The Middle Marker:

What can Africa's oldest sediments reveal about early life and its environment?

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Abstract

Whilst on an expedition to South Africa in Summer 2019 to examine how early life interacted with its environment, I conducted a preliminary investigation on a section of the Middle Marker sedimentary horizon. Samples were collected from each lithology, and analysed at the MagLab in Caltech. Preliminary results reveal the magnetic signatures present within these 3.47 Ga old rocks indicated the possible presence of fossilised Magnetotactic Bacteria (MTB) and Earth's oldest primary (unaltered) magnetisation fabrics. This has possible implications regarding how we understand the evolution of biomineralization and opens up exciting possibilities for future research into the evolution of both early life and Earth's geodynamo.

Introduction

Geological Background

The Middle Marker refers to a ~3-13 metre thick package of mostly volcanic-derived sedimentary rocks and cherts (Figure 2) preserved between a sequence of basalt lava flows within the Barberton Greenstone Belt of South Africa (Figure 1). At 3.47 billion years old (Ga)[1] it represents one of the oldest sedimentary horizons on Earth. For its age, it is astoundingly well preserved, with some sections only reaching lower Greenschist facies (<350°C) metamorphic conditions[2]. This means that the sediments are remarkably pristine, with the presence of primary depositional features and syn-depositional silicification pointing to a shallow marine hydrothermally active deposition environment a few 10's of metres deep[3,4]. This is well within the photic zone, with filamentous and mat-like structures preserved within these sediments being widely interpreted to represent evidence of ancient photosynthesising microbial life[4]. Indeed, an entire ecosystem of life flourishing off volcanic activity is thought to have existed here, representing the oldest know ecosystem and second oldest convincing evidence of life on Earth[4].

Magnetotactic Bacteria

Magnetotactic bacteria (MTB) are microorganisms capable of biomineralizing nano-sized particles of magnetic minerals (magnetite and/or greigite)[5]. These are produced in organelles called magnetosomes, which may organised into chains. This enables the cell to produce a magnetic dipole and, using the magnetosomes like a compass, orientate themselves along Earth's magnetic field, a behaviour known as magnetotaxis[6,7]. This provides them with an ability to navigate. Whereas microorganisms without this ability are forced to implement a 3D "run and tumble" search strategy to find their optimal microenvironment, MTB are able to reduce this to a 1D search along geomagnetic field lines. In the chemically stratified water columns where they are typically found, this enables them to more effectively locate their niche. MTB are polyphyletic, meaning that they do not belong to just one phylogenetic group but that the magnetotaxis behaviour exists across many. Either this means that this ability evolved multiple times, or more likely it is passed between distantly related groups of microorganism through horizontal and or vertical gene transfer[8] . Nevertheless, the origin of MTB remains enigmatic.

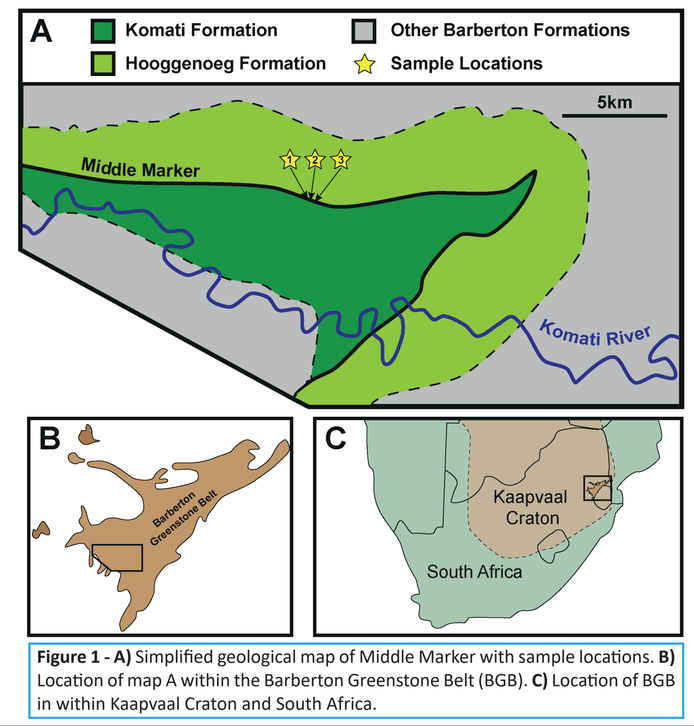


Figure 1 - A) Simplified geological map of Middle Marker with sample locations. **B)** Location of map A within the Barberton Greenstone Belt (BGB). **C)** Location of BGB in within Kaapvaal Craton and South Africa.

