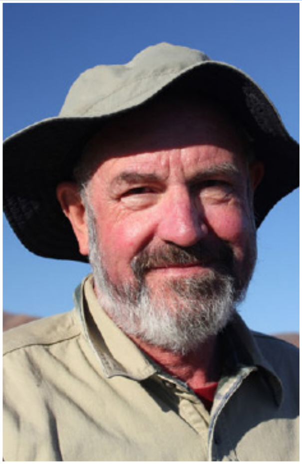
National Aeronautics and Space Administration

NASA Astrobiology Institute
2016 Annual Science Report
Team Report:

Foundations of Complex Life:
Evolution, Preservation and Detection
on Earth and Beyond,
Massachusetts Institute of Technology

Foundations of Complex Life
Evolution, Preservation and Detection on Earth and Beyond

Lead Institution:
Massachusetts Institute of Technology



Principal Investigator:
Roger Summons

Team Overview

Foundations of Complex Life is a research project investigating the early evolution and preservation of complex life on Earth.

We seek insight into the early evolution and preservation of complex life by refining our ability to identify evidence of environmental and biological change in the late Mesoproterozoic to Neoproterozoic eras. Better understanding how signatures of life and environment are preserved will guide how and where to look for evidence for life elsewhere in the universe—directly supporting the Curiosity mission on Mars and helping set strategic goals for future explorations of the Solar System and studies of the early Earth.

Our Team pursues these questions under five themes:

I. *The earliest history of animals:* We use methods from molecular biology, experimental taphonomy, and paleontology to explore what caused the early divergence of animals.

II. *Paleontology, sedimentology, and geochemistry:* We track the origin of complex protists and animals from their biologically simple origins by documenting the stratigraphy, isotopic records, and microfossil assemblages of well-preserved rock successions from 1200 to 650 million years ago.

III. *A preservation-induced oxygen tipping point:* We investigate how changes in the preservation of organic carbon may have driven the Neoproterozoic oxygenation of the oceans coincident with the appearance of complex life.

IV. *Taphonomy and Curiosity:* As the Mars rover Curiosity explores Gale Crater we integrate research on Mars and Earth to understand Martian environments and geochemistry.

V. *Synthesis:* We seek to generate an expanded view of major transitions on Earth, environmental and biological, and apply this to develop a synthesis of the history of biological habitability on Mars.

Team Website: http://www.complex-life.org

2016 Executive Summary

Complex Life and Environmental Evolution

Daniel Rothman has been studying the major environmental perturbations in the geologic past, including those associated with mass extinctions. By transforming geochemical signals to physical variables, he has found that mass extinctions are associated with rates of environmental change that exceed a limit imposed by mass conservation in a normal carbon cycle. External perturbations of the carbon cycle, such as extensive volcanism, can excite responses that breach this threshold.

Kristin Bergmann, Andy Knoll and their colleagues have been building a database of Precambrian sedimentary successions which currently houses over 65 kilometers of detailed meter-scale information. This will enhance insights into environmental changes across the Precambrian.

Doug Erwin and colleagues continued field work in Namibia and Nevada, with significant discoveries about the complexity of the ecological, geochemical and evolutionary changes at the Ediacaran-Cambrian boundary (542 Ma).

Francis Macdonald's group continued field studies in Mongolia, Peru, Newfoundland, and the Southwestern US to provide geological context and samples to further elucidate the relationships between Neoproterozoic glaciations and the emergence of complex animals.

David Johnston's group supported the above-mentioned field work through making S- and C- isotope and Fe speciation analyses. They finalized a new method for measuring ^{17}O in sulfate which carries links to the composition of atmospheric pO_2 at the time the mineral was formed.

David Jacobs and colleagues have been developing the snowball earth " cold cradle" hypothesis for the appearance of animals to the "warm grave" hypothesis of many Phanerozoic mass extinctions.

Members of Ann Pearson's laboratory have continued to investigate the geobiological history of the early nitrogen cycle through studies of bulk and porphyrin-specific nitrogen isotope ratios, both in the sedimentary record and in model organisms.

Fossil Records of Complex Life

Andrew Knoll has continued his empirical exploration of the Proterozoic fossil record, focusing on new Mesoproterozoic fossils assemblages and new ways of extracting biological information from microchemical analyses.

Phoebe Cohen and colleagues have been continuing their work on the patterns and context of eukaryotic evolution in the Neoproterozoic and discovered calcium phosphate biomineralization in ca. 810 million year old eukaryotic fossils.

Derek Briggs' team has addressed environments and processes of organic matter preservation demonstrating that the long-held explanation for the preservation of Ediacara-style fossil assemblages —the so-called Death Mask model, which involves pyritization—is inadequate. Paleontological, petrographic and geochemical data reveal that preservation of the Ediacara biota is the result of early silicification presumably due to high silica concentrations in the Ediacaran oceans.

