
Geobiology
2025
Program

Table of Contents

*Please note this table is linked. To navigate to each section, click its title. To navigate back to this table of contents, click the logo in the upper right corner of each page.

Conference Centre Information

Conference Rooms

- All **Speaker Series** and **Medallist** talks will take place in the Summit/Assiniboine room.
- **Lightning talks** will take place in both the Summit/Assiniboine room and Castle room.
- The Lightning talk **Discussion Session** will take place in the Glacier Salon and other conference rooms.
- Please refer to the Geobiology 2025 program for the location of all other talks.

Food & Beverage

All registered attendees for Geobiology 2025 will be provided with daytime meals and snacks.

- **Breakfast Buffet** *(7:00-8:45)*: Crave Restaurant, Wednesday to Friday
- **Lunch Buffet** *(13:00-14:00)*: Hallway leading to Alpine Meadows, seating in Crave Restaurant, Glacier Salon, or the conference rooms (Assiniboine/Summit or Castle)
- **Coffee Breaks** (*10:30-11:00*; *15:00-15:30*): Alpine Meadows, Wednesday to Friday
- **Reception** (*16:00-18:00*): Alpine Meadows, Wednesday to Friday
  - Beer, wine, and soft drinks will be available for your enjoyment during Lightning Talk sessions

Additional Information

Emergency Information:

For emergencies, dial 911

Police Services:

- Royal Canadian Mounted Police (RCMP)
  35 Lynx St. (403.763.6600)

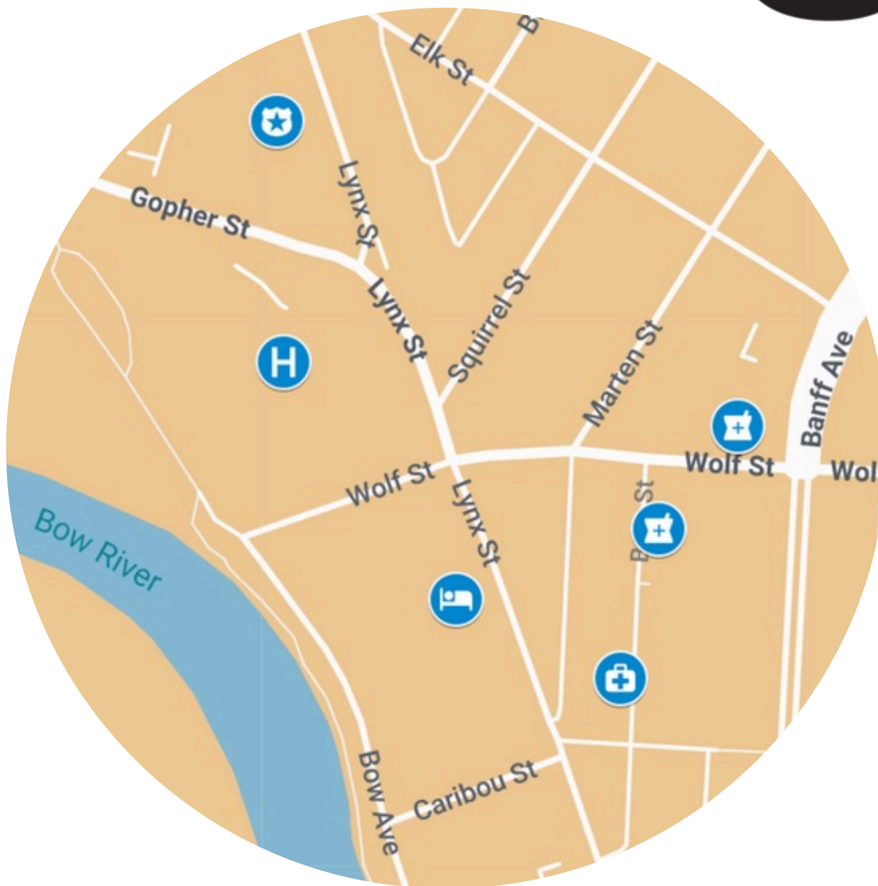
Local Health Services:

- *Banff Mineral Springs Hospital*
  305 Lynx St. (403.762.2222)
- *Alpine Medical Clinic*
  211 Bear St. (403.762.3155)

*Call 811 or 1.866.408.5465 to reach Alberta's non-emergency health line for health advice 24/7.

Pharmacies:

- *Gourlay's Pharmacy*
  220 Bear St. (403.672.2516)
- *I.D.A. Neighbourly Pharmacy* (located inside Cascade Mall)
  317 Banff Ave. (403.762.2245)



Wildlife Information:

As a reminder, Banff National Park is home to a rich diversity of wildlife including bears, elk and mountain goats. You may be lucky enough to spot these animals while exploring the area. For your safety, please never approach or feed them. To learn more about wildlife safety, visit the Parks Canada page on wilderness safety.

Geobiology Mentorship:

The 3rd International Geobiology Conference is scheduled to take place in Banff from May 20-24, 2025. A unique aspect of this conference is its focus on supporting early-career scientists. With this goal in mind we will be offering a mentorship program where early career scientists will be matched with mentor. Contact information for your mentor/mentee will be shared Wednesday evening (May 21) and you can decide to meet up during the conference or have a virtual chat at a later date.

Please fill out this form if you are interested in joining the mentorship program!

Geobiology 2025 Schedule

	Wednesday, May 21st	Thursday, May 22nd	Friday, May 23rd
8:45	**Intro**	**Intro**	**Intro**
9:00	Joanne Boden	Zachary Adam	Frankie Dunn
9:30	Aya Klos	Heda Agić	Lidya Tarhan
10:00	Elliott Mueller	Daniel Mills	Katie Maloney
10:30	**Coffee break**	**Coffee break**	**Coffee break**
11:00	Manuel Schad	Christina Woltz	Brandt Gibson
11:30	Nadja Drabon	Nabil Shawwa	Silvina Slagter
12:00	Chadlin Ostrander	Maxwell Lechte	Anna Waldeck
12:30	**Question Period**	**Question Period**	**Question Period**
13:00 **13:30**	**Lunch** Tiffany Lancaster *NSERC Presentation*	**Lunch** Tiffany Lancaster *NSERC Presentation*	**Lunch** Tiffany Lancaster *NSERC Presentation*
14:00	**Pemberton Medal Talk 1:** Eva Stüeken	**Beveridge Medal Talk 1:** David Johnston	**Garrels Medal Talk 1:** Timothy Lyons
14:30	**Pemberton Medal Talk 2:** Benjamin Mills	**Beveridge Medal Talk 2:** Tanja Bosak	**Garrels Medal Talk 2:** Andrew Knoll
15:00	Nature Geoscience and Nature Communications Editors Q&A	Frank Corsetti	Erik Sperling
15:45	**Lightning Talks**	**Lightning Talks**	**Lightning Talks**
16:45-18:00	**Discussion Session**	**Discussion Session** *Agilent* *(5:30 @ Castle Room)*	**Discussion Session**
Evening Events	Guided walks/free time	Guided walks/free time	Pub Crawl

Geobiology (After Dark)

Icebreaker

Tuesday, May 20th

Help us kick off Geobiology 2025 at **High Rollers Bowling & Beer Hall** for an evening full of bowling, beer, and pizza!
Timing: 6 PM - 1 AM
Location: 110 Banff Avenue, Banff, AB T1L 1A4
Conference packets and name tags will be distributed upon arrival. Appetizers, pizza, and 2 drink tickets (good for beer, wine, or soda) will be provided.

Guided Hikes

Tuesday, May 20th

"Welcome to Banff" guided hike (2-4 PM)
This easy 1.5-hour walk—including a 30-minute stop at the viewpoint—offers a perfect opportunity to unwind, take in the stunning surroundings, and connect with fellow attendees before the evening's icebreaker event

Wednesday, May 21st & Friday, May 23rd

"Sunset at Vermilion Lake" guided hike (8:30-10pm, weather dependent)
This guided outing will take approximately 2.5 hours, including a one-hour stop at the lakes, where you'll have time to explore further, capture breathtaking photos of the Vermilion Lakes framed by the majestic Mount Rundle, or simply relax on a lakeside deck and take in the view.

Pub Crawl

Friday, May 23rd

For our final evening, we bring to you our very own Banff Town Pub Crawl! Seats are limited, so first come first serve.

St James Gate Irish Pub *(7:00-8:00pm)*
207 Wolf St, Banff, AB T1L 1C2
Rose & Crown *(8:00-9:00pm)*
202 Banff Ave, Banff, AB T1L 1B5
Pump and Tap Tavern *(9:00-10:00pm) *cash only*
215 Banff Ave, Banff, AB T1L 1A9
The Dancing Sasquatch *(11:00pm onwards)*
120 Banff Ave, Banff, AB T1L 1A6

Acknowledgments

Conference Chair

Kurt Konhauser (University of Alberta)

Scientific Committee

Marc Laflamme (University of Toronto)
Benjamin Mills (University of Leeds)
Katie Maloney (Royal Ontario Museum)
Nagissa Mahmoudi (McGill University)
Daniel Mills (University of Munich)
Victoria Petryshyn (University of Southern California)

Organizing Committee

Sanaa Mughal (University of Alberta)
Yuhao Li (University of Alberta)
Jenifer Spence (University of Alberta)
Kelly Rozanitis (University of Alberta)
Daniela Gutierrez Rueda (University of Alberta)
Baptiste Coutret (University of Alberta)

Land Acknowledgement

As we gather for the Geobiology 2025 Conference in Banff, we do so with deep respect for the traditional territories on which we meet. Banff is located within Treaty 7 territory - ancestral lands of the Niitsitapi from the Blackfoot Confederacy, including the Siksika, Kainai, and Piikani First Nations; the Îyârhe Nakoda of the Chiniki, Bearspaw, and Goodstoney First Nations; the Tsuut'ina Nation; the Métis Nation of Alberta, as well as the many other Indigenous Peoples whose histories and ongoing stewardship shape these lands.

As scientists exploring the profound connections between Earth and life, we recognize that Indigenous Peoples have cultivated deep relationships with this land for millennia - observing, understanding, and caring for it in ways that align closely with many of our own inquiries. We offer this acknowledgement in gratitude, and as a commitment to reconciliation, respect, and continued learning from Indigenous knowledge systems.

S. George Pemberton Award

George Pemberton (1948-2018) is one of the founding fathers of applied ichnology. His interdisciplinary approach integrated trace fossils with sedimentological as well as stratigraphic principles that implicitly recognized the impact of biology on the stratigraphic record. George's integrative efforts were amongst the first to show that in establishing an understanding of the sedimentology, stratigraphy, and biology of the stratigraphic record the whole became greater than the sum of the parts. He is also well known for his prolific mentorship record that includes the supervision of over eighty graduate students. George took great pride in his role supervising impressionable young geologic minds and always encouraged his students to critically and creatively think about complex problems. His kind-hearted nature, robust laugh, and infamous stories will always be remembered.

The S. George Pemberton Award will be presented in his honour to an early career scientist(s) for significant achievements in geobiology. The award will normally be given biennially at the Geobiology Society Conference.

Awardees

Eva Stüeken

(University of St. Andrews)

Eva is interested in the origin and early evolution of life on Earth and implications for the habitability of other worlds. She uses a combination of field work, geochemical analyses, laboratory experiments and models to reconstruct biosignatures and biogeochemical cycles in deep time.

Benjamin Mills

(University of Leeds)

Ben's group builds 'Earth Evolution' computer models to better understand how life and the Earth interact over geological timescales. Specifically this work has aimed to map the processes that have caused oxygen to accumulate in the Atmosphere, and those that have driven large changes in Earth's surface temperature

Terry J. Beveridge Award

Terrance J. Beveridge (1945-2007) was one of the founding fathers of Geomicrobiology. His larger-than-life love for science and discovery brought together microbiology, geology, chemistry, physics, and medicine. His pioneering research on metal ions and bacterial surface reactivity opened the door to research on the role of bacteria in geochemical cycling and on the origin of life on Earth. He was also a renaissance man with a passion for music, food, wine, and everything else good in life. His laughter and amazing ability to listen will always be remembered.

The Terry J. Beveridge Award will be presented in his honour to a mid-career scientist(s) for significant achievements in geobiology. The award will normally be given biennially at the Geobiology Society Conference.

Awardees

David Johnston

(Harvard University)

David is an isotope Geobiologist who is interested in exploring large-scale changes to the ocean - atmosphere system through time while in parallel leveraging and unpacking the wonders of microbiology to tell those stories. This work extends from the study of meteorites and our earliest origins, through all of Earth's sedimentary history to our modern oceans, atmosphere and climate.

Tanja Bosak

(Massachusetts Institute of Technology)

Tanja is a Professor of Geobiology at MIT in Cambridge, Massachusetts, and a participating scientist on the Mars 2020 Perseverance Rover Mission. She uses experimental geobiology to reconstruct the co-evolution of life and the environment during the first 80% of Earth and guide the search for signs of past life on Mars. Tanja grew up in Croatia and has a strong interest in public outreach, travel and spicy food

Robert M. Garrels Award

Robert M. Garrels (1916-1988) was a pioneer of geochemistry and a strong proponent of recognizing and investigating the role of the biota in Earth surface processes. Although best known for his contributions to understanding and modelling the global cycles of the elements, he made seminal contributions to the fields of economic geology and aqueous geochemistry and demonstrated how Eh-pH and activity-activity diagrams could concisely characterize the stability of minerals and solutes in laboratory and natural settings. Forever young, he thrived on the enthusiasm and fresh ideas of students and early-career scientists and was always willing to exchange a game of tennis or ping pong for an intense discussion of scientific ideas.

The Robert M. Garrels Award will be presented in his honour to a senior scientist for sustained and distinguished achievements in geobiology, consisting of a series of publications that have had a major influence on the field. The award will normally be given biennially at the Geobiology Society Conference.

Awardees

Timothy Lyons

(University of California at Riverside)

Tim is a geochemist interested in the history of microbial life and its surroundings. He works in the complementary research spheres of astrobiology, ancient oceans and lakes and their modern analogs, geobiology, biogeochemical cycling, isotopic and elemental tracers of ancient environments, and co-evolving early life. He emphasizes early oxygenation of the atmosphere and oceans and concomitant impacts on nutrients and bioessential trace metals.

Andrew Knoll

(Harvard University)

Andy is a paleontologist whose research through the years has focused on the interplay between physical and biological processes across nearly the complete span of Earth history. He is particularly well known for his field-based research on the deep history of life.

Wednesday at a glance

Speaker Series

8:45	**Introduction**
9:00	**Joanne Boden** *Microbial phosphorous cycling in the Precambrian*
9:30	**Aya Klos** *The Archaeal and Bacterial biosphere*
10:00	**Elliott Mueller** *Microbial fermentation: The hidden metabolism of Precambrian biogeochemistry and its imprint on carbon isotope records of lipids biomarkers*
10:30	**Coffee break**
11:00	**Manuel Schad** *Tracing early primary production – What do trace metals tell us?*
11:30	**Nadja Drabon** *Effect of a giant meteorite impact on Paleoarchean surface environments and life*
12:00	**Chadlin Ostrander** *The Archean sedimentary thallium isotope record: what is it trying to tell us?*
12:30	**Question period**
13:00	**Lunch** *Tiffany Lancaster - NSERC Presentation*
13:30	
14:00	**Pemberton Medal Talk 1: Eva Stüeken**
14:30	**Pemberton Medal Talk 2: Benjamin Mills**
15:00	***Nature Geoscience* and *Nature Communications* Editors** *Q&A Session & Coffee break*
15:30	**Lightning Talks**
16:00 - 18:00	**Discussion session**

Wednesday - Lightning Talks

Assiniboine/Summit Room
Michael Babechuk *A new look at corrections for alkali-element metasomatism in Precambrian paleosols*
Leslie Robbins *New insights from high resolution mapping of trace elements in Iron Formations*
Christopher Jones *Evolving volcano-tectonic and biogeochemical processes controlling hydrothermal iron deposits of the Cristiana-Santorini-Kolumbo Volcanic Field*
Daniela Gutierrez-Rueda *Tracing the rise of continents through banded iron formations: Experimental insights into germanium partitioning*
Taiwo Kassim *Reconstructing the in situ and diagenetic evolution of precursor Banded Iron Formations: Constraints on fluid flow and implications for Paleoproterozoic seawater composition*
Carolin Dreher *Banded Iron Formations – interplay of iron, silica, phosphate and nickel*
Yuhao Li *Cyanobacteria-ferrihydrite aggregates as important primary BIF sediments and their implications for Archean-Paleoproterozoic oceans*
Loann Gros *Exploring trace element limitations in cyanobacteria prior to the Great Oxidation Event*
Andrey Ilin *Simulation of Precambrian banded iron sedimentation using microbial co-cultures in a controlled column setup*
Taro Matsuo *Green Ocean Hypothesis: Coevolution of surface environment and phototrophs in the Archean era*
Chihiro Arai *The Archaean underwater light environment: Implications for habitability of Earth's surface and potential biosignatures*
Catherine Fontana *Turning back the clock on ancient stromatolites: An experimental approach to cyanobacterial biofilm formation and encrustation*
Holly Rucker *Continuity of nitrogenase isotope signatures over 3 billion years of evolution*
Alia Sanger *Did the genetic capacity for exoenzyme production vary over Earth's history?*
Amanda Calhoun *Biosignature ranges of archaeal carbon isotope fractionation in geochemically diverse terrestrial hot springs*
David Madrigal-Trejo *Arsenic accumulation in microbial mats and the interpretation of signals of early arsenic-based metabolisms*

Castle Room
Maxence Le Picard *Silicon isotope signatures of the >3.4 Ga Apex and Strelley Pool Cherts: Implications for silica sources and the Paleoarchean seawater composition*
Amandine Migeon *Early hints of oxygen: New insights into Mesoarchean Mo cycling from the 2.87 Ga Red Lake carbonate platform*
Xueqi Liang *A seawater oxygen oscillation recorded by iron formations prior to the Great Oxidation Event*
Sabs Wimmer *Bridging the gap between Earth's initial oxygenation and a possible oxygen overshoot: A new look at the Espanola Formation, Canada*
Stacey Edmonsond *Timing and magnitude of the Lomagundi excursion and its relationship with Earth's Great Oxidation*
Colin Goldblatt *EONS: A new model of Earth's atmosphere and ocean evolution via C, N, O, and P cycles through Earth history*
James Gutoski *From sediments to signposts: The Paleoproterozoic phosphorus cycle and early Earth oxygenation*
Daniel Garduno Ruiz *Comparing oxygen proxies across the Great Oxidation Event: Iodine vs cerium anomalies*
Andrew Siciliano *Temporary oxygenation of Earth’s surface ~2.4 billion years ago*
Maxime Coutant *A multiscale approach to the investigation of carbon texture in putative microfossils from the Pilbara Craton (Western Australia)*
Sami Nabhan *Organic matter heterogeneity and population diversity in Precambrian strata*
Sean Jordan *Protobiosignatures: Signs of life's emergence*
Christopher Tino *Spatial and seasonal controls on phosphate accumulation at an origin-of-life analog environment*
Vanessa Helmbrecht *Testing emergence of life hypotheses in hydrothermal vent experiments*
Hanna Dienstbier *RNA dynamics in a hydrothermal vent model of the prebiotic Earth*
Penny Morrill *Using geochemical and biological methods to source microbial methane at serpentine-hosted springs*
Melonie Nguyen *Investigating the incorporation of organic matter into evaporite minerals as a tool to search for the record of life on Earth and elsewhere*

Thursday at a glance

Speaker Series

8:45	**Introduction**
9:00	**Zachary Adam** *Did iron suppress eukaryote emergence and early radiation?*
9:30	**Heda Agić** *New insights into Palaeoproterozoic microbial ecosystems*
10:00	**Daniel Mills** *The origin and earliest evolution of eukaryotes in the Proterozoic biosphere*
10:30	**Coffee break**
11:00	**Christina Woltz** *Preserving the eukaryotic fossil record: The impact of fossilisation processes on our view of early eukaryotes*
11:30	**Nabil Shawwa** *Earth’s oldest terrestrial red beds as direct evidence for the Great Oxidation Event ca. 2.3 Ga*
12:00	**Maxwell Lechte** *Sedimentary zinc deposition in the Palaeoproterozoic: implications for the evolution of the oceans and biosphere*
12:30	**Question period**
13:00 **13:30**	**Lunch** *Tiffany Lancaster - NSERC Presentation*
14:00	**Beveridge Medal Talk 1: David Johnston**
14:30	**Beveridge Medal Talk 2: Tanja Bosak**
15:00	**Frank Corsetti** *How not to blow the most important talk of your life*
15:30	**Lightning Talks**
16:00 - 18:00	**Discussion session** ____ **5:30pm: Agilent** (in Castle Room) *ICP-MS & ICP-MS\MS considerations and the keys to quality data*

Thursday - Lightning Talks

Assiniboine/Summit Room
Maya Thompson *Testing the efficacy of machine learning regression algorithms in predicting geochemical marine redox changes from the mid-Paleoproterozoic to the Holocene*
Emma Jager *Re-evaluating glauconite as a geochronometer: A coupled Rb–Sr and K–Ca approach via TIMS-ATONA and ICP-MS/MS*
Hunter Olson *Understanding the effect of thermal maturation on the mudrock TOC record in deep time analyses*
Jaden Olah *Estimating late Neoproterozoic temperature conditions for the western Laurentian margin with chemical weathering proxies*
Jingjun Liu *Evolution of the iodine cycle and the late stabilization of the Earth's ozone layer*
Keyi Cheng *Understanding the secular variation of marine* IO_3^- *reservoir and its paleoredox implications*
Brian Kendall *The emerging thallium isotope perspective on oxygenation of late Paleoproterozoic oceans leading up to the appearance of multicellular eukaryotes*
Lucy Webb *Thallium isotopic evidence for Tonian deep ocean oxygenation*
Huan Cui *The same and not the same: A tale of two contrasting origins of methane-derived authigenic calcite and their implications on Proterozoic carbon cycle*
Joe Marshall *Modelling of Snowball Earth events*
Mana Ryuba *Transitional contact at the base of the Nuccaleena Formation, Flinders Ranges: Implications to the timing and formation of cap carbonates*
Andrea Halling *Viscosity-driven shifts in microbial competition and community structure*
Jenifer Spence *Thawing the past: Using Canadian Arctic glaciers as a glimpse into Snowball Earth's retreat*
Sina Arnoldt *Modern carbon cycle dynamics: Unraveling petrographic OC cycling in arctic riverine and marine sediments*
Christopher Hansen *Preserving winter subglacial signatures: DOM and microbial communities in Greenland naled ice with implications for habitability on Mars*

Thursday - Lightning Talks

Castle Room
Anthony Dosseto *Middle age Earth: Ocean chemistry and evolution in the Boring Billion*
Shuhai Xiao *A paleontological perspective on the early evolution of eukaryotes*
Sanaa Mughal *The Precambrian microfossil record: A lens for understanding the ancient biosphere through time and space*
George Wedlake *New microfossil eukaryotes from the Tonian Little Dal Group, northwestern Canada*
Charlotte Spruzen *Stratigraphy and preservational variation of a Tonian thrombolite reef (Fifteenmile Group, Yukon Territory) and implications for the under-recognition of ancient thrombolites*
Victoria Cassady *Endolithic microboring as a micritizing force and early diagenetic step in microbialites*
Kelly Tingle *Buried alive: Extracellular polymeric substances promote clay templating of live eukaryotic algae*
Clémence Derambure *Mapping silica precipitation patterns in Rhodovulum iodosum extra polymeric substances*
Orin Lole Durbin *Early Cambrian Doushantuo-type microfossils from Mongolia: Implications for calibrating animal molecular clocks*
Ajani Bissick *Tracking climate expression in the late Ediacaran Huns shallow-marine platform*
Princess Aira Buma-at *Morphometric and spatial analyses of Charniodiscus from the Ediacaran of Newfoundland, Canada*
Danielle Fitzgerald *Microfossils from background mudstone of the Ediacaran Trepassey Formation at Mistaken Point Ecological Reserve, Newfoundland*
Baptiste Coutret *A unique snapshot of an Ediacaran microbialites assemblage from the Byng Formation (Neoproterozoic Miette Group, Alberta, Canada)*
Kelly Rozanitis *Surviving the depths: Metazoan resilience in sulfidic aquaria experiments*
Decla McParland *Looking back to look forward: Characterizing diurnal microbial elemental cycling across a wetland to understand biogeochemical relationships in community composition*