Results

- 12 samples were collected from three outcrops of the Middle Marker, including samples from each lithology. Stratigraphic positions of samples from two locations are indicated in the sedimentary logs in Figure 2.
- These locations were all on the western limb of the Onverwacht anticline (fold), which represents the least metamorphosed (altered by heat and/or pressure) samples within the Middle Marker[3].
- Samples were scanned (Figure 3) and analysed by Tim Raub at the Magnetic Field Laboratory at the California Institute of Technology using a variety of magnetic techniques.
- Magnetic granulometry (remFORC) of the black chert (RC19MM002) is consistent with the signature of rolled up fossilised magnetosomes of MTB.
- Magnetic microscope imaging appears to show that the volcanic glass shards/ mineral crystals at the centre of many lapilli (magmatic spherals in RC19MM009) are magnetised in random directions, giving a positive conglomerate test.
- Magnetic data is still being processed and figures will be available soon.

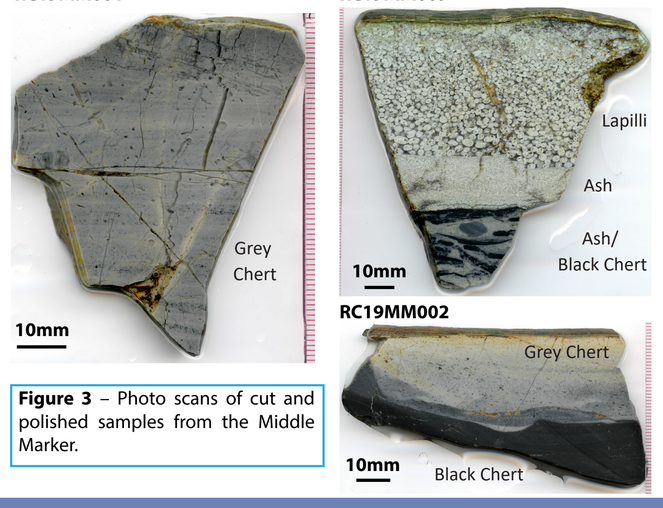


Figure 3 – Photo scans of cut and polished samples from the Middle Marker.