Members of Tanja Bosak's group identified new mechanisms by which microbial interactions with sediment grains and flow produce animal-like surface trails. They have also shown that microbial trapping of clays is critical

J. C. Creveling examining the Neoproterozoic record of Svalbard. Source: K. Bergmann (Harvard) / MIT for the preservation of photosynthetic structures in sandstones and siltstones and that fossils of agglutinated microbial eukaryotes were widespread during the deposition of cap carbonates during the Cryogenian.

Molecular Records of Complex Life
Kevin Peterson and collaborators have finalized "miRMiner", an open-access microRNA mining algorithm that identifies both conserved and novel miRNAs from small RNA libraries derived from both plants and animals. This resource will greatly enhance astrobiological investigations related to gene regulation and the evolution of morphological complexity.

Members of Roger Summons' lab have continued their work on the controversial 'sponge biomarker hypothesis'. Using a molecular clock approach, they demonstrated that a gene that codes for a key protein needed for the biosynthesis of 24-isopropylcholesterol (24-IPC) precursors arose from a gene duplication event that overlapped in time with the appearance of their chemical fossils in sediments.

Greg Fournier and his team have made headway in bringing best-practice molecular clock calibrations to deep microbial lineages directly involved with Earth's geochemical cycles, including oxygenic photosynthesis, sulfate reduction, and methanogenesis. Astrobiologically, these results show the close temporal associations between large planetary changes and microbial evolution, and the extent to which living systems continue to mediate geochemical processes, even as these change over geological timescales.

Missions to Mars
In the past year on MSL, John Grotzinger, Dawn Sumner, Ralph Milliken and other members of the MSL Team have tracked facies, elemental and mineralogical variations in the Murray mudstone for a total of 100 m of vertical elevation. Results demonstrate diverse environmental and taphonomic windows for accumulation and preservation of organics in the Murray Formation. Results are refining the understanding of the aqueous history of Gale Crater, for both ancient environments and diagenetic alteration.

Roger Summons and lab members have continued their studies of Mars analog soils and shown that all the organic molecules so far identified by SAM can be explained by an origin from the interaction between meteoritic organic matter and the oxychlorine compounds that have been accumulating in the Mars regolith over time.

Ralph Milliken and his team members at Brown continue to assess how near-infrared reflectance spectroscopy can be used to identify and quantify organic materials in sedimentary rocks and organic-bearing meteorites.

Team Members

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Kristen Bergmann
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Project Reports

Fossil Records of Complex Life

Our Team explores the fossil record of life between ~1.5 and 0.54 billion years ago. We identify, describe, and interpret the fossil record of this critical interval and work to understand the controls on fossil occurrences and preservation. This research helps us understand how complex life co-evolved with its environment. Kelsey Moore, graduate student at MIT, has shown that morphologically diverse agglutinating benthic eukaryotes were globally distributed during the Sturtian deglaciation (Moore et al., in press). Sharon Newman, a graduate student at MIT, has shown that photosynthetic microbes and microbial mats can be preserved on the surfaces of sand and silt. These experiments identified trapping of clays around microbial sheaths as the most important mechanism that preserves fossils (Newman et al., 2016). Research from Co-I Derek Briggs' lab suggested early silicification (Tarhan et al., 2016) and the inhibition of microbial activity by clays (McMahon et al., 2016) as additional factors that enabled fossil preservation during this time. Co-I Knoll's 2016 effort include the discovery of large filamentous eukaryotes in ca. 1500 Ma basinal shales from southern Russia (Sergeev et al., 2016) and macroscopic thalli of likely eukaryotic origin in 1536 Ma shales from China (Zhu et al., 2016). He also helped to document the evolutionary timetable for multicellular red algae, based on molecular clocks and the fossil record (Yang et al., 2016). Co-I Cohen's efforts include the identification of primary calcium phosphate biomineralization in ca. 800 Ma fossils from the Yukon and the relationship of this biomineralization to changing global redox and ecosystem dynamics (Cohen et al., in review). In addition, Cohen is collaborating with Yale graduate student Ross Anderson to investigate algal fossils found in Cryogenian strata of Mongolia.

