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General palaeontology (Palaeobiochemistry)

Early traces of life investigations in drilling Archean hydrothermal and sedimentary rocks of the Pilbara Craton, Western Australia and Barberton Greenstone Belt, South Africa

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Abstract

The Pilbara Craton of Western Australia and the Barberton Greenstone Belt of the Kaapvaal Craton, South Africa, contain some of the oldest and best preserved Archaean rocks and microfossils in the world. Two stratigraphic horizons in the Pilbara Craton were drilled as part of a collaborative effort between France and Australia (the Pilbara Drilling Project) during August 2004, including the 3481 Ma Dresser Formation (Warrawoona Group) and 2724 Ma Tumbiana Formation (Fortescue Group). A new diamond drill hole was cored in August 2008 through part of the ∼3250 Ma Fig Tree Group in the Barberton Greenstone Belt as part of a joint project between France and South Africa. These pristine diamond drill cores present a unique opportunity to constrain the chemistry of the earliest ocean, the composition of the atmosphere, and the settings and types of microbial ecosystems spanning the Archean Eon. These drill core samples can also provide new clues on the earliest metabolic pathways. ***To cite this article: P. Philippot et al., C. R. Palevol 8 (2009).***

Résumé

Recherche de traces de vie primitive dans des forages de séquences sédimentaires archéennes (Craton des Pilbara, Australie et Chaîne de Barberton, Afrique du Sud). Le craton des Pilbara en Australie occidentale et la chaîne de roches vertes de Barberton

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en Afrique du Sud contiennent les microfossiles les plus vieux et mieux préservés du monde. En 2004, dans le cadre d'une collaboration franco-australienne (IPGP/GSWA, Pilbara Drilling Project), deux niveaux stratigraphiques du Craton des Pilbara ont été forés: le Dresser à 3,5 Ga et le Tumbiana à 2,7 Ga. Un nouveau forage a été réalisé en août 2008 dans la chaîne du Barberton à la base du groupe du Fig Tree (3,25 Ga) dans le cadre d'une collaboration franco-sudafricaine (IPGP/AEON, projet ! Khure Africa, Barberton Barite Drilling Project). L'analyse des carottes collectées représente une opportunité unique pour contraindre le cadre environnemental des écosystèmes microbiens archéens. Il s'agit, en particulier, d'y rechercher les traces des premiers métabolismes microbiens et d'établir le lien avec l'évolution des compositions chimiques et isotopiques de l'atmosphère primitive et des premiers océans et continents. ***Pour citer cet article : P. Philippot et al., C. R. Palevol 8 (2009).***

Keywords: Archean; Early life; Diamond drill cores; Pilbara Craton; Barberton Belt; Stable isotopes

Mots clés : Archéen ; Vie primitive ; Forages ; Craton des Pilbara ; Chaîne de roches vertes de Barberton ; Isotopes stables

1. Introduction

Although several decades have passed since the first description of recognisable Early Archean microfossils [1,11,14,43], morphology-focused imaging techniques of fossil-like objects [5,46] and stable isotope (C, N, S) compositions [34,65] of putative Archean microbial remains have failed to absolutely confirm a biogenic origin. Additionally, several abiologic metamorphic and hydrothermal reactions have been identified that could produce kerogen-like polymers and graphite [5,65], and specific abiologic processes have been described that can generate complex structures that resemble microfossils [16] and stromatolites [18,31]. In view of these uncertainties and controversies, it is now recognized that studies of early life and the associated environmental conditions depend on identification of the geological context, hydrothermal and metamorphic processes, and detailed structural, isotopic and chemical description of mineral assemblages and organic microstructures that are indigenous to, and syngenetic with, the stratigraphic rock record.

One of the most serious problems for understanding the evolution of organisms and their biogeochemical environments from the ancient rock record has been the difficulty in obtaining fresh samples, i.e., rocks that have not been severely altered by post-depositional processes. For example, in the Pilbara Craton, extreme surface weathering is known to transform greenschist-facies ultramafic rocks into carbonates, and sedimentary carbonates and black shales into cherts [50]. This is a central factor in the current debate regarding the significance of the oldest stromatolite structures preserved on Earth, namely the ∼3.5 billion year-old Dresser Formation stromatolite, because surface exposures of these structures are represented by either red- and black-weathering iron oxides and/or layered chert, both of which may potentially mask the original protolith material and thus limit a confident interpretation of these structures (Fig. 1).

Similar uncertainty surrounds the protolith of layered chert, the main host rock of some putative Archean microfossils, which has been interpreted as either primary chemical precipitates out of a hot Archean ocean (e.g. [25]), or as carbonate sediments that were silicified during low-temperature hydrothermal fluid emanations on the seafloor [23,52]. More generally, the origin of the widespread silica alteration of volcanic rocks in Early Archean terranes remains unclear. Some authors have suggested that this silicification took place during subaerial or submarine weathering of volcanic flow tops, i.e. more or less concomitant with the precipitation of overlying cherts [32]. Others have proposed that seafloor alteration associated with low temperature hydrothermal activity is the most likely cause of silicification [12,13,21,36].

A final concern lies in the possibility that different generations of microbial communities may have colonized the rocks through time. Degradation of earlier biosignatures or the formation of new ones needs to be seriously considered before any safe conclusion can be reached about the nature and age of the oldest microbial lineages. Perhaps most problematic is that microbial colonization of subsurface environments in the recent past may have contributed to the accumulation of biogenic traces, casting a shadow on bulk analyses of early biological remains in general and soluble biomarkers in particular [17,41].

In order to address these problems in a critical way, two international drilling projects have been initiated in recent years to recover fresh, continuous cores of key geologic formations from the Pilbara Craton and Hamersley Basin of Western Australia and the Barberton Greenstone Belt of South Africa, from below the zone of surficial oxidative weathering (Fig. 1). These include: (i) the Pilbara Drilling Project (PDP) which was completed in 2004 and led by the Institut de Physique du Globe de Paris (IPGP), the Centre National de la Recherche Scientifique (CNRS) and the Geological Survey of Western

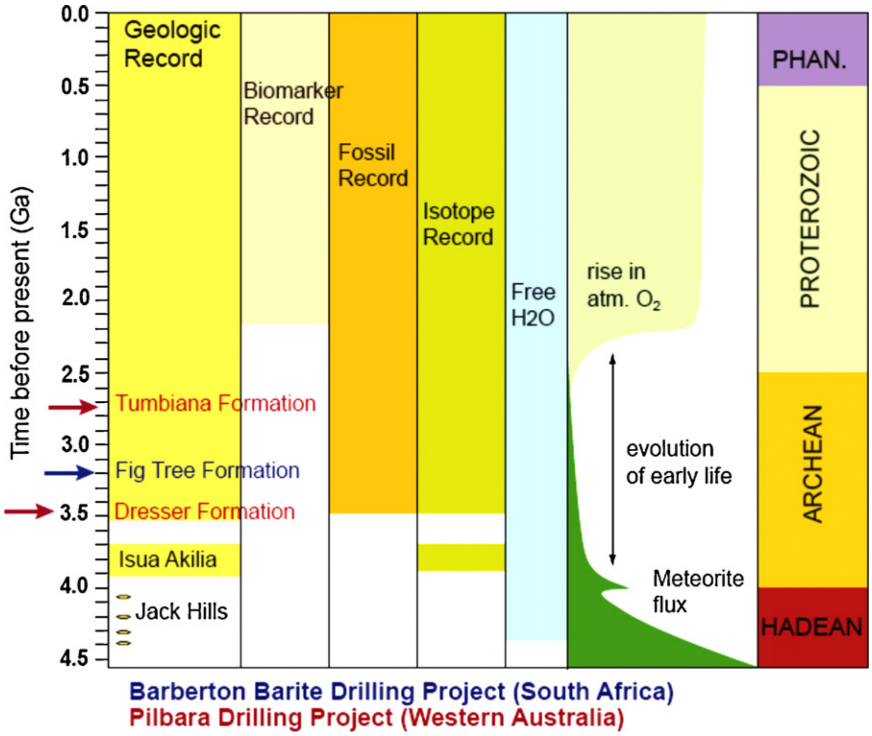

Fig. 1. Schematic diagram showing important biogeochemical events occurring on Earth. Pilbara Drilling Project (PDP 1 and PDP 2) and Barberton Barite Drilling Project (BBDP) indicated.

