carbonate–microquartz–pyrite veins that intrude volcaniclastic rocks and breccia of the underlying Member 3 (Figs 12 and 14a). The unconformity surface is marked by a 1 mm-thick zone of evenly spaced, small, euhedral tourmaline crystals and abundant white mica encrusted in pyrite (Figs 12 and 14b). This is overlain by a thin layer (1–2 mm) of very finely bedded carbonate that is partly replaced by pyrite, which in turn is overlain by a 1.5 cm-thick bed of conglomerate composed of tabular silicified carbonate clasts in a matrix of replacive microquartz. In PDP2b, Member 5 is represented by a 1 cm-thick bed of coarse-grained sandstone (Fig. 8).

Member 6

Conformably overlying Member 5 in PDP2c is 10 cm of finely laminated carbonates that are variably replaced by pyrite, grading up to black chert (that represents silicified carbonate) with finely dispersed clots and particles of carbonaceous material. Bedding is locally developed as very fine scale couplets of light (carbonate) and dark (pyrite-rich) bands, with local small-scale, low-amplitude cross-beds, that may represent either tidal (cf. Groves et al., 1981) or seasonal layering (Fig. 14c). Centimetre-thick bedded carbonate units overlie this. Hematite appears rather irregularly in the bedded carbonates at the top of this unit, in addition to the continued presence of the scattered pyrite crystals through the carbonate matrix that are characteristic of this member (see discussion below).

A 15 cm-thick unit of well-sorted, fine- to medium-grained felsic volcanolithic sandstone overlies the carbonates (Figs 12 and 14d). This unit contains clasts of white mica altered felsic volcanic rock, less common clasts of devitrified felsic glass, common euhedral to subhedral volcanic quartz phenocrysts, angular quartz crystal fragments, volcanic quartz crystals with resorbed margins, and zircon grains (Fig. 14e). Two main beds are represented in this unit, each of them fining upward to very fine grained felsic ash with small, but well-defined cross-bedding. At the top of the second bed is a 1.5–2 cm-thick unit of flat pebble conglomerate composed of curved tabular clasts (up to 1.5 cm in size) of bedded felsic ash — now altered to silica and white mica — in a matrix of dark-blue microquartz with rhombs of carbonate (Fig. 12). One quarter of the drillcore material has been submitted for geochronology, from which zircons have been extracted. Results will be published elsewhere.

Overlying the felsic volcaniclastic unit is about 2 cm of thinly bedded carbonates that have been completely replaced by very fine grained pyrite and intruded by