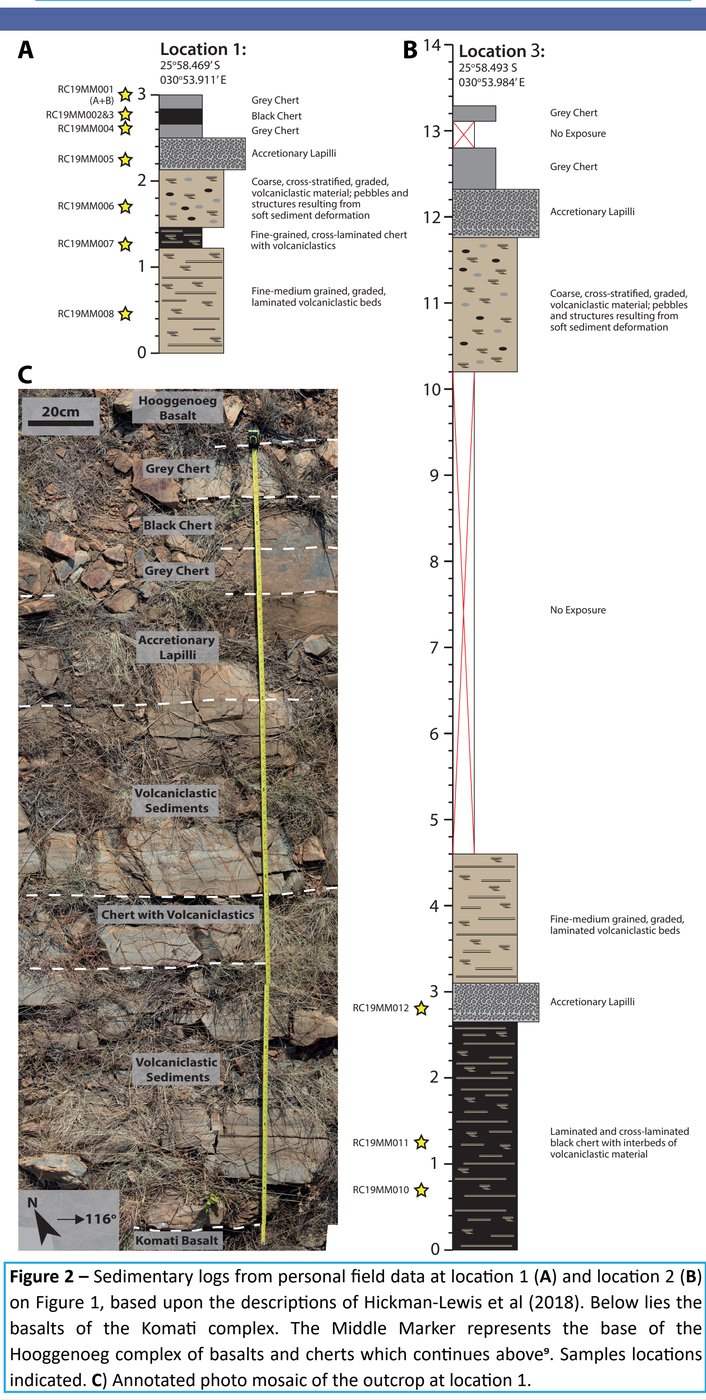


Figure 2 – Sedimentary logs from personal field data at location 1 (**A**) and location 2 (**B**) on Figure 1, based upon the descriptions of Hickman-Lewis et al (2018). Below lies the basalts of the Komati complex. The Middle Marker represents the base of the Hooggenoeg complex of basalts and cherts which continues above[9]. Samples locations indicated. **C**) Annotated photo mosaic of the outcrop at location 1.

Discussion

- Biomineralizing organisms contribute significantly to evolution of planetary environments, yet their origin and evolution remains poorly understood.
- MTB may represent some of the oldest microorganisms capable of synthesising minerals (biomineralization). The oldest fossilised MTB magnetosomes confidently identified are ~1.9Ga[10].
- By examining the placement, similarities, and differences between the genetic code responsible for magnetotaxis in different phylogenies of MTB, it is possible to estimate how long ago these groups last shared a common ancestry. Using this molecular clock approach, it has been estimated that MTB evolved during the Archean (~3.21-3.38Ga)[8].
- If these magnetic signatures do represent the magnetosomes of MTB, then this would be the earliest known example of fossilised biomineralizing microorganisms. This would demonstrate that MTB had evolved by 3.47Ga, agreeing approximately with the time estimation from molecular clocks.
- Other techniques can be implemented to test the remFORC data. Nine robust criteria for the identification of magnetofossils including MTB have been identified[7] (Figure 4).
- Magnetotaxis provides a selective advantage for magnetic field strengths >~6 μT[8], and thus the presence of magnetotaxy can be used to as a proxy for Earth's magnetic field intensity. Therefore, by inference if MTB existed 3.47Ga in the Middle Marker sediments, then Earth's geodynamo must have been active at this point.
- The positive conglomerate test for the lapilli indicates that the magnetic fabric present is primary (i.e. has been unaltered through time). By inference, this means that the other lithologies are also likely to exhibit primary magnetisation. This would represent the earliest primary magnetic fabric on Earth. Therefore, the Middle Marker provides an ideal location to perform palaeomagnetic investigations to establish the palaeolatitude of the Barberton Greenstone Belt, and the palaeointensity of Earth's magnetic field at this time.