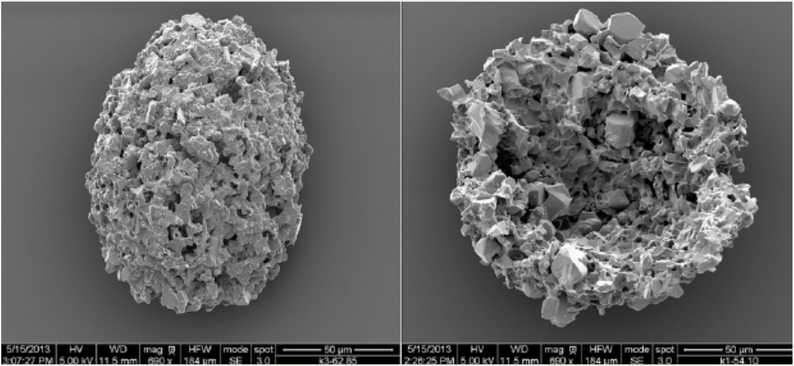


Fig.1. SEM images of agglutinated benthic eukaryotes from the Kakontwe Formation, Zambia. Left: Ovoid specimen. Right: Broken specimen demonstrates that structures are composed of a mineral rich wall and are hollow inside.

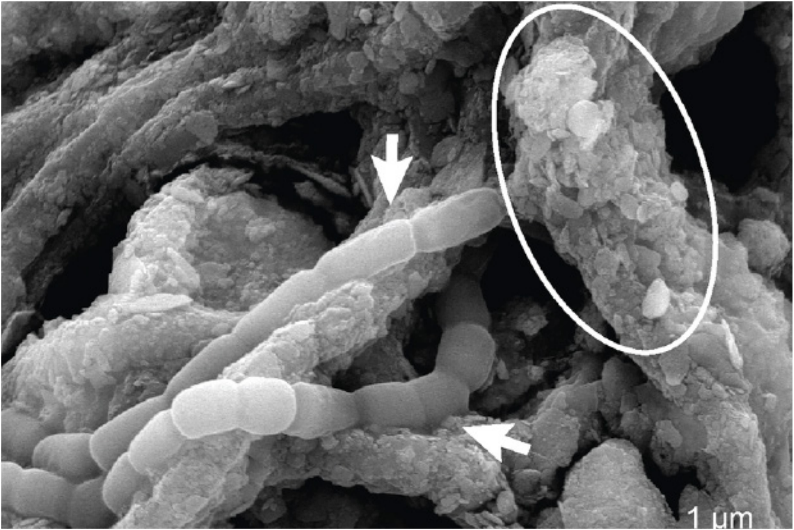


Fig. 2. Cyanobacterial cells were incubated on an illite powder substrate in the presence of artificial seawater. After 15 days of incubation, cyanobacteria with thickly sheathed filaments (>1 um-wide) were extensively coated by clay minerals (encircled area). However, unsheathed filaments with cylindrical cells (white arrows) remained uncoated throughout the duration of the experiment. These results suggest that cyanobacterial sheaths play a role in the coating of cells, and thus may be critical to the preservation of microorganisms in the siliciclastic rock record.

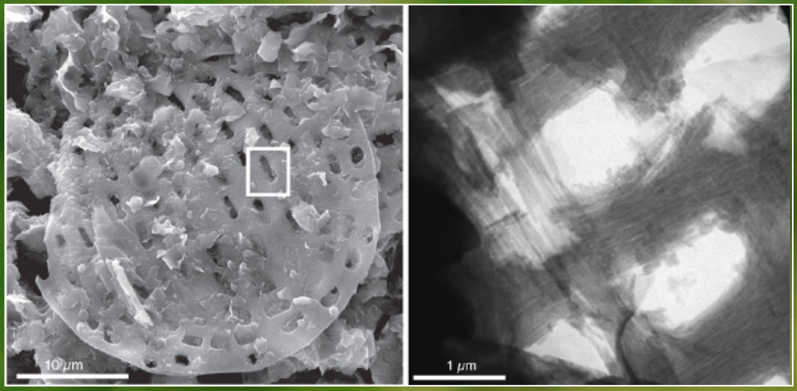


Fig. 3. Electron micrographs of biomineralized fossils from the Yukon. Left: scanning electron micrograph of single mineralized fossil. Right: high resolution transmission electron micrograph of the area in white box at left showing interwoven fibers of hydroxyapatite minerals.