Fig. 1. Diagramme synthétique des principaux événements biogéochimiques apparus sur Terre. Les forages Pilbara Drilling Project (PDP 1 et PDP 2) et Barberton Barite Drilling Project (BBDP) sont indiqués.

Australia (GSWA); and (ii) the Barberton Barite Drilling Project (BBDP), which was completed in August 2008 and led by the IPGP, the CNRS and the African Earth Observatory Network (AEON).

This article describes the geological features of the drill cores collected in Western Australia. Drill cores from the Barberton Greenstone Belt were collected only recently and were not investigated at the time of writing this paper. A brief introduction of the geological setting of the Barite Syncline is provided in the discussion.

2. General geology

The Pilbara Craton of Western Australia [61] developed from 3.65–2.83 Ga, and includes the 3.53–3.165 Ga Pilbara Supergroup, the unconformably overlying c. 3.02–2.94 Ga De Grey Supergroup, and several suites of granitic rocks that span the entire history of the craton [63]. The unconformably overlying Mount Bruce Supergroup of the Hamersley Basin contains a well-preserved succession of volcanic and sedimentary rocks deposited between 2.78 and 2.45 Ga on the granite-greenstone basement of the Pilbara Craton [55]. At the base of the Pilbara Supergroup is the Warrawoona Group [10], which is a succession of low-grade metavolcanic and metasedimentary rocks deposited from greater than 3.52 to 3.43 Ga [63].

Stratigraphic drilling in the Pilbara Craton was performed through the two stratigraphic horizons that are commonly cited as hosting evidence for early life [62] (Fig. 1): the 3481 Ma Dresser Formation of the Warrawoona Group and the 2724 Ma Tumbiana Formation of the Fortescue Group [52,53].

2.1. Tumbiana Formation

Surface outcrops of the Tumbiana Formation display abundant and diverse stromatolites, ranging in size from a metre to centimetre scale (Fig. 2a). 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. It was deposited at 2724 ± 5 Ma, as indicated by zircon U-Pb dating [3], either in a shallow marine or lacustrine environment associated with influx of riverine fresh water derived

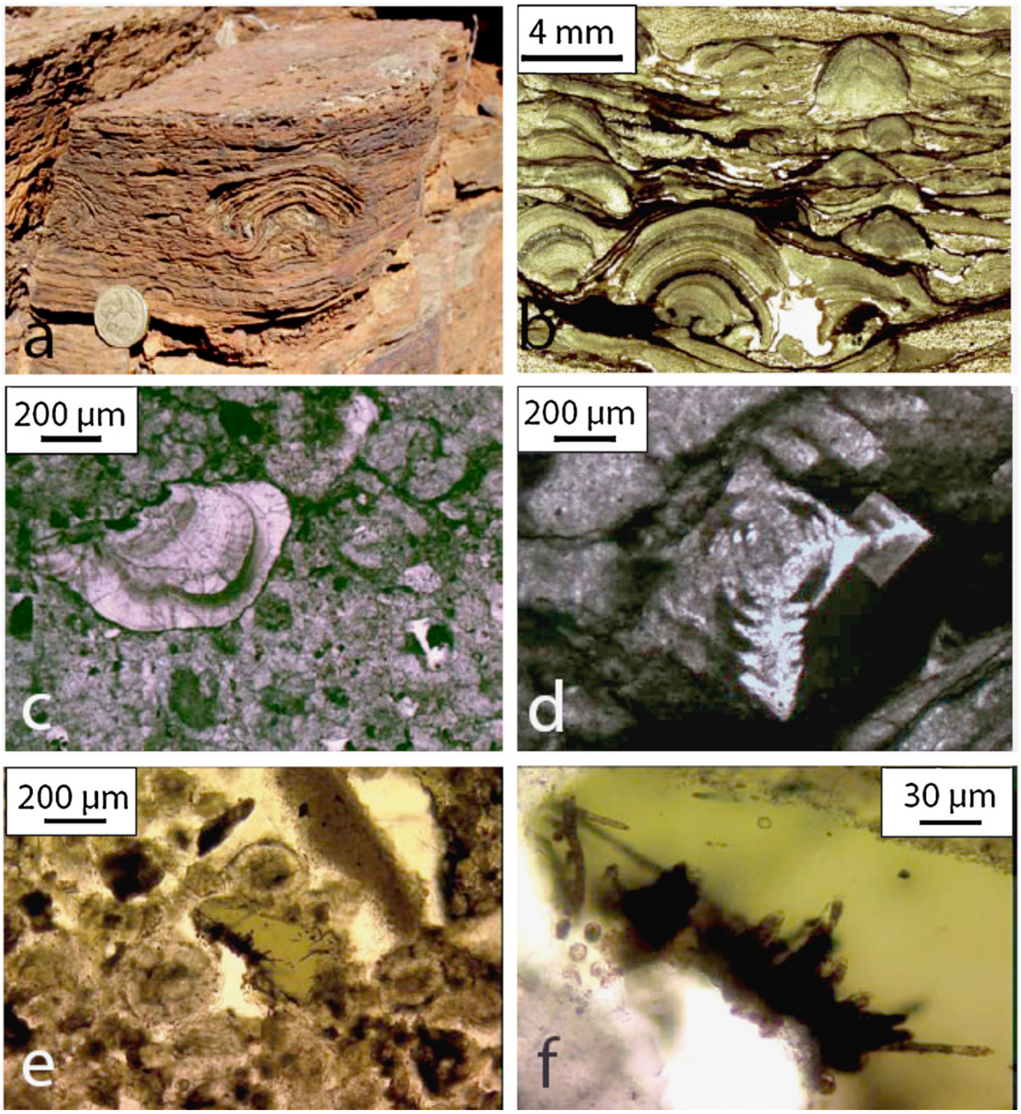

Fig. 2. **a**) Stromatolite from the Tumbiana Formation. **b**) Millimetre-scale bulbous stromatolites. **c**) Millimetre-scale fragment of stromatolite in tuffaceous material (sample 65.5c). **d**) Pseudomorph of hopper halite crystal in a carbonate stromatolite layer (sample 68.9b). **e**) Tuffaceous material (sample 70.2c). **f**) Detail of **e**) showing filament-like texture resembling microfossils.

Fig. 2. **a**) Stromatolite de la Formation de Tumbiana. **b**) Stromatolites millimétriques de forme bulbeuse. **c**) Fragment de stromatolite dans un tuff volcanique (échantillon 65,5c). **d**) Pseudomorphose d'un cristal de halite dans un niveau de stromatolite carbonaté (échantillon 68,9b). **e**) Tuff volcanique (échantillon 70,2c). **f**) Détail de **e**) montrant une texture filamenteuse ressemblant à un microfossile.

from the continents [4,9,42,52]. A maximum temperature of rock equilibration of about 300 °C has been estimated using metamorphic mineral assemblages and the degree of organization of organic matter on the PDP1 drill core samples [28].