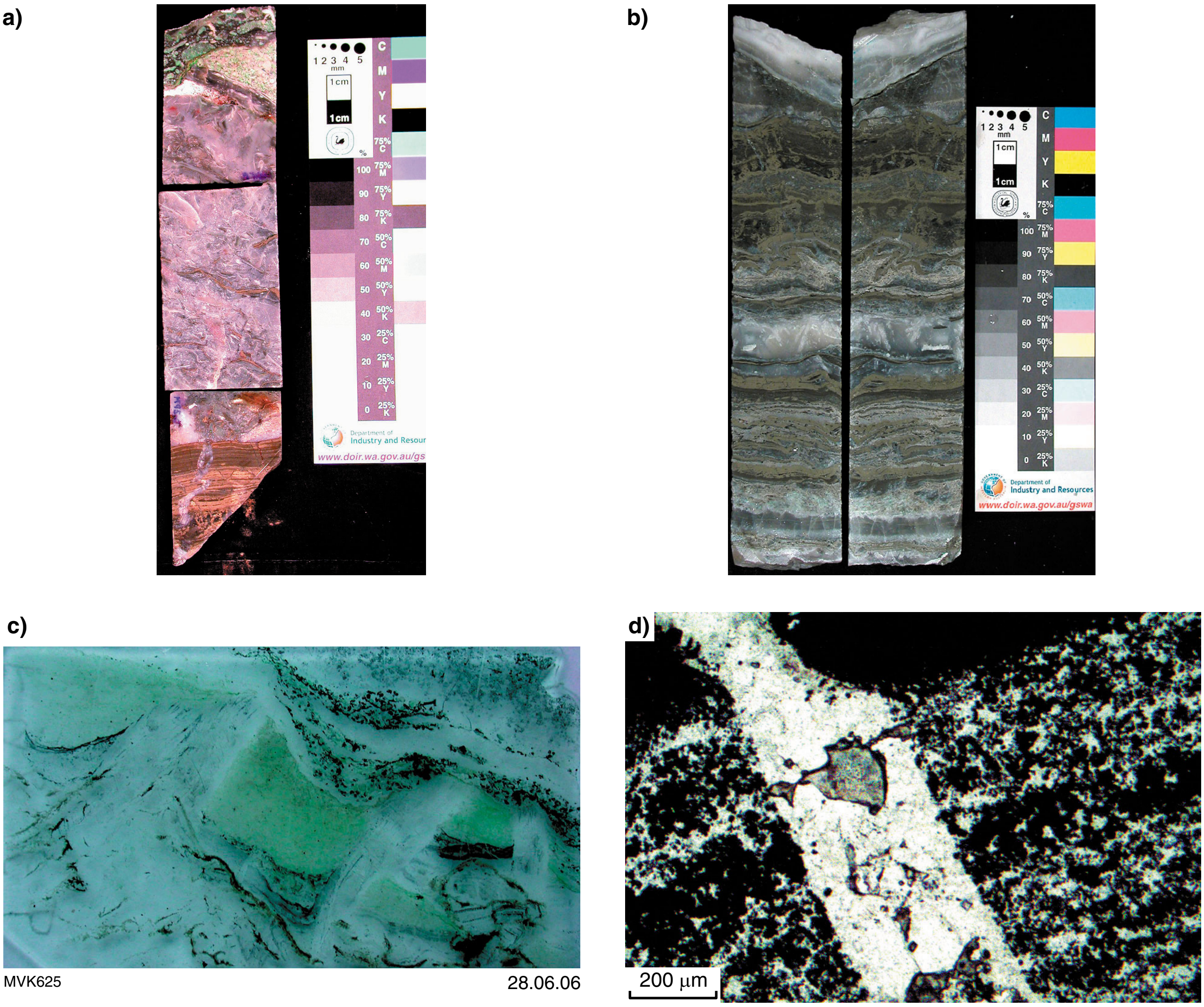


Figure 11. Drillcore and thin-section examples of specific textures in PDP2b and PDP2c: a) part of drillcore showing the disconformable contact between pyrite laminates of Member 2 (bottom of core section) and overlying conglomerate of Member 3, which contains long, thin clasts of pyrite laminates (from PDP2c, 94.8 – 95.1 m). Greenish coloured rocks at the top of the core section are intermediate to felsic volcaniclastic rocks (see Fig. 12); b) part of drillcore showing different types of pyrite laminates, including flat laminates, laminates affected by soft-sediment deformation, and laminates with stromatolite-like forms. White areas are chert and barite, and sphalerite is present below the lowest pyritic laminates (from PDP2b, Member 1, 88.4 – 88.6 m); c) whole thin-section view of barite crystals that cut through green carbonate that has been partly replaced by pyrite. The bedded carbonate and barite crystals are overlain by sandstone that is cut by subhorizontal veins of barite (from PDP2c, at 96.6 m; width of section = 4 cm); d) thin-section photomicrograph of barite (white) sphalerite vein cutting across pyrite(–carbonate–microquartz) laminates that display weak bedding (from PDP2c, Member 1, 95.0 m). Note that stratigraphic way up (and top of core samples) is at the top of each image

white quartz veins. This passes up to 1.25 m (from 94.45 to 93.2 m) of faintly bedded, dominantly greyish brown to greenish grey carbonate that is intruded by several bedding-parallel veins of microquartz with coarse carbonate rhombs, veins of coarse-grained carbonate, and crosscutting veins of microquartz–pyrite–chlorite. The mineralogy of the bedded carbonate consists of carbonate and microquartz(–pyrite–carbonaceous material–hematite). Millimetre- to centimetre-scale bedding is well developed throughout the unit, defined by slight changes in texture, the amount of pyrite, the number of irregular clots of carbonaceous material, and grain size. Graded bedding is common.

Carbonate rocks of this part of the section typically consist of a mosaic of very fine grained carbonate (micrite), sparsely distributed carbonate crystals up to 1 mm in size (sparry carbonate), and small euhedral crystals of pyrite (Fig. 14f). Microquartz varies in proportion across the unit, but locally accounts for up to 50% of the rock, having replaced the fine-grained carbonate. Replacement of primary carbonate by microquartz results in microquartz precipitation and recrystallization of the carbonate to clear carbonate rhombs, but this process does not affect the scattered pyrite crystals or the clots of carbonaceous material that remain unaltered and in situ in the replaced matrix. Elsewhere, carbonate rocks consist of dominantly

