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APS Lewis and Clark Fund for Exploration and Field Research in Astrobiology
awarded April, 2012

Evidence for Life on Land During the Mesoproterozoic: Evidence from the Midcontinent Rift System

Summary Report:

The Mesoproterozoic era (1.6-1.0 billion years ago) occurs during what has been casually referred to as the 'boring billion' stage of Earth's history. This moniker was given to the period of time between 1.85 and 0.85 billion years ago, due to the absence of iron formations and the relative stability of the ocean carbon reservoir. While the marine carbon cycle and pO_2 of the atmosphere may have been stable, the biosphere was far from quiescent. Marine life was especially dynamic during this era, with stromatolites reaching their peak diversity and abundance.

While the Mesoproterozoic remains poorly characterized in general, the terrestrial realm at this time is an even greater unknown. Although terrestrial rocks of this age are rare, the Mid-Continent Rift System (MCR) in the Lake Superior region contains a series of terrestrial deposits that date to approximately 1.1 billion years ago. These sedimentary rocks are thought to have been originally deposited in ancient riverine, floodplain, and lake environments. Despite their age, the rocks of the MCR remain relatively pristine and unmetamorphosed, offering a unique opportunity to characterize the terrestrial biosphere and paleoenvironment during the Mesoproterozoic.

The traditional narrative of Earth's history holds that life did not transition on to land until the Middle-Ordivician (~470 million years ago); however, there is reason to suspect microbial life existed in terrestrial settings much earlier. Understanding the Precambrian microbial biosphere is important because it altered the Earth's natural geochemical cycles and led to its oxygenation. It may also have driven global climatic events, such as 'Snowball Earth' glaciations. Thus, characterizing the Mesoproterozoic terrestrial biosphere and its environment will help develop a better understanding of the evolution, complexity, and controls of global biogeochemical cycles.

I completed two separate trips to the Lake Superior region during August and September 2012. The first trip encompassed visits to and sampling of 17 different sites spread across Michigan, Wisconsin, and Minnesota. For parts of this first trip, I was joined by my advisor as well as collaborators from the University of Indiana and Caltech. For the second trip I returned to the Iron River site and conducted detailed sampling of the Nonesuch formation.

Stromatolites and MISS

As stated above, perhaps the best evidence for a vibrant biosphere during the Mesoproterozoic is the abundance of stromatolites. These domed structures form when algalmats trap and bind sediment as they grow. Traditionally, they are thought to only be marine in origin, and they are abundant in shallow marine rocks from the Mesoproterozoic.

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As part of this fieldwork, we examined stromatolites found within the Copper Harbor Formation at two different locations on the Keweenaw Peninsula, Dan's Point and Horseshoe Harbor. What makes these stromatolites unique is that they are formed on large cobbles up to 20 cm in diameter. Transport and deposition of cobbles require very high flow velocities that are typically found only in alluvial deposits. Thus, we have evidence that suggests microbial life was indeed flourishing in terrestrial riverine environments

Another form of evidence of life on land in the MCR comes from microbially induced sedimentary structures (MISS). MISS are structures preserved in rocks that can only exist if there was some type of microbial organism living in the sediments that helped to bind the sediment grains together. At the Cutface Creek site near Grand Marais, Minnesota, we identified and examined a number of MISS that were preserved. For example, there are bi-directional ripple marks preserved in the same bedding plane. These can only be preserved with the aid of a microbial organism binding grains together; otherwise only one direction of ripples will be preserved. While the stromatolites and MISS illustrate that there was microbial life present in terrestrial environments during the Mesoproterozoic, they unfortunately do not shed any light on the paleoenvironment or what types of microbial organisms were present.

Life in the Nonesuch Lake

In an effort to better characterize microbial diversity at this time, I spent over a week working on the Nonesuch Formation. The Nonesuch formation is a relatively thin unit (100-250 meters) that runs along the Lake Superior shoreline from the Keweenaw Peninsula into Wisconsin. It is comprised primarily of fine grained siltstones and shales and is thought to have been originally deposited in a lake environment. The Nonesuch is one of only two known lake deposits in the world that date to this period in Earth's history. What makes the Nonesuch formation even more unique is that it is both high in organic carbon (up to 2% by weight) and it has never been exposed to any significant post-depositional alteration. It is this well-preserved organic carbon that is the key to developing a better understanding of the metabolic diversity that existed in terrestrial ecosystems in the Mesoproterozoic.

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I focused my attention on an outcrop of the Nonesuch formation that is exposed along the Iron River near Silver City, Michigan. I measured a 220 meter section and collected over 70 samples from this site. Within this section, there were dark laminated shales, massive siltstones, and claystones with preserved mudcracks. This indicates that the depth of the lake was changing over time, and that we have samples that represent both deeper water (the dark shales) and shallower water (the beds close to the mudcracks). In order to assess spatial variability within the

Nonesuch formation, I also collected samples from a site 50 miles away near Hancock, Michigan.

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Paleosols

Paleosols (fossil soils) are paleoclimate archive that can be used to assess the environmental and atmospheric composition during the Mesoproterozoic. Because soils are formed in contact with the atmosphere, analysis of their bulk geochemical composition can give insight about the extent of chemical weathering. Precambrian paleosols predate terrestrial plants, so the assumption is that most of the chemical weathering is a function of atmospheric $p\mathrm{CO_2}$. The chromium isotope composition can also give information about atmospheric $p\mathrm{O_2}$.
10 different paleosols, spread across Michigan and Minnesota, were identified and sampled as part of this fieldwork.

Characterizing the extent of chemical weathering in paleosols at this time is important in the context of the evolution of the biosphere. With evidence for life on land in both lakes and rivers, the question remains open whether or not microbial communities were present on floodplains. If they were present on floodplains, they would help stabilize the sediment from erosion and allow for greater soil development. Greater soil development would allow for more chemical weathering, and potentially a major shift in global biogeochemical cycles.

Future Work

Laboratory work on samples collected from this fieldwork is currently ongoing. Geochemical analyses on Nonesuch samples will include bulk carbon isotopic composition, organic biomarker, compound specific carbon isotopes, and trace element analyses. All of the organic geochemical results will be used to characterize the metabolic diversity of the ancient lake. For example, certain types of organic compounds, such as lipids and pigments, have high preservation potential and can be diagnostic of specific types of microorganisms. The trace element geochemistry will be used to reconstruct paleo-redox conditions. Certain elements tend to be more-soluble under oxidizing conditions and less-soluble under reducing conditions. For example, elevated concentrations of V, U, and Mo are indicative of euxinic conditions; whereas elevated concentrations of V and U, but not Mo indicate anoxic conditions. Initial results are very promising for the Nonesuch samples, and we plan to expand our sampling in future field seasons.

Analysis of the paleosols will include major and minor element bulk geochemistry as well as some chromium isotope work. The bulk geochemical results will help to assess the extent of chemical weathering as well as assess the pCO_2 levels during the Late Mesoproterozoic. The chromium isotopes will lend insight into the levels of atmospheric oxygen at that time.