In stromatolites, a few putative filamentous microfossils [45] and their palimpsests were interpreted as traces of phototrophic microbes [45,65]. In addition, 2α-methylhopane molecules that can be attributed to cyanobacteria [6] or an anoxygenic phototroph [40] were also detected in the Tumbiana Formation. It was thus proposed that these stromatolites formed primarily by the activity of photosynthesizers [65]. However, recent investigations of the carbon stable isotopes from different generations of carbonaceous material present in other Pilbara rocks analyzed for their molecular fossils were interpreted to indicate that the soluble hydrocarbons entered the rocks some 500 million years after deposition and therefore are not indigeneous to the original host rock [41].

Sedimentary organic matter strongly depleted in the carbon isotope ^{13}C down to −60‰ has long been attributed to growth of aerobic, methanotrophic bacteria [20]. However, Hinrichs [22] showed that anaerobic methanotrophy involving sulfate as the electron acceptor according to the reaction $CH_4 + SO_4^{2-} = HCO_3^- + HS^- + H_2O$ could be a viable mechanism for explaining the observed depletion of ^{13}C in sedimentary organic carbon. According to this model, the 2.7 Ga organic carbon isotope excursion could indicate that sulfate concentrations were high enough for utilization by sulfate-reducing bacteria. In either case, the isotopic signature provides strong evidence for the existence of archaeal methanogens.

2.2. Dresser Formation

The Dresser Formation consists of interbedded units of chert–carbonate–barite and basalt that form a ring of hills which dip shallowly away from the North Pole Monzogranite in the core of the North Pole Dome. The monzogranite was emplaced into the core of the dome as a subvolcanic laccolith during eruption of the overlying, c. 3.46–3.42 Ga Panorama Formation [58]. The lowermost chert unit is intercalated with several barite ($BaSO_4$) lenses and is overlain by silicified felsic volcanogenic, hydrothermal breccia and bedded carbonate sediments that were deposited in a shallow water environment [27,35,64]. This succession of chert, barite, volcanoclastic sandstone, hydrothermal breccia and carbonate is herein referred to as the chert–barite unit. This unit is overlain by pillowed basalt and underlain by spinifex-textured metabasalt that experienced low-grade metamorphism of between 100 and 350 °C [48]. The underlying komatiitic basalt is pervasively affected by intense hydrothermal alteration and transected by a myriad of veins–varying from centimeters to kilometers long–of barite and black and white cherts [21,54,56,60].

Pb–Pb isochron age of 3490 Ma was obtained from galena in barite of the chert–barite unit at North Pole [51]. This is in good agreement with a zircon U-Pb age of 3481 Ma recently obtained from a volcanoclastic layer of the PDP2 drill core [64] and a Sm–Nd age of 3480 Ma determined from volcanic, sedimentary and hydrothermal rocks of the chert–barite deposit and underlying volcanics [49].

Three models have been proposed for the setting of the chert–barite unit. One model suggests that the rocks were deposited as bedded carbonate–gypsum evaporites and mafic volcanogenic sediments in a quiet, shallow water marine lagoon separated from the open ocean by a sand bar [8,19]. In this model, the chert units were interpreted as silicified carbonates and bedded barite units as evaporative gypsum that were replaced by barite during early hydrothermal fluid circulation as attested by the extensive network of silica ± barite veins that underlie the formation. Subsequent hydrothermal circulation has been related either to structural doming [21], or rifting at 2.7 Ga during deposition of the Fortescue Group [7]. A second model suggests that the chert–barite

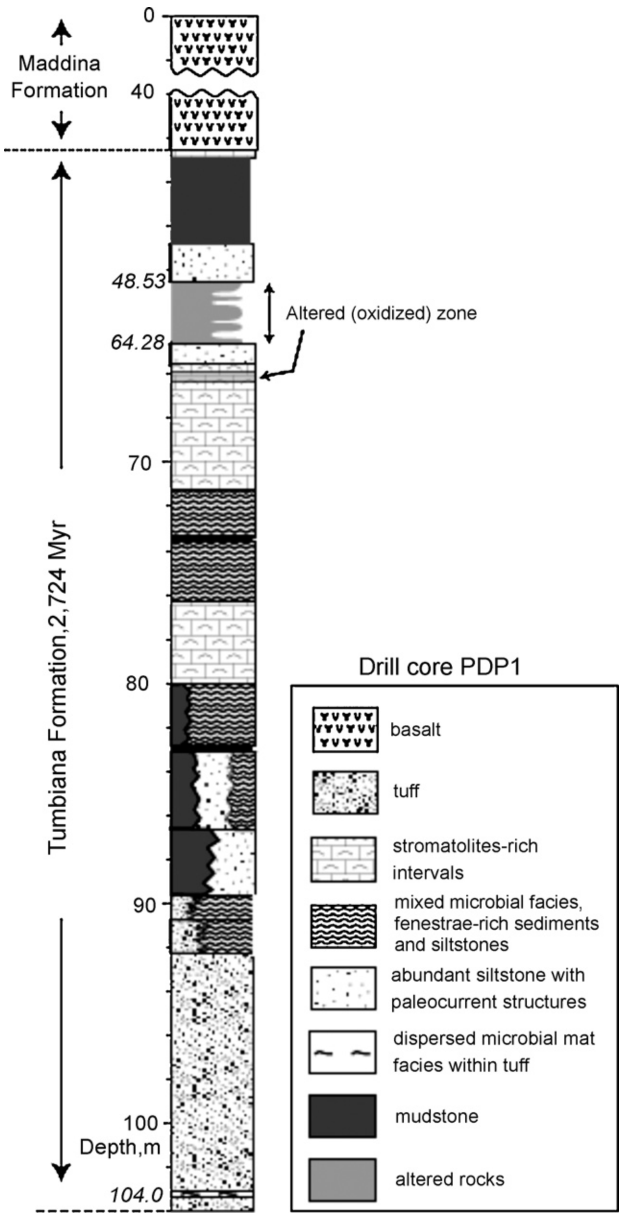

Fig. 3. Stratigraphic log of the 2.7 Ga Tumbiana Formation drill-core PDP1.

Fig. 3. Log stratigraphique de la Formation 2,7 Ga de Tumbiana (forage PDP1).

units were deposited on oceanic crust during off-axis hydrothermal circulation and that the regional stratigraphy represents a set of thrust-bound ophiolite slices [24,45]. A third model suggests that the protoliths of the chert–barite unit were deposited during hydrothermal circulation in a volcanic caldera [35,58,59,60]. In this model, the silica and barite veins that underlie the bedded chert–carbonate units are interpreted as fossil hydrothermal fluid pathways that formed synchronously with, and were the cause of, deposition of the bedded chert–barite unit. Support for this interpretation arises from recent ^{147}Sm–^{143}Nd data indicating isochronous relationship between volcanic, sedimentary and hydrothermal rock types, including barite, at about 3.481 Ga [49]. In addition, bulk and individual fluid inclusion analysis led to the recognition of three main types of fluid populations preserved in intra-pillow quartz pods [15] and underlying hydrothermally-altered komatiitic basalts [39]: a metal depleted fluid, a Ba-rich and S-depleted fluid, and a Fe–S-rich end-member. The Cl/Br ratio of the metal depleted fluid inclusions (630) is similar to that of modern seawater (649) and has been interpreted as a remnant of Archean "seawater" [15]. In contrast, Ba- and Fe-rich brines have Cl/Br ratios (350 and 390) close to that of the bulk Earth value (420), hence arguing for a hydrothermal origin of these fluids.

