Evidence of early life from drilling in the Pilbara

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Archaean life and environments

What we would like to know:

• Better knowledge of the rise of atmospheric oxygen
• More information on the early evolution of life
• Deeper understanding of the development of biogeochemical and metabolic cycling of critical elements for biology (e.g. C, O, S, N, Fe, Mo)
• Further evidence of early Earth environmental conditions (e.g. temperature history, ocean chemistry, atmospheric composition)
• Tighter constraints on the first appearance and rise to ecological dominance of complex organisms
• Finer details on the habitat preferences, ecological tolerances and environmental partitioning of ancient organisms
Why drill Archaean terrains?

When searching for evidence of Archean life and environments, diamond drill-core:

- Avoids contamination from modern organisms and organic chemicals
- Avoids destruction of redox-sensitive environmental signatures by surface oxygen
- Avoids mineralogical alteration from surface weathering
- Provides complete stratigraphic sections
Pilbara Drilling

In Pilbara Craton of northwest Australia, 4 drilling programs (in chronological order):

• Archean Biosphere Drilling Program (ABDP) run by the Pennsylvania State University, directed by Hiroshi Ohmoto;
• Deep Time Drilling Project (DTDP) run by the University of Washington, led by Roger Buick;
• Pilbara Drilling Project (PDP) run by the French Institute Physique du Globe and Universite de Paris VII Denis Diderot, directed by Pascal Philippot;
• Dixon Island-Cleaverville Drilling Project (DXCL-DP) directed by Shoichi Kiyokawa and Kosei Yamaguchi.
ABDP

- 6 short holes through strata from 3.46-2.72 Ga drilled 2003-2004
- Targets were sediments potentially showing evidence of Archean oxygen
- 2 studies published to date (Kato et al., 2009; Hoashi et al., 2009)
- Both on ABDP-1 at Marble Bar
ABDP- Marble Bar

- Kato et al. (2009) examined Apex Basalt stratigraphically above ~3.46Ga Marble Bar Chert
- abundant haematite in altered basalt at depths ~200m down-hole
- also pyrite and goethite veins
- performed petrologic study of cross-cutting and inclusion relationships to determine relative ages, Re-Os geochronology to determine absolute age
ABDP – Marble Bar

- Re-Os dating of pyrite veins to $2763 \pm 16$ Ma
ABDP – Marble Bar

- interpreted sequence of events as indicating haematite prior to 2763 Ma, formed by oxygenated groundwater during deposition of unconformably overlying Fortescue Gp.
- implies cyanobacteria and oxygenic photosynthesis had already evolved

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<th>Age (Ga)</th>
<th>Mineralization in greenstone</th>
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<td>Marble Bar Chert Member</td>
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<td>Chinaman Pool Chert Member</td>
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<td>North Star Basalt</td>
<td>&gt;3.49</td>
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<tr>
<td>Coouterunah Subgroup</td>
<td>3.52-3.50</td>
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ABDP – Marble Bar

But:

• dated pyrite veinlets only partially cross-cut haematite veins
• pyrite crystals surrounded by haematite and not vice versa
• goethite veinlets occur in same samples as haematite
• goethite shows alteration during Cenozoic weathering, despite depth below modern land surface
Hoashi et al. (2009) examined Marble Bar Chert, found haematite microcrystals
ABDP – Marble Bar

- included within diagenetic siderite and magnetite crystals
- argued that haematite precipitated from hot (>60°C) seawater ~3.46 Ga ago
- concluded that the early Archaean ocean was therefore highly oxygenated, implying an even earlier origin of oxygenic photosynthesis and cyanobacteria.
ABDP – Marble Bar

• in the absence of clear-cut and complete cross-cutting relationships, compounded by a lack of evidence of inclusions of haematite within Archean pyrite, it is plausible that the haematite was produced during Cenozoic weathering like goethite

• abundant submicron red haematite crystals are incompatible with the greenschist metamorphic grade of the surrounding Archaean rocks, as haematite recrystallizes to coarser grain-sizes of >20μm at lower metamorphic grades than greenschist facies

• petrographic relationships in these drill-core samples dont conclusively prove environmental oxygenation in the late Archaean, nor do they demonstrate the prior evolution of cyanobacteria or oxygenic photosynthesis
DTDP

- drilled 3 holes during 2004, 2 of which were either in partnership with or for the ABDP and hence all cores have ABDP hole numbers
- only published data resulting from this project come from ABDP-9, a ~1km deep hole drilled solely for the DTDP
DTDP – Mt McRae

- from lower Brockman Iron Fm down to lower Wittenoom Fm in Hamersley Gp
- spans interval ~2500-2590 Ma
- co-ordinated studies on same samples from Mt. McRae Shale near core top, mostly black kerogenous pyritic shale
- Kaufman et al. (2007) on S isotopes, Anbar et al. (2007) on trace-metal (Mo, Re, U) geochemistry, Garvin et al. (2009) on N, C isotopes
DTDP - Mo

• Mo excursion from 0-45ppm between 152-135m, also in Re but not U, correlates with TOC but not Al
• good Re-Os date of 2501 ± 8 Ma shows trace metals not remobilized
• abundance of Mo, Re in excursion requires oxidative weathering, removal by organic adsorption
• transient pulse (“whiff”) of atmospheric oxygen
DTDP - S

EXPLANATION

- deep subtidal
- grey carbonate/marl couplets or clastic carbonate
- organic rich marl
- black shale/marl couplets
- black laminated shale
- BIF (siderite)
- BIF (oxide)
  - sulfur isotope analysis
  - $\delta^{34}S$ (‰, VCDT)

- small chert nodules in carbonate
- zone of remobilized and nodular pyrite
- breccia
- deepening upward cycle
DTDP - S

