



Evidence of early life from international collaborative drilling in the Pilbara Craton

by A. H. Hickman

Abstract

The Geological Survey of Western Australia has played a major role in three international geoscientific drilling projects in the Pilbara region of Western Australia. Thirteen diamond drillcores, obtained from some of Earth's best preserved Archean sedimentary and volcanic rocks, are now starting to provide important new evidence on Earth's early life. Research teams in Japan, U.S.A., France, and Australia are searching for microscopic and chemical evidence that life existed in a range of ancient depositional environments between 3490 and 2490 Ma. The research is also attempting to resolve the controversy on whether or not Earth's early hydrosphere and atmosphere contained oxygen.

Early results support past suggestions, based on structures interpreted to be fossilized stromatolites and microfossils, that life existed on Earth from at least 3460 Ma. Additionally, there is new evidence to suggest that oxygen may have been present in the atmosphere at 2920 and 2760 Ma.

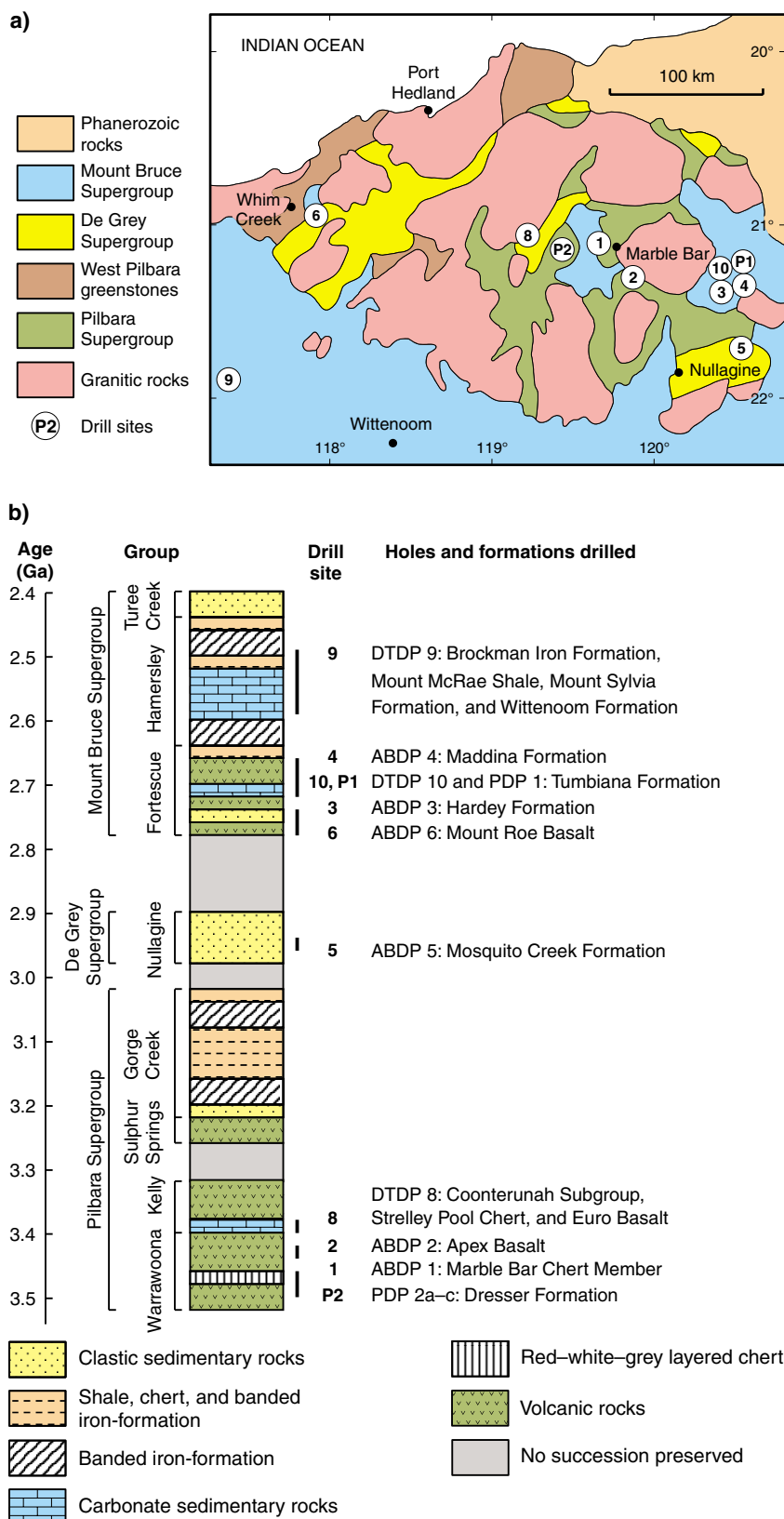
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Pilbara geoscientific drilling