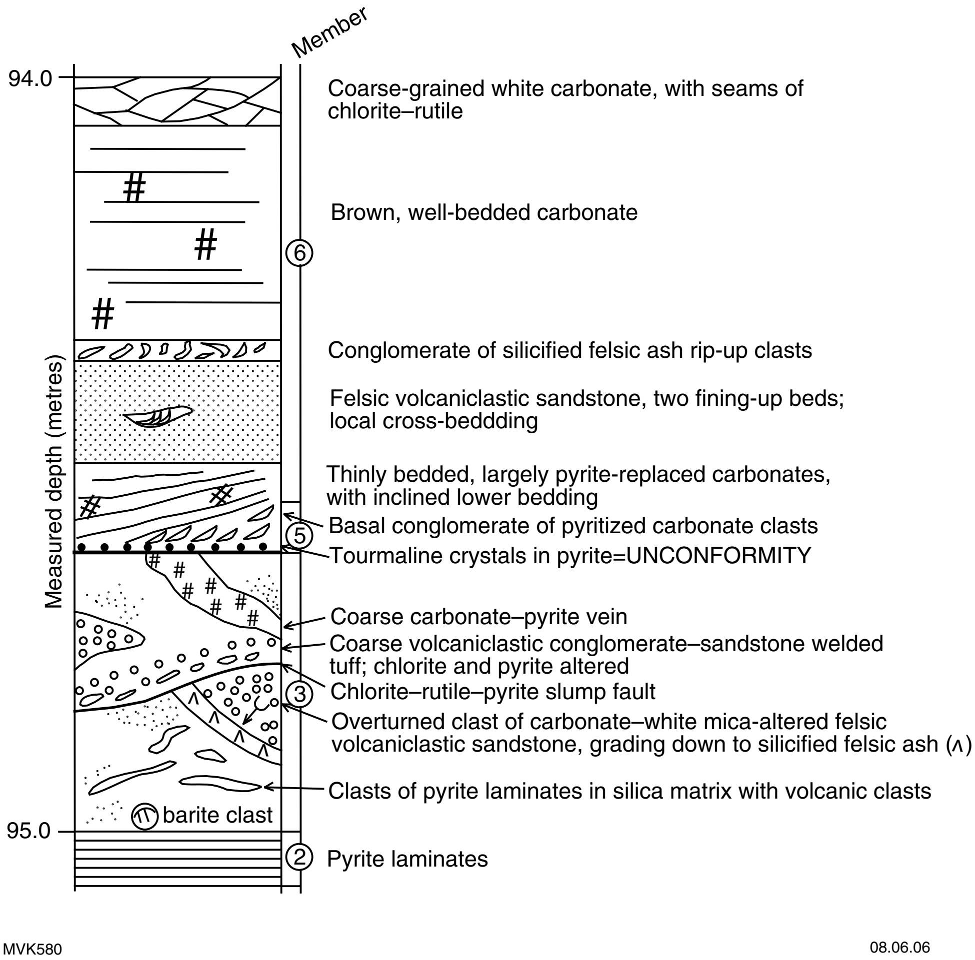


Figure 12. Detailed lithological log of part of diamond drillcore PDP2c, from 94.0 to 95.2 m, showing detailed lithological features of Members 3, 5, and 6. See Figures 11a, 14a, and 14d for photographs of sawn half-core splits

sparry carbonate, which is either well crystalline with dark, spotted cores and clearer rims, or less well crystalline.

The bedded carbonate rocks of this member are cut in both drillhole intersections by three layers of coarsely crystalline carbonate breccia. Lowest in the section (at 94.1 m in PDP2c) is a 10–15 cm-thick, white and green carbonate breccia composed of coarse-grained white carbonate with seams of dark-green chlorite. In PDP2b, the equivalent breccia contains angular fragments of the fine-grained, grey, bedded carbonate host rock (Fig. 15a). The white carbonate matrix has an angular, brecciated texture, with fragments lined by thin seams of chlorite and rutile; these minerals also fill spaces between carbonate crystals within the fragments. Contacts of the matrix carbonate with the bedded carbonate above and below vary from sharply planar to irregular.

Higher up in this member (at 93.3 m in PDP2c) is a 10–30 cm-thick breccia of tabular to rounded fragments of fine-grained, silicified grey carbonate in a matrix of coarsely crystalline carbonate spar with thin rinds of chlorite and rutile. Discontinuous stylolites lined by chlorite are found in this unit at all orientations, and chlorite veins cut the breccia.

Bedded carbonate rocks continue above the topmost breccia horizon to the top of the sedimentary succession. These rocks vary from fine- to medium-bedded rocks at the base, in which faint, irregular traces of hematite colouration appear (Fig. 15b). The upper 30 cm contains alternating layers of black to dark-brown, fine-grained carbonate, bedding-parallel veins of microquartz with scattered carbonate rhombs, and bright-red, fine-grained, hematite-altered carbonate that becomes dominant in the uppermost 10–30 cm of the section, although even at this level, hematite-altered siderite beds are interbedded with calcite beds (Fig. 15c). In thin section, much of the fine-grained, hematite-altered carbonate higher up in the section has a distinctive, weakly developed rhombic texture of slightly darker carbonate (siderite) surrounded by vaguely crystalline laths of clearer carbonate (?calcite). Significantly, pyrite in these beds is not altered to hematite, even though the pyrite formed prior to, and independently of, the hematite alteration. Lower down in the section, hematite is gradually developed across bedding, or concentrated along the margins of thin, bedding-parallel microquartz veins. In all cases, thin-section observations show that the hematite exists as tiny grains that replace the dusky cores of the weakly rhombic carbonate matrix and is not a primary precipitate. Furthermore, the hematite