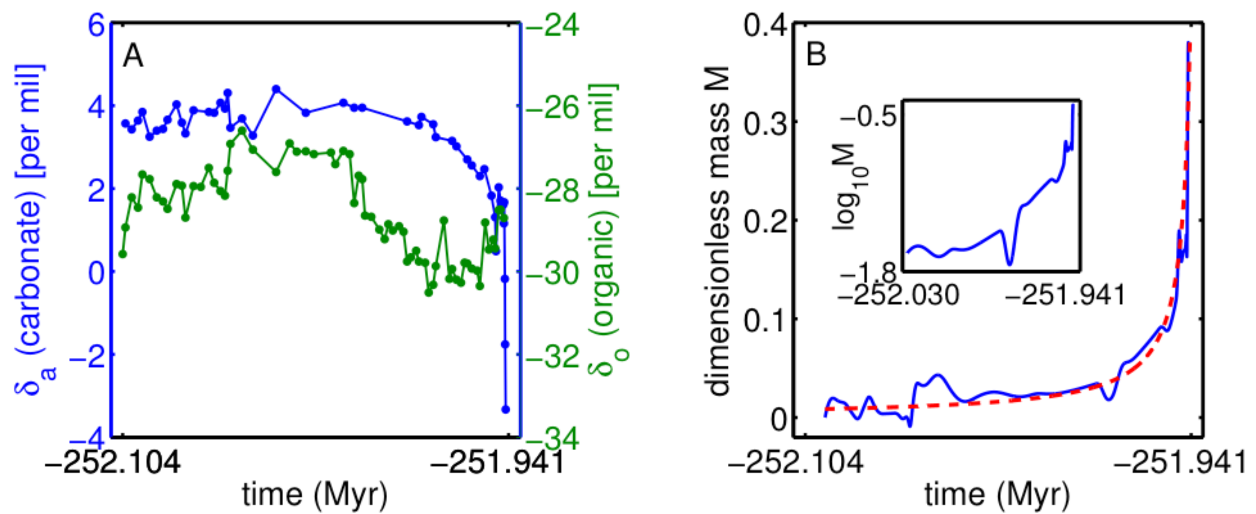


Fig. 4. Geochemical record of passage through a possible tipping point. (A) The isotopic composition of inorganic (carbonate) and organic carbon in the late-Permian sedimentary rocks. The end-Permian extinction begins 251.941 million years ago and terminates 60 ± 48 thousand years later [1]. (B) Transformation of the geochemical signals in (A) to the accumulation of mass M(t) of isotopically light carbon added to the oceans (smooth blue curve), normalized with respect to the mass prior to perturbation. The red dashed line is an incipient singularity of the form 1/(tc-t), where tc is the onset time of the extinction. The curvature of the semi-logarithmic plot in the inset shows that the growth of M(t) is faster than exponential. Modified from Ref. [2].

Tipping Points in the Earth System

The Earth system is composed of the physical environment and the life it supports. Nothing could be more familiar to us. But how does the Earth system respond to change? Evidence suggests that change comes episodically, in fits and starts. Many complex systems display such dynamics when small changes in parameters cause much larger changes in the system's qualitative behavior. Such systems are said to pass through a tipping point.

The classical notion that nature is "in balance" is distinguished from tipping points. In balanced systems, small perturbations of controlling parameters—e.g., CO_2 levels—create proportionate changes that do not alter the essential character of the original equilibrium. In the study of biogeochemical cycles this notion arises in the ubiquitous assumption of a stable steady exchange of matter between organisms and the environment. But if the Earth system has always been in balance, how did it evolve to its present state? The geologic record unequivocally shows that the journey has been composed of episodic bursts of activity. The bursts represent major events, such as mass extinctions and isolated periods of major biochemical change. The system is therefore anything but balanced. Instead it appears to pass through a series of tipping points, leading to permament change of the biogeochemical environment.

Daniel Rothman has been studying the major environmental perturbations in the geologic past, including those associated with mass extinctions. By transforming geochemical signals to physical variables, he has found that mass extinctions are associated with rates of environmental change that exceed a limit imposed by mass conservation in a normal carbon cycle. This work also suggests that external perturbations of the carbon cycle, such as extensive volcanism, can excite responses that breach this threshold. The time scale and magnitude of these responses decrease over the Phanerozoic, which may be related to the evolution of biogeochemical cycles. These observations point to a way in which the coevolution of life and the environment, one of astrobiology's principal themes, leads towards increasing stability in both the biosphere and geosphere. Tipping points do not disappear, but they seem to become less severe.

This work follows an earlier NAI-funded effort that revealed a possible tipping point related to Earth's greatest extinction, at the end of the Permian Period (Fig. 4). The American Mathematical Association recently produced a podcast featuring Rothman and this work. It can be found at http://www.ams.org/samplings/mathmoments/mm127-tipping-point-podcast.

References:
[1] S. D. Burgess and S. A. Bowring. High-precision geochronology confirms voluminous magmatism before, during, and after Earth's most severe extinction. Science Advances, 1(7):e1500470, 2015.
[2] D. H. Rothman, G. P. Fournier, K. L. French, E. J. Alm, E. A. Boyle, C. Cao, and R. E. Summons. Methanogenic burst in the end-Permian carbon cycle. Proceedings of the National Academy of Sciences, 111(15):5462–5467, 2014.