Friday at a glance

Speaker Series

8:45	**Introduction**
9:00	**Frankie Dunn** *The early evolution of animal life & the generation of form*
9:30	**Lidya Tarhan** *The evolution of the marine silica cycle and the exceptional fossilization of Earth's earliest animal communities*
10:00	**Katie Maloney** *The untold story of the Burgess Shale: Searching for a seaweed revolution*
10:30	**Coffee break**
11:00	**Brandt Gibson** *Exploring archaeocyaths in virtual environments*
11:30	**Silvina Slagter** *Arsenic preservation in silica-rich deposits: insights from modern and Jurassic hydrothermal systems*
12:00	**Anna Waldeck** *Marine sulphate captures a Paleozoic transition to a modern terrestrial weathering environment*
12:30	**Question period**
13:00 **13:30**	**Lunch** *Tiffany Lancaster - NSERC Presentation*
14:00	**Garrels Medal Talk 1: Timothy Lyons**
14:30	**Garrels Medal Talk 2: Andrew Knoll**
15:00	**Erik Sperling** *The Sedimentary Geochemistry and Paleoenvironments Project (SGP)*
15:30	**Lightning Talks**
16:00 - 18:00	**Discussion session**

Friday - Lightning Talks

Assiniboine/Summit Room
Teagan McGuire *Fossil abundance and diversity in the Middle Ordovician Table Point Formation, western Newfoundland: Insights into the Great Ordovician Biodiversification Event from eastern Laurentia*
Kate Pippenger *Bioturbation intensity as a control on organic carbon and reactive sulfur preservation in middle Paleozoic sediments*
Ashley Rivas *Bioturbation intensities and correlates in Cambrian–Ordovician strata of the Great Basin, USA*
Maya LaGrange Rao *Impacts of Pleistocene climate change on bioturbation at Willapa Bay, Washington*
Brian Beaty *Bioturbation shapes high-latitude marine biogeochemical cycling following the end-Permian mass extinction*
Ginny Winters *Impact of continental greening on the Paleozoic marine biosphere from a lipid biomarker perspective*
Khushboo Gurung *Carbon recycling rates on the Phanerozoic biosphere*
Zhikun Gai *The paleobiology of Galeaspids from the Silurian-Devonian of China*
Chenyi Tu *Origin of ancient phosphorites: Potential roles of alkalinity, evaporation, and hydrological conditions*
Kalev Hantsoo *Unsteady gypsum cycling may decouple ocean and atmosphere carbon reservoirs*
Jenine McCutcheon *Mapping strontium in modern Shark Bay stromatolites: A biogeochemical window into these historic organosedimentary structures*
Ana Clara Pelliciari Silva *Microbial mats as time capsules: Lessons from modern hydrothermal systems*
JuliAnn Panehal *Connecting microbial communities to deep Earth processes*
Mike McCormick *Potential-correlated enrichment identifies candidate electroactive bacteria in a meromictic lake using a multi-level electrode array*
Mitali Chitnis *Magnetoreception in an anaerobic ciliate via tripartite symbiosis*
Kabir Mohammed *Changing organic matter variability and sulfur isotope signals: Implications for Earth history*
Isabel Baker *Deciphering the geobiological formation of isotopically superheavy pyrites in the modern to understand their environmental relevance in oceans past*

Castle Room
Luke Parry *Exploring the impact of ecosystem engineers using evolutionary simulations*
Erik Tamre *Selection by differential survival among marine animals in the Phanerozoic*
Gordon Southam *Bacteria-mineral interactions; a career in 3 min.*
Nathan Marshall *Lipid biomarkers and Earth system models reveal enhanced ocean methane cycling during the early Phanerozoic*
Sydney Riemer *New insights into early vascular land plants as geobiological agents of phosphorus weathering*
Phillip Hüebenthal *Lichen biogeochemistry in the Atacama Desert, Chile: Adaptation to the driest place on Earth*
Liam Friar *Carbon isotope fractionation by the fern-cyanobacteria symbiosis Azolla disentangles photosynthesis by host and symbiont*
Christopher Greidanus *Experimental diagenesis of soil fossilizing in tree resin*
Kiri Maza *Tracing oxygen's role in early animal evolution: Non-traditional isotope insights from the Cambrian Wheeler Formation*
Juraj Farkas *Calibrating stable Sr isotope proxy (d88/86Sr) in modern coastal marine system: A 'new tool' to constrain past oceanic carbonate cycling and seawater saturation state through time?*
Jordan Todes *Local and diagenetic constraints on the structure and interpretation of Early Triassic chemostratigraphic records*
Harpreet Batther *Stable carbon isotope fractionation during steady-state methanogenesis as a function of DIC concentration*
Gage Coon *Mitigating methane emissions from municipal sewage treatment facilities by phosphogypsum bioconversion*
Selva Marroquin *Investigating the sedimentological and chemical feedbacks recorded in carbonate mounds across the early Carboniferous*
Bolton Howes *Reconstructing fluvial planform morphology*
Cody Lazowski *Lithium isotopes of the Peace River Arch in the Western Canada Sedimentary Basin: A framework for resolving deep basin lithium sources*
Lingyi Tang *PhreeFit: A tool to estimate the surface reactivity of biogeochemical surfaces*

Abstracts

Medallist Talks

S. George Pemberton Medallist

Eva E. Stüeken

Widespread volcanic fertilization of the biosphere 2.7 billion years ago?

University of St Andrews

Multiple localities around the world show unusually high $\delta^{15}N$ values over 20 ‰ in sedimentary rocks between ca. 2.7-2.65 billion years ago – termed the “nitrogen isotope event” (NIE) [1]. Multiple explanations have been put forward for individual units, including a transient change in the composition of the atmosphere due to meteoritic nitrogen input [2], partial oxygenation of the nitrogen cycle in a low-oxygen world [1], volatilization of ammonia gas under high-pH conditions [3], and partial biological assimilation of ammonium sourced from a large marine reservoir [4]. New evidence from the Belingwe Greenstone Belt in Zimbabwe links high positive $\delta^{15}N$ values in shallow-marine carbonates to unusually negative $\delta^{15}N$ values in deep-marine black shales [5]. Taken together and combined with other geological evidence, the data are most parsimoniously interpreted as evidence of volcanic-hydrothermal remobilization of ammonium from sediments, which generated a high dissolved load of ammonium in the deep ocean. Upwelling and progressive distillation of this reservoir into the photic zone could thus have produced the observed isotopic record. As bioavailable nitrogen is often a limiting nutrient in ecosystems around the world, the NIE perhaps marks an event of prolonged and widespread fertilization of the biosphere by volcanic activity. Along with ammonium, volcanism and hydrothermal activity can also release high concentrations of micronutrients and perhaps phosphorus. One may speculate that enhanced volcanic activity in the Neoarchean stimulated biological O_2 production and facilitated the rise of oxygen during the Paleoproterozoic Great Oxidation Event.

1. Pellerin, A. et al. Neoarchaean oxygen-based nitrogen cycle en route to the Great Oxidation Event. Nature 633, 365–370 (2024)
2. Jia, Y. & Kerrich, R. A reinterpretation of the crustal N-isotope record: evidence for a ^{15}N-enriched Archean atmosphere? Terra Nova 16, 102-108 (2004)
3. Stüeken, E. E., Buick, R. & Schauer, A. J. Nitrogen isotope evidence for alkaline lakes on late Archean continents. Earth and Planetary Science Letters 411, 1-10 (2015)
4. Martin, A. N. et al. Mechanisms of nitrogen isotope fractionation at an ancient black smoker in the 2.7 Ga Abitibi greenstone belt, Canada. Geology52, 181–186 (2024)
5. Martin, A. N. et al. Anomalous δ15N values in the Neoarchean associated with hydrothermal ammonium upwelling. Nature Communications 1873 (2025)

Abstracts

Medallist Talks

S. George Pemberton Medallist

Benjamin Mills

What are the drivers of Earth's oxygenation over deep time?

University of Leeds

Why have oxygen levels in the atmosphere and oceans generally risen over Earth history, and what controls the patterns of variation that we see on shorter timescales? These are fundamental considerations when trying to understand the evolution of Earth's biosphere and its interaction with its environment, and answering these questions quantitatively requires numerical models. But while Earth System Models for deep time have improved markedly at their representation of the inorganic carbon cycle, and in predicting CO_2 levels and surface temperatures, they remain poorly equipped to predict the organic carbon cycle and O_2 levels. In addition to this, there are strikingly few reliable geological proxies for atmospheric O_2 levels, and proxies for marine redox are difficult to link to the global O_2 reservoir. I will present what I think is the current state of the art in models of Earth's long-term oxygenation, and will present a theory for O_2 rise and subsequent variation that is compatible with currently-available evidence. But I will also outline the major problems we have in making models and comparing to sparse geological proxy data, which allows for the development of many competing hypotheses.

Terry J. Beveridge Medallist

David T. Johnston

Oxic respiration: a gateway to estimating global oxygen production

Harvard University

Primary production on land and in the surface ocean is a critical component of Earth's carbon and oxygen cycles, modulating the uptake and release of CO_2 and O_2, respectively. Quantitatively estimating these exchanges, and of particular interest here marine O_2 production/consumption, remains challenging. Of the methods available, leveraging the triple oxygen isotope composition of O_2 in seawater (and the atmosphere) is in practice one of the more robust approaches to this problem. Under the hood of this approach is a suite of presumptions – some rooted in physics and others in biogeochemistry. In this talk, we take aim at the central importance of oxic respiration (and associated isotope effects) as the key to refining estimates of gross oxygen production on Earth. This begins with a quantitative argument regarding the centrality and importance of the oxygen isotope effect(s) associated with oxic respiration. From here, the geobiological aspects of the system rise to the surface. What are the physiological controls on the oxygen isotope effects associated with oxic respiration? How are these effects reflective of the innerworkings of the cell? Are all respiring organisms created equal from an isotope perspective? And finally, is oxic respiration even the correct (lone) target for these sorts of global scale consideration? In this talk, we begin this much larger conversation and lean on both experimental and environmental case studies – in places extended to isotopic clumping in O_2 – for guidance.

Abstracts

Medallist Talks

Terry J. Beveridge Medallist

Tanja Bosak
Limestone shaped by life
Massachusetts Institute of Technology

Carbonate deposits on the surfaces of Earth and Mars attest to the interactions among water, inorganic carbon and cations derived from rocks. On Earth, 3.4-0.5 billion-year-old carbonates contain additional signals of biological processes and major evolutionary and environmental changes. Over the past two decades, my group has sought to recognize and interpret these signals, asking how photosynthetic microbes influence the textures and shapes of carbonate rocks and how these and other minerals can form in a world without oxygen. By combining laboratory experiments, theory and sample analyses, we have identified the oldest rocks that preserve evidence for microbial photosynthesis and other rocks that retain textures shaped by the oldest oxygen bubbles produced by cyanobacteria. The same approach demonstrated a remarkable ability of anoxygenic photosynthetic and other anaerobic microbes to stimulate the formation of carbonates. More recently, we have examined > 3.5 billion year old sedimentary rocks sampled by the Perseverance rover in Jezero crater, Mars, which, unlike those on Earth, contain iron and magnesium carbonate. These martian carbonates occur primarily as sand grains, grain coatings and pore-filling cements. The future search for and interpretations of any potential signs of prebiotic processes or life in these extraterrestrial carbonates now motivate mechanistic studies of carbonate precipitation in surface environments that do not contain cyanobacteria and oxygen.

Abstracts

Medallist Talks

Robert M. Garrels Medallist

Timothy W. Lyons

An unexpected journey to questions about life’s beginnings and its future

University of California, Riverside

The first steps began with a fortuitous invitation to sail in the Black Sea, launching decades of research exploring with the world’s best students, postdocs, and colleagues the evolving early atmosphere, oceans, and life using a wide range of traditional and novel elemental and isotopic geochemical proxies. Another fortuitous step was an introduction to the Precambrian and its secrets, thanks to an unexpected invitation to the remarkable rocks of the Belt Supergroup in Montana. I could never have guessed that this work, started during my postdoc, would rise from boutique to must-do science in the late 90s. In the wake of Allan Hills, life detection on early Earth and, by extrapolation, elsewhere within and beyond the solar system drew a new generation of extraordinary scientists to the biggest questions — how life started, how it first evolved in phase with shifting surface environments, and whether we are alone in the universe. Some geoscientists, us included, are pulled fundamentally to rocks that give up their stories reluctantly — because they are often big stories, if unraveled. From this commitment, a remarkable team emerged that used the many chapters of Earth history, or alternative Earths, to understand how to build and sustain a detectable biosphere by exploring four billion years of persistent habitability on a dynamic early Earth. The ultimate goal was and is to help guide NASA’s mission-specific search for life on distant worlds, exoplanets in particular. This path was already many steps beyond my initial studies in the modern Black Sea, but as luck would have it, two additional opportunities emerged more recently. One centers on the importance of the records and models for Earth’s earliest surface environments more than four billion years ago to put constraints on the most and least plausible pathways to life’s beginnings through a progression from simple prebiotic compounds to complex metabolisms. At the same time, but at the other end of the time scale, a career in biogeochemistry found a niche in the present and closer to home by exploring the ecological and human health challenges linked to shrinking terminal lakes throughout the world and permafrost thaw in the Arctic. Studies of these latest alternative Earths are a service, we hope, that adds value to the earlier indulgences driven by the bluer sky questions of when and where life found early and distant footholds on and beyond Earth.

Robert M. Garrels Medallist

Andrew H. Knoll

Silica Biomineralization: Biological and Geologic Consequences

Harvard University

Silica biomineralization plays an important structural role in some sponges, but is otherwise a minor phenomenon within animals. Vascular plants, perhaps especially grasses and horsetails, also biomineralize silica, forming phytoliths that provide low cost structural support for epidermal tissues and a defense against grazers. It is among protists, however, that silica biomineralization is most widespread, and genes for silica transport are even more widely distributed. Chert deposits long antedate the evolution of eukaryotes; silicon isotopes suggest that hydrothermal processes were a major source of SiO_2 in Archean oceans, with continental weathering assuming importance in the wake of widespread continental emergence near the Archean-Proterozoic boundary. In early oceans silica appears to have been removed either as a component of iron formation, with silica adsorbed onto iron hydroxides, or in coastal environments, driven by evaporation. With the early Paleozoic radiations of radiolarians and siliceous sponges, chert deposits came to reflect the environmental distribution of these organisms. And as diatoms radiated in later Mesozoic oceans, these algae emerged as the major sinks for silica in the marine realm. Biomineralization, then, has played a principal role in the secular distribution of chert in sedimentary successions. Moreover, as silica-precipitating organisms restricted silica concentrations in the photic zone to low values, this equally influenced the evolution of silica biomineralizers. Sponges show evidence of changes in spicule morphology as diatoms radiated, and radiolarians appear to reflect their influence, as well, although radiolarian taxa do not exhibit a uniform response to decreasing silica availability. Diatoms, themselves, also appear to show a secular trend in silica usage, although, again, experimental studies suggest that diatom responses to decreasing silica availability have been species-specific. All in all, silica biomineralization has influenced the biogeochemical cycling of SiO_2 through time, and these changes, in turn, have influenced the evolutionary trajectories of silica biomineralizers – an illuminating example of geobiology in the Earth system.

The Archaeal and Bacterial Biosphere

Joanne Boden

Microbial Phosphorus Cycling in the Precambrian

University of St. Andrews

Phosphorus (P) is one of the fundamental building blocks of life, so restricted P availability limits biological productivity in large regions of both the terrestrial (Hou et al., 2020) and marine biospheres (Ustick et al., 2021). To mitigate this limitation, micro-organisms have evolved metabolic strategies to scavenge phosphorus from organic (namely organic esters and phosphonates) and inorganic compounds (including polyphosphates and phosphite). How often these are used can depend on the concentration of orthophosphate (otherwise known as 'soluble reactive phosphorus'), which is arguably the most easily accessible form of phosphorus from the environment. To address how much orthophosphate was available to microbes through Earth history, and whether other sources of P supported microbial growth during the early establishment of the planet's biosphere in the Archean, we reconstructed genomic records of life spanning the last 3.5 billion years.

Results of Bayesian molecular clocks and gene-tree-species-tree reconciliations suggest that Paleoarchean microbial communities began scavenging P from small organic P-bearing compounds (via phoA) and orthophosphate (via pnas) ca. 3.5 to 3.3 Ga. Additional components of the dissolved organic phosphorus pool (including phosphonoacetaldehyde and phosphate diesters) became accessible to microbial communities in the Mesoarchaean (ca. 3.2 to 2.8 Ga) with the emergence of genes to metabolize more complex organic phosphorus-bearing compounds (via phnX, phoX and phoD). By the end of the Neoarchean, several microbial lineages were capable of assimilating both organic and inorganic phosphorus sources, and genes (namely ptxD) to access additional inorganic phosphorus molecules, which may have been relatively more soluble than orthophosphate, had emerged. This expanding repertoire of phosphorus acquisition strategies, combined with the early Paleoarchean emergence of a gene (pnas) associated with higher than modern phosphate concentrations (> 3 uM) and the Paleoproterozoic emergence of two genes (namely phnJ and phnM) associated with low orthophosphate concentrations (< 0.1 uM), suggest that the concentrations of orthophosphate in microbial ecosystems declined throughout the Archean. Put together, genomic records point towards the early pre-Great-Oxygenation-Event establishment of a relatively complex biogeochemical phosphorus cycle, involving several microbial processes and biological phosphorus acquisition strategies.

Abstracts

Speaker Series - Wednesday

Aya S. Klos

Biological molybdenum usage stems back to 3.4 billion years ago

University of Wisconsin-Madison

Molybdenum (Mo) is an essential nutrient for most living organisms, serving as a cofactor in a diverse array of molybdoenzymes that catalyze key reactions in several global elemental cycles. However, previous geochemical data has suggested that dissolved Mo concentrations in the Archean ocean were 1-2 orders of magnitude lower than today, raising questions about its bioavailability to early life. We applied a phylogenomic approach to chart the modern biological and environmental distribution of Mo-related enzymes and used phylogenetic reconciliations to reconstruct the evolutionary history of biological Mo usage. Our results reveal the ubiquity of molybdoenzymes across contemporary organisms inhabiting diverse environments. Furthermore, phylogenetic evidence indicates that the earliest molybdoenzymes stem back to the Paleo/Mesoarchean (~3.5-3.0 Gya), facilitating critical energy-harnessing reactions in some of Earth's most ancient life forms. Taken together, our findings challenge the prevailing view of limited Mo bioavailability on the anoxic early Earth.

Elliott Mueller

Microbial fermentation: The hidden metabolism of Precambrian biogeochemistry and its imprint on carbon isotope records of lipids biomarkers

University of Colorado Boulder
Caltech

Fermentation is an anaerobic metabolism performed within every domain of life. In anoxic environments like marine sediments, microbial fermenters breakdown large biopolymers into labile products (e.g. acetate), which fuel sulfate reduction and methanogenesis. As such, fermenters operate at the nexus of several important biogeochemical cycles like the carbon, sulfur, and phosphorus cycles. However, this metabolic guild is commonly overlooked in studies of Precambrian geobiology, largely due to a lack of lipidomic, genomic, or isotopic biomarkers that would otherwise constrain the activity of microbial fermenters. It has long been assumed that fermentation, like respiration, does not express carbon isotope fractionations, precluding isotopic signals as a means of studying it in nature. Here, we tested this idea by growing cultures of four fermenting bacteria and measuring the carbon isotope composition of the organic acids and alcohols produced. We found that fermentation exhibits a strong carbon isotope fractionation, ranging from -6‰ (normal) to +16‰ (inverse), depending on the fermentation product. This range can even be observed within a single organism. Using bioisotopic models that track site-specific isotope enrichments through metabolic networks, we constrained the enzymes responsible for these fractionations. Our models predict that fermentation products like acetate will be consistently ^{13}C-enriched relative to the fermented substrate. In the environment, this isotopic enrichment would be inherited by microbial heterotrophs consuming fermentation products, causing a trophic fractionation of carbon isotopes between organic matter (^{13}C-depleted) and heterotrophic biomass (^{13}C-enriched). Looking to the geologic past, such a trophic fractionation may explain the inverse $\delta^{13}C$ pattern of acyclic isoprenoid and n-alkyl biomarkers in Precambrian sediments. We hypothesize that this lipid biomarker signature − found throughout the Proterozoic − may be a signal of ancient microbial fermentation. Such pervasive evidence of fermentation in the rock record would suggest its significant role in biogeochemical cycles throughout Earth history, highlighting the need for further research into this hidden metabolism.

Manuel Schad

Tracing early primary production - What do trace metals tell us?

University of Alberta

Precambrian banded iron formations (BIFs) are Fe- and Si-rich (bio)chemical sedimentary deposits that offer a unique window into the Earth's past. Therefore, they potentially allow us to reconstruct the Earth's earliest marine environments and biosphere (ca. 3.8 to 1.85 Ga ago). However, their utility for these paleo-environmental reconstructions might be limited due to diagenetic and metamorphic overprint obscuring the nature of the primary precipitate as well as signatures indicative of mechanisms involved in its formation and alteration. Consequently, key aspects of BIF biogenicity, precipitation and post-depositional alteration remain controversially debated.

Although early primary producers, such as anoxygenic photoautotrophic Fe(II)-oxidizing bacteria (photoferrotrophs) and early cyanobacteria, are considered key players during BIF deposition we currently lack unique signatures to track their presence in the rock record. Traditional geochemical and petrological analytical methods employed on Fe-bearing minerals have so far struggled to clearly distinguish both microbial metabolisms. However, recent work has provided a new avenue for identifying microbial metabolisms in the ancient rock record by comparing the unique trace metal quota of a model photoferrotroph (Rhodovulum iodosum) with the trace metal signature of the Dales Gorge Member of the Brockman iron formation[1]. Nevertheless, it remains uncertain; (1) if these findings extend to other photoferrotrophs, (2) how the photoferrotroph trace metal quotas compare to cyanobacterial quotas, and (3) if we can trace early primary production by comparing these quotas to e.g. BIFs.

Our results show that photoferrotrophs and cyanobacteria have distinctly different trace metal profiles. Photoferrotrophs have on average a higher P and Co content while cyanobacteria show higher concentrations for all other elements analysed (S, Mn, Fe, Cu, Zn, and Mo). When comparing the bacterial trace metal quotas obtained with the trace metal content of the Hamersley Group iron formations (ca. 2.6-2.44 Ga) we find a surprisingly good fit. Generally, photoferrotroph trace metal quotas better match the older BIFs, whereas the trace metal quotas of cyanobacteria show a good fit for the younger BIFs.

In summary, bacterial trace metal quotas represent a novel tool for identifying early primary production in the BIF rock record. Nonetheless, it remains uncertain whether these findings also extend to other BIFs. Additionally, there are two potential problems to be considered when employing these trace metal quotas: (1) cell death with subsequent release of nutrients and trace metals, and (2) growth of bacteria under P-limiting conditions relevant to the (early) ocean and its influence on their trace metal composition.

1. Konhauser, K. O. et al. Phytoplankton contributions to the trace-element composition of Precambrian banded iron formations. Geol. Soc. Am. Bull. 130, 941-951 (2018)

Nadja Drabon

The effect of a giant 3.26 Ga meteorite impact on the early surface environment and life

Harvard University

Meteorite impacts significantly influenced early Earth's habitability. At least 16 major impact events (>10 km bolide diameter) are recorded in Archean rocks. Though unlikely to cause total ecosystem annihilation, these impacts had severe environmental effects. We studied the sedimentology, petrography, and geochemistry across the 3.26 Ga S2 impact event (bolide diameter 37–58 km) in both shelfal and shallow-water sections to assess its environmental impact and potential effects on early life.