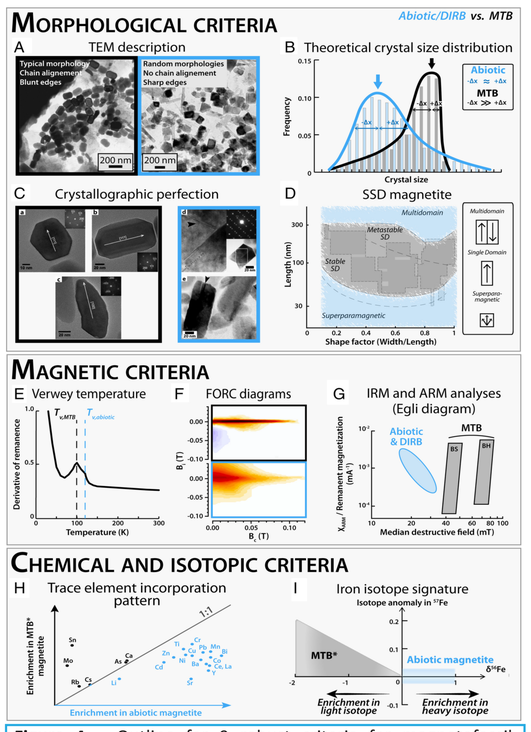


Figure 4 – Outline for 9 robust criteria for magnetofossil identification[7]. Blue indicates abiotic/induced magnetite, black indicates the signal for MTB.

Significance

1) **Biomineralizing organisms, such as MTB, contribute significantly to the evolution of planetary environments however their origin and evolution remains poorly understood. Magnetic data indicates the potential presence of MTB within the 3.47Ga Middle Marker Bed. This would be the earliest evidence of fossilised biomineralizing organisms.**
2) **If the Middle Marker does contain fossilised MTB, then it would support the molecular clock dating which estimates that MTB evolved by or during the Palaeoarchean.**
3) **The positive conglomerate test indicating randomly orientated magnetic fabrics within the lapilli represents Earth's oldest unambiguously demonstrated proven primary magnetisation.**

Next Steps

1) **Process the RemFORC data and produce figures.**
2) **Conduct further experiments using the nine robust criteria (Figure 4). Principally iron isotope signatures and Verwey temperature analysis as these are most achievable.**
3) **An extensive palaeomagnetic survey is recommended for this section of the Middle Marker in order to reconstruct the palaeolatitude of the Barberton Greenstone Belt. This would involve going back to the field and drilling a sample succession.**

References

1. Armstrong R.A., Compston W., de Wit M.J., & Williams I.S. (1990) The stratigraphy of the 3.5-3.2Ga Barberton Greenstone Belt revisited: A single zircon ion microprobe study. Earth and Planetary Science Letters 101: 1, p90-106.
2. Delarue F., Rouzaud J-N., Derenne S., Bourbin M., Westall F., Kremer B., Sugitani K., Deldicque D., & Robert F. (2016) The Raman-Derived Carbonization Continuum: A Tool to Select the Best Preserved Molecular Structures in Archean Kerogens. Astrobiology 16: 6.
3. Lanier W. P., & Lowe D. R. (1982) Sedimentology of the Middle Marker (3.4Ga), Onverwacht Group, Transvaal, South Africa. Precambrian Research 18: 3, p237-260.
4. Hickman-Lewis K., Cavalazzi B., Roucher F., & Westall F. (2018) Most ancient evidence for life in the Barberton greenstone belt: Microbial mats and biofabrics of the ~3.47 Ga Middle Marker horizon. Precambrian Research 312, p45-67.
5. Jogler C., & Schuler D. (2009) Genomics, Genetics, and Cell Biology of Magnetosome Formation. Annual Reviews of Microbiology 63, p501-521.
6. Frankel R. B., Bazylinski D. A., Johnson M. S., & Taylor B. L. (1997) Magneto-Aerotaxis in Marine Coccoid Bacteria. Biophysical Journal 73, p994-1000.
7. Amor M., Mathon F. P., Monteil C. L., Busigny V., & Lefevre C. T. (2020) Iron-biomineralizing organelle in Magnetotactic bacteria: function, synthesis and preservation in ancient rock samples. Environmental Microbiology 00(00), p00-00.
8. Lin W., Paterson G. A., Zhu Q., Wang Y., Kopylova E., Li Y., Knight R., Bazylinski D. A., Zhu R., Kirschvink J. L. & Pan Y. (2017) Origin of microbial biomineralization and magnetotaxis during the Archean. PNAS 114: 9, p2171-2176.
9. De Wit M. J., Furnes H., & Robins B. (2011) Geological and tectonostratigraphy of the Onverwacht Suite, Barberton Greenstone Belt, South Africa. Precambrian Research 186: 1-4, p.1-27.
10. Chang S. B. R., Kirschvink J. L. (1989) Magnetofossils, the Magnetization of Sediments, and the Evolution of Magnetite Biomineralization. Annual Reviews of Earth and Planetary Sciences 17, 169-195.

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