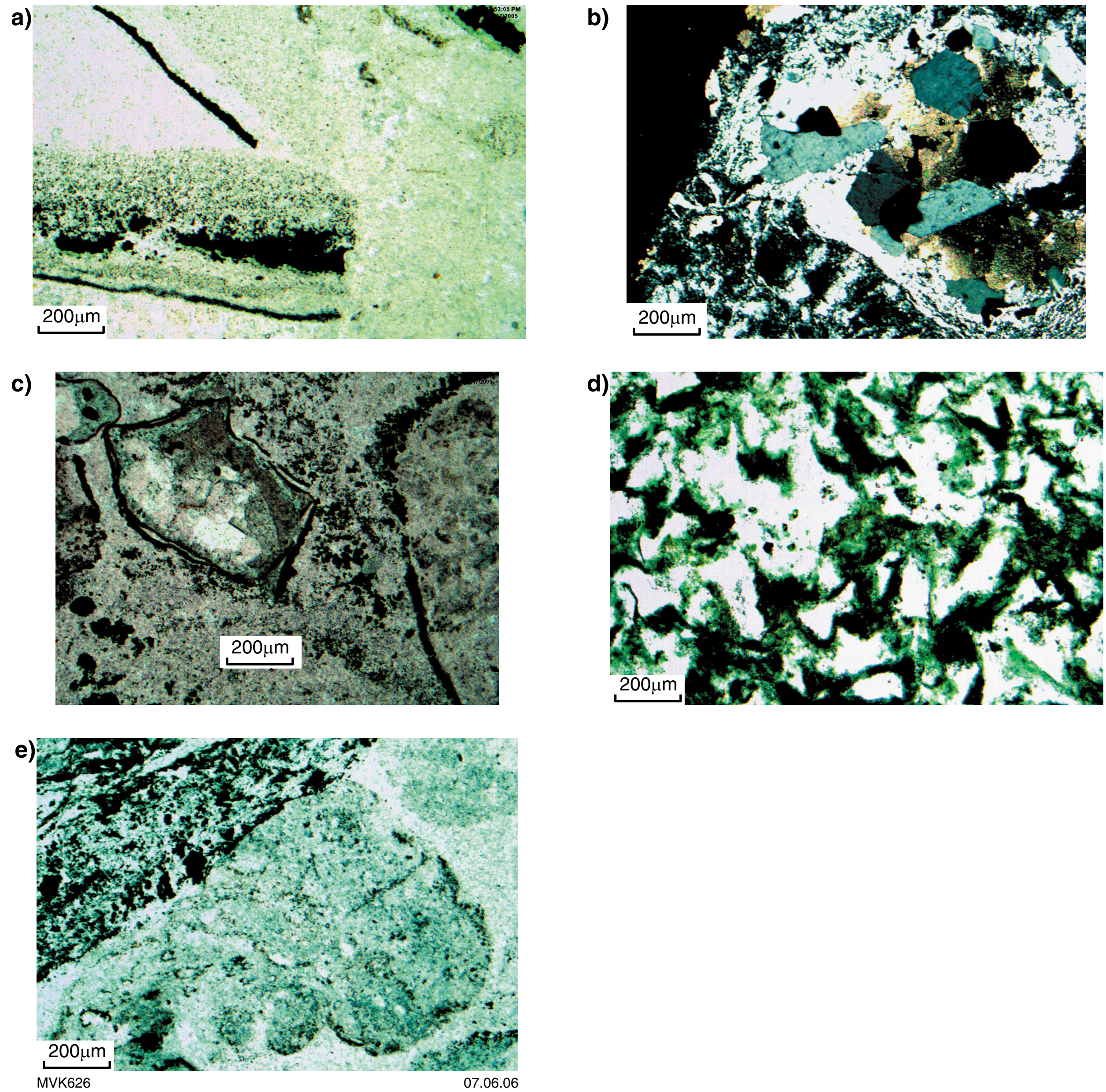
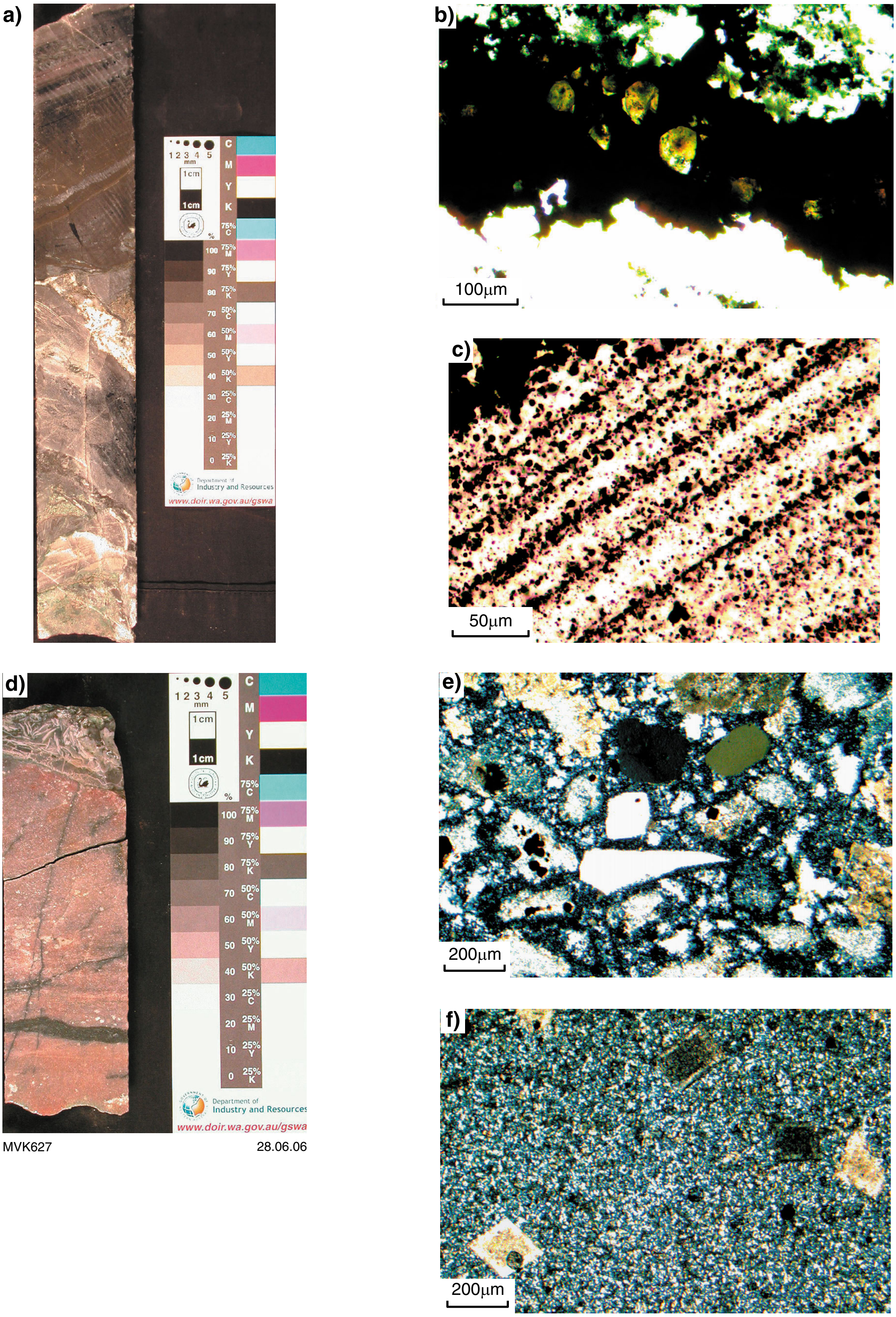