The Geological Survey of Western Australia (GSWA) is a participant of three international geoscientific drilling projects in the Pilbara region of Western Australia. Thirteen diamond drillholes, varying in depth between 100 and 1000 m, were drilled during 2003 and 2004, and intersected sedimentary and volcanic rocks ranging in age from 3490 to 2490 Ma (Fig. 1). Drilling avoids the near-surface chemical and biological contamination in rock outcrops.

In 2003 the Archean Biosphere Drilling Project (ABDP) was jointly conducted with the Pennsylvania State Astrobiology Research Center (PSARC), Kagoshima University (KU), and The University of Western Australia (UWA). GSWA's initial role was to advise on the best drilling locations to obtain the rock types required. GSWA then undertook much of the work required to obtain necessary approvals and permits before drilling. After drilling GSWA provided facilities to cut the core (about 1400 m from 6 holes) at the Perth Core Library, where 50% of all core was retained with the remainder being exported to KU and PSARC.

In 2004 the Deep Time Drilling Project (DTDP) included all members of the ABDP, with the addition of researchers from the University of



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Figure 1. Stratigraphy and locations of the geoscientific diamond drilling projects in the Pilbara Craton, 2003–04: a) stratigraphic positions of the geoscientific drillholes; b) simplified geology of the northeast Pilbara Craton showing locations of the drilling sites. Note: drilling of site 7 was never undertaken

Washington (UW) and Arizona State University (ASU). This project drilled three holes, one almost 1000 m deep. As in 2003, GSWA's main role was advisory and logistical. In the same year the Pilbara Drilling Project (PDP), by GSWA and the Institut de Physique du Globe de Paris (IPGP), drilled four holes, including two through the 3490 Ma Dresser Formation, which is the oldest known fossiliferous unit in the Pilbara region. GSWA is currently assisting with research on the PDP cores.

Project aims The time that life first appeared on Earth and what forms this life took are currently very controversial subjects. Some geoscientists and biogeochemists believe that life did not appear on Earth until the Paleoproterozoic era (commencing at 2500 Ma), and many believe that Earth's atmosphere was essentially anoxic before c. 2350 Ma (see below). Others maintain that the fossil record is adequate to establish that life was already well developed on Earth at 3500 Ma, and some geochemists have argued that the Earth's atmosphere contained oxygen as far back as 4000 Ma (e.g. Ohmoto, 2004). The level of controversy reflects a lack of data from Archean rocks (older than 2500 Ma). Outside the Pilbara Craton of Western Australia and the Kaapvaal Craton of South Africa, there are few Archean rocks of sufficiently low metamorphic grade to preserve good evidence of ancient life.

The Pilbara drilling targeted particular rock types. Archean life was probably bacterial, inhabiting hot springs, volcanic calderas, freshwater lakes, continental margins, or deep-sea hydrothermal-vent environments. The most prospective rock types are chemically precipitated chert and carbonate sedimentary rocks, which in Proterozoic and Phanerozoic successions contain bacterial fossils, and carbonaceous and sulfidic shales and sandstones, which in post-Archean successions commonly owe their compositions to accumulations of biological organic material.