Silica veins underlying the chert–barite unit contain small amounts of sulfides, carbonaceous filaments [14] and CH_4-bearing fluid inclusions with $\delta^{13}C$ values between −30 and −35‰ [58] and as low as −56‰ [57], respectively. The carbonaceous filaments have been interpreted as microfossils of chemoautotrophs [58], whereas the associated ^{13}C-depleted inclusion fluids are thought to have been produced by methanogens in surficial environments and recycled in the silica veins by hydrothermal fluids [57]. It is from similar intrusive silica veins beneath the 3460 Ma Apex chert that Schopf et al., [44,46] interpreted in situ carbonaceous material as "cellular microfossils", whereas Brasier et al. [5] and Lindsay et al. [30] advocated a non-biogenic origin associated with Fischer–Tropsch synthesis for this material. The chert–barite unit contains the oldest known occurrence of stromatolites [19,66], but debates continue over the biogenicity of these structures [11,31]. Because of

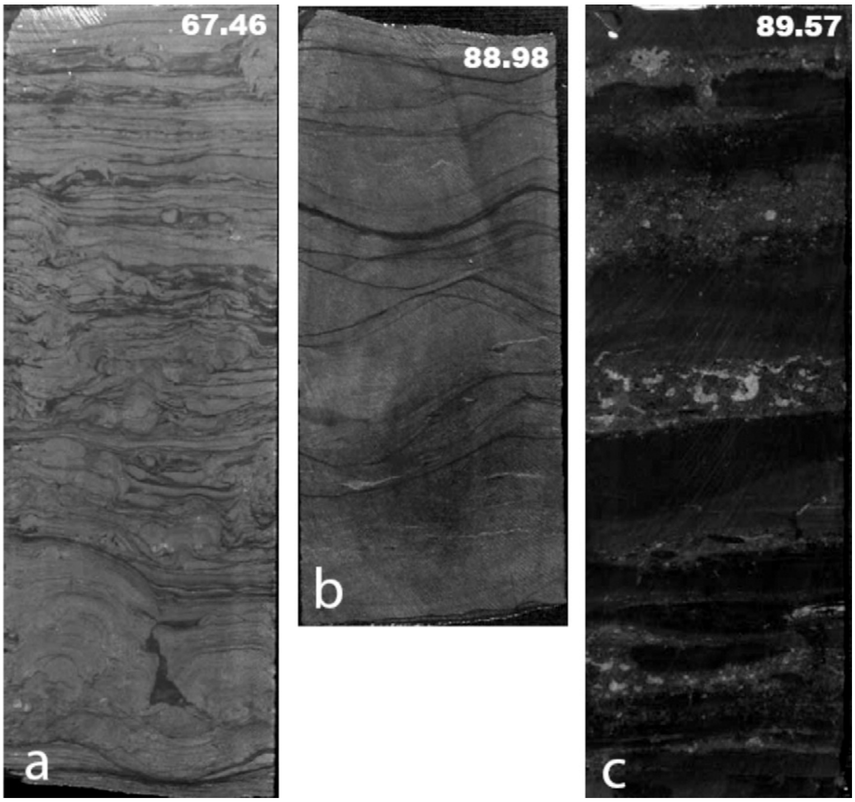

Fig. 4. Drill core samples from the Tumbiana Formation. **a**) Carbonate stromatolite with local columnar shape. **b**) Wave-rippled siltstone. **c**) Alternating mudstone and tuff layers containing fenestrae. All cores are 5 cm across.

Fig. 4. Échantillons de la carotte de forage de la Formation de Tumbiana. **a**) Stromatolite carbonaté montrant une géométrie en colonne. **b**) Figures de courant dans une pélite. **c**) Alternance de pélite et de tuff volcanique. Tous les échantillons ont une section de 5 cm.

Table 1
Drillhole data for the Pilbara Drilling Project (Western Australia) and Barberton Barite Drilling Project (South Africa).
Tableau 1
Données des forages Pilbara Drilling Project (Australie occidentale) et Barberton Barite Drilling Project (Afrique du Sud).

Drill hole number	Direction Plunge ⇒ azimuth	Surface location Latitude	Longitude	Interval drilled HQ core (m)	RC hammer (m)	NQ core (m)
PDP1	75° ⇒ 323°	21°18′15″S	120°24′40″E			0–104.0
PDP2a	50° ⇒ 330°	21°10′33″S	119°25′50″E	0–50.6		
PDP2b	50° ⇒ 330°	21°10′34″S	119°25′50.9″E		0–84.0	84.0–109.6
PDP2c	50° ⇒ 330°	21°10′34.5″S	119°25′51″E		0–69.3	69.3–114.6
BBDP1	50° ⇒ 295°	25°54′21.3″S	31°03′32.7″E	0–30.57		30.57–102.54
BBDP2	50° ⇒ 288°	25°54′24.8″S	31°03′23.9″E	0–18.18		18.18–125.09
				125.09–144.31		144.31–154.36
				154.36–163.36		163.36–182.39

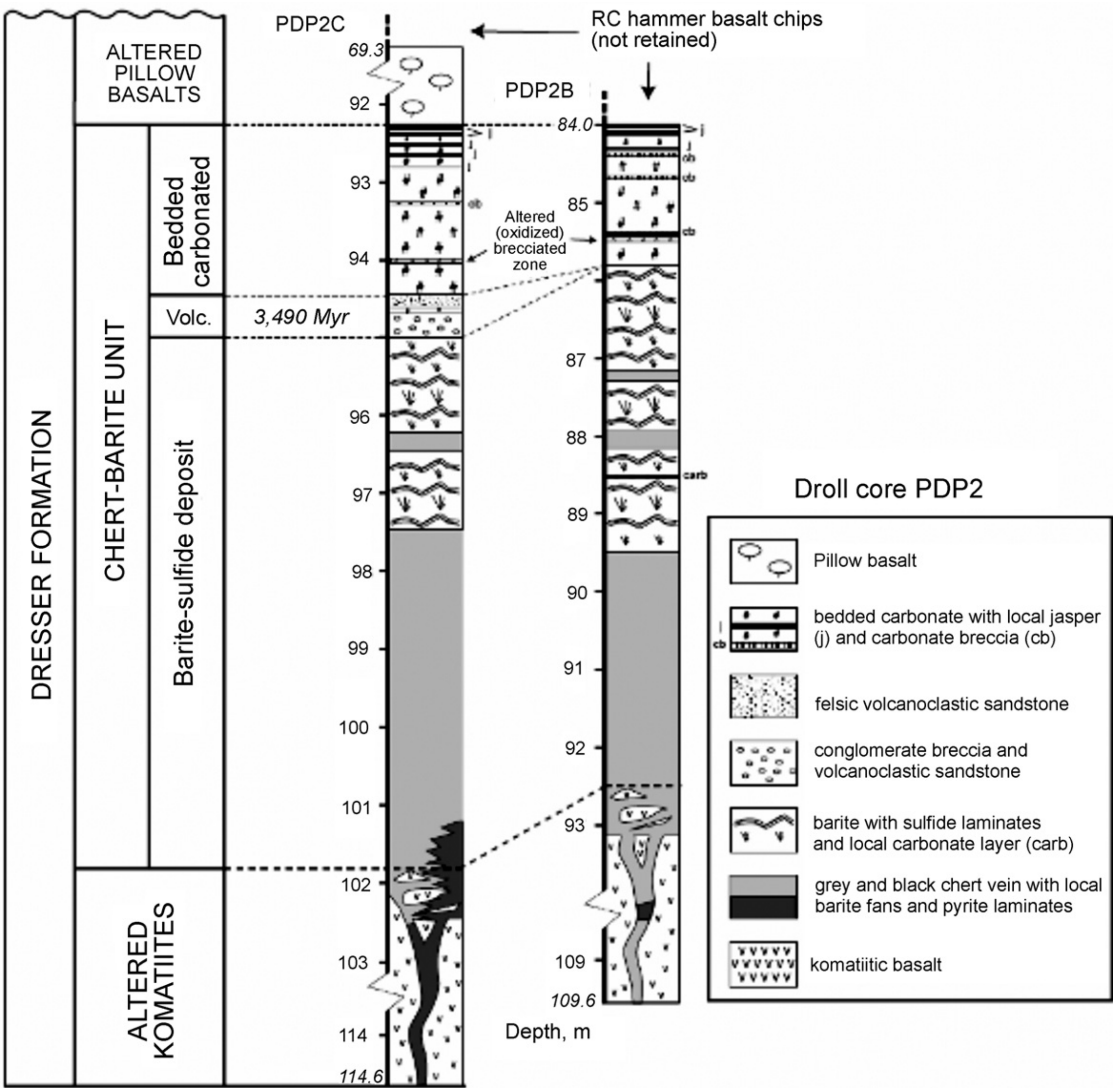

Fig. 5. Stratigraphic log of the ca. 3.5 Ga Dresser Formation drill-cores PDP2b and PDP2c.
Fig. 5. Log stratigraphique de la Formation de Dresser (forages PDP2b et PDP2c).