Missions to Mars

Our Team continues to analyze data acquired by the Mars Curiosity rover to understand the geological and geochemical evolution of an ancient lake system in Gale crater. The rover has traversed through over 100 m of sedimentary rock, largely mudstones, that exhibit changes in mineralogy and chemistry as a function of stratigraphic position and thus time. Distinct mineral assemblages have been identified, and the oxidation state and mineral host(s) of Fe are observed to vary. A working hypothesis is that Gale once hosted a redox-stratified lake, fed by ferrous-bearing groundwater that was overlain by ferric waters resulting from UV oxidation. We continue to explore this possibility and the extent to which the observed mineral assemblages record interactions between groundwater, lake waters, and the early Martian atmosphere. Recent data also indicate an increase in salts and provide textural evidence for subaerial exposure (e.g., mudcracks), both suggestive of decreasing lake level. Our Team is integrating these new rover observations with orbital data to determine if Curiosity is seeing the first glimpses of the 'drying out' of Gale crater and, by extension, Mars. By comparing these new results with previous evidence for a habitable environment in older rocks, we are working to better constrain the timing of habitable conditions within Gale crater. Additional work includes lab measurements to understand links between clay mineralogy and organic preservation for terrestrial rocks and carbonaceous chondrites. We are applying microscope FTIR and Raman spectroscopy methods to a variety of Proterozoic shales and their extracted kerogen as well as C chondrite meteorites and their extracted insoluble organic material to understand links between mineralogy and organics in these materials. This work is expected to provide an important foundation for helping guide sample selection by the Mars 2020 rover and the OSIRIS-REx and Hayabusa2 missions that will target nearby C-type asteroids.

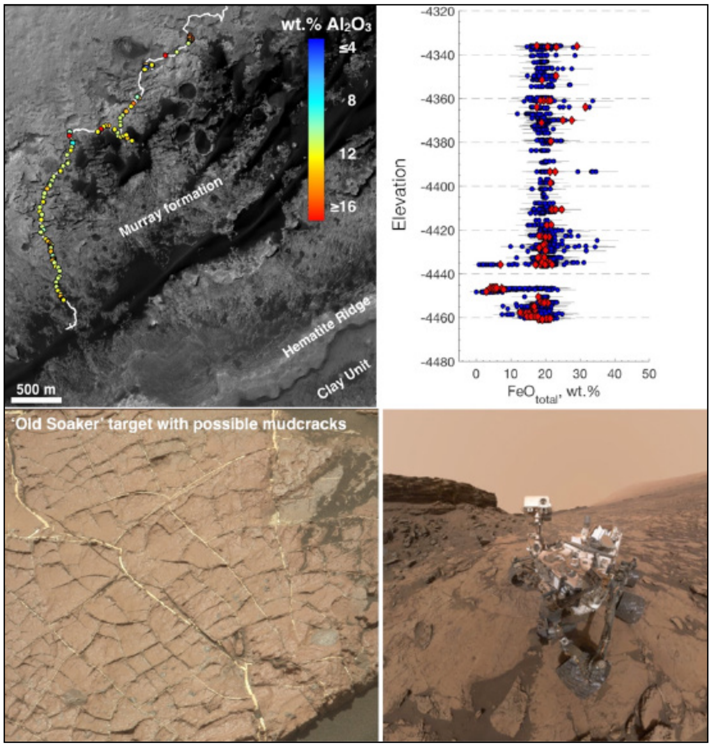


Fig. 5. Chemical and textural variations observed by the Curiosity rover in Gale crater, Mars. Top left: Variations in Al are observed along the drive path, possibly related to changes in the degree of chemical weathering. Top right: Changes in Fe content as a function of elevation, showing that recent rocks are enriched in Fe-oxides that may indicate more oxidizing conditions. Lower left: Potential mudcracks that may indicate drier environments in Gale. Lower right: Rover self-portrait showing eolian sandstones (background) capping finely laminated lacustrine mudstone.