Both sections exhibit similar sedimentary transitions: (1) Below the S2 spherule layer, black-and-white banded cherts reflect background sedimentation. (2) A conglomerate containing impact-derived spherules marks the impact event and the passage of an impact-initiated tsunami. (3) A ~1-meter-thick, normally graded black chert bed above it represents settling of fine particles post-tsunami and contains evaporite pseudomorphs, indicating partial ocean evaporation. In both sections, abrupt increases in grain size and/or Al_2O_3 content suggest prolonged detrital input after the tsunami. (4) Lastly, the sections transition from black chert to iron-bearing cherts (FeO* up to 7.4 wt%). The FeO* increase does not correlate with deepening, provenance shifts, volcanic activity, or hydrothermal input. Hence, the increase likely resulted from tsunami-induced water column mixing, introducing Fe^{2+}-rich deep waters into Fe^{2+}-poor shallow environments.

Meteorite impacts are often viewed as catastrophic events. The S2 impact undoubtedly had short-term devastating effects on the early biosphere, decimating phototrophic microbes in shallow waters and life on land's surface. However, in the medium term, ocean mixing would have made Fe^{2+} available in the photic zone, a potential electron donor for microbial life. Additionally, tsunami-driven erosion and intense post-impact weathering in a hothouse climate may have introduced nutrients like phosphorus into the nutrient-starved Archean oceans. Thus, meteorite impacts may have provided transient benefits to early life.

Abstracts

Speaker Series - Wednesday

Chadlin M. Ostrander
The Archean sedimentary thallium isotope record: what is it trying to tell us?
University of Utah

In 2019, my colleagues and I reported evidence of "Fully oxygenated water columns over continental shelves before the Great Oxidation Event" (Ostrander et al., 2019, Nature Geoscience 12, 186-190). We have continued to test this hypothesis in the years that have passed. Namely, by forming a better understanding of the geochemical tool at the root of this claim: thallium isotopes. In this presentation I will summarize our journey. I will discuss findings from modern sites that continue to bolster the claim for oxygenation specifically at the sediment-water interface. And I will discuss findings from the ancient sedimentary record that provide more evidence of the same (sometimes in even older rocks). All data considered, Archean marine muds may have been more oxygenated than commonly thought.

Abstracts

Speaker Series - Thursday

The Origin & Flourishing of Nucleated Cells

Zachary Adam

Did Iron Suppress Eukaryote Emergence and Early Radiation?

University of Wisconsin – Madison

The last eukaryotic common ancestor (LECA) is thought to have been an oxygen-respiring organism, emerging from an endosymbiosis event in which a free-living bacterium became the mitochondrion. Oxygen availability has long been considered a possible driver of eukaryogenesis. However, this hypothesis is complicated by a temporal gap of several hundred million years between the first indications of planetary oxygen (~3.2-2.5 Ga) and the oldest widely accepted evidence of eukaryotic fossils (~1.7 Ga). Notably, the earliest candidate eukaryotes coincide with the cessation of major iron deposits and rise of sulfide- and sulfate-rich marine sediments along coastal environments. Here, we synthesize key Proterozoic surface geochemical changes alongside the microbial biochemistry of iron to explore the potential constraints on early eukaryotic evolution. Iron availability is implicated in a range of antagonistic biochemical and physiological effects that could have suppressed the establishment and cosmopolitan spread of early eukaryotes by disrupting cellular homeostasis. In particular, elevated iron levels likely had a damaging effect on intracellular labile iron pools and aerobic bacterial lipids. The programmed cell death pathways known as ferroptosis, which is widespread among eukaryotic clades, may trace its origins to iron-rich conditions in Archaean and Paleoproterozoic seawater, and may have been present in the LECA. Testing these hypotheses offers new avenues for understanding the critical palaeobiological gap separating the first indicators of planetary oxygen and the emergence of eukaryotic life.

The Origin & Flourishing of Nucleated Cells

Heda Agić

New insights into Palaeoproterozoic microbial ecosystems from the Changcheng Group

University College Cork

Domain Eukarya is estimated to have originated in the Paleoproterozoic Era and the earliest unambiguous eukaryotic fossils (organic-walled microfossils/acritarchs, OWM) appear around 1650 Ma, yet little is known about their early diversity, abundance, and paleoecology. The Earth system remained at low oxygen state during most of the Proterozoic, but with fluctuating oxygen levels. Here, we examine one of the oldest eukaryote fossil assemblages to assess their habitats and relationships between diversity change and temporal and spatial heterogeneity in the ocean redox chemistry.

The Changcheng Group on the North China Craton (Hebei Province), recently constrained to 1678-1634 Ma, hosts some of the oldest eukaryotes. Shales and siltstones throughout the Chuanlinggou Formation (lower Changcheng Group) were sampled at high resolution. To better understand the environment in which early complex cells evolved, a quantitative analysis of the microfossil assemblage was combined with palaeoenvironmental reconstruction (sedimentology and palaeoredox proxies). Further, we measured the C-isotopic composition of a broad array of individual OWM using nano-EA-IRMS to gain insight into their palaeoecology.

The assemblage is dominated by sphaeromorphic and fusiform organic-walled microfossils and microbial mat-builders, but also includes morphologically complex taxa with cell wall patterning, as well as taxa with long stratigraphic ranges that extend into the Neoproterozoic, and most OWM are common in anoxic samples (74% of the assemblage). The mat-builder prokaryotes are characterized by negative $\delta^{13}C$ values, on average -30.4‰. Such values would be expected at depth, in case of a stratified water column with a ^{13}C gradient. Most eukaryotic taxa have close values to the benthic prokaryotes (on average -28.9‰, indicating that they incorporated C from the same pool and thus likely lived in the vicinity of the mats, which may have provided an oxygenated microhabitat. Yet not all eukaryotes have the same isotopic composition: a long-ranging taxon Simia is consistently ^{13}C-enriched (average -20.4 ‰) and it potentially had a planktonic lifestyle in surface waters. The morphological diversity and isotopic variability of the Changcheng assemblage suggest heterogeneity of habitats or metabolisms, which shows that the eukaryotes were already quite diverse by the end of Paleoproterozoic.

Abstracts

Speaker Series - Thursday

Daniel Brady Mills

The origin and earliest evolution of eukaryotes in the Proterozoic biosphere

University of Munich

Eukaryotes evolved via the fusion of an archaeal host and a bacterial symbiont in a process known as symbiogenesis. The earliest known eukaryote body fossils suggest that this ancestral symbiosis was established no later than the end-Paleoproterozoic Era, although the environment that hosted this two-domain merger remains unclear. The recent cultivation of archaeal lineages most closely related to eukaryotes corroborates the prediction that syntrophic H_2 exchange under anoxia drove at least the initial stages of eukaryogenesis. At the same time, the last eukaryote common ancestor (LECA) unequivocally respired O_2, and exposure to persistent anoxia early in eukaryogenesis would have arguably led to the irreversible loss of the electron transport chain in the ancestral mitochondrion. To reconcile both of these conclusions, the origin of mitochondria at the onset of eukaryogenesis conceivably commenced under fluctuating redox conditions (e.g., in cyanobacterial mats or seafloor sediments), rather than in the persistent presence or absence of O_2. Once LECA emerged and eukaryogenesis was completed, crown-eukaryotes potentially achieved modern levels of richness and phylogenetic diversity if pO_2 was already at or above 2-3% of present atmospheric levels (neglecting other environmental factors). While the earliest crown-eukaryotes were likely osmotrophs and/or bacterivores, the subsequent origin of eukaryote phototrophy and eukaryovory helped drive the evolution of more modern marine food webs, establishing the trophic linkages necessary for sustaining the earliest metazoan communities in the Neoproterozoic Era.

Christina Woltz

Preserving the eukaryotic fossil record: the impact of fossilization processes on our view of early eukaryotes

Imperial College London

Our understanding of early eukaryotic diversity and ecology relies heavily on the record of organic-walled microfossils—the organic (non-mineralized) remains of microorganisms. However, variation in the conditions that preserve organic remains can introduce bias into fossil diversity patterns. It has long been assumed that bottom-water anoxia is a necessary condition for organic fossilization. Although this relationship is well documented in the Phanerozoic record of soft-bodied animal fossils, it remains unclear whether the same conditions apply to the Proterozoic record of organic-walled microfossils. To test the role of local redox conditions on the preservation of organic-walled microfossils, we employed statistical learning techniques on a dataset of fossil quality— measured by ranking fossil features associated with degradation—paired with an iron-based proxy for local bottom-water redox conditions. The model also incorporated a range of factors that may influence or correlate with fossil preservation, including total organic carbon (TOC) content, lithology, depositional environment, metamorphic alteration, and age. Contrary to long-standing assumptions, local redox state is not a primary predictor of fossil preservation, indicating that the fossilization of organic-walled microfossils is not tightly linked to bottom-water anoxia. Instead, the most influential variables were TOC—confirming prior studies—and paleoenvironment, which emerged as a significant predictor. These results suggest that nearshore marine environments, characterized by more rapid sedimentation and consequently lower TOC, enhance the preservation potential of organic-walled microfossils. Taken together, this work implies that the preservation of early eukaryotic fossils was largely independent of local redox conditions, despite the dynamic and heterogeneous redox landscape of the Proterozoic oceans.

Nabil A. Shawwa

Earth’s oldest terrestrial red beds as direct evidence for the Great Oxidation Event ca. 2.3 Ga

Carleton University
University of Regina

The early Paleoproterozoic marks a pivotal transition in Earth’s history: the initial rise of atmospheric oxygen. While this episode is traditionally tracked through mass-independent fractionation of sulfur isotopes, the precise timing and mechanisms of oxygenation remain unresolved. Here, I present evidence from terrestrial red beds (i.e., oxidized fluvial sandstones) from the upper Huronian Supergroup of Ontario and Quebec, Canada, as a complementary proxy for atmospheric oxygenation. Penecontemporaneous oxidizing surface conditions are inferred from the red beds by the occurrence of pigmentary hematite dust rims on detrital quartz grains, which are encased by syntaxial quartz overgrowths, implying that the hematite dust was formed and deposited prior to burial and lithification of the sandstone. Evidence for anoxic atmospheric conditions is captured lower in the Huronian succession by the preservation of detrital pyrite and uraninite in drab fluvial conglomerates. The emergence of terrestrial red beds, which signifies a fundamental shift in Earth’s surface redox state, follows an extensive (possibly global-scale) glaciation and coincides with evidence for post-glacial climate warming. Deglacial to post-glacial fluvial sandstones increase in maturity up-section, indicating an up-section intensification of climate-related chemical weathering. This would have promoted red bed development, particularly since the hematite dust rims are observed in relatively mature subfeldspathic arenites that were affected by post-depositional in situ chemical weathering. The close temporal association between deglaciation and the appearance of oxidized terrestrial sediments suggests a causal link, where enhanced weathering and nutrient fluxes may have fueled biogeochemical feedbacks that amplified oxygen production. The findings of this study constrain the onset of persistent terrestrial oxidative weathering to ~2.31 Ga, offering an alternative geologic benchmark for atmospheric oxygenation and its coupling to climate transitions. This record complements traditional isotopic proxies and highlights the critical role of continental processes in stabilizing Earth's biosphere during the Paleoproterozoic.

Maxwell Lechte

Sedimentary zinc deposition in the Palaeoproterozoic: implications for the evolution of the oceans and biosphere

University of Melbourne

Sedimentary enrichments of redox-sensitive metals can provide key constraints on the redox evolution of Earth's surface environments. Massive zinc sulphide deposits hosted by Palaeoproterozoic shales have been cited as evidence for the development of sulphidic marine conditions following the oxygenation of the atmosphere, leading to the sequestration of zinc and sulphide from seawater. These deposits broadly coincide with the first appearance of eukaryotes in the fossil record, and have major implications for eukaryote ecology as sulphidic conditions can deplete bioessential trace elements. However, more recent models for the genesis of many shale-hosted zinc sulphide deposits posit that the mineralisation significantly post-dates the deposition of the host rocks, in which case these deposits cannot inform our understanding of environmental conditions or secular changes in global biogeochemical cycles. Here, we present a high-resolution stratigraphic, petrographic and geochemical study of drill cores from the major zinc sulphide deposits of the ca. 1640 Ma Barney Creek Formation (McArthur Basin, Northern Territory, Australia). We compare these insights to broadly coeval deposits globally to test hypotheses about the implications of synsedimentary zinc sulphide mineralisation, and discuss implications for the environmental and chemical conditions of early eukaryote evolution.

Abstracts

Speaker Series - Friday

The Rise of Complex Life

Frankie Dunn
The early evolution of animal life and the generation of form
University of Oxford

The radiation of animals across the Ediacaran-Cambrian transition is one of the most transformational events in Earth history, representing a step change in the evolution of the biosphere. While fossils from the Cambrian are readily recognised as belonging to extant groups, those from the late Ediacaran Period document organisms with distinctive forms and no counterparts among living species. This has resulted in a number of different phylogenetic interpretations, ranging from animals to fungi to an extinct Kingdom but with little historical consensus. In this talk, I will focus on the rangeomorphs – frond-like taxa with 'fractal' branching – which are among the oldest Ediacaran macrofossils. My work uses morphogenetic pattern to produce a phylogenetic bracket for the rangeomorphs and this study of Ediacaran developmental biology has identified them as animals and stem-group eumetazoans to the exclusion of alternatives. Rangeomorphs thus occupy a critical position in the tree of animal life, post-dating the origin of true tissues and body axes, but likely pre-dating the origins of a gut and other defining eumetazoan characters. This conclusion enables us to integrate rangeomorphs into debates concerning the mode of early animal evolution, for example, in the influence of the evolving regulatory genome on the evolution of animal complexity. Some authors have suggested that a step-change in the regulation of early-acting genes implicated in development may explain the burst of morphological variety which underpins the Cambrian Explosion. However, our data suggest that rangeomorph growth was conserved and predictable with a morphogenetic strategy that was highly regulated, demonstrating that the most ancient eumetazoan fossils known already manifest evidence of complex developmental regulation. Instead, we suggest that the evolution of the rangeomorphs (and other Ediacaran macrofossils) may have catalysed the explosion of morphological variety observed during the Cambrian Explosion by promoting the diversification of novel phenotypes and behaviours through the introduction of space- and time-limited resources, resulting in a rougher fitness landscape than earlier in Earth history. Previous studies have implicated a roughening of the fitness landscape as a potential driver for the Cambrian Explosion but this hypothesis remains untested. Using eco-evolutionary simulations we propose that morphological disparity is an emergent property of a roughening fitness landscape providing a possible mechanism for saltational jumps in the evolution of morphological disparity through time, including during the Cambrian Explosion.

Lidya Tarhan

The evolution of the marine silica cycle and the exceptional fossilization of Earth's earliest animal communities

Yale University

The enigmatic fossils of the Ediacara Biota, preserved in upper Ediacaran strata across multiple paleocontinents, record the emergence and radiation of complex multicellular, macroscopic life. Ediacara fossil assemblages are dominated by soft-bodied organisms that are exceptionally preserved as sandstone casts and molds in what has been termed "Ediacara-style" fossilization. One of the longest-standing debates in the history of complex multicellular life revolves around the nature of this extraordinary mode of fossilization. Resolving the mechanisms responsible for Ediacara-style fossilization is essential to robustly reconstruct the affinities, community structure and habitats of these ancient organisms; assess the fidelity of the Precambrian fossil record; and evaluate competing hypotheses for drivers of potential Ediacaran radiations and extinctions. Petrographic, paleontological and geochemical evidence from a range of Ediacara-style fossil assemblages of Ediacaran and Cambrian age indicates that these fossils are commonly associated with pervasive early diagenetic siliceous cements. Prior to the radiation of silica-biomineralizing organisms, elevated seawater dissolved silica levels may have driven extensive early diagenetic precipitation of siliceous phases, including both amorphous silica and authigenic clays, on decaying macroorganism carcasses and in surrounding sediments, facilitating this exceptional moldic fossilization. Both fossil data and experiments conducted under conditions analogous to Ediacaran seawater indicate that the presence of silica-reactive functional groups in the organic substrates provided by buried macroorganism carcasses and microbial matgrounds permitted these systems to overcome kinetic barriers to silica precipitation, fostering silicification even under silica-undersaturated conditions, and that seafloor sediment mineralogy may have also played a key role in the nucleation of specific authigenic phases. More broadly, these coupled fossil-based and experimental observations indicate that a wide range of Neoproterozoic and early Paleozoic seafloor settings were shaped by dynamic sedimentary and diagenetic processes linked to silica-rich seawater chemistry and substrate character.

Katie Maloney

The Untold Story of the Burgess Shale: Searching for a Seaweed Revolution

Royal Ontario Museum

The original Burgess Shale site in Yoho National Park, British Columbia, Canada is celebrated for its exceptional preservation of soft-bodied fossils that document the rapid radiation of animals in the Cambrian Period. Compared to the fauna, the flora has received relatively less attention since the first descriptions by Walcott (1919). However, several genera originally erected by Walcott (1919) interpreted as cyanobacteria (Morania, Marpolia) and macroalgae (Yuknessia, Waputikia, Dalyia, Wahpia, Bosworthia) are now interpreted as organic hemichordate tubes (Dalyia, Margaretia, Yuknessia) and other forms are poorly known. Burgess Shale macroalgae require restudy to investigate their ecological role and evolutionary trends during the rapid radiation of animals. Modern macroalgae are vital components of marine ecosystems governing nutrient cycling, constructing seafloor habitats, and influencing oxygenation. However, Cambrian macroalgae maintain simple morphology inherited from the Ediacaran while animal lineages are diversifying. This presents a conundrum, which might signal a delayed development of herbivory in the early evolution of Phanerozoic food webs.

Over the last 50 years, the Royal Ontario Museum has built the world's largest collection of Burgess Shale fossils with high resolution stratigraphic control and new sites (e.g., Tulip Beds on Mount Stephen). Here, I will systematically review macroalgal specimens in the ROM collections aided by scanning electron microscopy-backscattered electrons (SEM-BSE) imaging. The specimens are from three localities of the Burgess Shale Formation: the Tulip Beds, the Trilobite Beds and the Walcott Quarry (oldest to youngest stratigraphically). Two new species of Burgess Shale non-calcified macroalgae have been identified and their ecological importance will be assessed in terms of sediment binding (via complex holdfasts) and benthic tiering to provide insight into the "Cambrian seaweed conundrum".

Silvina Slagter

Arsenic preservation in silica-rich deposits: insights from modern and Jurassic hydrothermal systems

Universidad de O'Higgins

Silicified deposits provide a unique opportunity to detect early-life remnants due to their resistance to alteration and preservation of biosignatures. This study examines arsenic (As) speciation as a biosignature in silicified microbial mats from the modern El Tatio geothermal field (Atacama Desert, Chile) and Jurassic geyserites from the Claudia paleo-hydrothermal system (Deseado Massif, Argentina). We use synchrotron-based techniques, along with detailed petrographic, mineralogic, and in situ characterization of sinter facies. Both sites exhibit preserved As(III) and As(V) associated with organic matter, indicating potential metabolic processes linked to arsenic cycling. Modern El Tatio samples demonstrate active microbial arsenic oxidation and reduction, along thermal channels, while Jurassic samples reveal preserved arsenic-rich organic globules, highlighting mechanisms of long-term preservation in silica-rich environments. These findings establish a robust framework for interpreting arsenic-based biosignatures in the rock record, shedding light on early Earth's microbial life and highlighting the preservation potential in silica-rich deposits.

Anna Waldeck

Triple oxygen isotopes in marine sulphate lend insights into atmospheric oxygen levels and terrestrial weathering

Pennsylvania State University

I will report on our studies of the triple oxygen isotope composition of marine sulphate over the last billion years. Triple oxygen isotopes in sulphate minerals have been used to constrain the evolution of atmospheric pO_2 and pCO_2 throughout the Proterozoic Eon. This approach presumes the incorporation of atmospheric O_2 atoms into sulphate either through oxidative weathering of pyrite (FeS_2) or through oxidation of sulphide in the water column. Although atmospheric oxygen isotope anomalies are pronounced in Proterozoic sulphate minerals, these signatures are imperceptible in recent and modern sulphate records.

I will discuss our recently generated record of the Phanerozoic marine sulphate triple oxygen isotope composition, based on marine evaporite and marine barite minerals. A main feature of the record is a step-like transition in measured triple oxygen isotope compositions during the mid-Paleozoic (420 to 387.7 million years ago). I propose that this shift reflects (1) a rise in atmospheric pO_2 to modern-like levels, and (2) a state change in oxidative sulphur weathering, coincident with the rise of land plants. For these reasons, sulphate triple oxygen isotope records <420 million years old are most useful as tracers of weathering and microbial processes, while >420 million year old records reflect atmospheric changes.

Abstracts

Lightning Talks - Wednesday

Assiniboine/Summit Room

A new look at corrections for alkali-element metasomatism in Precambrian paleosols

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Most siliciclastic sedimentary rocks and paleosols that have undergone burial diagenesis and metasomatism after formation have experienced some degree of alkali-element enrichment, adding K, Rb, and Cs in abundances far exceeding original sedimentary (or protolith) budgets. Correcting for the metasomatically added K is important to extracting original mobile element depletion signatures that in turn can be linked to the degree of weathering and thus paleoenvironmental factors such as paleoclimate. Most K-corrective procedures rely on an assumed ideal weathering trend (IWT) in molar Al_2O_3–CaO^*+Na_2O–K_2O (A–CN–K) ternary space; however, misuse of this assumption through its application to inappropriate samples or without sufficient geological-mineralogical context has led to recent calls to abandon the concept of an IWT. Stemming from this has also been a new hypothesis that some paleosols formed near the Archean-Proterozoic boundary may retain a previously unrecognized primary alkali-element signature that reflects unusual chemical weathering conditions, possibly related to the Great Oxidation/Oxygenation Event/Episode (GOE). Here, we broadly support the need for a measured use of any IWT, noting that petrographic constraints on pre-metasomatic compositions remain critical, but reject both proposals that the IWT approach should be abandoned and that the alkali-element geochemistry of Precambrian paleosols records primary, synpedogenic, signatures. Instead, we refine the K-corrective approach applied in A–CN–K space, provide supporting evidence for a metasomatic origin of alkali-element enrichments existing in the literature, and demonstrate that the IWT approach can be further expanded with application to mafic rock-hosted paleosol data. In the latter case, ternary and tetrahedral plots where the alteration of ferromagnesian minerals can be accounted for by including FeO(T)/Fe_2O_3(T) and MgO data (A–C–N–K–F–M) allow the reversal of K added to both kaolinite and FM-bearing clay minerals to a pre-metasomatic composition and mafic index of alteration (MIA) value. Examples from paleosols formed across the GOE reveal no association of the GOE with alkali-element geochemistry, but they do reaffirm the fundamental, redox-driven, shift in Fe behaviour across this time interval.

New Insights from High Resolution Mapping of Trace Elements in Iron Formations

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Iron formations (IFs) are enigmatic chemical sediments deposited primarily during the Archean to Paleoproterozoic (3.8 to 1.88 billion years ago). These formations have provided information regarding the evolution of oxygen on Earth's surface, changes in trace metal availability, and the activity of the …

… early biosphere. Despite a wealth of past work on IFs, these sediments are still yielding novel insights into changes in Earth's early surface environments. Advances in laser ablation ICP-MS mapping and data processing have the potential to help yield novel insights through studying the high-resolution chemostratigraphy of IFs. Here, we provide a brief example of how this new high-resolution laser-ablation mapping may help to better inform how metal cycles operated in the lead up to the Great Oxidation Event.