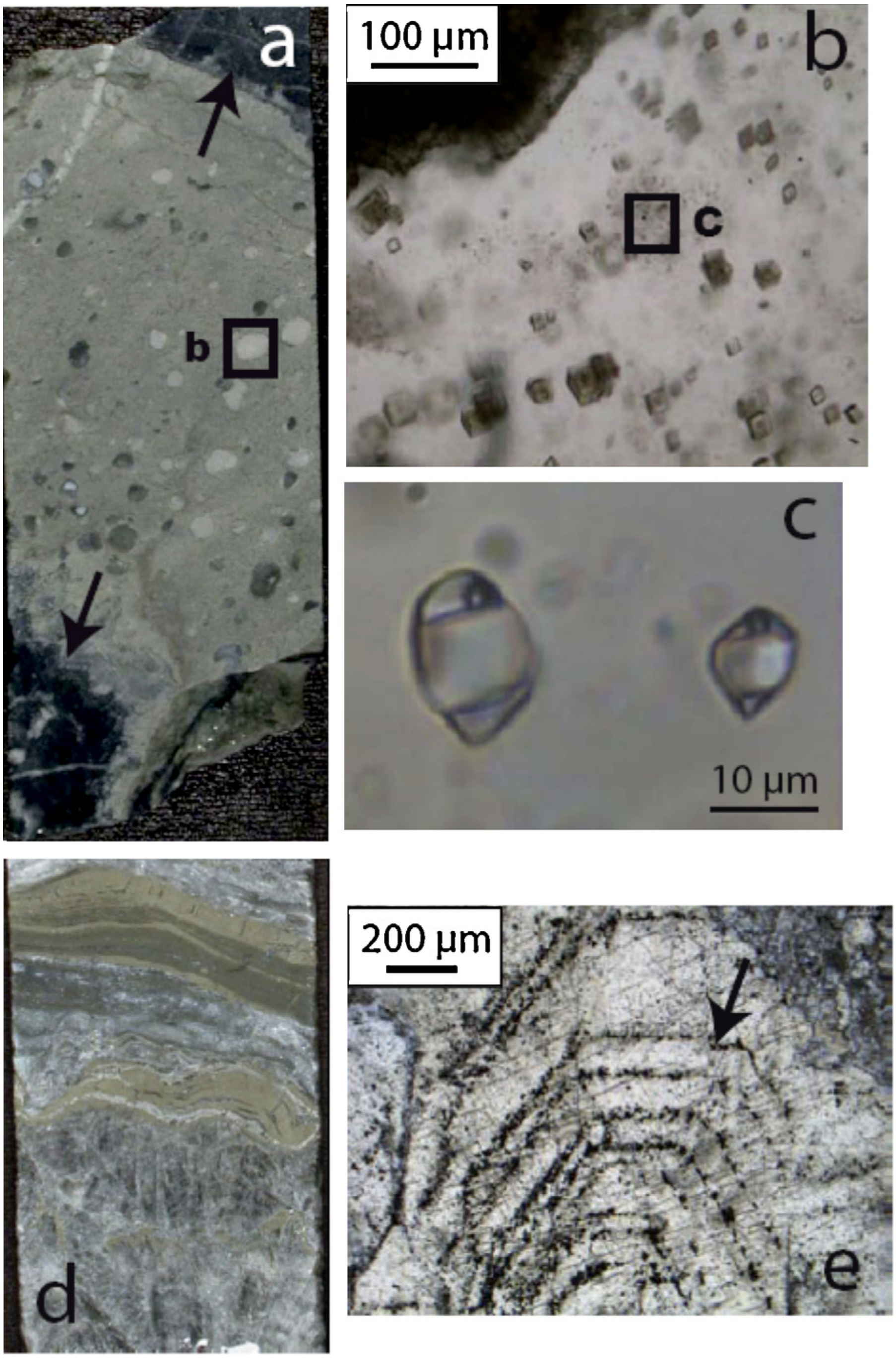

Fig. 6. **a**) Hydrothermally-altered komatiitic basalt showing vesicles filled by an early phase of carbonate and a subsequent assemblage of microquartz, recrystallized carbonate rhombs, and **b**) white mica that was introduced by cross-cutting black chert veins (arrowed). **c**) The fluid phase leading to the recrystallization of the secondary carbonate occurs preserved in fluid inclusions surrounding microscopic carbonate grains (sample 113.5, drill core PDP2C). **d**) Bedded barite composed of coarse crystalline barite fans that alternate with macroscopic pyrite ± sphalerite laminites and variable amounts of cherty material (sample 89.0, drill core PDP2b). **e**) Individual barite crystal containing microscopic sulfides lining barite overgrowth zones (sample 88.4, drill core PDP2b). **f**) Felsic volcaniclastic sandstone overlain with curved pebble conglomerate. **g**) Detail of the angular felsic volcaniclastic sandstone (sample 94.5, drill core PDP2c). All cores are 5 cm across.

Fig. 6. **a**) Basalte komatiitique altéré montrant des vésicules remplies par un carbonate précoce et un assemblage secondaire à quartz microcristallin, rhomboèdres de carbonates recristallisés et **b**) micas blancs introduits par un fluide issu de veines de silex noirs (indiquées par une flêche). **c**) La phase fluide responsable de la cristallisation du carbonate secondaire est préservée sous forme d'inclusions fluides entourant des micrograins de carbonate

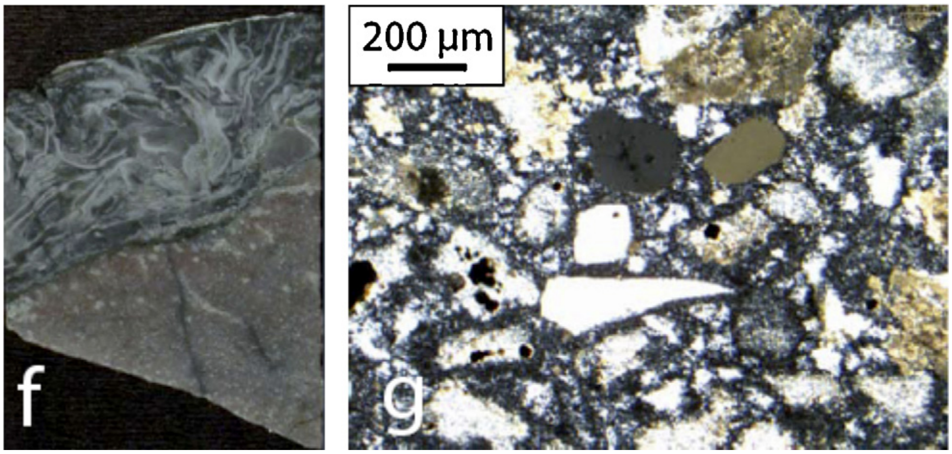

Fig. 6. (*Continued*).

their uncertain origin, Buick et al. [11] used the term "stromatoloids" to describe these dome-shaped structures. Another important finding at North Pole concerns the oldest evidence of sulfur metabolisms, being either sulfate reducers [47] and/or elemental sulfur disproportionators [37,38] (see below).