Figure 13. **Photomicrographs of detailed textural features of Member 3 conglomerate from PDP2c at 94.8 m: a) plane-polarized light view of angular clasts of carbonate that have been partly replaced by pyrite prior to incorporation into the conglomerate; b) cross-polarized light view of an intermediate to felsic volcanic clast containing euhedral, pseudohexagonal (triclinic) feldspar phenocrysts (?albite) in a matrix affected by carbonate alteration; c) plane-polarized light view of clasts that have been affected by almost complete carbonate alteration and are rimmed by pyrite, indicating pyrite alteration after incorporation of clasts into the sediment; d) plane-polarized light view of welded felsic volcanic tuff; e) plane-polarized light view of felsic volcanic fragment cut by chlorite–rutile–pyrite slump fault**

Figure 14. **(opposite) Drillcore and thin-section features of units in PDP2c: a) upper part of the conglomerate of Member 3 and overlying Members 5 and 6 (from PDP2c, 94.5–94.8 m); b) plane-polarized light view of the unconformable contact between Member 3 (white area at bottom) and Member 5, showing a basal layer of euhedral tourmaline crystals encased in secondary pyrite (from PDP2c, 94.6 m); c) plane-polarized light view of very thinly bedded carbonate rocks from Member 6, which are partly replaced by pyrite (from PDP2c, 94.6 m); d) weakly hematite-altered felsic volcanolithic sandstone and overlying conglomerate (from PDP2c, 94.35–94.5 m); e) cross-polarized light, thin-section view of felsic volcanolithic sandstone with a prominent angular quartz crystal fragment, subhedral volcanic quartz clasts, and finely recrystallized felsic volcanic rock in a silicified matrix (from PDP2c, 94.45 m); f) cross-polarized light view of well-preserved carbonate from Member 6, showing zoned, sparry dolomite rhombs overgrowing micritic carbonate matrix with scattered small subhedral pyrite crystals (from PDP2c, 92.7 m). Note that stratigraphic way up (and top of core samples) is at the top of each image**


a)
b)
100µm
c)
50µm
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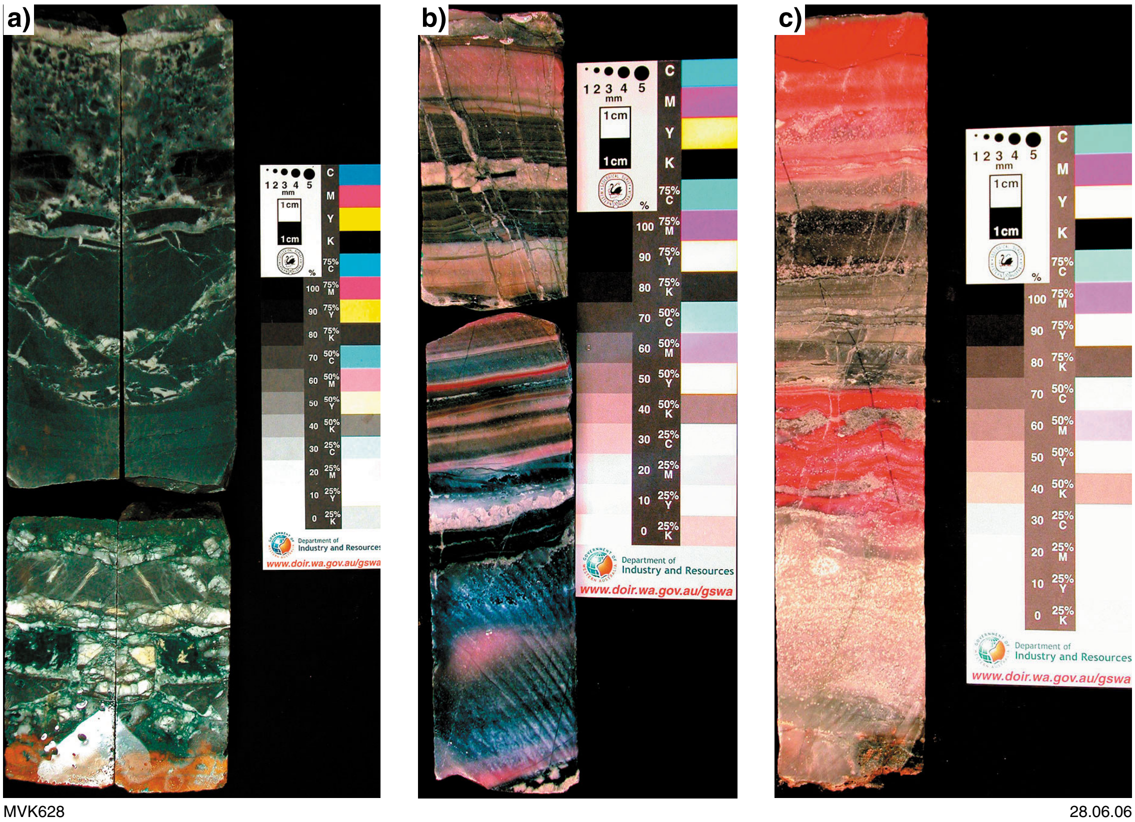

Figure 15. Drillcore textures in the upper parts of PDP2b and PDP2c: a) dissolution breccias in bedded carbonate of Member 6 (from PDP2b, 85.15–85.35 m); b) weakly hematite altered, bedded carbonate of Member 6 (from PDP2c, 92.7–92.9 m); c) strong, but variable hematite alteration of bedded carbonate from the top of Member 6 (from PDP2c, 92.3–92.5 m). Note that stratigraphic way up (and top of core samples) is at the top of each image

alteration is restricted to the topmost part of the section, near the contact with overlying basalt, even though Fe-rich carbonate is present lower down in the section. This unequivocally indicates that the generation of hematite is a product of later fluid alteration, as discussed below.