- $\delta^{34}\text{S}_{\text{pyrite}}$ changes from +ve to −ve, $\Delta^{33}\text{S}_{\text{pyrite}}$ goes from very +ve to near 0 in Mo excursion
- similar trends in another core ~30km away, also in similarly old rocks in S. Africa
- interpreted as oxidative weathering increasing seawater sulphate, allowing microbial sulphate reduction, changing mass-independent fractionation
- whiff of oxygen $>10^{-6}$ to $<10^{-5}$ present atmospheric level
- $\delta^{15}\text{N}_{\text{org}}$ goes from $+1\%_\text{o}$ to $+8\%_\text{o}$ and back to $+3\%_\text{o}$ over same interval (152-130m) as Mo and Re excursions, S isotope shifts
- roughly correlated with wt% TOC but C/N nearly constant
DTDP - N

- not a diagenetic or metamorphic trend, as late degassing of isotopically light N\textsubscript{2} should cause negative correlation between $\delta^{15}\text{N}_{\text{org}}$/TN wt %, but opposite is evident
- interpreted as shift from purely anaerobic to aerobic N cycle
- isotopic shift caused by start of nitrification allowing denitrification fractionation to drive marine nitrate $\delta^{15}\text{N}$ heavy, thus forcing $\delta^{15}\text{N}_{\text{org}}$ heavy
- also indicates whiff of oxygen allowing nitrification
• denitrifiers widespread on SSU rRNA tree
• but marine nitrifiers only known from 2 groups, both peripheral branches on late-branching microbial phyla
• implies that major evolution of Bacteria and/or Archaea was largely over by end of Archaean
PDP

• drilled cores in 2004 from the 3.48 Ga Dresser Formation at North Pole and the 2.72 Ga Tumbiana Formation at Meentheena
• to investigate the habitat of life on early Earth
PDP Tumbiana

- Lepot et al. (2008) found 2μm organic globules with 100nm clusters of preserved aragonite nanocrystals (10nm) in stromatolites
- similar structures in modern microbially-accreted stromatolites
- implies that late Archaean stromatolites are similarly biogenic
- discovery of aragonite surprising in low-grade metamorphic rocks
• Thomazo et al. (2009) found in same rocks correlated carbon and sulphur isotope anomalies
bimodal $\delta^{13}$C$_{\text{org}}$ (extremely light near -50‰ and moderately heavy near -30 ‰) coupled with positive $\Delta^{33}$S mass-independent isotope fractionations but little $\delta^{34}$S fractionation
PDP - Tumbiana

- interpreted as feedback loop:
- more methanotrophy (lighter $\delta^{13}C_{org}$) reduced methane flux to atmosphere, limiting organic haze and thus increasing UV photodissociation of sulphur gases inducing greater $\Delta^{33}S$ fractionation
Philippot et al. (2007) found that ~3.48 Ga Dresser Fm rocks consisting of chert, barite and iron oxide on the surface are pyritic barite and carbonates at depth. They analyzed $\Delta^{33}S$ and $\delta^{34}S$ in barite, pyrite.
PDP - North Pole

- microscopic sulphides in barite crystals have positive $\Delta^{33}S$ and negative $\delta^{34}S$
- host sulphates have negative $\Delta^{33}S$ and positive $\delta^{34}S$
- argued sulphides couldn't come from enclosing barite via microbial sulphate reduction given their opposite $\Delta^{33}S$ mass-independent fractionation signals
• interpreted microscopic sulphides as product of microbial sulphur disproportionation

\(2S^0 \rightarrow H_2S + SO_4^{2-}\), \(S^0\) with mass-independently fractionated \(+\Delta^{33}S\) ultimately derived by photolysis of volcanic \(SO_2\)
PDP – North Pole

- studies of similar samples by Ueno et al. (2008), Shen et al. (2009) didn't find microscopic pyrites with $+ve$ $\Delta^{33}S$
- only micro-pyrites with $-ve$ $\Delta^{33}S$ like host sulphates
- thus isotopic signatures more likely from microbial sulphate reduction
- if $S^0$ disproportionation occurs, then its volumetrically insignificant
• completed in 2007 with no publications yet
• 3 cores through 2 sedimentary formations in ~3.2 Ga Cleaverville Group, intersecting mostly kerogenous black shales ± pyrite
• examines effects of submarine hydrothermal activity on biological and geochemical ($C_{org}$, N, S, Fe isotopes) signatures to reconstruct mid-Archaean environmental conditions
Future Agouron drilling?

- Program of ~15 holes starting 2010?
- Led by Roger Buick, managed by University of Washington, funded by Agouron Institute, with 13 participants currently
- From 3.52-0.54 Ga in Pilbara Craton and surrounding Proterozoic basins
- Complementary to previous Agouron drilling in Archaean and Palaeoproterozoic of South Africa
- Targets: evidence of early life and environments, particularly associated with changing oxygen levels
- Other aim: to resolve controversy about age and origin of early Precambrian hydrocarbon biomarkers
- ~3 x 600m holes to be drilled each year with dedicated steam-cleaned drill-string, core-barrels, swivel, hoses to avoid organic contaminants, using fluorescein as a contamination tracer
Conclusions

Pilbara drilling:
• revealed abundant and diverse evidence for early life that would have been otherwise unobtainable from deeply-weathered surface samples
• particularly for metabolic processes involving redox transformations that are masked at the surface by modern oxidation,
• allowed recognition of oxygenic photosynthesis, nitrification & denitrification, methanogenesis & methanotrophy, possibly sulphur disproportionation & sulphate reduction, prior to advent of oxygenated atmosphere ~2.4 Ga ago,
• constrained bacterial and archaeal evolution, implying that macro-evolution of microbes was largely complete by the end of the Archaean
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