3. Geology of the drillcores

3.1. Pilbara drilling project 1 (PDP1): Tumbiana Formation

The top of drillhole PDP1 intersected generally fresh, low-grade vesicular metabasalt of the Maddina Formation from the surface to a depth of 42.72 m (Fig. 3). 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. At the bottom of the metabasalt section, the rocks are recrystallized to a coarser-grained assemblage of chlorite porphyroblasts and anatase (40.28–42.66 m). The lower contact of the metabasalt is a 5 cm-thick zone (42.66–42.72 m) of eutaxitic breccia that lies directly on the Tumbiana Formation. 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 brecciated interval with large clasts of siltstone in a volcanoclastic matrix. Below this (42.89–46.7 m) are interbedded black mudstones (locally pyritic) with local volcaniclastic siltstone (46.3–46.9 m). The interval comprised between 46.7 and 48.53 m is predominantly composed of siltstones displaying cross-bedding, lenticular bedding and flaser structures, with interbeds of laminated mudstones. A stromatolitic build-up is present at 47.02 m, on top of dm-thick interval of fragmented microbial-like sedimentary rocks. Below a brownish oxidized zone between 48.53 and 64.28 m is volcaniclastic siltstone with ripples, and shale (64.28–65.54 m) with some microbial-like laminated intervals between 64.54 and 64.78 m. The underlying interval is dominated by microbial deposits comprising fenestrae-rich laminated sedimentary rocks, finely wavy laminated microbial deposits, pluricentimetric-high domal stromatolites (between 65.65 and 71.3 m; Figs. 2b, 4a) preserving salt pseudomorphs (Fig. 2d), and flat pebble breccias composed of stromatolite fragments (see Fig. 2c). These deposits are interbedded with tuffaceous siltstone (Fig. 2e), mudstone and accretionary lapilli tuff. Locally, individual tuffaceous grains display a filamentous network of ichnofossil-like textures along their boundaries (Fig. 2f). Stromatolite build-ups are again well developed between 76.15 and 79.98 m, with domal structures reaching 20 cm in height. Between 79.98 and 89.56 m are interbedded mudstone, wave-rippled siltstsone (Fig. 4b) and microbialite that grade down into a more volcaniclastic sediment between 86.68 and 89.56 m. The lower part of the hole, from 89.56 to 104.0 m, is monotonous tuffaceous material with accretionary lapilli. Flat-pebble conglomerates are present in the upper 10 cm of the interval and fenestrae occur

(échantillon 113,5, carotte PDP2C). **d**) Dépôt de barytine litée, caractérisé par une alternance de barytine en rosette et de lamines de pyrite ± sphalérite associées à du quartz microscristallin (échantillon 89,0, carotte PDP2b). **e**) Cristal de barytine contenant des sulfures microcristallins alignés le long des zones de croissance de la bartyine (échantillon 88,4, carotte PDP2b). **f**) Grauwacke felsique associé à un niveau de conglomérat. **g**) Détail du grauwacke felsique (échantillon 94,5, carotte PDP2c). Tous les échantillons ont une section de 5 cm.

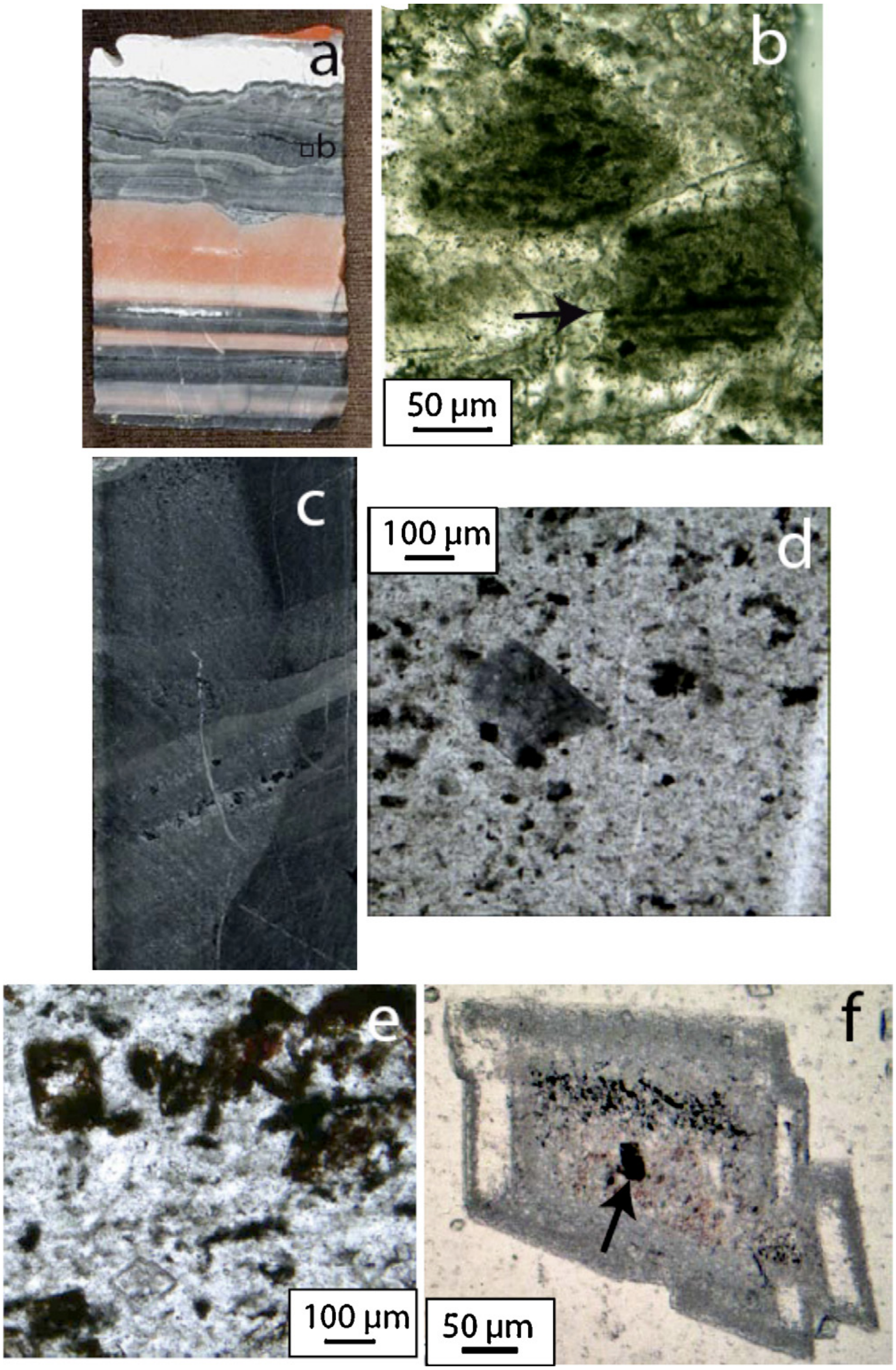

Fig. 7. **a**) Layered sedimentary silicified carbonate with local jaspilitic beds (hematite bearing; sample 84.1; drill core PDP2b). **b**) Micron-thick wavy carbonaceous laminae (arrowed) preserved in the core of large euhedral ankerite crystals interpreted as relics of sedimentary layering and microbial mats (sample 84.1b; drill core PDP2b). **c-d**) Layered silicified carbonate showing dispersed fluffy 'clots' of remobilized carbonaceous material dispersed in a strongly silicified matrix (sample 93.4; drill core PDP2C). **e**) Secondary hematite pseudomorphing carbonate rhombs (sample 84.7, drill core PDP2b). **f**) Possibly primary hematite coexisting with organic material (arrowed) in the core of euhedral ankerite crystals (sample 92.5c, drill core PDP2c). All cores are 5 cm large.

down to 91.46 m (Fig. 4c). Some microbial mat-like layers occur between 103.31 and 103.85 m. Drilling was stopped at 104.0 m depth.