Mineral paragenesis

Micritic carbonate and carbonaceous material are the primary minerals in the carbonate rocks of this member. The micritic carbonate is overgrown by pyrite crystals and carbonate rhombs (sparry carbonate) that are interpreted to represent the products of diagenesis. Diagenetic replacement of bedded carbonate by pyrite was extensive lower in the section, indicating reducing conditions. The sparry carbonate rhombs are zoned, with dusky cores and clear rims. The pattern of hematite alteration of the carbonate in drillcore, combined with multispectral analyses of the drillcore samples, indicates that bedded carbonate is an interbedded mixture of siderite, ankerite, and calcite.

Secondary hematite alteration and recrystallization of the primary carbonate material is prominent higher up in the section, and becomes pervasive at the top. The middle part of the section is little altered, allowing for the preservation of carbonaceous biofilms and micrite; however, secondary fluids rich in carbonate, iron, and titanium caused the alteration (and ?formation) of the three coarse crystalline carbonate(–chlorite–rutile) horizons between 93.0–94.2 m in PDP2c. As discussed below, it is considered significant that these fluids contain the same mineral assemblage as the alteration mineral assemblage of the overlying pillow basalt.

Overlying pillow basalt

The upper part of the drillcore (69.3–92.3 m in PDP2c) is composed of pale-green amygdaloidal pillow basalt of the Dresser Formation, which has abundant interpillow hyaloclastite breccia. The mineral assemblage of this unit is a fine-grained mixture of Fe-rich chlorite–carbonate–pyrite(–rutile–microquartz). Amygdales are filled by a rim of microquartz and a core of coarse-grained carbonate. The carbonate core of one amygdale contains hematite grains as well as minor amounts of very fine grained pyrite. No chert, carbonate, or barite veins cut this basalt unit, which is consistent with observations in outcrop. Multispectral mapping of the core shows that the composition of chlorite changes about half way through the basalt section (at about 77 m), from intermediate chlorite (in terms of Fe/Mg composition) at the top, to more Fe-rich chlorite in the lower half. Epidote is found towards the top of the hole, where secondary montmorillonite (a product of surficial weathering) was also identified from multispectral mapping. The multispectral mapping has identified the carbonate composition as a mixture of siderite, calcite, and ankerite.

Conclusions

The results of diamond drilling through the c. 2.72 Ga Meentheena Carbonate Member of the Tumbiana Formation (Fortescue Group, Mount Bruce Supergroup: PDP1) and c. 3.49 Ga Dresser Formation (Warrawoona Group, Pilbara Supergroup: PDP2) has resulted in the successful acquisition of fresh rock samples from below the zone of surficial oxidative weathering.

Primary mineralogy and textures are preserved in all drillcores, reflecting the remarkable preservation of these very old rocks. Carbonate rocks from the top parts of the drillcore sections of both the Tumbiana and Dresser Formations have been affected by chlorite–rutile alteration, which is interpreted to be the result of hydrothermal fluid circulation beneath the overlying basaltic rocks. More pristine material is preserved below these areas.

The section through the Tumbiana Formation shows that stromatolitic limestones are interbedded with two types of clastic sedimentary material derived from two different sources: a volcaniclastic sedimentary source derived from deposition of volcanic ash, and quartz-rich terrigenous material derived from weathering of the basement granite–greenstone rocks of the Pilbara Craton. Volcaniclastic material is more common in the lower parts of the section (Mingah Member), with influx of more-terrigenous material in the upper half. Domical, columnar, and stratiform stromatolites are found interbedded with the volcaniclastic material, indicating a fight for survival against high rates of influx of volcaniclastic material. Abundant ripples throughout the section indicate a shallow-water environment of deposition. Overlying basalts of the Maddina Formation became subaerial within 2.27 m of the base of the renewed mafic volcanism.

The results from drillcore sections and surface geology show that Dresser Formation stratigraphy varies significantly over short distances. This is attributed to active tectonism during sediment deposition, which brought about tilting of the lower members of the sedimentary succession. Sediment accumulation was accompanied by intermediate to felsic volcanism throughout, and by extensive hydrothermal-fluid circulation that resulted in precipitation of pyrite, chert, and barite(–sphalerite). These observations preclude deposition in a quiet-water lagoon, as previously suggested (e.g. Groves et al., 1981; Buick and Dunlop, 1990), but support the more recent model of deposition within a volcanic caldera (Van Kranendonk, 2006). Mineral paragenesis indicates that carbonate was a primary sedimentary precipitate that was partly replaced by pyrite and then by barite–chert–sphalerite during pulses of hydrothermal fluid circulation. Clasts of barite in sandstone and conglomerate beds that are overlain by bedded carbonates attest to the repeated nature of events during this period, including: carbonate precipitation from seawater; hydrothermal fluid circulation and crystallization of related minerals; and erosion. The downcutting erosional surface at the base of the upper unit (Members 5 and 6) is interpreted to reflect a period of subaerial erosion following tilting of the older units (Members 1–3) and uplift during a maximum period of felsic volcanism (possible caldera formation). This was followed by a return to deeper water conditions during the final stages of felsic volcanism and sediment deposition. The results of more-detailed scientific analysis of the drillcore material will be presented in scientific journals.

Future research

The following research is currently being conducted on both the PDP1 and PDP2 cores:

- study of carbon isotope ($\delta^{13}C$) compositions of organic material
- study of sulfur isotope compositions of sulfide and sulfate minerals ($\delta^{34}S$)
- study of iron isotopes in hematite grains
- Laser–Raman spectroscopic imagery on organic material from PDP1, PDP2b, and PDP2c
- detailed Transmission Electron Microscopy (TEM) studies on a variety of fine-scale microstructures in the core to search for additional textural evidence of ancient life
- U–Pb dating of zircons from the felsic volcaniclastic horizon in PDP2c, conducted at GSWA
- microbiological study of drillcore material.