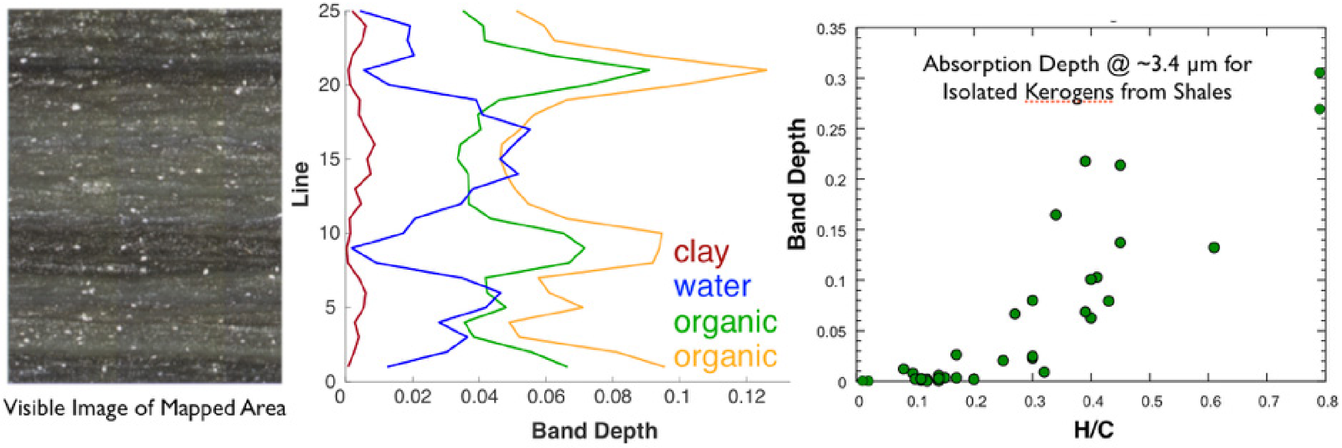


Fig. 6. Left & Center: Example of results from FTIR reflectance mapping for organic-bearing shale. Absorptions associated with organics are associated with darker-toned laminations. Right: Relationship between organic absorption from reflectance spectra and H/C values.

Exploring the Advent of Morphological Complexity with microRNAs

To understand the origin(s) of morphological complexity, it is necessary to understand how complexity is encoded in a genome. Although it has long been known that neither genome size nor gene number correlate in any simple way with morphology, one metric that seems to capture the extent of morphological complexity, as measured by cell type numbers, are microRNAs (miRNAs), small non-coding RNAs that negatively regulate the translation of select messenger RNAs. By regulating a core set of transcription factors and cellular signaling pathways during development, miRNAs are essential regulators of cellular differentiation, and are often mis-regulated in cellular diseases like cancer. Thus, miRNAs can legitimately be used to ask questions about the acquisition of cell types in complex multicellular organisms like animals and plants. We have developed an open-source miRNA mining algorithm that accurately (by reducing false positives) and precisely (by reducing false negatives) ascertains the miRNA complement of any given organism given a small RNA library and a genome sequence. This bioinformatic pipeline, called MirMiner, is intimately linked with a new open-access and hand-curated database called MirGeneDB (http://www.mirgenedb.org/). Using these new tools, we have explored the miRNA complements in a wide array of uni- and multicellular organisms, including arthropods, flatworms, mammals, and several different single-celled protist species, and have confirmed that miRNAs evolve in a manner that tracks morphological complexity such that organisms with high cell-type numbers have high numbers of miRNA gene families, and those with few or one primary cell type have few, if any, miRNAs. Further, many basal and morphologically simple organisms have secondarily lost the miRNA processing machinery early in their evolutionary history, and thus the potential for morphological complexity was realized in this clade over a billion years ago in Earth history, but was only realized in a few descendants.