Evolving volcano-tectonic and biogeochemical processes controlling hydrothermal iron deposits of the Cristiana-Santorini-Kolumbo Volcanic Field

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Iron formations are important mineral resources often used in ancient environmental reconstructions, though their depositional and preservational mechanisms remain poorly known. Santorini, an active volcanic system in the Eastern Mediterranean, hosts intra-caldera iron-rich hydrothermal vents. Metagenomic studies indicate iron oxide biomineralization in the sediments and iron-rich bacterial mats.

International Ocean Discovery Program (IODP) Expedition 398 drilled sites within the Santorini caldera and in nearby extensional basins with the goal of recovering sediments and volcanic material to characterize the formation and eruptive history of the Christiana-Santorini-Kolumbo system. Two sites were selected for this study: U1595 within the Santorini caldera and U1599 in the nearby Anafi Basin. We analyzed their pore water chemistry and solid phase iron speciation to reconstruct the past variability and spatial extent of hydrothermal activity, geochemical signals preserved in the sediments, and diagenetic effects on discrete iron-rich layers. Microbiological sampling and characterization were performed on complementary intervals. In intra-caldera sediments, which were deposited after the ~1650 BCE Minoan eruption, we identified two intervals of elevated iron content: the uppermost sediments and between 55-60 meters below seafloor. This deeper interval underlies an eruption in 726 CE, suggesting enhanced iron-rich hydrothermal activity prior to volcanic events. Sediments recovered outside the caldera are older (up to 5.33 Ma) but still have discrete iron-rich intervals. Genomic analyses within the caldera and Anafi Basin indicate active mercury cycling and resistance to high metal concentrations.

By comparing these two sites, we are better constraining the timing of hydrothermal activity, the spatial extent of hydrothermal deposits, and the preservation of iron-rich layers through diagenesis. Geochemical data and microbiological analyses indicate ongoing processes at depth, showing how iron formations involve post-depositional iron, manganese, and metal cycling by a diverse community of microorganisms. These processes range across deposition in (likely) oxic shallow waters to anoxic, …

… diagenetic alteration and interaction with brines and hydrothermal fluids. These findings yield new insights into the mechanisms and environmental controls on volcanically derived iron formations and their chemistry, microbiological signatures, and mineralogy, which in turn provide greater clarity in our interpretations of analogous deposits in the rock record and their environments.

Tracing the Rise of Continents Through Banded Iron Formations: Experimental Insights into Germanium Partitioning

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Banded iron formations (BIFs) are chemical sediments that archive early ocean chemistry. In particular, the germanium/silicon (Ge/Si) ratio in BIF silica has emerged as a powerful proxy for the onset of continental weathering. A recent study shows that the Archean BIF records a dramatic shift in Ge/Si ca. 3.5 billion years ago, signaling the first riverine influx of continental material into oceans [1]. However, the behavior of Ge during interaction with Si- and Fe-rich phases after their precipitation remains poorly understood. To address this knowledge gap, we synthesized three analogues of BIF precursors—silica gel, silica-rich ferrihydrite, and ferrihydrite—and conducted batch adsorption experiments by equilibrating these solids with varying concentrations of dissolved Ge at pH 4, 6, and 8. These experiments explore the adsorption behavior of Ge onto precipitated silica and ferric oxyhydroxide phases under different environmental conditions. Preliminary results indicate that Ge is readily scavenged by ferrihydrite, and that the presence of silica modulates adsorption efficiency. Our findings provide experimental constraints on Ge uptake onto BIF-precursor phases after formation, helping to bridge field observations with geochemical mechanisms. This work enhances our ability to decipher BIF Ge/Si records, ultimately strengthening the use of germanium as a tracer for the rise of continental landmasses and early biosphere evolution.

1. Wang, C., *et al.* (2025), The onset of continental weathering recorded in Archean banded iron formations. *Geology*

Reconstructing the In Situ and Diagenetic Evolution of Precursor Banded Iron Formation: Constraints on Fluid Flow and Implications for Paleoproterozoic Seawater Composition

Taiwo Kassim*[1], Yuhao Li[1], Manuel Schad[1], Murray K. Gingras[1], Janaina Rodrigues De Paula[2], Carolin Dreher[3], Andreas Kappler[3], Rick Chalaturnky[4], Kevin Taylor[5], and Kurt O. Konhauser[1]
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Banded Iron Formations (BIFs), which were precipitated during much of the Archean and Paleoproterozoic eons, are critical archives of early Earth's seawater chemistry, oceanic redox conditions, and atmospheric evolution. Although the minerals observed in BIFs today are products of diagenesis and metamorphism, their precursors, likely ferric oxyhydroxides (e.g., ferrihydrite) or ferrous silicates (greenalite), remain debated. Recent studies propose that BIFs may have formed …

… through large-scale fluid-driven oxidation of buried ferrous silicate precursors. To evaluate this fluid-sediment relationship and test whether post-depositional fluid oxidation on a basin-wide scale shaped BIFs, we analyzed the petrophysical properties of aggregated ferrihydrite and silica-ferrihydrite ("Iron Mud") to simulate pre-diagenesis and diagenetic conditions (25 MPa, equivalent to ~1 km burial depth). Our experiments reveal that, although ferrihydrite aggregates are initially porous, consolidation under moderate burial conditions at room temperature drastically reduces both porosity and permeability with behavior similar to clay-rich muds. This significant reduction in fluid flow challenges the plausibility of large-scale fluid oxidation throughout the basin, where BIFs are formed. By demonstrating that early overburden pressure would have limited fluid permeability, our study supports the idea that BIFs retain genuine records of early Earth's geochemical and biological history rather than being products of widespread secondary fluid alteration.

Banded Iron Formations – interplay of iron, silica, phosphate and nickel

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Survival and activity of cyanobacteria and Fe(III)-reducing microbes during the genesis of Precambrian Banded iron formations (BIF) are 3.8 to 1.85 Ga old marine chemical sedimentary rocks that were formed on passive continental margins. They consist of alternating Fe- and Si-rich bands deposited from Fe^{2+}- and $Si(OH)_4$-containing seawater. However, their depositional pathways are still debated. Prior to the emergence of free oxygen on Earth, the most probable pathway was Fe cycling by anoxygenic phototrophic Fe(II)-oxidizing bacteria in combination with dissimilatory Fe(III)-reducing bacteria. However, after the evolution of oxygenic photosynthesis, abiotic Fe(II) oxidation by O_2 is also likely to have contributed to, or even dominated, the deposition of younger BIFs. Challenging the microbial role in BIF deposition, the early ocean was reportedly hostile to early bacteria due to radical formation (reactive oxygen species; ROS), nutrient limitation (e.g., 0.2 μM phosphate(aq)) and high toxic metal concentrations (e.g., 0.04-0.4 μM nickel(aq)).

To investigate the survival of cyanobacteria in a hostile early ocean, we first set up batch experiments using the marine cyanobacterium *Synechococcus* PCC 7002. We grew strain PCC 7002 in anoxic seawater medium with Fe^{2+} (0.5 to 5 mM) and silica (0 to 2.2 mM) in alternating day/night cycles to track toxicity effects caused by ROS formation. We found that Fe^{2+} concentrations (0.5 mM) did not lead to distinct toxicity effects, and at 5 mM Fe^{2+}, silica inhibited ROS formation, indicating that even in regions with elevated Fe^{2+} concentrations (e.g., in upwelling systems) ROS formation was suppressed, and bacteria could have thrived in the early ocean. Secondly, we set up batch experiments containing 0.5 mM Fe^{2+} and 0.67 mM silica to test the influence of phosphate (3.7 and 370 μM) and nickel (0.4, 4, and 40 μM) on *Synechococcus* PCC 7002 and the marine Fe(III)-reducer *Shewanella colwelliana*. Fe(II) oxidation by cyanobacterial O_2 followed by microbial Fe(III) reduction was controlled by alternating light-dark cycles and addition of lactate (facilitating Fe(III) reduction). In all setups containing 40 μM nickel, severe toxicity effects such as inhibited culture growth and O_2-production were observed. At lower nickel concentrations (0.4 and 4 μM), high phosphate …

… concentrations (367 µM) allowed cell growth. Even at limiting phosphate concentrations (3.67 µM), growing bacteria were observed in the presence of low nickel concentrations, indicating some bioavailability of phosphate bound to Fe(III) minerals.

Our studies suggest that in the early ocean cyanobacteria and Fe(III)-reducers were active at nickel concentrations <4 µM, while the presence of silica prevented ROS formation at Fe^{2+} concentrations of up to 5 mM.

Cyanobacteria-ferrihydrite aggregates as important primary BIF sediments and their implications for Archean-Paleoproterozoic oceans

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Precambrian banded iron formations (BIF) are iron- and silica-rich chemical sedimentary rocks that are commonly used as paleo-redox proxies for the chemical composition of Archean and Paleoproterozoic seawater. At the onset of the Great Oxidation Event (herein GOE) around 2.4 Ga, cyanobacteria flourished, which in turn led to increased primary productivity that facilitated the permanent shift from a reducing Earth atmosphere to an oxidizing one. Interestingly, the duration of GOE also overlapped with one of the most prolific periods of BIF deposition. Cyanobacteria likely played a pivotal role in BIF deposition through the indirect oxidation of dissolved Fe(II) by oxygen via oxygenic photosynthesis. As a result, a metastable yet thermodynamically more favorable primary Fe mineral phase, ferrihydrite or $Fe(OH)_3$, was formed. Not only are the highly reactive surfaces of ferrihydrite particles important shuttles for trace element transport from the water column to the sediment pile, but previous studies have also demonstrated that cyanobacterial cells and ferrihydrite tend to aggregate at seawater pH to form cyanobacteria-ferrihydrite aggregates, which likely constituted a significant part of the primary BIF sediment pile. This potentially important primary BIF sediment, however, has only received little attention.

This work briefly touches on three inter-connected studies to demonstrate the importance of cyanobacteria-ferrihydrite aggregates in the context of BIFs. The first study investigated the physical behaviours and sedimentation velocities of the aggregates in seawater by conducting sedimentation experiments in a laboratory setting and subsequently analyzing these experiments using a novel fluid-dynamic modelling approach. Following the sedimentation experiment, we examined the combined surface reactivities of the aggregates using a Surface Complexation Modelling approach with a newly developed software called Phreefit. This study allowed us to describe and quantify the binding dynamics between the aggregates and trace metals and importantly elucidate how trace-element cycling was affected by the aggregates during the time of active BIF formation. Lastly, we used simple incubation experiments to quantify the amount of phosphorous that could have been transported by kaolinite from acidic freshwater to seawater. Importantly, we successfully proved that the desorbed phosphorous was sufficient to support and even augment healthy cyanobacteria populations nearshore, a prerequisite of the most extensive and anomalously positive carbon isotope excursion in earth's history, the Lomagundi Event.

Exploring trace element limitations in cyanobacteria prior to the Great Oxidation Event

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It is now widely accepted that oxygenic photosynthesis evolved well before the onset of the Great Oxidation Event (GOE). This consensus is supported by multiple lines of evidence, including recent findings of manganese deposits in China and Africa, which suggest the existence of widespread oxygen oases in the Mesoarchean [1], as well as geological calibrations of bacterial evolution indicating that aerobic bacteria emerged approximately 900 million years prior to the GOE [2]. However, these findings underscore a significant temporal gap between the evolution of photosynthetic organisms and the protracted oxygenation of Earth's atmosphere.

To reconstruct the factors contributing to this delay, various hypotheses have been proposed. A widely discussed explanation is that low phosphate concentrations may have limited cyanobacterial proliferation over extended periods. However, recent hypotheses suggest that other bio-essential trace elements may have played a similar role, particularly when phosphate was not limiting [3]. This idea aligns with prior work on nickel limitation, which may have constrained methanogenic activity before the GOE [4]. Such micronutrients are vital to key metabolic processes; for instance, cobalt is an essential component of cobalamin, a cofactor involved in DNA synthesis and cellular energy metabolism [5].

In this study, we cultured the cyanobacterium *Synechococcus* PCC 7002 in media individually depleted of key trace elements (Zn, Co, B, Cu, Mo, and Mn) and monitored growth across multiple reinoculation stages over several months. This long-term cultivation approach allowed us to assess the physiological impact of each trace element on cyanobacterial fitness and proliferation. Our results identify specific micronutrients whose absence significantly impairs growth, suggesting potential nutrient limitations for oxygen production in Archean environments.

As a follow-up, we aim to incrementally increase trace element concentrations to determine the minimum thresholds required to sustain stable populations. We anticipate that by comparing these biological thresholds to geochemical reconstructions of Archean trace-elements availability, we will obtain better constraints on the environmental conditions that governed the tempo of Earth's oxygenation.

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Simulation of Precambrian banded iron sedimentation using microbial co-cultures in a controlled column setup

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The alternating iron- and silica-rich layers, composing banded iron formations (BIFs), were deposited in Neoarchean to Paleoproterozoic oceans (3.8–1.85 Ga) and are commonly attributed to a combination of biological and abiotic Fe(II) oxidation processes [1]. However, the relative contributions of different microbial metabolisms to Fe(III) mineral precipitation, in particularly by O_2-producing cyanobacteria and anoxygenic phototrophic Fe(II)-oxidizers, along with their interaction in the early oceans, remain a topic of active research [2-4]. In this study, we use a 1.8-meter-long (12 L) dynamic column system to simulate redox-stratified Archean seawater conditions and investigate microbial Fe(II) oxidation and Fe-Si mineral formation. The setup allows spatially and temporally resolved monitoring of biogeochemical gradients and mineral precipitation under hydrogeochemically stable conditions. Continuous inflow of Fe(II) and dissolved silica, as well as biogenic oxygen, constrain geochemical gradients throughout the water column. Within this setting, we cultivate model marine cyanobacteria (*Synechococcus* sp. PCC 7002) and a marine anoxygenic phototrophic Fe(II)-oxidizer (the green-sulfur bacterium *Chlorobium* sp. strain N1), both individually and in co-culture to quantify Fe(II) oxidation dynamics, microbial interactions, and their influence on mineral formation. This enables comparison of the rates of Fe(II) oxidation across different metabolic strategies and assessment of whether these microbial groups could have coexisted and functioned within overlapping redox zones in early oceans. Unlike prior work that focused on individual strains or static setups, our dynamic column allows spatially resolved tracking of geochemical gradients and microbial activity along the extensive water column. This includes continuous non-invasive monitoring of pH and O_2 along the vertical profile and periodic sampling (e.g., for determining Fe(II)/Fe(III) ratio). Solid-phase products are characterized (e.g., μ-XRD, SEM, TEM) to determine mineralogy, crystallinity, and potential microbe-mineral associations. The larger spatial scale also allows tracking potential transformation of primary Fe(III) phases during settling, better simulating pre-diagenetic processes. Additionally, the column allows introducing controlled temperature shifts to simulate natural Precambrian variability (e.g., seasonal) and explore whether such fluctuations could modulate microbial activity reproducing laminated nature of BIF successions [5]. Overall, our integrated microbiological, geochemical, and mineralogical approach is aimed to provide new constraints on how microbial life could have mediated large-scale mineral deposition in Earth's deep past and specific mechanisms underlying Fe(II) oxidation and Fe-Si mineral precipitation in early oceans. We anticipate that the results will offer a novel perspective on the origins of BIFs and the evolution of early marine ecosystems.

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Green Ocean Hypothesis: Coevolution of Surface Environment and Phototrophs in the Archean era

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Carl Sagan described Earth as a “pale blue dot,” as seen by Voyager 1 from 6 billion kilometers away. This blue hue results from Rayleigh scattering of sunlight in the atmosphere combined with the reflection from the oceans, symbolizing Earth as the cradle of life. But does a blue hue alone indicate a planet’s potential to support life? Over 4.5 billion years, Earth’s surface has been reshaped by both geological forces and life. Cyanobacteria—the first oxygenic photosynthetic organisms—used sunlight to split water, releasing oxygen and triggering the Great Oxidation Event (GOE) around 2.4 billion years ago. This pivotal event paved the way for aerobic life. Cyanobacteria capture light using large, complex phycobilisomes that channel energy to photosystems I and II. Although all phototrophs rely on chlorophyll, cyanobacteria also employ additional pigments called phycobilins to absorb wavelengths that complement chlorophyll. This raises an intriguing question: why did cyanobacteria evolve phycobilisomes? Here, we propose the "Green Sea Hypothesis," which describes the co-evolutionary relationship between oxygenic phototrophs and light environments that defined the aquatic landscape of the Archaean Earth. We hypothesize that during the Archean era, the underwater light spectrum was predominantly green due to the precipitation of oxidized iron (Fe(III)). In this green-light environment, the evolution of photosynthesis may have been driven by the need to harness green light. Our hypothesis is supported by experiments simulating Darwinian evolution and molecular phylogenetic analyses. This hypothesis also indicates that a green color may serve as a marker of a distinct evolutionary stage on inhabited planets. In this presentation, we discuss the Green Sea Hypothesis from an astrobiological perspective.

The Archean Underwater Light Environment: Implications for Habitability of Earth’s Surface and Potential Biosignatures

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In the Archean era, oxygenic photosynthesis dramatically transformed the water environment from a reducing to an oxidizing state, leading to the formation of large-scale banded iron formations (BIF) as dissolved Fe(II) was oxidized into iron hydroxide. The oxidation of the oceans may have triggered a significant, global-scale change in the underwater light environment, driven by the unique optical properties of the precipitated iron hydroxide. While iron hydroxide absorbed ultraviolet light, which allowed the biosphere to expand to the ocean surface, it might have also absorbed blue light, resulting in a green-light environment.

Understanding the light environment in the Archean oceans will not only provide insights into the habitability of the Earth's surface in the Archean era but also potentially offer a new approach to detecting signs of life on distant planets. In this study, we simulate the underwater light ...

... transmission and reflectance of the Archean oceans by combining measured absorption coefficients from iron hydroxide samples with scattering coefficients calculated using Mie theory. We will also discuss how the concentration of iron hydroxide could affect the color of the sea as potential biosignatures.

Turning Back the Clock on Ancient Stromatolites: An Experimental Approach to Cyanobacterial Biofilm Formation and Encrustation

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Ancient stromatolites (>3.0 Ga) have been posited as evidence of the oldest life on Earth. Similarly, ancient stromatolites are often interpreted as dutiful records of both ancient life and its environment. However, for decades, the biogenicity of these stromatolites has been debated due to both the complex interplay of biological, chemical, and physical components that comprise stromatolites and the diagenetic erasure of primary biotic biosignatures by recrystallization. Therefore, a key challenge in assessing the biogenicity of these ancient stromatolites is the absence of direct evidence indicating that biological processes contributed to their formation.

To address the knowledge gap in direct biological evidence for stromatolite formation, I am developing a comparative experimental system to mechanistically investigate the initial stages of biofilm formation and encrustation. Phylogenetic analyses suggest that cyanobacteria emerged in the Archean prior to the rise in atmospheric oxygen and that these organisms were likely 1-2 um in diameter, unicellular, planktic, and freshwater-dwelling. As cyanobacterial biofilms are typically implicated in stromatolite formation, the experimental system consists of six cyanobacterial strains cultured separately in well-defined media under controlled environmental conditions. Four of the six cyanobacteria are closely related strains of *Synechococcus elongatus* that have either a mutated, induced, or natural biofilm-forming capability, and two additional strains will serve as positive and negative controls (*Scytonema hofmannii* and *S. elongatus* PCC 7942, respectively). After exposure to both modern and Archean-derived conditions for a set time, strains will be analyzed for five trait responses: [1] biomass production, [2] biofilm formation, [3] extracellular polymeric substance (EPS) production, [4] stable carbon isotope fractionation, and [5] microbially induced Ca-Mg carbonate precipitation. This system will explore the traits necessary to form biofilms and their phenotypic correlations, such as the potential relationship between biofilm formation, induced carbonate precipitation, and the production and preservation of carbon isotope fractionation. A unique aspect of this system is that it will be used to assess if and how cyanobacterial biofilms are "predestined" to form stromatolites.

Continuity of Nitrogenase Isotope Signatures Over 3 Billion Years of Evolution

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Nitrogen isotopic fractionation ($\varepsilon^{15}N$) signatures have been observed within the rock record for over 3 billion years. A subset of these fractionations is attributed to biological nitrogen fixation via the enzyme Mo-nitrogenase. The nitrogen isotope fractionation signatures of extant nitrogen fixers have been used to interpret ancient nitrogen fixation activity, yet it remains uncertain how billions of years of molecular evolution could have impacted isotope signatures produced by nitrogenase. Here, we measure the $\varepsilon^{15}N$ values produced by ancestrally reconstructed Mo-nitrogenases in the cellular biomass of model nitrogen-fixing bacteria, Azotobactervinelandii. We find that the engineered microbes generate $\varepsilon^{15}N$ values similar to extant A. vinelandii. Our results suggest that the biotic $\varepsilon^{15}N$ values associated with Mo-nitrogenase are robust to evolutionary change and have remained so since the early evolution of biological nitrogen fixation.

Did the genetic capacity for exoenzyme production vary over Earth's history?

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The cycling of organic matter in Earth's early oceans was driven by microbial heterotrophs, whose ability to break down complex organic matter relies on extracellular hydrolytic enzymes, or exoenzymes. Exoenzymes allow microbes to exploit large polymers that would otherwise persist in the environment, thereby mediating the efficiency and extent of organic matter recycling in the oceans. Heterotrophic microbes couple the decomposition of organic compounds to the reduction of electron acceptors such as ferric iron, sulfate and O_2, via redox reactions. This has led to the emergence of diverse metabolisms, whose evolution and proliferation are closely tied to the availability of reducing equivalents on Earth's surface. Determining whether the genetic potential to secrete exoenzymes varies across microbial metabolisms is key to understanding biogeochemical cycling in the early oceans.

To assess the genetic capacity for exoenzyme production, we used molecular markers to construct a database of high-quality genomes, representing distinct microbial metabolisms. We searched for known protein- and carbohydrate-acting hydrolytic enzymes within these genomes. Subsequently, we determined whether these genes contained signal peptide secretion sequences and predicted the localization of the enzymes they encoded. This allowed us to quantify the fraction of each metabolic group likely to produce exoenzymes. Our results show that the genetic potential to produce exoenzymes is unevenly distributed across metabolic groups and concentrated in 'high-energy' metabolisms, reflecting the metabolic cost of their production. Specifically, over 90% of the putative exoenzymes across all genomes were found in genomes associated with four groups: dissimilatory iron reduction, aerobic heterotrophy, dissimilatory nitrate reduction and fermentation. ...

… We detected almost no exoenzymes in genomes associated with dissimilatory sulfate reduction, methanogenesis and methanotrophy. While an oxidant-poor Archaean ocean would have suppressed remineralization, our analysis reveals that the absence of efficient exo-enzymatic pathways may have also played a prominent role. In addition to carbon burial, the lower recycling efficiency of OM would have reduced the release of nutrients back into the water column, potentially limiting primary productivity. The emergence and expansion of 'high-energy' metabolisms in the Neoarchean to early Proterozoic would have bolstered the recycling efficiency of OM and enhanced the regeneration of nutrients.

Biosignature ranges of archaeal carbon isotope fractionation in geochemically diverse terrestrial hot springs

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The carbon isotope ($\delta^{13}C$) composition of organic matter in the geologic record is used as evidence for or against the presence of life in Earth's early history. While the modern biosphere is dominated by Calvin cycle-based oxygenic photosynthesis that fractionates biomass carbon by ~25‰, anaerobic autotrophs that predominated during the Archean (>2.5 Ga) may have utilized carbon fixation pathways that fractionate carbon differently. Phylogenetic, genomic, and thermodynamic/bioenergetic data suggest that the earliest forms of life were anaerobic thermophilic chemolithoautotrophs, which are well-represented among archaeal and bacterial organisms in contemporary hot springs. To better constrain biological carbon isotope fractionation (ε) in hot springs and the potential environmental influences on fractionation, we measured the $\delta^{13}C$ values of microbial biomass in diverse modern terrestrial hot springs from Yellowstone National Park (Wyoming), California, Nevada, and El Tatio (Chile). We focus on archaeal carbon assimilation, providing the first $\delta^{13}C$ measurements of intact isoprenoid glycerol dibiphytanyl glycerol tetraethers (iGDGTs) in terrestrial hot springs using spooling-wire micro-combustion isotope ratio mass spectrometry. Archaeal ε values are calculated relative to DIC, TOC, and DOC to assess the activity of autotrophic and heterotrophic carbon assimilation pathways, while $\delta^{13}C$ measurements of C16 fatty acids illuminate net isotope fractionation of the bacterial community. We examine the effects of environmental variables (e.g., pH, temperature, oxidation-reduction potential, geography) on ε ranges and contextualize our results with paired metagenomic analyses to examine the presence and activity of different carbon fixation pathways across different springs.