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HyLogging Analysis of Drill Hole PDP2C Marble Bar, Western Australia

Summary Results

V1 - Subject to revision

June 24th 2005

DRAFT

CSIRO MERIWA GSWA

This report summarises selected results from MERIWA Project M375 sponsored by GSWA, Placer Dome Asia Pacific and Gold Fields Australia. It does not comprise the full findings nor the full HyLogging data sets collected. These will be available in due course from the GSWA, and may be viewed with the software package *TSG-Viewer* available from http://www.thespectralgeologist.com

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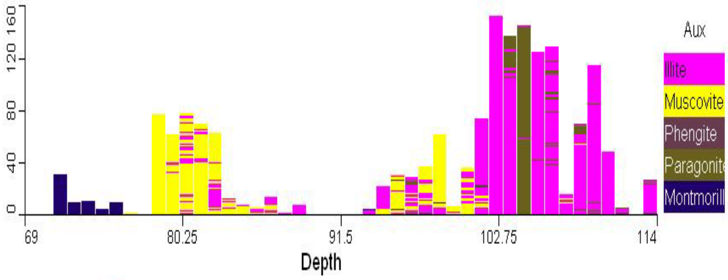
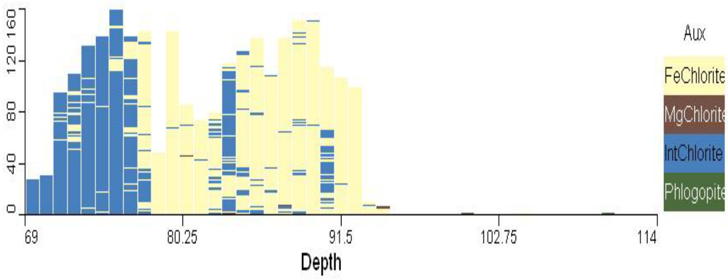
Phone: +61 (02) 9490-8839. Email: jon.huntington@csiro.au

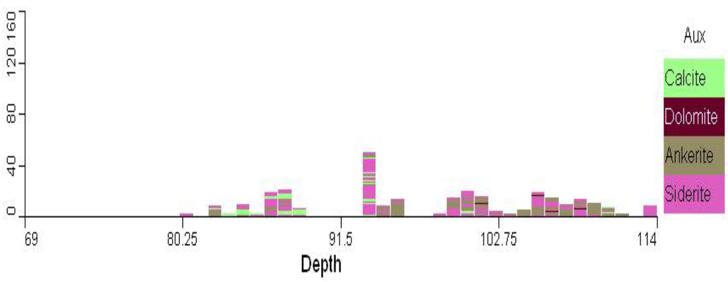
Marble Bar - 1
DDH PDP2C Overview

1


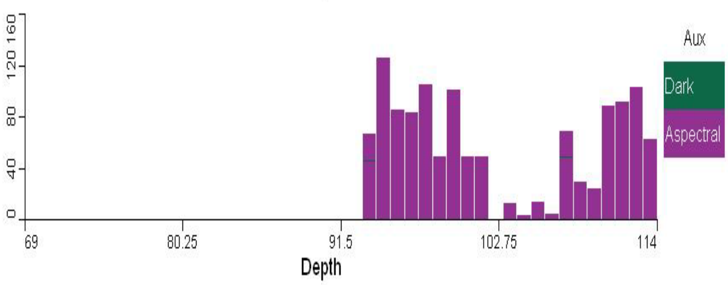
1. No. of Al(OH)-1) class samples (mica, montmorillonite, etc.) per 1 m interval. The illite is probably actually muscovite. There is one paragonite interval (brown) near 103-105 metres.

2


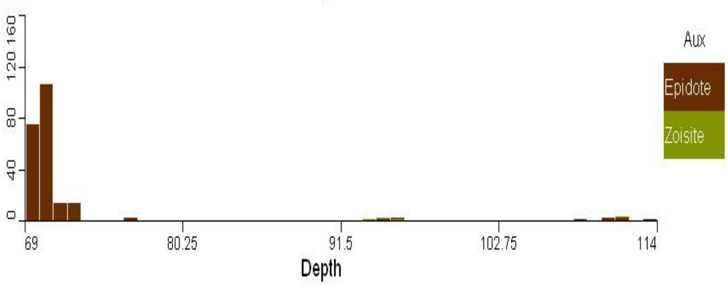
2. Chlorite-bearing samples. There appears to be two different populations, one Fe-rich and the other more intermediate in terms of Fe/Mg content.

3


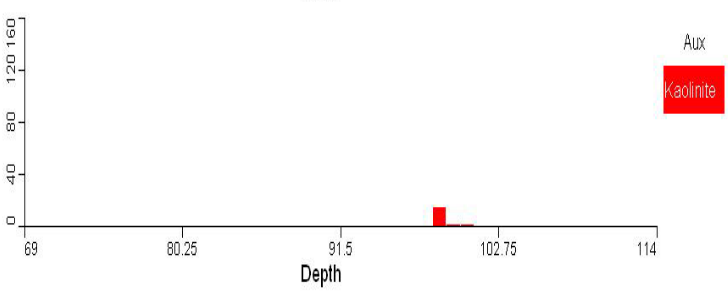
3. Carbonate-bearing samples. Compare also with Fe^{2+} index on next page.