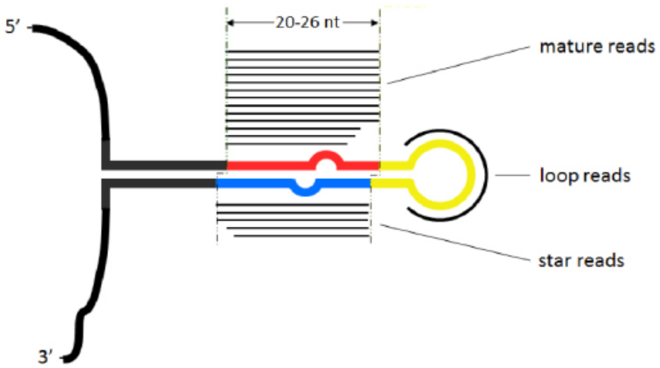
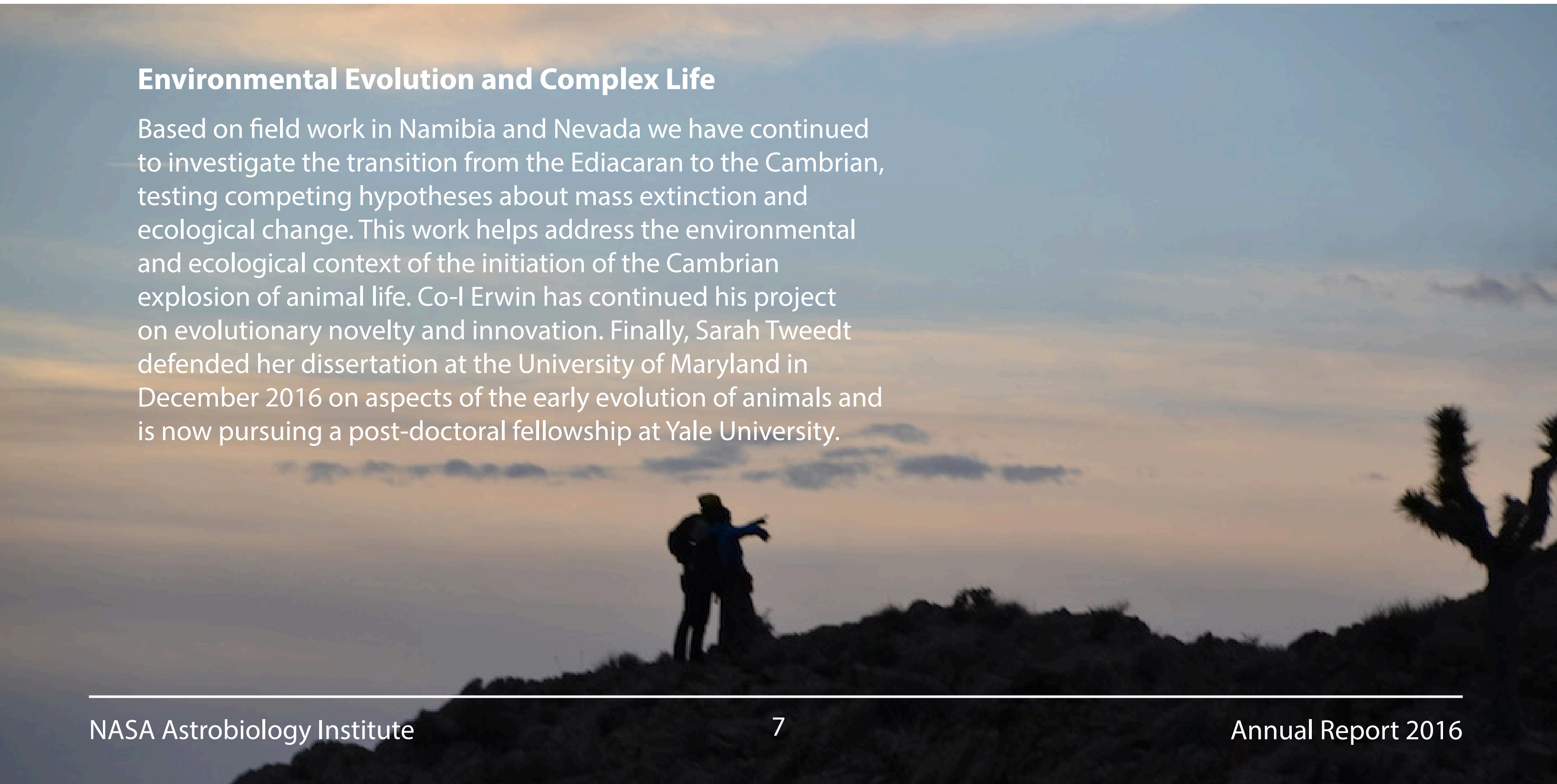


Fig. 7. A simplified structure of a canonical metazoan miRNA and its read representation. Mirminer is able to ascertain the structural details of miRNA processing, including the 5′ read homogeneity, the 2nt overlap between the mature and star strands, the length of the loop, the amount of mismatch between the mature and star reads, and the pattern of nucleotide substitution of the mature strand, to accurately and precisely call a miRNA from the myriad RNAs present in any small RNA library. Further, in conjunction with MirGeneDB, it will identify the miRNA if it has already been discovered in another taxon.

Environmental Evolution and Complex Life

Based on field work in Namibia and Nevada we have continued to investigate the transition from the Ediacaran to the Cambrian, testing competing hypotheses about mass extinction and ecological change. This work helps address the environmental and ecological context of the initiation of the Cambrian explosion of animal life. Co-I Erwin has continued his project on evolutionary novelty and innovation. Finally, Sarah Tweedt defended her dissertation at the University of Maryland in December 2016 on aspects of the early evolution of animals and is now pursuing a post-doctoral fellowship at Yale University.



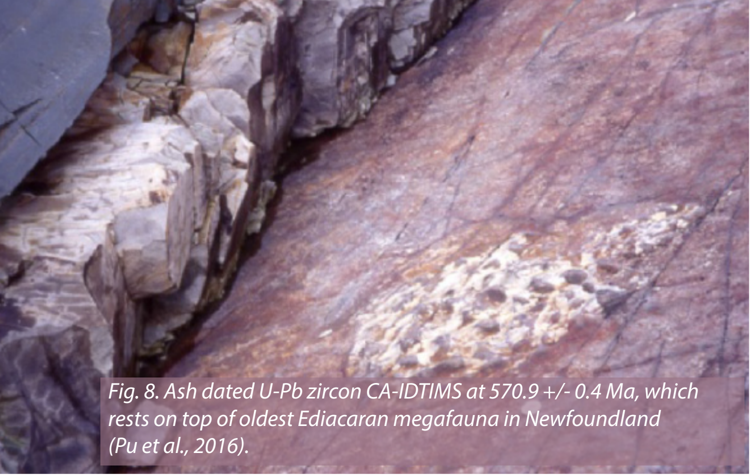


Fig. 8. Ash dated U-Pb zircon CA-IDTIMS at 570.9 +/- 0.4 Ma, which rests on top of oldest Ediacaran megafauna in Newfoundland (Pu et al., 2016).