Arsenic accumulation in microbial mats and the interpretation of signals of early arsenic-based metabolisms

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Organic inclusions that are enriched in arsenic are present in microbialites as old as 3.5 Ga and some modern microbialites, suggesting accumulation of As by carbonaceous matter throughout Earth history. At present, it is unclear if this accumulation is a consequence of microbial metabolisms or passive post-mortem binding of arsenic by organic matter during diagenesis in volcanically influenced environments. Here, we address this uncertainty by evaluating the absolute concentrations, speciation and detectability of As in active or heat-killed biofilms formed by cyanobacteria or anoxygenic photosynthetic microbes exposed to environmentally relevant concentrations of As(III) or As(V) (50 µM to 3 mM). Biomass accumulates As from the solution in a concentration-dependent manner and with a preference for oxidized As(V) over As(III). Autoclaved biomass accumulates As more strongly than active biomass, suggesting a reduced accumulation in the presence of As removal and detoxification processes in the living biofilms. Active biofilms oxidize and reduce As and accumulate both As(III) and As(V), whereas As that is passively bound on heat-inactivated biomass contains primarily the redox species that is present in the solution. These findings enable the reconstruction of past active metabolisms and passive interactions of microbial biomass with arsenic in fossilized microbial biofilms and microbialites from the early Earth. These mechanistic insights are now used to reconstruct biological and abiotic processes that shaped the distribution and speciation of As in drill core and outcrop stromatolite samples from the ~2.7 Ga Tumbiana Fm. In these samples, As enrichments are limited to micrometer-sized particles of As(III)-sulfide, most consistent with the presence of As-rich pyrites originating during diagenesis.

A Paleoarchean microbial ecosystem in the aftermath of the S8 giant impact event

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Impacts have played a key role in shaping Earth's surface environments and influencing the evolution of life. Yet, little is known about their effects on the early biosphere, when both the frequency and size of impactors were greater and their environmental consequences likely more severe. The origin of tourmaline-rich stromatolites in the ~3.3 Ga Mendon Formation (Barberton Greenstone Belt, South Africa) has been debated since their discovery. Initially thought to be biogenic stromatolites, these structures were later reinterpreted as sinter deposits, and more recently as abiotic precipitates formed by ocean evaporation triggered by the giant S8 meteorite impact. In this study, we investigate these stromatolite deposits to evaluate their biogenicity and the potential influence of the S8 impact —preserved as a spherule bed directly beneath the stromatolites. The sedimentary sequence records a transition from seafloor-altered komatiite and massive black cherts deposited in a marine environment before the impact to stromatolite-bearing units afterward. Although black chert dykes...

… cross-cut the underlying komatiite, they show no spatial relationship suggesting they did not serve as point sources for possible abiotic stromatolite formation. The stromatolites consist of carbonaceous laminations hosted in chert and enriched in ~100 μm-wide tourmaline crystals. These laminations exhibit non-isopachous thicknesses, microcrenulations, and gentle draping over underlying clasts—features consistent with biological accretion. Carbon isotope data reveal a heavier and less variable $\delta^{13}C$ signature in the stromatolites (mean = –28.3‰, SD = 1.27) compared to the pre-impact bedded black cherts (mean ≈ –32.8‰, SD = 2.87), suggesting different processes of organic carbon fixation before and after the impact. Smooth and isopachous laminations are commonly associated with Na-rich tourmaline crystals that and may record episodes of precipitation in an evaporative environment. Together, these observations support both biological and abiotic mechanisms for the origin of the stromatolites. The presence of spherules interspersed within both in situ and brecciated stromatolitic laminations, indicating rapid biogenic development shortly after the impact and imply that early microbial communities were able to swiftly establish themselves following the S8 impact – which is striking as stromatolites are otherwise largely absent in the Barberton greenstone belt. Further geochemical and petrographic work will help constrain the environmental transition from shallow marine to dominantly evaporitic conditions after the impact.

Castle Room

Silicon isotope signatures of the >3.4 Ga Apex and Strelley Pool Cherts: implications for silica sources and the Paleoarchean seawater composition

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Silicon (Si) isotopes in Archean cherts provide important constraints on the environmental conditions of Earth's early oceans and the preservation of early life traces. We present new $\delta^{30}Si$ data from two iconic formations of the Pilbara Craton, the 3.43 Ga Strelley Pool Chert and the 3.46 Ga Apex Chert, the former known for its diverse microbialites and the latter for its organic microstructures that have generated significant debate regarding their potential biogenic origin. Across a range of chert types at Strelley Pool, including black laminated cherts, banded cherts, and silica veins, $\delta^{30}Si$ values fall mostly between 0‰ and +1‰. Remarkably, $\delta^{30}Si$ values from the Apex Chert are of similar magnitude, suggesting that both formations drew from a common silica reservoir, which we interpret to represent Paleoarchean seawater. Unexpectedly, our data indicate a marine depositional environment compatible with life for the Apex Chert and supports the hydrothermal pump model of Duda et al. (2018) whereby surface-derived biosignatures may be preserved at depth in ancient marine hydrothermal systems. Finally, to better understand this dataset and the Paleoarchean ocean $\delta^{30}Si$ composition it indicates, we elaborate a simple isotope mass balance model that draws on insights from modern hydrothermal systems, laboratory experiments, and the rock record, which we use to better constrain the parameter space for factors governing the Paleoarchean Si cycle. Our results offer new perspective on early Earth silicon cycling and reinforce the importance of isotopic tools in decoding links between geological processes and life in the Archean rock record.

Early hints of oxygen: new insights into Mesoarchean Mo cycling from the 2.87 Ga Red Lake carbonate platform

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Before 2.5 Ga, Earth's oceans were largely anoxic, with oxygen restricted to localized oases in shallow marine settings. The 2.87 Ga Ball Assemblage of the Red Lake Greenstone Belt (Ontario, Canada) hosts one of the oldest thick carbonate platforms preserved on Earth, and industry drill cores from this site offer a rare window into Mesoarchean redox conditions. Previous outcrop-based studies identified negative Ce anomalies and isotopically heavy molybdenum (Mo) signatures, together interpreted as evidence of transient oxygenation, while La-Ce geochronology confirmed that the Ce anomalies formed syndepositionally.

Here, we present high-resolution Mo isotope chemostratigraphy from two correlative drill cores that span microbialitic dolomites and calcites, oxide-facies iron formations (IF), and (sulfidic) black shales. $\delta^{98/95}$Mo values range from –2.22‰ to +0.53‰, revealing substantial Mo isotope fractionation driven by redox processes as early as 2.87 Ga. Although Mo is enriched in IF and carbonates relative to crustal values, absolute concentrations remain low, consistent with a small marine Mo reservoir. Carbonate $\delta^{98/95}$Mo data are generally close to crustal values, suggesting that seawater at this time had a near-zero $\delta^{98/95}$Mo composition. This implies that early oxidative Mo cycling did not generate an isotopically heavy marine reservoir, unlike in the modern ocean. Using a steady-state isotope mass balance model, we show that such light seawater values are expected under conditions of diminished riverine Mo input, enhanced hydrothermal fluxes, and a small seawater Mo reservoir. These findings support and refine the application of Mo-isotope-based redox proxies during the earliest stages of Earth's oxygenation.

A seawater oxygen oscillation recorded by iron formations prior to the Great Oxidation Event

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Earth's atmosphere underwent permanent oxidation during the Great Oxidation Event approximately 2.45–2.22 billion years ago (Ga), due to excess oxygen (O_2) generated by marine cyanobacteria. However, understanding the timing and tempo of seawater oxygenation before the Great Oxidation Event has been hindered by the absence of sensitive tracers. Nitrogen (N) isotopes can be an indicator of marine oxygenation. Here, we present a ~ 200-million-year nitrogen isotope oscillation recorded by Neoarchean and Paleoproterozoic banded iron formations from the Hamersley Basin, Western Australia that were deposited in relatively deep marine shelf environments. Paired with the Jeerinah Formation shale record, our data from the Marra Mamba Iron Formation suggest that oxic conditions expanded to banded iron formation depositional environments from ca. 2.63 to 2.60 Ga. Subsequently, a positive δ^{15}N excursion occurred in the ca. 2.48 Ga Dale Gorge Member, marking a ...

... decline in seawater O_2 and enhanced denitrification. This O_2 deficit was followed by a second phase of increasing O_2 levels as indicated by a gradual return to moderately positive $\delta^{15}N$ values in the ca. 2.46 Ga Joffre Member and 2.45 Ga Weeli Wolli Iron Formation. These variations underscore a nonlinear history of marine oxygenation and reveal a previously unrecognized oscillation in seawater O_2 levels preceding the Great Oxidation Event.

Bridging the gap between Earth's initial oxygenation and a possible oxygen overshoot: a new look at the Espanola Formation, Canada

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Earth's Great Oxidation (GOE) remains one of the most transformative events in Earth's past. However, this broad interval of time between ≈2.45 Ga and 2.0 Ga encapsulates both the initial rise in atmospheric oxygen above proxy thresholds, as well as the Lomagundi-Jatuli positive carbon isotope excursion (LJE) which some have interpreted as a possible oxygen overshoot. Between the constraints placed on these two intervals within the GOE are potentially 5 orders of magnitude of permissible levels of atmospheric oxygen. Recent work has highlighted a potentially much more dynamic and variable range of oxygen levels throughout the GOE. This presentation will showcase new geochemical and sedimentological results from an interval of drill core which houses the Espanola Formation located in the Huronian Supergroup of Ontario, Canada. These new samples show remarkable preservation and a low degree of post-depositional alteration therefore offering a new window into the time between Earth's initial rise in atmospheric oxygen and the LJE.

Timing and magnitude of the Lomagundi excursion and its relationship with Earth's Great Oxidation

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The initial oxygenation of Earth’s atmosphere during the ca. 2.5 to 2.1 Ga Great Oxidation Event (GOE) set the stage for the emergence and diversification of complex life. Elevated carbon isotope ($\delta^{13}C$) values of contemporaneous marine carbonates suggest this redox transformation was accompanied by a major carbon cycle perturbation. This large and sustained increase in $\delta^{13}C$, termed the Lomagundi-Jatuli Excursion (LJE), canonically is interpreted as an increase in global organic matter burial that drove surface oxygenation. However, uncertainties in the timing, magnitude, and global versus local nature of the LJE have sparked intense debate surrounding its cause and relationship with the GOE. These uncertainties are rooted in the incomplete, time-uncertain, and spatially heterogeneous nature of the shallow-water sedimentary record. Here, we use Bayesian inference to reconstruct Paleoproterozoic $\delta^{13}C$ from a global compilation of 7,959 stratigraphic $\delta^{13}C$ observations and 124 geochronological age constraints. Our statistical approach relies on only two ...

… assumptions: that sediments get younger upwards (superposition), and that all stratigraphic sections may record information about global $\delta^{13}C$ change over time. Individual observations are allowed to deviate from the global $\delta^{13}C$ signal due to local syndepositional processes (e.g., biological activity in restricted waters) and diagenesis. Our inference results reaffirm that the Paleoproterozoic data are consistent with a large and long-lived positive $\delta^{13}C$ excursion that is preserved across a wide range of depositional environments. However, the excursion has an earlier onset, longer duration, and lower magnitude than previously thought. Specifically, we find that $\delta^{13}C$ very likely (95% probability) began increasing between 2539 and 2235 Ma, with the most likely excursion onset occurring at 2445 Ma. The most likely excursion peak of 7.1‰ occurs at 2130 Ma, with a subsequent return to baseline values at 2018 Ma. The maximum $\delta^{13}C$ value achieved during the excursion is very unlikely (5% probability) to have exceeded 9.2‰. The initial upturn in $\delta^{13}C$ occurs before or synchronously with the earliest rise of atmospheric oxygen, precedes permanent oxygenation, and is co-eval with the Paleoproterozoic ‘snowball’ glacial epoch, while the excursion peak succeeds both permanent oxygenation and glaciation. The temporal correlation among changes in $\delta^{13}C$, surface redox, and glaciation is consistent with, but does not require, a mechanistic link among the LJE, the GOE, and global climate.

EONS: a new model of Earth's atmosphere and ocean evolution via C, N, O, and P cycles through Earth history

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We present Earth's Oxygenation and Natural Systematics (EONS): a new, fully coupled biogeochemical model of the atmosphere, ocean, and their interactions with the geosphere, which can reproduce major features of Earth's evolution following the origin of life to the present day. The model, consisting of 257 unique fluxes between 96 unique chemical reservoirs, includes an interactive biosphere, cycles of carbon, nitrogen, phosphorus, and oxygen, and climate. A nominal model run initialized in the Eoarchean resolves emergent surface oxygenation, nutrient limitations, and climate feedbacks. The modeled atmosphere oxygenates in stepwise fashion over the course of the Proterozoic; a nearly billion year lag after the evolution of photosynthesis at 3.5 Ga is followed by a great oxidation event at 2.4 Ga, which appears to be caused by the gradual buildup of organic matter on the continents imposing nutrient limitation on the biosphere by removing key nutrients from the ocean system. The simple climate system shows significant temperature shifts punctuate the oxygenation process, implying that major biological transitions possibly destabilized Earth's climate. This work demonstrates that forward modeling the entirety of Earth's history with relatively few imposed boundary forcings is feasible, that the Earth system is not at steady state, and that our understanding of coupled C-N-P-O cycling as it functions today can explain much of the Earth's evolution.

From Sediments to Signposts: The Paleoproterozoic Phosphorus Cycle and Early Earth Oxygenation

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The Paleoproterozoic Era was a transformative phase in Earth's history, witnessing profound changes in the atmosphere, biosphere, and lithosphere. Beginning 2.4 billion years ago, the Great Oxidation Event (GOE) marked a pivotal shift in atmospheric oxygen levels and shallow marine environments driven by the rise of cyanobacteria capable of oxygenic photosynthesis. While the GOE is primarily known for establishing an O_2-rich atmosphere, it also fundamentally reshaped the cycling and availability of Phosphorus (P). P is a crucial element for cellular processes: it forms the backbone of genetic material, provides structural integrity to cell membranes, and drives energy metabolism. Without P, life as we know it would not exist. On geological timescales, P imposes the ultimate nutrient limitation. The bioavailability of P regulates the consumption of CO_2, modulates the burial of organic carbon, and influences photosynthetic O_2 production, establishing links between P-cycling and atmospheric and oceanic redox states.

The earliest evidence of P-bearing sedimentary rocks dates back to ~3.5 Ga. However, the sedimentary record is characterized by low [P] until the Paleoproterozoic. The synchronous global emergence of phosphorites marked a shift in the sequestration and cycling of P. This shift has been interpreted as a geochemical response to early-stage oxygenation of the atmosphere-ocean system, indicating an underlying causal mechanism that linked redox with P availability and deposition. However, the mechanisms governing P retention, release, bioavailability, and utilization during the Paleoproterozoic remain poorly constrained. Estimates of P availability during the GOE span several orders of magnitude, with conflicting evidence emerging from biological and geological proxies. Phylogenomic analysis suggests elevated [P] back to 3.6 Ga, while carbonate-associated phosphate records indicate high [P], though only extending back to the Neoarchean. In contrast, P/Fe ratios and bulk shale P provide evidence of significant P limitation until ~1.7 Ga and ~750 Ma, respectively.

To resolve these discrepancies, a multi-proxy investigation of early marine redox states, microbial metabolisms, and nutrient feedback mechanisms is necessary to understand how the earliest phosphorites not only reflected but may also have driven the emergence of oxygen and complex life.

Comparing oxygen proxies across the Great Oxidation Event: iodine vs cerium anomalies

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The presence of iodine (I/Ca) and cerium anomalies (Ce/Ce*) in carbonates are two independent proxies for oxygen in surface water environments. These proxies have been extensively used to investigate oxygen levels across Earth's history. We measure iodine concentrations and cerium anomalies in Archean and paleo-Proterozoic carbonates encompassing the start of significant oxygen accumulation in the atmosphere across the Great Oxidation Event (GOE). Our samples include carbonates from the Mosher Formation (deposited before the GOE), Espanola Formation (deposited ...

... during the GOE), and Gordon Lake Formation (deposited after the GOE) in Canada. We find that these oxygen proxies do not always agree, and carbonates can preserve negative cerium anomalies without iodine and vice versa. The Mosher carbonates preserve negative cerium anomalies (Ce/Ce*~ 0.6), but no iodine. The Espanola carbonates do not preserve iodine nor negative cerium anomalies. The Gordon Lake carbonates preserve iodine (I/Ca > 0.1 μmol/mol) but no cerium anomalies. We propose two scenarios to explain the disagreement. First, differential alteration of carbonates could erase the signal of iodine, while preserving the negative cerium anomalies. Second, detrital input in coastal environments could override the signal of negative cerium anomalies, while preserving iodine concentrations.

Temporary oxygenation of Earth's surface ~2.4 billion years ago

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The permanent oxygenation of surface environments during the Great Oxidation Event (GOE, ca. 2.45-2.22 Ga) represents perhaps life's foremost impact on Earth's environment. Orchestrated by cyanobacteria, the GOE reshaped the nature of our planet's habitability, forever changing biogeochemical cycles and eventually enabling the rise of more complex modes of life. It is now recognized that this initial rise of O_2 played out over a protracted and oscillatory episode, as opposed to a unidirectional switch. Within this new understanding, very little is known about the magnitude and duration of oxygenation during the early stages of the GOE, particularly with respect to ocean oxygenation. To bridge this gap, we report stable thallium isotope ratio data ($\varepsilon^{205}Tl = (^{205/203}Tl_{sample}/^{205/203}TlNIST\text{-}997 - 1) \times 10{,}000)$) and trace element abundances from the Mooidraai Formation (drill core M10) (2392 ± 23 Ma) of the Transvaal Supergroup, South Africa.

The Mooidraai Formation is a dolomitized, stromatolitic, prograding carbonate platform characterized by upward-shallowing facies transitions from slope environments below storm-wave base to shelf and peritidal settings. Directly underlying the Mooidraai is the world's most enriched terrestrial manganese (Mn) deposit (the Hotazel Formation) and the oldest Snowball Earth Glaciation (the Makganyene Glaciation)—both interpreted as consequences of O_2 accumulation. Stable Tl isotope ratios indirectly track marine oxygenation through a sensitivity to seafloor Mn oxide burial, which preferentially sequesters the heavier mass ^{205}Tl isotope.

Bulk $\varepsilon^{205}Tl$ values (n=21) in the Mooidraai are, barring one sample, ubiquitously heavier than global ocean inputs ($\varepsilon^{205}Tl_{in}$ » -2 ‰), averaging -0.2 ‰ and reaching as high as +2.3 ‰. No trends exist between $\varepsilon^{205}Tl$ values and geochemical proxies for the extent or style of diagenesis ($\delta^{18}O$, $\delta^{13}C$, Mg/Ca, Mn/Sr), while an asymptotic trend is observed with Mn enrichment factors. The most parsimonious explanation of the ^{205}Tl enrichments is the formation and burial of local hydrogenetic Mn oxides, which necessitates dissolved O_2 in marine bottom waters. The persistence of heavier-than-input $\varepsilon^{205}Tl$ values throughout the ~90 m section indicates that an oxygenated water column extended at least below the storm-wave base throughout the deposition of the Mooidraai. The ^{205}Tl enrichments, ...

... together with an absence of mass-independent sulfur isotope fractionation effects, point to an oxidizing Earth surface environment ~2.4 billion years ago. These data fingerprint a productive microbial community that may have both facilitated the deposition of the Hotazel Formation and been driven by enhanced nutrient delivery due to post-glacial weathering in the wake of the Makganyene Snowball Earth Glaciation.

A multiscale approach to the investigation of carbon texture in putative microfossils from the Pilbara Craton (Western Australia)

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Morphological features used to define the biogenicity of the oldest microfossils on Earth have long been debated, particularly with the development of new analytical techniques. Archean-aged carbonaceous microstructures found in sedimentary siliciclastic and chemical deposits may represent some of the earliest microbial remains. Cherts, ubiquitous in the Archean record, formed through sedimentary and/or hydrothermal processes, offer efficient protection of fragile organic components, promoting preservation of carbonaceous molecules and microstructures under advanced diagenesis and even low-grade metamorphism.

Amorphous or poorly crystallised mineral phases may mimic microfossil morphologies. Hydrothermal fluids can also alter primary organic compounds through remobilization, contamination, or sequestration, while abiotically derived organic molecules may form via Fischer-Tropsch-type reactions and migrate before deposition onto pre-existing structures.

Lenticular specimens represent some of the most distinctive and promising objects for study. Their unique morphology has been documented in coeval formations from the Barberton Greenstone Belt (South Africa) and the Pilbara Craton (Western Australia).

This study investigates chert samples from the 3.4 Ga Strelley Pool Formation and the 3.0 Ga Farrel Quartzite. While previous work focused on morphological descriptions, recent nanoscale analyses emphasize the importance of ultrastructural insights into carbon organization. In this study, the syngeneity and endogeneity of both carbonaceous textures and the quartz matrix were examined at micro-to-nanoscale. The biogenicity of carbonaceous microstructures was investigated through scanning transmission electron microscope (STEM) on ultrathin focused ion beam (FIB) sections, and the atomic scale has been reached using high resolution (HR) mode of the STEM.

A refined typology revealed significant differences between lens-shaped microstructure subtypes, suggesting variable post-depositional alteration and preservation states along a potential continuum. Nanoscale investigations show heterogeneous structures in carbon granules vs. homogeneous structures in the reticulated carbon textures, with very common fibre-like carbon nanotexture and more extended ones. HR-STEM imaging further revealed kerogen structural heterogeneity within FQ single specimens, likely reflecting variations in molecular composition, crystallisation kinetics, ...

... and/or fluid-rock interactions. Turbostratic carbon, displaying both oriented and disordered structures, was confirmed by Fourier-transform analysis, supporting poorly-graphitized, but with highly variable carbon crystallite/domain size within these ancient microstructures.

Further studies will systematically compare the evidenced structures with synthesised abiotic membrane structures, before and after simulated diagenetic processes. The composition of carbonaceous macromolecules that form these organic biomorphs will be compared to insoluble phases preserved in Archean microstructures in order to further elucidate approaches to investigating biogenicity.

Organic matter heterogeneity and population diversity in Precambrian strata

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Organic matter (OM) is one of the most important components in Precambrian sedimentary and meta-sedimentary strata to reconstruct life and environments during the time of their deposition. However, due to its opaque nature, its homogenization, its molecular diversity and its tendency to migrate OM is also one of the most difficult rock components to handle and access. One of the most commonly used and easy to access methods to characterize OM in Precambrian rocks is Raman spectroscopy. The spatial resolution of this method (~ 1-2 μm spot size) however, often results in interpretations that show OM to be homogeneous within individual samples or even at the level of stratigraphic units up to the scale of a Formation and thus seemingly limits its usefulness.

Here we show, using Raman spectroscopy combined with meticulous microscopic characterization, that OM is actually far from homogeneous in many Proterozoic and Archean sedimentary and meta-sedimentary rocks. Fine grained siliciclastics often display a wide variety of OM populations of distinct characteristics that indicate the presence of recycled or petrogenic OM (OM_{petro}) from older strata at the time of the deposition of the sediment. High OM_{petro} concentrations might easily falsify any bulk analysis (e.g.: bulk $\delta^{13}C$) conducted on OM. And indeed, this material is a natural but mostly underestimated part of the total organic carbon (TOC) content of fine grained siliciclastics and can make up to 80% of the estimated TOC concentration in exceptional circumstances. In general, over the Proterozoic era the concentration and relative proportion of OM_{petro} appear to steadily increase.