3.2. Pilbara drilling project 2 (PDP2): Dresser Formation

The drilling site was chosen in the southeastern part of the North Pole Dome, where bedded sedimentary rocks of the Dresser Formation dip 40° south-southeast. Three closely spaced drillholes were sited to the South of the surface outcrops, in the stratigraphic hangingwall, and were oriented at 50°→330° in order to intersect the bedding at right angles (Table 1). The first hole (PDP2a) was drilled with HQ core (75.7 mm diameter) to a depth of 50.6 m through pillowed metabasalt affected by heavy surficial weathering, at which depth the hole was abandoned. No analysis of this core has been made. The second hole (PDP2b) was located further away from the surface outcrops and drilled through metabasalt by RC hammer to a depth of 84.0m, when red flakes of jaspilitic chert emerged from the hole. Diamond drilling with NQ core (47.6 mm diameter) commenced at this depth and continued from 84.0–109.6 m, through the bedded sedimentary rocks, into the underlying metabasalt. The third hole (PDP2c) was sited 14 m further to the south-southeast. Knowing the depth of weathering from the PDP2b hole and the dip and continuity of the bedded sedimentary rocks, the first 69.3 m of this hole was drilled by RC hammer to penetrate below the zone of weathering but remain within the overlying metabasalts. From this depth, drilling continued by NQ diamond drillcore. Metabasalt was intersected to a depth of 92.3 m, where the upper contact of the bedded sedimentary rocks was reached. Diamond drilling was continued through the chert–barite unit to a depth of 114.6 m, well into the underlying komatiitic metabasalt.

The different stratigraphic units in the drill cores are described below from stratigraphic base to top (Fig. 5). The bottom unit consists of hydrothermally-altered komatiitic metabasalt that is transected by numerous veins of grey to black silica and barite. These komatiitic metabasalts preserve relict pyroxene spinifex texture that is now replaced by a carbonate, white mica and pyrite assemblage (Fig. 6a). Vesicles are filled by an early phase of carbonate and a subsequent assemblage of microquartz, recrystallized carbonate rhombs (Fig. 6b) and white mica that was introduced by cross-cutting veins. Locally, the fluid phase that led to the recrystallization of the secondary carbonate is preserved as fluid inclusions surrounding microscopic carbonate grains (Fig. 6c). Cross-cutting veins consist of an early generation of black chert (Fig. 6a) composed of recrystallized carbonate rhombs, abundant carbonaceous material and minor sulfides dispersed in a cherty matrix, and a later generation of grey to white chert with fibrous quartz and carbonate rhombs.

Overlying the komatiitic basalt are 2.5 to 3.6 m of bedded barite composed of coarse crystalline barite fans that alternate with macroscopic pyrite ± sphalerite laminates, and variable amounts of cherty material (Fig. 6d). Centimetre-thick carbonate layers are also present. Locally, large barite crystal fans display sector- and oscillatory-zonation characteristic of hydrothermal environments. Well-preserved overgrowth zones are lined with microscopic, rounded, Ni-bearing sulfides (Fig. 6e; [37]). In most cases, however, barite fans have been extensively recrystallized into a fine-grained assemblage of secondary barite coexisting with fine-grained silica of hydrothermal origin. Associated sulfides lining barite overgrowth zones were also recrystallized into larger, subhedral and Ni-depleted pyrite crystals, which commonly form networks connected to the neighbouring macroscopic sulfide laminates.

In PDP2c, above the bedded barite is a 55 cm thick sequence that is absent in drill core PDP2b. This consists from bottom to top of a hydrothermally-altered volcanoclastic conglomerate (95.0–94.7 m) with rounded clasts of barite and pyrite laminates, a 10 cm thick layer of finely laminated sulfides possibly replacing bedded carbonate (94.7–94.6 cm), a 15 cm thick bed of well sorted, fine-grained felsic volcaniclastic sandstone and a 2 cm thick unit of flat pebble conglomerate composed of curved tabular clasts of bedded felsic ash, now altered to silica and white mica (Fig. 6f).

Variably silicified bedded carbonates overly the felsic volcaniclastic unit in drill core PDP2c and lie directly on the bedded barite in drill core PDP2b. The mineralogy of the bedded carbonate consists of a mixture of ankerite, siderite and calcite, fine-

Fig. 7. **a**) Sédiment lité montrant des alternances de carbonates silicifiés et de niveaux de jaspe (riches en oxydes de fer; échantillon 84.1; carotte PDP2b). **b**) Lamines d'épaisseur de l'ordre du micron, composées de matière carbonée (indiquées par une flêche) préservée dans le cœur de cristaux d'ankérite et interprétées comme des vestiges de tapis microbiens fossilisés (échantillon 84.1b; carotte PDP2b). **c-d**) Niveau de carbonate silicifié contenant des agrégats de matière carbonée, dispersés dans la matrice siliceuse (échantillon 93,4 ; carotte PDP2C). **e**) Hématite secondaire se développant au détriment de rhomboèdres de carbonate (échantillon 84,7, carotte PDP2b). **f**) Hématite primaire probable coexistant avec de la matière carbonée (flêche) dans le cœur d'un cristal d'ankérite (échantillon 92.5c, carotte PDP2c). Tous les échantillons ont une section de 5 cm.

grained silica, pyrite ± carbonaceous material and hematite. Millimetre-to centimetre-scale bedding is well-developed throughout the unit, defined by slight changes in texture and the amount of silica, pyrite, carbonaceous material and hematite (Fig. 7a, c). Although absent in the lower part of the bedded carbonates, the abundance of hematite increases progressively from 84.6 to 84.1 m in PDP2b and from 92.9 to 92.6 m in PDP2c, to become a dominant component of the uppermost 10–30 cm of the drill core (PDP2b, 84.1–84.0 m; PDP2c, 92.6–92.3 m). At several points within the carbonate/jasper beds, there has been a clear infiltration of secondary hydrothermal fluid flow. Hydrothermally-derived silica varies in proportion across the unit, but locally accounts for up to 80% of the rock, where it has replaced the original micritic carbonate and resulted in recrystallization of the micritic primary carbonate to zoned ankerite rhombs with characteristic dusky cores and clear rims. In these layers, it is important to note that recrystallization has also affected the carbonaceous material, which appears remobilized in the replaced matrix (Fig. 7d). This contrasts with the occurrence of micron-thick wavy carbonaceous laminae preserved in the core of large euhedral ankerite crystals in one sample of drill core PDP2b (84.1b; Fig. 7b). In this layer, although the ankerite crystals and carbonaceous lamina are rotated relative to the general bedding plane, the overall trend of the carbonaceous laminate inclusions remains subparallel to the sedimentary bedding. These carbonaceous structures can be interpreted as sub-mm sedimentary layering, potentially the remnants of shallow marine microbial mats preserved in the micritic part of the carbonate rhombs. This morphology is distinctively different from the carbonaceous matter that occurs in adjacent silicified carbonate layers and deeper-seated hydrothermal chert feeder veins. Carbonaceous matter in these rocks appears as dispersed fluffy 'clots' remobilized by fluid infiltration without any indication of sedimentary layering (Fig. 7d). Finally, in some of the bedded carbonate samples (e.g. PDP2b sample 84.7), hematite clearly occurs as a secondary pseudomorph of primary ankerite crystals (Fig. 7e). However, not all of the hematite in these sediments is clearly secondary. In several samples (92.5c of PDP2c and 84.6 of PDP2b), some euhedral ankerite crystals contain sub-micron size hematite crystals together with carbonaceous matter (Fig. 7f). This hematite is possibly a primary feature, and was not obviously introduced during later infiltration by oxidized hydrothermal or meteoric waters. Combined carbon and iron stable isotope analysis led to the interpretation that the primary hematite and associated organic material may represent relict activity of anoxygenic photosynthesizers [66].