Fig. 9. Ash dated with U-Pb zircon CA-IDTIMS and black shale dated with Re-Os above the Sturtian diamictite (grey rock at hammer height) in South China, to compare the two geochronometers. Both techniques yielded ages of ca. 659 Ma.

Field Work

Geological Records of Complex Life

Our Team explores the geological record of life between ~ 1.5 and 0.54 billion years ago. We reconstruct environmental records of this critical interval and work to understand the geological context of the development of complex life.

Over the reporting period our Team has conducted field campaigns in Peru, China, Namibia, Newfoundland, Svalbard and the Southwestern US. Many of these sites have time equivalent strata. Work in these diverse yet comparable locations aims to build a more global picture of different environments and the life contained in them across the various diversification events of complex life. Particularly, work in China, Namibia, Peru, and Newfoundland has been focused on developing a better age model for Cryogenian and Ediacaran glaciations, large perturbations to the carbon cycle, and evolutionary milestones (e.g. Fig. 8; Pu et al., 2016).

Preliminary geochronological data from China and Namibia is further refining the timing and nature of Neoproterozoic glaciation using both the U/Pb zircon CA-IDTIMS technique and Re/Os on shale (Fig. 9). In the SW US we have focused on refining the relationship between the last appearance of tubular Ediacaran fossil assemblages and the Precambrian-Cambrian carbon isotope excursion (Fig. 10; Smith et al., 2016).

Additional work in Svalbard, Newfoundland and the SW US is focused on detailed sedimentologic characterization of the carbonate fabrics and siliciclastics including micro-analytical trace metal characterization, carbonate clumped isotope thermometry and high resolution XRD analysis (Fig. 11).

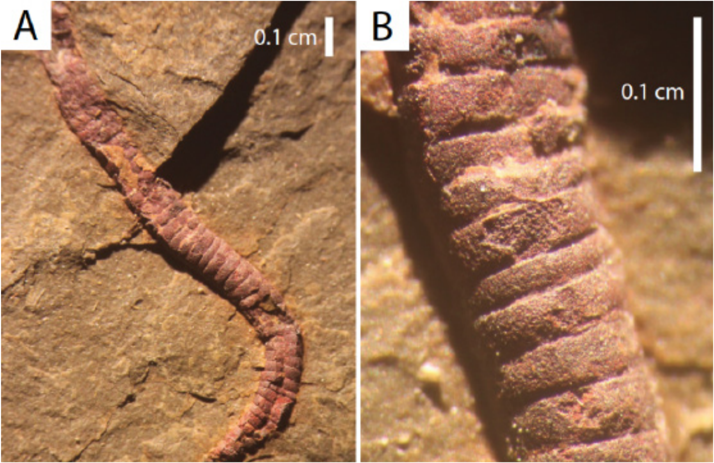


Fig. 10. Tube fossils from Mt. Dunfee Nevada, described in Smith et al. (2016) as the last Ediacaran assemblage which occurs within the downturn of the carbon isotope excursion at the Precambrian-Cambrian boundary.

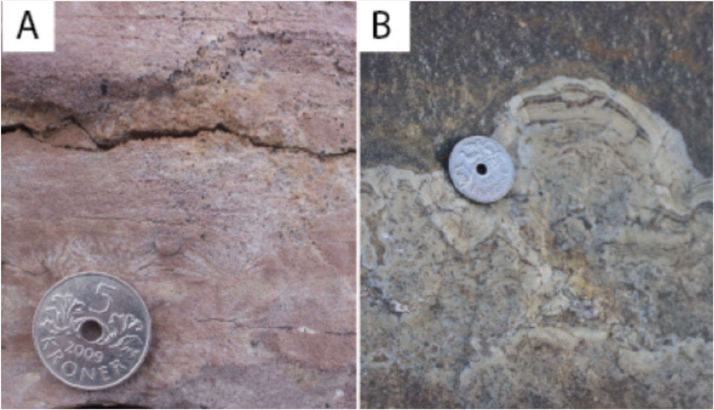


Fig. 11. Specific carbonate fabrics from Svalbard currently being analyzed for trace metals, carbonate clumped isotopes and biomarkers. A. Seafloor precipitated crystal fans from the onset of the Bitter Springs Anomaly. B. Lacustrine or marginal marine stromatolite from the syn-glacial Marinoan deposits.

Foundations of Complex Life: 2016 Publications

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