Additionally, in sedimentary and meta-sedimentary rocks that experienced partial cementation or metamorphic recrystallization OM repeatedly shows bimodality. OM within authigenic cements or metamorphically recrystallized areas frequently shows a significantly higher structural order than adjacent OM in the rock matrix of the same sample that is not affected by the formation or recrystallization of authigenic minerals. This can lead to a significant overestimation of the maximum burial or metamorphic temperature when using geothermometers based on Raman spectroscopy of carbonaceous matter and is also an important factor in ascertaining areas of interest for high resolution (nm-scale) analytical methods to precisely characterize OM chemically and structurally.

Protobiosignatures: Signs of life's emergence

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Life on Earth likely emerged somewhere between 4.2 and 3.9 billion years ago. It is thought that life could also have begun on Mars around the same time due to the similarity in environmental conditions between early Mars and early Earth. However, it remains to be seen whether evidence exists for either extant or extinct life on Mars. Similarly, signs of life from other planetary bodies in our Solar System have not yet been observed. The possibility remains that Earth is the only living planet in our vicinity, or indeed in the universe as a whole. This could be due to a number of scenarios including that life is a unique event that only occurred and will only occur once, or that life can occur multiple times, but Earth is the first planet in the 4.6 billion-year history of our Solar System to become inhabited. There are myriad other possibilities, but in the latter scenario it is reasonable to assume that life may currently be in the process of emerging on other planetary bodies, or may have begun to form but never completed the transition from chemistry to biology. In this case, the signs of emerging life—similar to but also distinct from the signs of life—may be observable but overlooked. Protocols for searching for 'protobiosignatures' are required alongside those for biosignature detection in order to increase our chances of identifying this phenomenon on neighbouring planets. We are currently developing a range of possible protobiosignatures that could be referenced when interrogating the early Earth rock record or extraterrestrial samples. Drawing on prebiotic chemistry and palaeontological knowledge, we synthesise analogues of the molecular and supramolecular species we would expect to find during origins scenarios. These are artificially fossilised to investigate their preservation potential, analysed by molecular techniques, and compared with samples of both known and uncertain biogenicity. It is hoped that we can develop a systematic approach that will simultaneously elucidate the search for extinct, extant, and emerging life in the Solar System.

Spatial and seasonal controls on phosphate accumulation at an origin-of-life analog environment

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Alkaline lakes represent a relatively clement form of extreme environment. They can be immensely bioproductive and have been touted for being rare sites with high dissolved phosphate [1], a sought-after attribute in origin-of-life research. Yet dissolved phosphate accumulation is a delicate process that depends on (at least) evaporation rate versus the flux and chemistry of inflow waters, as well as the solubilities of key minerals such as apatite and natron. Here we examine Last Chance Lake (British Columbia, Canada), the site of the highest recorded lacustrine alkalinity (3.7 Eq/L) and phosphate (38.3 mmol/l) on Earth [2], with a focus on spatial and temporal geochemical trends and their implications for prebiotic research.

Sediment cores were collected across two field seasons (June 2021 and April 2024) at basin ...

… margin and interior locations. Porewater concentrations of phosphate and alkalinity notably increase moving toward the basin interior. For instance, there is a more than five-fold increase in average phosphate concentrations when comparing marginal (0.6 mmol/kg, n = 16) versus interior (3.4 mmol/kg, n = 21) porewaters. Additionally, key anions (sulfate, phosphate, and Cl^-) within interior porewaters become more concentrated with depth relative to their margin counterparts, while certain cations either stay constant (Ca^{2+} and Mg^{2+}) or increase less than Na^+ (e.g., K^+). We hypothesize "sink-switching" for cations on seasonal timescales, from non-carbonate (during freezing conditions) to carbonate (during spring thaw) anions. This modulates Ca^{2+} and thus limits apatite precipitation, facilitating high phosphate concentrations.

These data stress the importance of groundwater recharge chemistry and seasonality on alkaline lakes as origin-of-life environments. The shorelines of aqueous environments may be considered preferable for prebiotic chemistry, as life may have originated in part through the development of organic polymers via repeated wet-dry cycles [3]. However, Last Chance Lake shows that calcium-bearing input waters will tend around the margins and act as a localized sink for phosphate. Additionally, freeze-thaw conditions may facilitate phosphate buildup, implying periodically cold temperatures and dynamic seasons are desirable for de novo origin scenarios in alkaline lakes.

1. Toner & Catling (2020) A carbonate-rich lake solution to the phosphate problem of the origin of life. *PNAS*; 2. Hirst (1995) University of Saskatchewan; 3. Damer & Deamer (2020) The hot spring hypothesis for an origin of life. *Astrobiology*

Testing emergence of life hypotheses in hydrothermal vent experiments

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The emergence of life is one of the greatest secrets humankind has yet to unravel. Hydrothermal vent environments are among the most likely sites of life's origin, since they provide a variety of physical-chemical conditions and energy gradients, creating a natural "flow-through bioreactor". We simulate early Earth and Enceladus vent environments in controlled "chemical garden" experiments that take place in an anaerobic chamber with O_2 <0.5 ppm. With this setup we show (1) RNA accumulation in green rust chimneys under Hadean/Archaean conditions and (2) H_2-dependent methanogenesis and growth of archaea at simulated early Earth iron-sulfide vents. We also use this setup to study (3) the formation mechanism of hydrothermal vents on Saturn's icy moon Enceladus, and whether geochemical processes supporting microbial growth could take place in such a high pH soda ocean.

RNA dynamics in a hydrothermal vent model of the prebiotic earth

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How life emerged on Earth is one of the most important, yet difficult questions to answer. While the exact geological setting for life's emergence is unknown, there is a growing consensus that hydrothermal environments likely played a major role in the emergence and early evolution of life. Hydrothermal springs result in steep temperature, proton, and redox gradients as well as create far-from-equilibrium states. Hydrogen gas is produced abiotically as a natural energy source for the hydrothermal vents, which potentially fueled the first metabolisms. In addition to this "metabolism first" hypothesis, an "information first" hypothesis for the emergence of life describes an 'RNA-world' where self-replicating RNAs were a necessary precursor to the first cells. It remains to be seen whether or not the "information first" and "metabolism first" hypotheses are mutually exclusive. Until now, few studies have investigated the potential for self-replicating RNAs within analog ferruginous oceans and hydrothermal vents. We seek to investigate potential compatibilities between these two major hypotheses with experiments.

Here, we investigate RNA dynamics in ferruginous chemical gardens as models for hydrothermal vents of the Hadean ocean. By injecting an alkaline sodium hydroxide solution into a ferruginous acidic solution under an anoxic atmosphere we simulate alkaline hydrothermal vents on the ancient ocean floor. The resulting chimney structures that precipitate along the steep pH gradient are composed primarily of the mineral green rust, confirming predictions that this mineral would have been abundant in Hadean vents. We showed that RNA accumulates in the green rust chimneys under ferruginous conditions, thereby demonstrating that green rust chimneys in ferruginous ancient oceans could have concentrated RNA at the emergence of life. We are continuing to investigate RNA integrity and structural preferences in these ferruginous hydrothermal experiments, to better understand the effects of ferruginous environments on RNA at the emergence of life.

Using geochemical and biological methods to source microbial methane at serpentine-hosted springs

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Sourcing microbial methane requires multiple lines of evidence because methane can be formed microbially, thermogenically, or abiotically. All three sources are possible at sites of serpentinization. This talk will focus on the use of geochemistry, stable isotopes, lipid biomarkers and genomics to source methane from three serpentine-hosted springs with three putatively different sources of methane: Tablelands, NL, CAN; The Cedars, CA, US; and Aqua de Ney, CA, USA.

Investigating the incorporation of organic matter into evaporite minerals as a tool to search for the record of life on Earth and elsewhere

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Evaporites (minerals that precipitate from fluids during evaporation, e.g., gypsum, halite, carbonates, and other salts) are a target for exobiological study because, on Earth, organic material can become incorporated as the minerals precipitate from the fluid and potentially preserved over geologic time. However, it is not as well understood exactly how the organic matter/microbes are incorporated or where they might reside (e.g., intracrystalline areas, fluid inclusions, etc.) when evaporites form. In order to have the best search image when prospecting for life elsewhere, it is important to know the relationship between organic matter in the environment and how and where the organics might reside within the evaporite minerals. Fluid inclusions in evaporites also have the potential to inform about the chemistry of the environment during evaporite formation. Evaporite minerals, like gypsum, are found on Mars are potential hosts for microbial life or contain organic matter that can support life. We aim to understand how and where organic matter is incorporated into minerals and to recreate the starting geochemical and biological conditions of the precipitating environment. Key questions include: How does organic matter incorporate into evaporites/what is the relationship between the starting concentrations of organics and what ends up in the evaporite crystal? Are fluid inclusions representative of the precipitating environment? Is it possible to recreate starting geochemical conditions of a precipitating environment from a salt? While natural evaporative systems are abundant and straightforward to access on Earth, studying such deposits can be complicated by the uncontrolled variables (sediment reworking, secondary crystallization). Great Salt Lake and Searles Lake saline lakes were chosen as field sites to collect brine and evaporites. These sites, Searles Lake and Great Salt Lake, are notable in their comparability to Mars. Our approach will include laboratory experiments on composed brines where experimental conditions (introduction of known quantities of organics/microbes) can be controlled as well as natural samples to compare to the experimental results.

Assiniboine/Summit Room

Testing the efficacy of machine learning regression algorithms in predicting geochemical marine redox. changes from the mid-Paleoproterozoic to the Holocene

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Historical changes in the Earth's marine redox state are important for determining how marine organisms evolved, lived, and died through time. These changes are recorded in our fossil assemblages and in various geochemical proxies such as Molybdenum (Mo), Uranium (U), and Vanadium (V). Using statistical analyses and mass balance modelling, researchers have attempted to quantify global redox changes through time using sedimentary abundances of these redox-sensitive trace metals. Specifically, as oceans become less oxygenated/more reducing, the dissolved seawater inventory of these metals will be drawn down, and this will be reflected in lower sedimentary trace metal concentrations. As we build bigger sedimentary geochemical databases through the Sedimentary Geochemistry and Paleoenvironments Project (SGP), it is important to revisit what the redox-sensitive trace metal dataset is telling us with increasingly sophisticated statistical tools at our disposal.

This research builds on work done in Stockey *et al.* (2024; Nature Geoscience), who developed stratigraphy-based age modelling and applied a Monte Carlo random forest analysis to sedimentary trace metal data ranging from 1000 Ma – 300 Ma. In modifying this framework for use with Python's (v3.12.4) sci-kit learn (v1.5.1) and xgboost (v.2.1.3) packages, we can determine feature importance on a finer scale via numerical encoding of categorical variables. Using the larger SGP Phase 2 dataset, here we test the predictive efficacy of six machine learning algorithms (plus random forests as used by Stockey *et al.*) across an expand temporal dataset (2200 Ma – 15 Ma). The ultimate goals are to determine algorithm performances based on root mean squared error, identify variable importance of predictor variables, and to present our statistical reconstructions of Mo, U, and V concentrations through time.

The current pipeline is still in progress as we are focused on the parallelization of hyperparameter fine-tuning and model-data interpolation. For now, we can produce model outputs along a smaller parameter grid-search with fewer iterations. Once the pipeline is complete, we will be able to run the full grid-search with 100 iterations, thereby giving us the best parameters for each algorithm, trace metal partial dependencies, and variable importance plots.

Re-evaluating Glauconite as a Geochronometer: A Coupled Rb–Sr and K–Ca Approach via TIMS-ATONA and ICP-MS/MS

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Glauconite is an authigenic marine clay mineral of the mica group that forms at the sediment–seawater interface during sediment deposition and early marine diagenesis. Due to its relatively high potassium (K) and rubidium (Rb) contents, glauconite has been widely used for direct dating of sedimentary rocks [1,2] As immature glauconitic precursors (e.g., smectite clays) mature into K-rich, micaceous glauconite, they become progressively enriched in K and Rb, and depleted in aluminium (Al), calcium (Ca) and strontium (Sr) [1,3]. This elemental and mineralogical evolution makes glauconite a suitable mineral or archive for Rb–Sr, K–Ar, and potentially K–Ca isotopic dating.

However, glauconites from ancient (e.g., Palaeozoic and Precambrian) depositional systems often yield systematically younger ages than the expected depositional age of their host sediment and rocks [2,4]. This discrepancy raises concerns regarding possible post-depositional element and isotope mobility, open-system behaviour, and the reliability of glauconite 'ages' and isochrons—some of which may also reflect possible 'pseudochrons' or mixing trends.

In this study, we apply a coupled Rb–Sr and K–Ca isotopic method to further assess glauconite's reliability as a geochronometer. Following the leaching protocol of Gopalan (2008), we separated each glauconite sample into leachate, residue, and bulk sub-samples, generating a broad range of Rb/Sr and K/Ca elemental ratios and thus variable radiogenic enrichments in ^{87}Rb and ^{40}Ca. These were analysed using TIMS-ATONA and ICP-MS/MS techniques, providing relatively high precision data.

We validated our methodology using the glauconite standard GL-O (stratigraphic age: 100.5 ± 0.14 Ma; reference published isotope dilution (ID) Rb–Sr age: 90.4 ± 0.4 Ma [5]). Our analyses yielded coupled Rb–Sr and K–Ca ages of 86.9 ± 1.2 Ma and 90.6 ± 5.6 Ma, respectively.

Ongoing work will extend this novel dating technique to Proterozoic and Early Palaeozoic glauconites, which are significantly older than the measured GL-O, and therefore assumedly more radiogenic and potentially more amenable to precise K-Ca and Rb-Sr geochronology. We anticipate improved resolution and further validation through the integration of ID methods, combined with sequential leaching and possible 'concordia' plotting.

This study demonstrates that coupled Rb–Sr and K–Ca isotopic dating—when applied through a sequential leaching protocol and novel TIMS-ATONA and ICP-MS/MS—offers a promising path for re-establishing glauconite as a viable tool for high-resolution sedimentary geochronology.

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Understanding the Effect of Thermal Maturation on the Mudrock TOC Record in Deep Time Analyses

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Total Organic Carbon (TOC) concentrations are utilized as a proxy for marine productivity and to normalize many geochemical proxies. However, thermal maturity affects original TOC concentrations, and organic carbon loss from thermal maturation can be up to 70%. Thus, using uncorrected measured TOC concentrations (as has been done in database-scale temporal analyses to date) can lead to erroneous application of geochemical proxies and misinterpretation of paleoenvironmental conditions. Empirical methods for reconstructing TOC require an estimate of the original Hydrogen Index (HI; the amount of generative hydrocarbons relative to TOC) at the time of deposition. HI, like TOC, decreases with increasing thermal maturity; HI values will eventually reach zero at high levels of thermal maturity. Our previous studies, using machine learning random forest models trained on thermally immature geochemical data with paired organic geochemical data, have demonstrated accurate predictions of original HI values using only inorganic data, which is robust to thermal alteration. Here, we 1) develop a new random forest model with geochemical data from thermally immature samples from the Sedimentary Geochemistry and Paleoenvironments Project (SGP) database, 2) reconstruct original HI values in thermally mature rocks in the SGP database using that model, and 3) use the reconstructed HI values to correct the TOC concentrations for thermally mature samples throughout Earth's history. While the model showed an increase in TOC concentrations, overall trends in the rock record did not change. Trends observed in previous studies remain after the data are corrected for thermal maturity, including low TOC in Neoproterozoic samples followed by a sharp rise in TOC concentrations at the Ediacaran to Cambrian, and higher TOC in Paleoproterozoic and Mesoproterozoic samples than the Neoproterozoic samples.

Estimating late Neoproterozoic temperature conditions for the western Laurentian margin with chemical weathering proxies

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The late Neoproterozoic and early Cambrian saw major swings in global climate broadly coincident with the emergence and diversification of animal life. Recent work into marine animal physiology has established that the oxygen requirements for sustained activity are closely related to temperature (through metabolic effects). Therefore, examining marine oxygen and temperature dynamics in conjunction is critical to obtaining a complete understanding of changing marine environmental habitability. To this end, we investigate the temperature dynamics of the late Neoproterozoic and early Cambrian using the Chemical Index of Alteration (CIA) of fine-grained siliciclastic rocks as a proxy. CIA values are calculated by comparing the ratio of immobile Al cations to the more mobile cations of Ca, K, Na. This can produce an estimate for the degree of chemical weathering, which is largely a function of temperature along the sediment transport path (albeit with confounding ...

… variables such as provenance, sorting, and diagenesis). Larger values of CIA (80-100) are more likely to correspond to higher temperatures. Values of 40-60 are more likely to correspond to lower temperatures.

In this study, we investigate CIA values from fine-grained siliciclastic rocks deposited along the western Laurentian margin through the Neoproterozoic and early Cambrian. Paleogeographic reconstructions suggest that the paleolatitude of western Laurentia remained relatively constant (and tropical) through this time interval, suggesting that local temperature fluctuation would reflect global climate change rather than relative plate motion. Geochemical data for ~1400 fine-grained siliciclastic samples were obtained from the Sedimentary Geochemistry and Paleoenvironments Project (SGP). Preliminary results reveal lower CIA values at ~800 Ma that transition to higher values by ~750 Ma, and moderate values through the Cryogenian interglacial episode and the Ediacaran, transitioning back to lower values by the early Cambrian. This may indicate that CIA values in the late Neoproterozoic broadly track a decrease in global temperature consistent with known glacial intervals through the Cryogenian and the Ediacaran-Cambrian boundary. We will expand this initial data set by generating new CIA data from stratigraphic sequences in California, Washington, Idaho, and British Columbia, sites whose paleolongitude corresponds to most of Laurentia's western margin. We will use multivariate statistical analyses and machine learning to incorporate grain size, provenance, and estimated paleolatitude as predictor variables, resulting in partial dependency plots tracking CIA (with other confounding factors held constant) through the late Neoproterozoic and early Cambrian. Ultimately this will help constrain temperature and climate conditions during critical intervals of early animal evolution.

Evolution of the iodine cycle and the late stabilization of the Earth's ozone layer

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We present evidence for a protracted stabilization of the Earth's ozone layer. The destruction of atmospheric ozone today is inherently linked to the cycling of marine and atmospheric iodine. Supported by multiple independent lines of geological evidence and examined through an iodine mass balance model, we find that elevated marine iodide content prevailed through most of Earth's history. Since the rise of oxygen ~2.4 billion years ago, high marine iodide concentrations would have led to significant inorganic iodine emissions to the atmosphere, facilitating catalytic ozone destruction and resulting in atmospheric ozone instability with periodic or persistently lower ozone levels. At a global scale, unstable and low ozone levels likely persisted for about two billion years until the early Phanerozoic, roughly 0.5 billion years ago. The delayed stabilization of the Earth's ozone layer holds significant implications for the tempo and direction of the evolution of life, in particular life on land.

Understanding the secular variation of marine IO_3^- reservoir and its paleoredox implications

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Iodine to calcium ratio (I/Ca or I/(Ca+Mg)) in marine carbonate rocks, which reflects iodate (IO_3^-) in ancient seawater, has been applied as a paleoredox proxy. A compilation of secular I/Ca through the Earth's history reveals two stepwise transitions in seawater IO_3^- reservoir: (1) the initial appearance of non-zero IO_3^- accumulation in temporal proximity with the Great Oxygenation Event (GOE), and (2) a baseline shift to the close-to-modern values around 200 million years ago (Ma). These baseline shifts of seawater IO_3^- reservoir probably reflect fundamental changes in the redox evolution of the Earth's atmosphere and the ocean. However, the drivers of these baseline changes remain unclear, due to limitations of current knowledge in quantifying the requirements of IO_3^- accumulation in surface seawater.

Here, we conduct a series of microbial experiments to quantify IO_3^- reduction by bacterial strain *Shewanella oneidensis* MR-1 in low O_2 conditions to explore the essential threshold for non-zero IO_3^- accumulation. In addition, we use the Earth System Model with an active iodine cycle and incorporating atmospheric and oceanic biogeochemical and physical processes (cGENIE) to determine broader redox and nutrient conditions that maintain IO_3^- concentrations in seawater.

The experiment results indicate that IO_3^- reduction is insignificant until the dissolved O_2 in medium is below 0.1 μM (~3×10^{-4} modern saturation level). This microbial threshold for IO_3^- reduction is identified for the first time, which also provides the minimum constraint of seawater dissolved O_2 during the GOE. Following the GOE, under low atmospheric O_2 (~3% PAL) and ocean nutrient state (<10% of modern PO_4^{3-}), the "Proterozoic baseline" of I/Ca, equivalent to 50 nM IO_3^- could be sustained. The second baseline shift in I/Ca occurred during the Paleozoic-Mesozoic, when atmospheric oxygen neared modern levels. However, cGENIE predicts it should have occurred much earlier, as only 30% PAL O_2 was enough to accumulate modern-like IO_3^- (>250 nM), even with high Phanerozoic PO_4^{3-}. This discrepancy indicates this second baseline shift in I/Ca in the Phanerozoic may have been driven by factors beyond atmospheric oxygenation, including nutrient levels and deep ocean oxygenation. Together, our model and experimental results indicate that baseline changes of IO_3^- through Earth history are sensitive to O_2 variations as well as additional, non-redox factors that were not previously considered.

The emerging thallium isotope perspective on oxygenation of late Paleoproterozoic oceans leading up to the appearance of multicellular eukaryotes

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Accurate reconstructions of environmental O_2 provide insight into the conditions at the time when early eukaryotes initially appear and diversify in the fossil record. Estimates of mid-Proterozoic (1.8-0.8 Ga) atmospheric O_2 levels typically range from <0.1-1% present atmospheric level (PAL) to a few tens of % PAL. Oceans were likely redox-stratified with oxygenated surface waters, euxinic mid-depth ...

… waters, and ferruginous deep waters, interrupted by intervals with increased oxygenation of uncertain number, duration and extent. The emerging Tl isotope paleoredox proxy has its own story to tell because seawater ε^{205}Tl is sensitive to Mn oxide burial in marine sediments beneath oxygenated water columns (ε^{205}Tl = parts-per-ten-thousand deviation from a standard). Application of Tl isotopes has focused on Archean–early Paleoproterozoic and Neoproterozoic oxygenation events and Phanerozoic deoxygenation events. Thallium isotope studies on the mid-Proterozoic are limited yet may help inform how oceanic O_2 influenced eukaryotic evolution, alongside other factors like nutrient availability, ecology, and genetic development.

We generated Tl isotope data from late Paleoproterozoic organic-rich mudrocks deposited in the intracratonic McArthur Basin (northern Australia) and ranging in age between 1.8 and 1.6 Ga. Samples from the 1.78 Ga McDermott and 1.73 Ga Wollogorang formations have average $\varepsilon^{205}Tl_{authigenic}$ of –3.5 ± 0.7‰ and –3.0 ± 1.0‰ (1σ), with values as low as –4.7‰ and –4.9‰, respectively. Two apparent excursions to −5.2‰ (baseline = −3.5 ± 1.2‰) are observed in the ~1.65 Ga Mallapunyah Formation, with one excursion just below occurrences of the unicellular eukaryotic microfossil Valeria lophostriata. Samples from the upper and lower portions of the ~1.64 Ga Barney Creek Formation have $\varepsilon^{205}Tl_{authigenic}$ of −3.9 ± 0.3‰ and −2.7 ± 0.4‰, respectively. Many compositions are distinguishable from presumed average oceanic Tl inputs (−2; based on modern data). We consider the impact of local redox, basin restriction, and post-depositional hydrothermal fluid flow on sedimentary $\varepsilon^{205}Tl_{authigenic}$. At least some of the more negative $\varepsilon^{205}Tl_{authigenic}$ likely reflects lower ε^{205}Tlseawater produced by preferential burial of ^{205}Tl with Mn oxides in shallow-water oxygenated sediments, which has also been reported for the early Paleoproterozoic and late Archean oceans. These findings raise the possibility that regionally widespread shallow-water oxygenation was common in the McArthur Basin ~150 Myr before the first known appearance of multicellular eukaryotes in the rock record at ~1.65-1.63 Ga (Limbunya Group from the coeval Birrindudu basin in Australia; Chuanlinggou Formation in China), by which time the diversity of unicellular eukaryotes had also significantly increased.