4


4. Aspectral samples per 1 metre interval. These indicate the presence of minerals not applicable to the current technologies range. May relate to other framework silicates. Subdivides lower part of the hole into two.

5


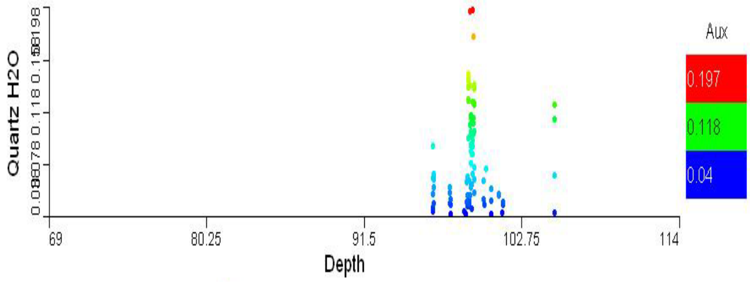
5. Epidote samples per 1 metre interval.

6


6. Kaolinite samples per 1 metre interval.

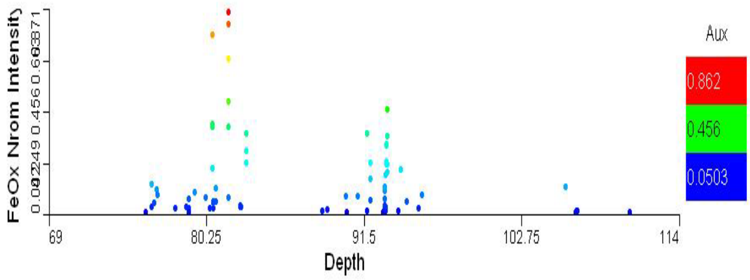
Marble Bar - 2
DDH PDP2C Overview

1



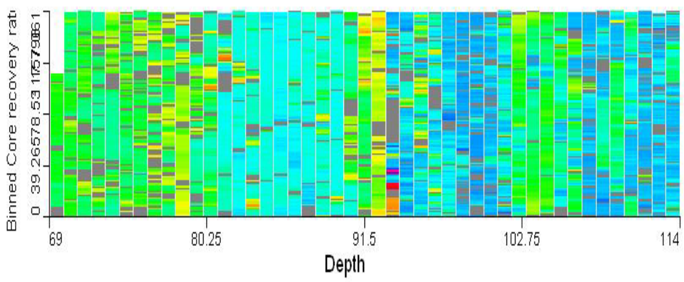
1. Bound water index highlights both quartz veins and "wet" possibly smectitic zones.

2



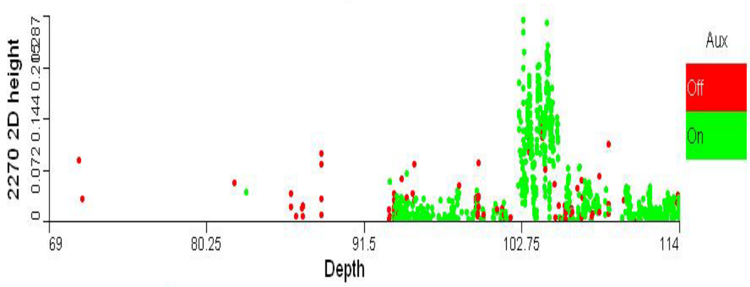
2. Iron oxide index highlights yellow and red, goethite and hematite zones.

3



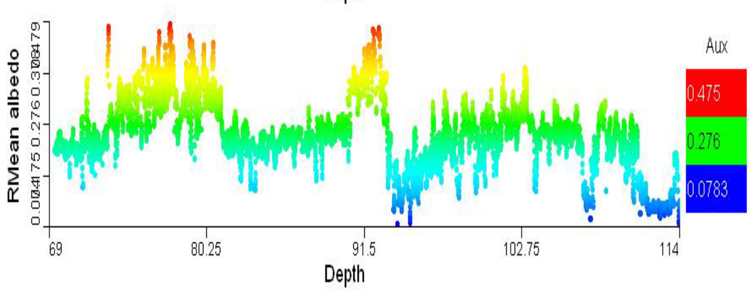
3. Enhanced core colour (intensity component removed). Grey samples are wooden blocks.

4



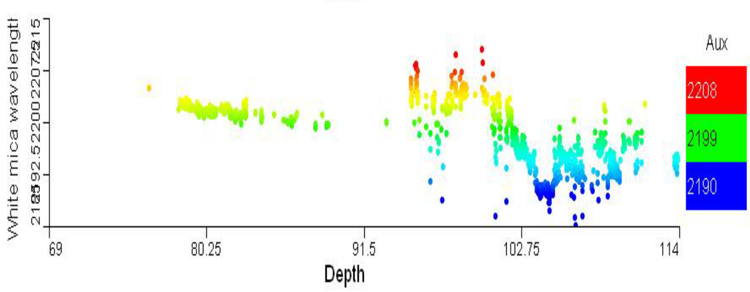
4. Absorption intensity of a feature at 2270 nm highlights a unique subdivision within the lower part of the hole. This is an unusual wavelength and longer than most chlorite absorptions that occur at shorter wavelengths. XRD of this material would be worthwhile.

5



5. Running mean of the sample brightness further characterises parts of the hole.

6



6. Absorption wavelength for white mica suggest compositional variations within the micas. The short wavelength (dark blue) interval equates to the paragonite zone shown on plot 1 on the previous page.

VAN KRANENDONK et al.

The Pilbara drilling project: c. 2.72 Ga Tambiana Formation and c. 3.49 Ga Dresser Formation, Pilbara Craton, Western Australia

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