Archean life Throughout the post-2500 Ma geological record, bacterial colonies have built structures, termed 'stromatolites', that range from a few millimetres to several metres in height. These structures are biochemical precipitates of carbonate or siliceous minerals that are preserved as fossils. Some 2720 Ma stromatolites from the Pilbara region (e.g. Fig. 2) have morphologies very similar to Proterozoic stromatolites that are universally accepted as biogenic. Much older structures interpreted as stromatolites or fossilized microbial mats have been discovered in the Pilbara region, in rocks as old as

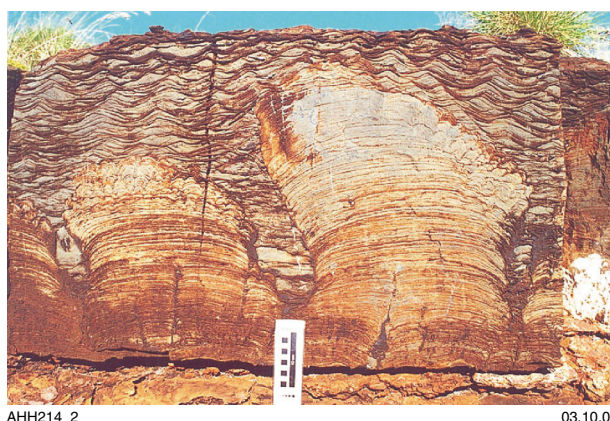


Figure 2. Cross-section exposure of columnar stromatolites in carbonate rocks of the c. 2720 Ma Tumbiana Formation of the Fortescue Group, Meentheena, Pilbara Craton. This unit was drilled in ABDP 10 and PDP 1



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Figure 3. *Wavy-laminated chert (interpreted as fossilized bacterial mats) and domical stromatolites in the c. 3490 Ma Dresser Formation, North Pole, Pilbara Craton. This unit was drilled in PDP 2b and 2c*

c. 3490 Ma (Fig. 3). Although many geoscientists accept the stromatolite-like morphology of these structures as adequate evidence of their bacterial origin, others question a bacterial origin. Likewise, examples of ‘microfossils’ reported from early Archean Pilbara Craton chert (Schopf, 1993) have recently been reinterpreted as products of inorganic mineral crystallization (Brasier et al., in press). Ratios between the stable isotopes of carbon are generally agreed to be useful in distinguishing biological from nonbiological carbonaceous material in sedimentary rocks of low metamorphic grade. Most workers agree that strongly depleted $\delta^{13}\text{C}$ compositions (–15 to –60 per mil) indicate a biological origin.

Astrobiology

The Pilbara drilling projects are not only aimed at uncovering diagnostic proof of early life on Earth. Mars probably had similar environments to Earth during the early Archean, and the two planets may at that time have supported similar life. The rarity and the currently contentious nature of early Archean fossils on Earth highlights how difficult it may be to discover convincing evidence of early Archean Martian life, if it existed. Astrobiologists therefore need high-quality data from Earth to assist their exploration of Mars.

Selected early research results

ABDP Hole 1, Marble Bar Chert Member and Apex Basalt (c. 3460 Ma)

The Marble Bar Chert Member of the Duffer Formation is well known for its distinctive red, white, and grey layering (Fig. 4). This results from different proportions of hematite (in red chert), magnetite (in grey to black chert), and siderite (in rare green chert). The Apex Basalt, which stratigraphically overlies the chert, also contains hematite. ABDP 1 was drilled to determine if the hematite is merely a near-surface alteration product of primary minerals such as siderite or pyrite or if it extends to depths below the effects of oxidation by today’s atmosphere.

Red chert typically makes up about 30% of surface exposures of the Marble Bar Chert Member, but is far less common in the ABDP 1 drillcore. This supports hematite formation by near-surface alteration. However, red chert does form part of the chert at depths to about 200 m (Fig. 5a), and hematite fills fractures in the Apex Basalt (Fig. 5b) at deeper levels. Hematite cannot be dated directly, but Kato et al. (in prep.) dated crosscutting pyrite veins at 2762 ± 16 Ma by the Re–Os method. This result indicates that the hematite in ABDP 1 is Archean, although its precise age remains uncertain. Kato et al. (in prep.) argued that their data support Archean oxidation at least 400 million years before the generally accepted date for the development of atmospheric oxygen (c. 2350 Ma).