Thallium isotopic evidence for Tonian deep ocean oxygenation

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Estimating oxygen concentrations during the Neoproterozoic is central to testing hypotheses about the role of oxygen in the evolution of early animal life. This study provides the first constraint on the global extent of marine bottom water oxygenation during the early Neoproterozoic by applying the thallium (Tl) isotope paleoredox proxy to shales from the Tonian Reefal Assemblage in the Coal Creek and Tatonduk inliers of Yukon, Canada. Samples analyzed in this study are stratigraphically below the ca. 810 million year old Bitter Springs Carbon Isotope Excursion (BSE). Thallium isotopes can be used to reconstruct the global extent of oxygenated oceanic bottom waters because the primary control on seawater Tl isotope compositions (ε^{205}Tl) over thousand- to single-million-year timescales …

… is changes in the extent of ^{205}Tl removal by manganese oxides on the seafloor. Samples from the Reefal Assemblage (n = 18/30) yield $\varepsilon^{205}Tl_{auth}$ values lower than global oceanic inputs ($\varepsilon^{205}Tl$ ~ –2‰), with some samples approaching the modern seawater $\varepsilon^{205}Tl$ value of –6‰. Such low $\varepsilon^{205}Tl_{auth}$ values require oxygenated bottom waters over regions of the global seafloor prior to the BSE. Tonian $\varepsilon^{205}Tl_{auth}$ values from this study are lower than published $\varepsilon^{205}Tl_{auth}$ values from younger Ediacaran strata, suggesting that Earth's oceans may have been more fully oxygenated prior to early animal evolution than during their rise to ecological importance.

The Same and Not the Same: A Tale of Two Contrasting Origins of Methane-Derived Authigenic Calcite and Their Implications on Proterozoic Carbon Cycle

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Methane has long been regarded as a key greenhouse gas modulating Earth's paleoclimate. Notably, methane-derived authigenic calcite (MDAC) cements, characterized by extremely low carbon isotopic values ($\delta^{13}C_{carb}$ < –30 ‰), have been reported from both the basal (within post-Marinoan cap dolostones) and upper (within the EN3 interval) parts of the Ediacaran Doushantuo Formation in South China. These anomalous geochemical signals have been proposed to bear profound implications for methane's critical role in global biogeochemical cycles. However, the origin and diagenetic history of these MDACs remain ambiguous due to the lack of detailed petrographic and geochemical investigations at a micron scale. Here we present new insights by integrating secondary ion mass spectrometry (SIMS) and petrographic observations.

Our new data sets reveal contrasting origins for MDAC cements. In the basal Doushantuo Formation, the MDAC cements ($\delta^{13}C_{carb}$ down to –53.1‰) are post-depositional, void-filling, and rich in Mn. Importantly, petrographic and SIMS results consistently show that MDAC cements post-date disrupted dolomite laminae that bear surprisingly positive $\delta^{13}C_{carb}$ values up to +6.3‰. This is the first report of positive $\delta^{13}C_{carb}$ signals within post-Marinoan cap dolostone. The dolomite laminae and MDAC cements thus represent distinct post-depositional, exogenous, diagenetic carbon signals unrelated to Marinoan deglaciation. Our findings challenge the hypothesis that methane played a central role at the end of, or immediately following, the Marinoan glaciation. Instead, methane infiltration into cap dolostones may have occurred at a relatively later stage.

In contrast, SIMS results of MDACs in the upper Doushantuo Formation reveal remarkable micron-scale heterogeneity of $\delta^{13}C_{carb}$ (with values down to –37.5‰) at outer shelf shoal settings. We interpret these calcite cements as resulting from microbial sulfate reduction and anaerobic oxidation of methane during syndepositional or early diagenesis. These findings suggest that the heterogeneous expressions of the Shuram excursion in South China — manifest on micrometer, centimeter, and basinal scales — was modulated by methane oxidation under variable local redox and water depth conditions. The Shuram excursion, therefore, was coupled with different degrees of methane oxidation in individual basins and globally triggered by enhanced seawater sulfate during an …

… atmospheric oxygenation event.

Our study demonstrates that integrated SIMS and petrographic analysis can distinguish different generations of isotopically distinct carbonate cements that are otherwise undetected by conventional analysis and, therefore, is an effective approach to assess the origin and diagenetic history of carbon isotope anomalies in the sedimentary record.

Modelling of Snowball Earth Events

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Snowball Earth events are amongst the most substantial instances of climate change observed in our planet's history, with the geological record giving evidence of three such occurrences, spanning the Proterozoic. Global glaciation is achieved following a reduction in pCO_2 sufficient to trigger the ice-albedo feed-back, brought on by a reduction in volcanic outgassing and / or an increase in the rate of weathering. Snowball Earth during the Paleoproterozoic is unique amongst these events, owing to the coincident oxygenation of the atmosphere and formation of an ozone layer. We use the GCM 'ExoCAM' to investigate climate bi-stability, assessing how the initiation and deglaciation thresholds respond to changes in O_2 & O_3 concentrations for both aqua planet and modern continental configurations, at a range of solar constants. We present preliminary results in which a substantive difference in the glaciation behaviour is observed between model configurations.

Transitional contact at the base of the Nuccaleena Formation, Flinders Ranges: implications to the timing and formation of cap carbonates

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Cap carbonates are enigmatic and globally extensive carbonate units that overlie Cryogenian glacial sediments. These carbonate units have been the focus of many studies as they potentially record environmental conditions and ocean chemistry in the aftermath of the severe 'snowball Earth' glaciations. However, the process through which cap carbonates were formed is still debated, and in particular, the timing of cap carbonate formation remains unclear. In this study, we present findings from a sedimentological and geochemical study of the Nuccaleena Formation (the Marinoan cap carbonate unit) in the Flinders Ranges, South Australia. Specifically, we focus on the stratigraphic sections showing the contact between the Marinoan glacial Elatina Formation and the overlying Nuccaleena Formation. In the southern Flinders Ranges, the base of the Nuccaleena Formation is transitional over 2-3 m, rather than showing a sharp basal contact. Both carbonate analysis and Mg concentrations from pXRF analysis reflect this transitional contact, showing a gradual increase in dolomite content up section. The Nuccaleena Formation is predominantly composed of interbedded red shale and dolomite (of ~10% to 90% dolomite, mean = 50% dolomite), which is consistent with other cap carbonate sequences in Australia. Characteristic features include cm-scale graded beds, where a clay-rich bed becomes increasingly dolomitic upwards before being terminated by an …

… erosional surface. In addition, petrographic analysis shows authigenic dolomite precipitation in the form of mm-scale nodules and microcrystalline dolomite. These features are all consistent with authigenic dolomite precipitation in submarine hardgrounds resulting from a period of sediment starvation following glaciation. Overall, these results indicate that cap carbonate precipitation is more likely to have occurred over longer time periods (e.g. hundreds of thousands to millions of years), challenging interpretations of a rapid deglaciation scenario. This has implications for our understanding of the termination and aftermath of one of Earth's most severe glaciations.

Viscosity-Driven Shifts in Microbial Competition and Community Structure

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The evolution of multicellularity was a major transition in the history of life, yet the ecological conditions that accompanied its emergence remain unclear. Environmental viscosity—modulated by temperature and salinity—strongly influences nutrient uptake in aquatic microbes and may create selective pressures for multicellular forms. Using the Volvocine algae as a model system, we tested whether viscosity alters competitive outcomes between unicellular (*Chlamydomonas reinhardtii*) and simple multicellular (*Gonium pectorale*) species. Co-cultures grown across a gradient of viscosities revealed that multicellular forms gain a relative fitness advantage in higher viscosity environments, with growth curve analysis showing positive selection coefficients for *Gonium* under these conditions. These results suggest that viscosity-driven constraints could have created ecological niches favoring multicellularity in Earth's past, particularly during Cryogenian glaciations when low temperatures would have elevated ocean viscosity. Furthermore, they highlight an ongoing role for physical properties like viscosity in structuring modern planktonic communities—especially in variable or extreme environments such as hypersaline lakes and polar seas. Understanding these dynamics improves our grasp of how environmental factors interact with organismal traits to drive evolutionary transitions and maintain morphological diversity today.

Thawing the Past: Using Canadian Arctic Glaciers as a Glimpse into Snowball Earth's Retreat

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Throughout Earth's history, periods of glaciation and deglaciation have been among the most transformative processes, continually re-shaping the planet's landscape and climate. For instance, the onset of Neoproterozoic Snowball Earth (1,000-540 Mya), a time when most of the planet was covered in ice, has been linked to decreased marine nutrient bioavailability, reduced primary productivity and large-scale microbial extinctions. The deglaciation of Snowball Earth led to an equally dramatic shift in the marine environment, as increased weathering of newly exposed bedrock enriched the meltwater with bioessential nutrients, and likely fueled microbial growth and diversification. Despite advances in sample resolution and modeling efforts it remains challenging to predict how the delivery of this nutrient-enriched meltwater may have impacted microbial …

... community growth and composition during different phases of deglaciation.

Modern glacierized regions, such as the Canadian Arctic Archipelago (CAA), are a valuable analog for studying these processes. The CAA features both tidewater glaciers (with termini that end below seawater surface) and land-terminating glaciers (with termini that end on land), which may represent two distinct phases of Snowball glacial retreat. These glaciers deliver nutrients via: (1) lateral meltwater input directly enriching the ocean surface, and (2) discharge of meltwater beneath the ocean's surface driving entrainment and upwelling of nutrient-rich deep seawater. Tidewater glaciers, capable of both mechanisms, support high primary productivity in spring and summer, while land-terminating glaciers, limited to lateral inputs, show reduced summer productivity.

In this study, we assess the influence of tidewater glaciers on the marine prokaryotic community by comparing regions with varying degrees of tidewater glacier influence. To achieve this, we undertook sampling campaigns in the summers of 2021 and 2022 spanning two distinct waterways in the CAA – Nares Strait and Jones Sound. We characterized physical water column properties, nutrient concentrations, and microbial community composition (16S rRNA gene amplicon sequencing). Our findings reveal geochemical characteristics that may be associated with a shift in microbial community structure and show that community composition significantly differs during periods of nutrient enrichment driven by glacial upwelling. These results will help to inform how glacial retreated may have shaped the microbial biosphere during late-stage Snowball Earth deglaciation.

Modern Carbon Cycle Dynamics: Unraveling Petrographic OC cycling in Arctic Riverine and Marine Sediments

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The carbon cycle is driven by interactions between the biosphere, atmosphere, hydrosphere, and geosphere. Photosynthetic organisms transform CO_2 into O_2 and organic carbon (OC), with the burial of OC in sediments influencing atmospheric composition over time. [1] When buried OC is re-exposed to weathering as petrographic OC, the rate and extent of its oxidation are influenced by various factors, including atmospheric O_2 concentration. Thus, declining O_2 levels may lead to greater accumulation of unweathered petrographic OC in marine sediments, suggesting that OC recycling could serve as a proxy for reconstructing past atmospheric O_2 levels [2]. However, in modern times, it has been demonstrated that much petrographic OC can escape oxidation to be redeposited into marine sediments after being weathered [3], even under today's high atmospheric oxygen levels. However, quantifying petrographic OC recycling into modern sediments, and distinguishing it from recently formed OC, is challenging. This project uses Raman spectroscopy to investigate the oxidation and recycling efficiency of petrographic OC from rocks to rivers and into marine sediments. Thus, we hope to help quantify the role of petrographic OC recycling in the modern carbon cycle.

The project first involves developing a method to isolate petrographic OC from rocks and modern river and marine sediments. This process includes several key steps: decarbonation, density separation, and microwave-assisted digestion using hydrofluoric acid. Subsequently, the ...

… concentrations of petrographic OC can be quantified, and its maturity can be analysed by Raman spectroscopy with minimal thermal alteration [4].

This method is used to explore the recycling of petrographic OC from outcrop rocks, to riverbeds and to fjord sediments in Svalbard. Our Raman data is supplemented with ^{14}C dating to compare alternative methods for exploring petrographic OC recycling.

This approach offers key insights into the carbon cycle in the past and present, while also enhancing the accuracy of climate change models.

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Preserving Winter Subglacial Signatures: DOM and Microbial Communities in Greenland Naled Ice with Implications for Habitability on Mars

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Ice deposits at the polar caps and mid-latitudes of Mars lack widespread basal melting today (Arnold et al., 2019). However, radar measurements, putative warm-based glacial landforms, and high-resolution morphological analyses suggest that some deposits may have once supported subglacial water flow, similar to warm-based glaciers on Earth (e.g., Butcher *et al.,* 2022; Gallagher *et al.*, 2021; Grau Galofre *et al.*, 2022). Without an orbit-stabilizing moon, the obliquity of Mars can shift between < 10° and > 45°, potentially driving rapid glacier melt (e.g., Holo *et al.*, 2018). If liquid water existed, subglacial environments could have sheltered microbial life (Cockell *et al.*, 2014). While current Mars missions will not access subglacial areas, Greenland Ice Sheet (GrIS) glaciers may offer insight into early Martian habitability under glaciated, accelerated-melt climate scenarios (e.g., Fastook & Head, 2015).

Microbial communities beneath GrIS outlet glaciers respond to seasonal changes in hydrology. During winter, slow-moving anoxic or hypoxic meltwater isolated from surface inputs favors anaerobic processes (Nienow *et al.*, 2017), including methane production from dissolved organic matter (DOM) breakdown. In contrast, summer melt introduces oxygen-rich surface meltwater to the glacier bed, supporting aerobic metabolisms and exporting microorganisms, gases, DOM, and other solutes downstream (e.g., Lamarche-Gagnon *et al.*, 2019; Kellerman *et al.*, 2021). Microbial communities and carbon cycling have been characterized during the summer melt season, while winter processes remain less understood. Naled ice forms when subglacial water upwells and freezes in a glacier forefield. Here, we test whether naled ice captures an overwintering signature of subglacial biogeochemical cycling by comparing microbial community composition and predominant DOM signatures in naled ice to those of meltwater from warmer months. …

... We sampled naled ice (winter), meltwater (spring/fall), and source endmembers in the forefield of Isunnguata Sermia, a western GrIS outlet glacier, over three years. We identified spatiotemporal differences in microbial community composition and both the composition and concentration of dissolved organic carbon (DOC and DOM). We also observed depth-dependent differences in DOM characteristics from naled ice. Ongoing work will use metagenomics, qPCR, and Fourier-transform ion cyclotron resonance mass spectrometry (FT-ICR MS) to compare functional potential and molecular DOM composition across space and time in our dataset. Results will reveal whether naled ice deposits preserve subglacial winter conditions and improve our understanding of seasonal biogeochemical cycling beneath GrIS glaciers, possible microbial impacts on downstream nutrient flux, and the potential for subglacial life under warm-based glacial conditions hypothesized for early Mars.

Castle Room

Middle Age Earth: Ocean Chemistry and Evolution in the Boring Billion

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The Mid Proterozoic (1,800–800 Ma), often dubbed the "Boring Billion," is traditionally viewed as a time of tectonic, climatic, and evolutionary stasis. However, emerging evidence suggests this interval was far more dynamic than previously appreciated, particularly regarding the early evolution and diversification of eukaryotic life. Despite this, the drivers of evolutionary change during this time remain poorly constrained, largely due to the challenges of reconstructing ancient ocean chemistry from altered sedimentary records.

Our project, Middle Age Earth, seeks to uncover how changes in the availability of nutrients and bio-essential trace metals in the Mid Proterozoic oceans influenced early eukaryotic evolution. We aim to generate high-resolution geochemical and palaeontological datasets from key sedimentary archives that span this critical interval. Specifically, we will: (1) evaluate the impact of diagenesis on the chemical integrity of Mid Proterozoic shales and carbonates and refine the chronology of these records; (2) reconstruct the temporal evolution of key nutrient and trace metal concentrations; and (3) characterise the nature and diversity of contemporaneous ecosystems, linking geochemical changes to evolutionary innovations.

To achieve these goals, we will apply novel isotopic approaches—including in situ Rb-Sr dating of clay minerals in shales and combined Mg, Ca, and stable Sr isotopes in carbonates—to overcome the effects of post-depositional alteration. These geochemical data will be integrated with fossil evidence, including both macrofossils and microfossils, from the same stratigraphic sections, allowing us to directly correlate environmental and evolutionary change.

Our study will focus on well-preserved and well-dated sequences from the Belt-Purcell Supergroup (Canada/USA) and the McArthur Group (Australia), which provide exceptional coverage of the period between 1.64 and 1.38 Ga. By combining innovative geochemical proxies with palaeontological ...

... insights, this project will deliver a refined understanding of Mid Proterozoic ocean chemistry and its role in shaping the trajectory of life on Earth. In doing so, it challenges the notion of the "Boring Billion" and highlights a pivotal chapter in Earth's evolutionary history.

A Paleontological Perspective on the Early Evolution of Eukaryotes

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The fossil record provides the only direct evidence for us to assess the diversity and evolutionary dynamics of early eukaryotes. In this presentation, I will summarize recent advances in the study of eukaryotic fossils from the Proterozoic eon (2500–539 million years ago, Ma), with a focus on the evolution of eukaryote diversity and the origins of major eukaryote clades. Eukaryotes first appeared in the fossil record in the Paleoproterozoic, concurrently with or shortly after the ~2400–2300 Ma Great Oxidation Event. For much of the Mesoproterozoic (1600–1000 Ma) and early Neoproterozoic (1000–720 Ma), the diversity of eukaryotes increased slowly and remained at a relatively low level; this period roughly corresponds to the Boring Billion, – a geological period characterized by relative quiescence in geodynamics, indicating long-term equilibrium of the Earth-life system. However, it is during the Boring Billion when crown-group eukaryotes first appeared in the fossil record and major eukaryote groups diverged, including the Archaeplastida (e.g., Rhodophyta and Viridiplantae), Opisthokonta (e.g., Fungi), SAR or Harosa (Rhizaria and possibly Stramenopila), and Amoebozoa. Despite their early divergences, these eukaryotes apparently did not leave a large ecological footprint in the Mesoproterozoic Earth-life system. The Cryogenian Period (720–635 Ma) following the Boring Billion served as a major divide in eukaryote evolution. After Cryogenian snowball Earth events, eukaryote diversity rose rapidly and featured major diversification and extinction events in the Ediacaran Period (635–639 Ma). It is during the Ediacaran Period when animals diverged and diversified, along with the quick rise and fall of several morphologically distinct groups of unicellular and multicellular eukaryotic groups. The currently available and emerging data from paleontology, phylogenomics, and geochemistry allow us to establish a holistic understanding of the interaction between life and Earth during the Proterozoic eon, – a formative age in the history of our planet.

The Precambrian microfossil record: a lens for understanding the ancient biosphere through time and space

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Quantifying macroevolutionary patterns using fossil data has enabled scientists to untangle the complex interplay between biological innovation, origination and extinction rates, ecosystem structure, and the dynamic transformations of Earth's atmosphere, oceans, and land across deep time. Yet, despite Earth's rich and dynamic history, the scarcity and often poor preservation of the ...

… Precambrian (>538 Ma) fossil record—the most tangible evidence of early life—pose major challenges for palaeobiologists seeking to reconstruct the earliest evolutionary trajectories. Building on the influential work of Sepkoski, who identified the 'Big Five' mass extinction events of the Phanerozoic through the marine invertebrate fossil record, researchers since the early 1980s have worked to reconstruct the diversity dynamics of Precambrian life. Broad trends emerging from these efforts suggest a Paleoproterozoic origin of eukaryotes, a prolonged period of 'stability' during the Mesoproterozoic, and a dynamic Neoproterozoic, during which the biosphere experienced major upheavals alongside transformative environmental events such as global oxygenation and 'Snowball Earth' glaciations. However, most previous studies have focused almost exclusively on the eukaryotic fossil record, leaving the relationship between prokaryotes and eukaryotes comparatively unexplored. Here, we present results from a comprehensive new database, compiling over 2,000 occurrences of both eukaryotic and prokaryotic microfossils reported in the literature between 2.0 and 0.54 Ga. Using this dataset, we investigate patterns of microbial community composition across deep time, while considering the effects of preservation, depositional environment, and paleogeography.

New microfossil eukaryotes from the Tonian Little Dal Group, northwestern Canada

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The early Tonian Period was a key interval for the proliferation and diversification of eukaryotes. Molecular clocks predict the emergence of major eukaryotic clades by 1000 million years ago (Ma), and cholestane biomarkers document the rise of red algae as primary producers. However, the microfossil record between ~900–850 Ma is limited. The ~890-million-year-old Little Dal Group, a ~2.5-kilometre-thick low-grade succession of mixed carbonate, siliciclastic and evaporitic strata exposed in the Mackenzie Mountains, Canada, provides an excellent target for recovering new microfossils that will address this gap in our knowledge. Recent studies of Little Dal reef-forming carbonates have focused on vermiform microstructures that workers interpret as the fossilised tissue of keratose sponges. Here, we focus on the Little Dal shales, which remain understudied despite previous reconnaissance level studies yielding well-preserved microfossils. We report preliminary results from new, high-resolution sampling of these shales, documenting a diversity of exceptionally preserved microfossils. These include: (i) cells arranged in large discoidal clusters ~400 μm in maximum dimension that resemble material from the Tonian Wynniatt Formation, Canada, (ii) irregular clusters of unornamented spheroids, likely *Synsphaeridium* and *Symplassosphaeridium*, (iii) banded filamentous forms akin to *Oscillatoriopsis*, (iv) sheathed fossils assigned to *Palaeolyngbya*, and (v) multicellular forms, likely *Palaeastrum* and *Ostiana*. These initial discoveries demonstrate the potential of Little Dal shales to provide new fossil evidence for the diversification of eukaryotes. Ongoing detailed characterisation of the palaeoenvironments and geochemistry of fossiliferous Little Dal strata will provide vital context to these discoveries, helping to discern how the evolution of eukaryotic and microbial communities was influenced by environmental gradients (e.g., redox or nutrient availability).

Stratigraphy and preservational variation of a Tonian thrombolite reef (Fifteenmile Group, Yukon Territory) and implications for the under-recognition of ancient thrombolites

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Stromatolites – laminated organosedimentary structures – have a rich documented history throughout the Precambrian and provide some of the earliest evidence of life on Earth. Trends in stromatolite morphology and abundance have been extensively studied, providing insights into depositional environments, carbonate chemistry and marine ecosystems in deep time. However, stromatolites represent only one endmember of the range of microbialite morphologies found in modern and ancient environments, and comparatively little attention has been paid to their unlaminated counterparts. For example, thrombolites, defined by their clotted mesostructure, have a sparse Precambrian record. Temporal trends in thrombolite morphology, abundance, and environmental context are therefore poorly understood, although it has been suggested that the Tonian Period (1000 – ca. 720 Ma) marks a critical transition in microbialite reef construction. The first substantial thrombolite reef systems are found in the mid-Tonian Little Dal Group of the Northwest Territories, Canada, followed by similar framework-constructing microbialite reefs from the interglacial Cryogenian and the Ediacaran. Currently, this small number of case studies inhibits our understanding of this transition in reef architecture.