The upper part of drill core PDP2c (69.3-92.3 m) is composed of amygdaloidal pillow basalt with 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.

4. Discussion

Continuous drill cores of key Archean localities provide a great source of material for performing geologically-relevant integrated studies on a large number of unweathered samples. Multiple investigations of the morphology, texture, chemistry, isotopes and present-day microbial diversity have been performed on drill core samples from the Tumbiana and Dresser Formations by different groups in recent years. These include:

1) reconstruction of the environmental conditions pertaining to the development of microbial ecosystems combining field, petrographical and U-Pb and Sm-Nd dating [47,64];
2) integrated carbon (^{12}C, ^{13}C), nitrogen (^{14}N, ^{15}N), iron (^{54}Fe, ^{56}Fe) and multiple sulfur (^{32}S, ^{33}S, ^{34}S, ^{36}S) isotope studies of the different lithologies forming the Tumbiana and Dresser drill cores [51,66];
3) integrated neon isotopic, ^{36}Ar and ^{40}Ar, ^{84}Kr, ^{129}Xe, ^{132}Xe and ^{136}Xe analysis of bulk inclusion fluids extracted from hydrothermally-altered pillow basalts and komatiites [39];
4) in situ high-resolution microanalyses of the structure and chemical composition of carbonaceous material from single fossil-like objects or fluid inclusions using state-of-the-art analytical techniques such as scanning and transmission electron microscopy, confocal laser microscopy, laser Raman spectroscopy, synchrotron transmission X-ray microscopy and synchrotron X-ray microfluorescence [15,28,29];
5) in situ high-resolution microanalysis of the sulfur (^{32}S, ^{33}S, ^{34}S) stable isotopic composition of sulfide and sulfate using SIMS [37,38];
6) probing the Tumbiana drill core samples for the presence of living indigenous microorganisms using molecular methods based on the amplification of small ribosomal RNA genes [17].

An important issue affecting most, if not all, Archean geobiological studies concerns the extrapolation of global conditions from local measurements that could represent unusual settings or episodes. For instance, Philippot et al. [37] proposed that the ^{34}S-depleted microscopic sulfides lining barite overgrowth zones of the ~3.5 Ga Dresser Formation at North Pole were not formed by sulfate reducers [47], but rather by microorganisms that used elemental sulfur as an electron acceptor. Considering that disproportionation of elemental sulfur produces sulfate according to the reaction:

$$4S^0 + 4H_2O \rightarrow 3H_2S + SO_4^{2-} + 2H^+$$

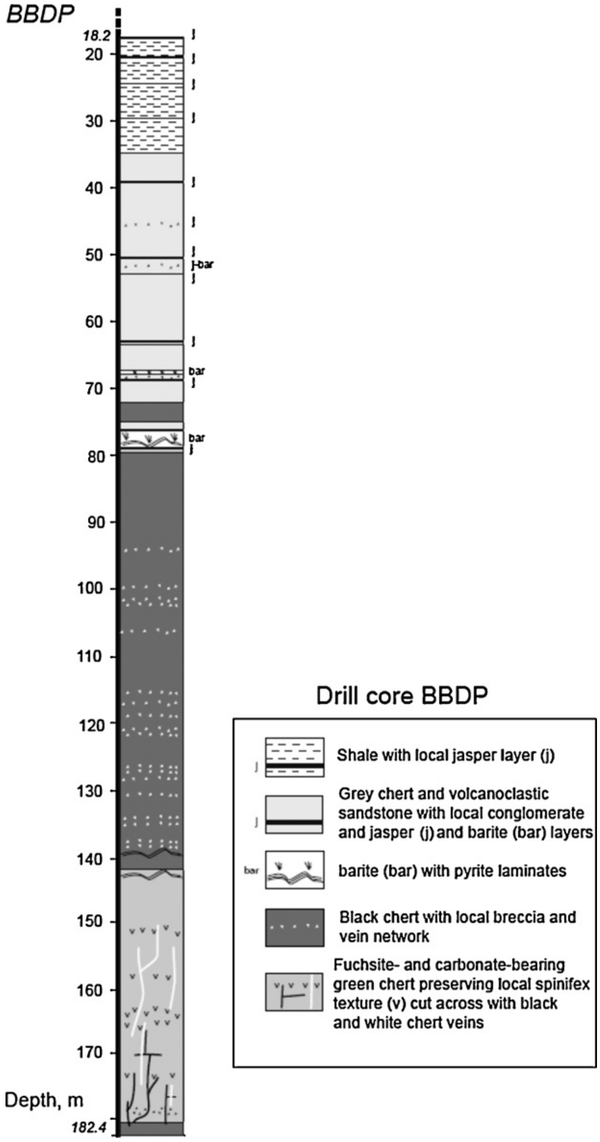

Fig. 8. Preliminary stratigraphic log of the base of the Fig Tree Group, South Africa (Barberton Barite Drilling Project, BBDP).
Fig. 8. Log tratigraphique préliminaire de la base du groupe de Fig Tree, Foramtion de Mapeepe, Afrique du Sud (Barberton Barite Drilling Project, BBDP).

these two metabolic processes are not mutually exclusive, however, and so could have coexisted at the time of sulfide formation. Nevertheless, the range of $\delta^{34}S$ values reported for the microscopic sulfides at North Pole is unique for Early Archean sedimentary rocks and therefore raises questions concerning how widespread the proposed sulfur-based metabolisms really were at a global scale, over longer time periods [2,37,47].

In order to address this issue, a new drill hole was completed in August 2008 through the base of the 3.25 Ga Fig Tree Group of the Barberton Greenstone Belt, South Africa. The sequence investigated is part of the Mapepe Formation at the so-called "barite syncline" locality. The Mapepe Formation consists of a variety of lithofacies, including chert clast conglomerate, micaceous and carbonate-cemented sandstone, green and grey chert, and jasper and barite layers [23,33]. This stratigraphic succession of chemical and clastic sedimentary rocks overlies highly-silicified hydrothermally-altered carbonaceous chert and komatiites [23]. The Mapepe Formation was deposited in a variety of sedimentary environments, ranging from deep- to shallow-water, fan delta and alluvial environments [33]. Zircon dates range from 3.26 to 3.23 Ga [26].

The goal of this drilling operation was to obtain a representative sequence of the hydrothermally-altered komatiites, black cherts, jasper deposits, and bedded barite. A preliminary stratigraphic log of the drill core is shown in Fig. 8. This sequence of ultramafic rocks and chemical sediments represents a conspicuous assemblage of rock types that is typically seen in Early Archean hydrothermal settings and which closely resembles the stratigraphic assemblage of the 3.5 Ga Dresser Formation. Detailed petrographic and geochemical studies of the drill core from this unit can therefore potentially greatly expand our insight into Early Archean environments and associated sulfur-based microbial life.

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