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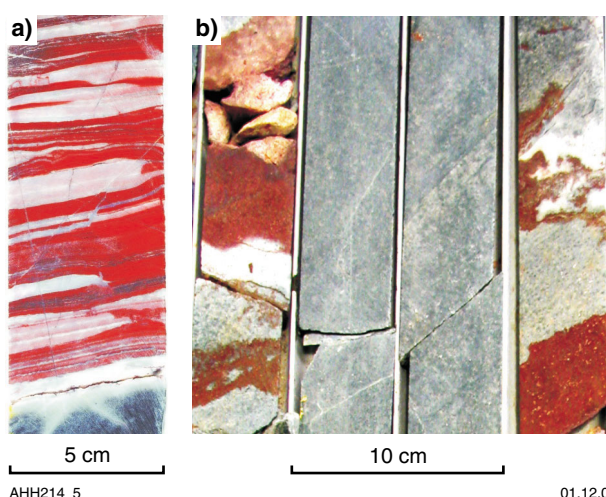
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Figure 4. *Red-white-grey layering in the Marble Bar Chert Member at Marble Bar Pool. One of the main reasons for drilling ADBP 1 was to determine if the red chert (containing hematite) persists at depth*

**ABDP Hole 3, Hardey Formation
(c. 2760 Ma)**

Watanabe et al. (2004) reported that the mean $\delta^{13}\text{C}$ value of samples of black shale over a 60 m intersection in ADBP 3 is -33.4 per mil, and that the mean $\delta^{13}\text{C}$ value in a calcareous sandstone stratigraphically above the shale is -30.4 per mil. They interpreted these variations to indicate changing microbial communities as the depositional environment of the Hardey Formation changed.

Sulfur isotope analysis of 18 samples of shale from ADBP 3 (Ohmoto et al., 2005) revealed no evidence of mass independent fractionation (MIF-S). Sulfur is present entirely in finely disseminated pyrite, and averages only 0.04 wt% of the rock. Various workers (e.g. Farquhar et al., 2000; Pavlov and Kasting, 2002; Bekker et al., 2004) have observed that the few Archean sedimentary rocks so far analysed exhibit MIF-S, whereas numerous post-



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Figure 5. *a) Red and white chert in ADBP 1 at the 170 m level, about 200 m below the present land surface; b) hematite and quartz filling fractures in the Apex Basalt at the 213–215 m level (about 250 m below the present land surface). Small veins of pyrite crosscutting the hematite were dated at 2762 Ma*

2350 Ma sedimentary rocks do not. Because MIF-S can originate through ultraviolet radiation of volcanic sulfur dioxide in the absence of ozone or oxygen, these previous workers have argued that the MIF-S data provide evidence that Earth's atmosphere changed from anoxic to oxic at c. 2350 Ma. However, the sulfur isotope results from ABDP 3 do not support an anoxic atmosphere at 2760 Ma, and highlight the need for more sulfur isotope studies on rocks older than 2350 Ma.

**ABDP Hole 5,
Mosquito Creek Formation
(c. 2920 Ma)**

At Eastern Creek the Mosquito Creek Formation includes black carbonaceous shale and intercalated sandstone metamorphosed only to pumpellyite–prehnite facies (Farrell, in prep.). The shale was deposited in relatively shallow water close to the northern margin of the Mosquito Creek Basin. ABDP research has revealed constant $\delta^{13}\text{C}$ values of about -31 ± 0.9 per mil over a 35 m intersection. Ohmoto et al. (2005) determined $\delta^{33}\text{S}$ and $\delta^{34}\text{S}$ values on bulk-rock sulfur from a total of 40 samples of shale. As in the 2760 Ma Hardey Formation (see above), this work revealed an absence of MIF-S in all but one of the 40 samples.

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