Here, we present our work on the ca. 850–800 Ma Reefal assemblage in the Ogilvie Mountains in Yukon Territory, Canada. We find that this unit comprises a substantial, prograding platformal reef system, with alternating laminated and unlaminated microbialite building up on areas of uplifted paleotopography. Recrystallization and silicification heavily obscure primary growth features in most platformal reef settings, but we identify a three-part preservational sequence in outcrop and in petrographic thin section, demonstrating that the reef is constructed by thrombolite with strong similarities to the approximately co-eval Little Dal Group.

Notably, ~75% of unlaminated microbialite in our study area (by stratigraphic height) is preserved as massive dolostone, which would be unrecognisable as microbialite – much less thrombolite – without stratigraphic context and a complete preservational sequence. In petrographic section, stromatolites have similar crystal sizes and silicification as these massive dolostones, but they retain their primary lamination, suggesting that late-stage dolomitization and recrystallization preferentially overprint thrombolite textures in the Reefal assemblage. We propose that our case study may reflect a wider preservational bias in favour of stromatolites over thrombolites, and that the sparse documented record of thrombolites in the Precambrian may be at least partly attributable to preservation rather than absence.

Endolithic Microboring as a Micritizing Force and Early Diagenetic Step in Microbialites

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Microbialites serve as macroscopic manifestations of ancient microbial life and are recognizable as trace fossils by their textures, often composed of micritic $CaCO_3$. Despite the importance of a microbialite's texture in diagnosing its biogenicity, the role of microbes in forming texture is poorly understood. We used fluorescently labelled embedded coring to study texture formation in Little Hot Creek (LHC), a geothermal complex in eastern California hosting lithifying incipient microbialites with a dendrolitic morphology similar to some Cambrian and Neoproterozoic microbialites. We found that the framework of the LHC microbialites initially precipitates in situ as spar calcite, whereas most ancient examples are composed of micrite. The spar also hosts prolific microboring by endolithic bacteria, which chemically and mechanically disrupt primary sparry fabric as microboring progresses, transforming the spar to micrite. Calcite crystals with high microboring density display tunnel intersections, entrances, and exits which divide the original crystal into smaller fragments <4 μm in diameter, satisfying the sedimentological definition of micrite. We hypothesize that ancient dendrolitic microbialites might have precipitated initially as spar and been micritized through endolithic microboring as an initial diagenetic step. To better describe microboring progression and calcite fabric alteration, we used plane polarized light micrographs of endolithic microboring in spar and greyscale pixel value thresholding in python to calculate percentage of microbored crystal area as a percentage of total crystal area. We used this dataset to create an "endolithic microboring intensity index," which uses total microbored area of a mineral in thin section and assigns it an index number between 1 (least microbored/sparitic) and 5 (most microbored/micritic). We then map index values back onto crystals in thin section photomosaics such that gradients of microboring intensity can be compared to depth within the microbialite, nature of microbial biofabric association, etc. Additionally, we show preliminary data from incubation experiments in both hot spring and marine environments where microbial communities were incubated with sterile calcite crystals (Iceland spar), then sampled over several weeks-months to constrain the timescales upon which microboring occurs. Our findings indicate that microboring may initiate days-weeks after minerals precipitate, and that it may be possible to achieve micritization within the short timescales that precede rapid lithification necessary for microbialite formation. In modern or ancient microbial carbonates in which authigenic $CaCO_3$ precipitation occurred, the presence of micrite may signal a micritizing biological force such as endolithic microboring. Thus, the presence of micrite in such structures could constitute a biosignature.

Buried alive: extracellular polymeric substances promote clay templating of live eukaryotic algae

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Understanding the fossil record of early eukaryotes is a crucial goal in evolutionary biology. Realizing this goal relies not only on exceptional fossil deposits ('Lagerstätten') that preserve entirely soft organisms with high fidelity, but also an understanding of the taphonomic pathways by which these fossils form. Clays are associated with a significant proportion of Proterozoic Lagerstätten and have been implicated in the preservation of organic-walled microfossils of early eukaryotes. Interpreting the roles of clays in exceptional preservation has a direct bearing on our interpretation of the early eukaryotic fossil record. Here, we perform a suite of experiments on modern algae using two clay substrates and controlling key environmental parameters to investigate the physical mechanisms by which clay minerals 'template' to organisms, as well as the timescales involved. Our experiments show that clay templating of the green alga Cladophora begins immediately in the presence of a clay mineral substrate, i.e., while the organism is alive. After 1 year, a cast-like clay crust forms around the alga. Our experiments illustrate that extracellular polymeric substances are the initial sites of clay templating, and that the extent and rate of clay templating is affected both by clay mineralogy and the amount of light. We propose a model involving a three-step process for clay-templating of Cladophora: cation adsorption, particle attachment, and authigenic growth. Our results provide new insights into the roles played by clay minerals in organic preservation, and hint at secular biases impacting the Proterozoic fossil record.

Mapping Silica Precipitation Patterns in *Rhodovulum iodosum* Extra Polymeric Substances

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The fossilization of bacterial cells and communities during the Proterozoic is a well-established phenomenon, with numerous studies highlighting the key role that extracellular polymeric substances (EPS) play in the biomineralization. For instance, microbial mats preserved in Precambrian cherts show evidence of early silicification, with fossilized remains of bacterial EPS embedded within silica deposits. EPS can act as preferential sites for silica precipitation through the ionization of biofunctional groups, facilitating the binding of environmental cations (Ca^{2+}, Mg^{2+}, Fe^{3+}). Dissolved silica (SiO_2) then precipitates onto these cation-rich zones, forming silica particles.

Despite extensive literature on biosilicification within EPS, it remains unclear whether silica precipitates uniformly or if preferential nucleation zones exist on bacterial surfaces during their silicification. This study thus aims to explore whether bacterial EPS impacts the distribution and pattern of silica precipitation. To investigate this, we cultured *Rhodovulum iodosum*, a photoferrotrophic marine bacterium that has been previously implicated in the precipitation of ...

… silica. *Rhodovulum iodosum* was grown in media with differing silica concentrations (0, 50, 100 ppm) that encompass both the estimated Proterozoic conditions (60 ppm) as well as more silica-rich environments, such as modern hot springs. Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) were used to observe silica precipitation patterns at different stages of growth, and Inductively Coupled Plasma (ICP) analysis quantified dissolved silica concentrations across conditions.

Previous work on the silicification of cyanobacterial EPS shows an even distribution of silica deposition, with some conditions leading to sparse clay deposition. In our study, *R. iodosum* has demonstrated a relatively slower growth and development of EPS in the presence of silica compared to cyanobacteria. This will allow for us to better constrain and visualize silica precipitation on the *R. iodosum* EPS. Overall, the results of this work will help to improve reconstructions of the Proterozoic silica cycle and, therefore, improve our understanding of contemporaneous ocean chemistry and the conditions promoting early fossilization.

Early Cambrian Doushantuo-type Microfossils from Mongolia: Implications for Calibrating Animal Molecular Clocks

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Doushantuo-Pertatataka-type acanthomorphic acritarchs and embryo-like microfossils are found globally in early Ediacaran rocks. Phosphorites within the Kheseen Formation, northern Mongolia, recently demonstrated to be earliest Cambrian (Terreneuvian, Fortunian) in age, have been reported to contain a moderately diverse microfossil assemblage. The Kheseen Biota is, therefore, one of the youngest Doushantuo-Pertatataka-type assemblages currently recognised. Here we report an expanded Kheseen Biota, including the acanthomorphic acritarch taxa *Appendisphaera grandis*, *A. tenuis*, *Asterocapsoides wenganensis*, *Knollisphaeridium maximum* and *Mengeosphaera reticulata* alongside potential new species of *Appendisphaera*, *Sinosphaera* and *Variomargosphaeridium*. The phosphorites also preserve additional species of the embryo-like taxon *Megasphaera*; *M. inornata* and *M. ornata* are identified within the assemblage. The Kheseen Formation shares multiple taxa, including *Megasphaera* and *Mengeosphaera*, with the early Ediacaran Weng'an Biota (South China), which is also similar in taphonomy and depositional setting. None of the microfossils recognised within the Kheseen Formation can be identified unambiguously as animals, in contrast to those identified from younger Cambrian phosphorites. The lack of definitive evidence of animals in this earliest Cambrian microbiota, when they were clearly present elsewhere, suggests that Weng'an does not provide a reliable early Ediacaran molecular clock calibration for their evolutionary absence. The Kheseen Formation assemblage demonstrates that a lack of animals in phosphatised microbiotas may be a result of taphonomy and/or ecology.

Tracking Climate Expression in the late Ediacaran Huns Shallow-Marine Platform

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The expression of climate in shallow-marine environments has been extensively documented in the Mesozoic, where warm periods favoured microbialite reef development and cooler intervals corresponded with increased siliciclastic input and lagoonal conditions. This study investigates whether similar climatic patterns can be detected much further back in time—within the late Ediacaran Huns Member of the Schwarzrand Subgroup (southern Namibia). Situated in the Witputs sub-basin, the Huns Member preserves a remarkably well-exposed carbonate platform that records a succession of high-frequency depositional sequences superimposed on a long-term transgression. These sequences offer a unique opportunity to explore how orbital-scale climate forcing may have influenced facies development during a critical interval in Earth history, just prior to the Cambrian explosion.

Using integrated field mapping, drone photogrammetry, and cyclostratigraphic analysis, we identify approximately ten fourth-order depositional sequences (H1–H10). The lower two sequences (H1–H2) are dominated by transgressive, siliciclastic-rich intervals. The middle sequences (H3–H6) are characterized by a transition into carbonate-rich units with transient thrombolitic reefs, occasional dolomitic marker beds, and increasing evidence of marine flooding. The uppermost sequences (H7–H10) represent a "catch-up" phase, marked by the development of subtidal laminated carbonate facies, punctuated by lagoonal shales and repeated exposure surfaces.

Preliminary age constraints from U-Pb zircon geochronology suggest that the cyclicity recorded in these sequences may correspond to short eccentricity (~100 kyr), comparable to patterns seen in the Jurassic and Cretaceous. The recurring shifts between siliciclastic- and carbonate-dominated systems, along with microbialite development and changes in water depth, appear to reflect climatic oscillations—likely in response to climate-modulated changes in sea level and sediment supply.

By tracing sequence architecture and associated facies shifts back to the Ediacaran, this study presents one of the earliest stratigraphic records of climate expression in a shallow-marine carbonate platform. It suggests that, much like in the Phanerozoic, orbital-scale climate processes exerted a fundamental control on sedimentation and ecosystem development in the latest Neoproterozoic.

Morphometric and spatial analyses of Charniodiscus from the Ediacaran of Newfoundland, Canada

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Ediacaran macrofossils (580-539 Ma) represent the earliest-known complex animals, revealing critical insight into the evolution of macroscopic life. This study examines *Charniodiscus*, an upright, sessile, frondose organism that is morphologically simpler than rangeomorphs, enabling the refinement of ...

… new quantitative techniques. One of the largest *Charniodiscus* populations occurs within the Main E Surface community in the UNESCO Mistaken Point Ecological Reserve, Newfoundland. This in situ population can be utilized to explore physical variation across specimens, as well as the spatial distributions of traits within a community. We generated a photogrammetric map of the main E Surface and obtained morphological traits by marking up the branching architecture of 116 *Charniodiscus* specimens. We used multivariate cluster techniques to identify different morphogroups and to constrain defining physical traits. We then used random labelling analyses to investigate how the spatial patterns of specific characteristics varied across the population, and to identify the spatial patterns of the different morphogroups identified. We find that traits showing distinctive spatial patterns and defined morphogroups are likely to be more ecologically significant than those which vary randomly. Therefore, this novel approach helps elucidate which morphological traits, or combinations of traits, are key drivers of Ediacaran evolutionary dynamics.

Microfossils from background mudstone of the Ediacaran Trepassey Formation at Mistaken Point Ecological Reserve, Newfoundland

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The abundant Ediacaran macrofossil impressions of Earth's earliest large and architecturally complex animals preserved at the Mistaken Point Ecological Reserve (575-562 Ma) represent early soft-bodied animals that were preserved when they were catastrophically cast by volcanic ash beds covering the living community (Conception-style preservation). Although multiple teams of researchers have well characterized the macrofossil assemblages at Mistaken Point and reliably dated key ashes, correlating these strata with global successions lacking the Avalon assemblage and volcanic ash remains challenging. To date, there has been limited exploration for microfossils in the Mistaken Point Ecological Reserve; acanthomorphic acritarch biostratigraphy has been proposed as a potential correlative tool in the Ediacaran. Therefore, our team conducted a preliminary palynological study in the Mistaken Point Ecological Reserve to improve global correlation between Ediacaran microfossil and macrofossil deposits. Eleven samples were collected from the Trepassey Formation at the Shingle Head locality and, thus far, two background mudstone samples have been processed using hydrofluoric acid maceration. These preliminary macerations uncovered a low abundance and a low diversity of simple spheres, filaments, and a potential tube. Notably, the simple sphere microfossils resemble those identified in the slightly younger Fermeuse Formation in Newfoundland, Canada, as reported by Hofmann *et al.*, (1979). The low abundance and diversity of microfossils may result from high sedimentation rates in the deep water turbidite-dominated environment, which dilute fossil concentrations. The absence of acanthomorphic acritarchs at the Mistaken Point Ecological Reserve could be due to an ecological bias related to the deep-water depositional environment rather than taphonomic bias. The newly identified microfossils from the Trepassey Formation have limited usefulness for global correlations due to their simple morphologies and, consequently, our inability to recognize biostratigraphically diagnostic taxa.

A unique snapshot of an Ediacaran microbialites assemblage from the Byng Formation (Neoproterozoic Miette Group, Alberta, Canada)

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Microbialites are key components of carbonate deposits and the most abundant fossilized life form in Precambrian rocks. These accretionary structures, including thrombolites and stromatolites, form as microbial mats trap sediments and induce mineral precipitation. This study characterizes an extensive shallow-water microbialite facies in the Byng Formation (Late Neoproterozoic, Miette Group) near Jasper, Alberta. The microbialites, densely packed and well-preserved, range from planar-wrinkly laminated to columnar and domal stromatolites. They occur within a biohermal facies overlying ~50 m of dolostone interbedded with carbonate–siliciclastic beds, some showing laminae and high-amplitude hummocky cross-stratification. SEM imaging reveals secondary Mg precipitation (dolomitization) and distinct Ca- and Si-rich mineral phases in stromatolites. The Byng Formation represents a high-energy carbonate ramp influenced by oscillatory processes, with localized low-energy conditions fostering microbial bioherms. Carbon and oxygen isotope data ($\delta^{13}C_{carb}$: -7.3‰ to -0.1‰; $\delta^{18}O_{carb}$: -18.6‰ to -4.3‰) suggest local microbial-driven authigenic carbonate precipitation and change in water source rather than a direct link to the global Ediacaran Ocean. This study provides new insights into the development of shallow-water carbonate ramp influenced by microbial activity during the Late Proterozoic Ediacaran Period.

Surviving the Depths: Metazoan resilience in sulfidic aquaria experiments

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The shallow seas of the latest-Neoproterozoic Ediacaran period are understood to have been mat-dominated environments prone to fluctuating oxygen (O_2) levels and high concentrations of hydrogen sulfide (H_2S), a well-known respiratory toxin for aerobic eukaryotes. Despite this, the metazoan clade is rooted in the Ediacaran, implying that early animals evolved strategies to survive in low-O_2, high- H_2S environments. Fossil evidence often documents a relationship between early animals in association with microbially induced sedimentary structures (MISS), and early animals may have exploited the photosynthetic O_2 and organic carbon produced by these mats as a means of survival. While some hypothesize that euxinia stifled early animal evolution or lead to extinction, the appearance of modern metazoan lineages during the Ediacaran suggests otherwise. Furthermore, modern examples of macrofaunal assemblages in environments with elevated H_2S concentrations demonstrate survival through physiological adaptations or behavioral strategies.

Here, we report observations from a saltwater aquarium housing a community of invertebrates alongside an epibenthic microbial mat. The aquarium was left undisturbed for the duration of the COVID-19 pandemic stay-at-home order (>12 months), allowing for the accumulation of high ...

... concentrations of H_2S. Remarkably, the invertebrate community did not collapse, offering valuable insights into how invertebrates respond to physiochemical stressors at both individual and community levels.

We also observed sustained disequilibrium between H_2S and O_2, exhibiting periodic out-of-phase cycles driven by a simulated solar cycle. During daylight, photosynthetic O_2 production increased, prompting more active behavior from the metazoan community. Conversely, H_2S production peaked during the dark cycle, causing a moribund animal community. Over time, overall community diversity declined, though macrofaunal abundance remained relatively stable. Polychaete worms and cnidarians demonstrated the most resilience to H_2S throughout the experiment, whereas other taxa declined and eventually perished. These findings challenge conventional expectations of metazoan tolerance to H_2S and underscore the significance of behavioral adaptations in withstanding high-sulfide environments. Our findings provide a valuable analog for understanding how primitive metazoans may have survived in sulfidic to euxinic Ediacaran seas.

Looking back to look forward: Characterizing diurnal microbial elemental cycling across a wetland to understand biogeochemical relationships in community composition

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Diversification of chemolithoautotrophic pathways during the Proterozoic Eon, instigated by increased levels of free oxygen, allowed for greater complexity in elemental cycling. Microbial mats provide modern-day insights into the impact of these diverse metabolisms, as they are reliant on the metabolic coupling between different microorganisms to cycle essential nutrients between mat layers and are typically organized according to energetically favourable metabolic pathways determined by redox conditions. A wetland located in a hydromagnesite-magnesite playa near Atlin, British Columbia offers an analogue to early Earth when phototrophic bacteria generated O_2 and dissolved inorganic carbon that supported a diverse range of metabolisms, sequestering atmospheric CO_2 in the process. This wetland was studied along a 12 m transect, where microbial community, mineral precipitates, and water chemistry were measured diurnally at the surface, the photosynthetic mats, and within the sediment. Resolving geochemistry with depth revealed the diurnal influence of microbes on their environment, specifically in terms of carbon and sulfur cycling. Conversely, geochemical constraints at each depth determine the diversity of the presiding microbial community. Daytime geochemical variation was primarily associated with sulfur cycling, while nocturnal variations were dominated by shifts in alkalinity, Mg^{2+}, and sulfide concentrations. Coupling of redox driven metabolic processes, through the enhanced production of terminal electron acceptors, likely influenced the atmospheric carbon and methane cycles that shaped early Earth. Metabolisms at this site were classified by key functional genes present in 16S sequencing data into biofunctional groups, including oxygenic photosynthetic bacteria, anoxygenic photosynthetic bacteria, aerobic heterotrophs, and sulfate-reducing bacteria. Bray-Curtis dissimilarities with Principal coordinates analysis indicated that chemolithoautotrophs (methanogens, nitrogen-oxidizing ...

... bacteria, and sulfur-oxidizing bacteria) were primary metabolic drivers in community variance across the wetland. This activity corresponded to an observed increase in stability of carbonate mineral phases with distance across the transect from a potential location of groundwater inflow, suggesting distance may serve as a proxy for time when considering the formation of the mat system. This snapshot into the fundamental microbial principles that drove global changes during the Proterozoic Eon not only provides an understanding of our past – these principles of microbial interconnection and elemental cycling can drive change in our future as we develop biogeochemical solutions to address current issues, such as CO_2 sequestration.

Assiniboine/Summit Room

Fossil abundance and diversity in the Middle Ordovician Table Point Formation, western Newfoundland: Insights into the Great Ordovician Biodiversification Event from eastern Laurentia

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The Great Ordovician Biodiversification Event (GOBE) marked a dramatic increase in marine faunal biodiversity and ecospace occupation during the Early Paleozoic. Here we report results from a high-resolution study of the Middle Ordovician Table Point and Table Cove formations of the Table Head Group in western Newfoundland, a succession which provides an exceptional window into seafloor diversity and carbonate factory evolution across a range of settings during this key interval. Our two-meter resolution sampling covers over 300 meters of section and captures the transition from the shallow marine Table Point Formation to the deeper-water Table Cove Formation. Thin sections were point counted for non-skeletal and skeletal grains, and fossils were identified to the highest taxonomic level possible. Common and abundant fossil components of the thin sections include sponges, gastropods, and echinoderms. Skeletal wackestone dominates the section, though fossil presence remains notable on both macroscopic and microscopic scales. Multiple meter-sized sponge bioherm mounds occurred around 110 meters above the base of the section, with a final large sponge biostromal unit capping the section from meter 206 to 236, just below the transition to the Table Cove. Our resulting dataset highlights a number of intriguing patterns: (1) The abundance of skeletal organisms varies through both the Table Point and Table Cove units rather than increasing monotonically and appears to be influenced by lithofacies and environmental variation, both within and between the distinct units. (2) The biostromal unit has some of the highest abundance of skeletal organisms in the entire Table Point section, including a prevalence of sponges, the putative calcareous alga *Nuia*, and *Halysis*, a problematic calcareous microfossil often described as a red coralline algae. (3) The enigmatic calcifier *Nuia* is most prevalent in the sponge biostromal unit and disappears above meter 302. (4) The Table Cove contains a lower abundance of skeletal organisms compared to the underlying uppermost Table Point Formation, likely reflecting a major deepening event. These findings represent a localized view of the ongoing global increase in biodiversity and abundance signals that have come to characterize the GOBE.

Bioturbation intensity as a control on organic carbon and reactive sulfur preservation in middle Paleozoic sediments

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Bioturbation plays an important role in regulating organic carbon and reduced sulfur preservation in marine sediments. In modern marine settings, bioturbation generally increases rates of decomposition, which decreases the size of the preserved sedimentary reactive organic carbon and sulfur pools. However, how organic carbon preservation in marine sediments is shaped by differences in bioturbation intensity (i.e., degree of disruption of sedimentary fabric) and style (i.e., biodiffusive sediment churning versus the flushing of burrow structures by bioirrigation) remains poorly constrained, and largely unquantified for previous intervals of Earth's history. Here we explore the nature of the relationship between bioturbation intensity and organic carbon and reduced sulfur burial using sedimentary drill cores from Devonian- and Carboniferous-aged strata in the Appalachian, Antler, Paradox, and Anadarko Basins recording oxygenated shallow marine settings. Paired, high-resolution sediment geochemistry measurements (total organic carbon (TOC), total sulfur (TS), and redox state proxies) and observations of bioturbation intensity and style indicate that highly bioturbated intervals are consistently characterized by low TOC and TS values. However, lightly to moderately bioturbated strata display a range of TOC and TS values also observed in unbioturbated sediments, suggesting that low to moderate intensities of sediment disruption may not have strongly impacted organic carbon and reactive sulfur burial in these basins. This more quantitative and mechanistic understanding of bioturbation-TOC-TS relationships provides critical context for reconstruction of the long-term evolution of the coupled global carbon, oxygen, and sulfur cycles, particularly for intervals like the middle Paleozoic, when bioturbation intensities were, on average, lower than the intensities of sediment-mixing observed in modern seafloor settings.

Bioturbation intensities and correlates in Cambrian–Ordovician strata of the Great Basin, USA

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The development of complex animal body plans, ecologies, and the expansion of biomineralization during the Cambrian Explosion and the subsequent Great Ordovician Biodiversification Event mark two of the most significant radiation events of the Phanerozoic. The trace fossil records—burrows, trackways, and trails, suggest that burrowing animals also experienced substantial radiations at this time. However, sedimentary archives record a more gradual expansion of sediment mixing behaviors. A range of studies have previously documented both regional and global patterns of protracted increases in sediment mixing intensities in Cambrian and Early Ordovician shallow marine settings. However, potential drivers for this pattern, and the extent to and frequency with which bioturbation varied across different lithofacies and depositional settings and how this impacted ocean biogeochemistry and seafloor ecology remain more poorly constrained. Herein, we showcase a new dataset (n = 1388 observations) of bioturbation intensities (e.g., ichnofabric index), logged at the ...

… decimeter scale, and associated lithofacies data from upper Cambrian through Middle Ordovician (i.e., ca. 500–460 million-year-old) strata from the western Laurentian paleocontinent. We performed statistical analyses to assess patterns in and potential correlates for changes in bioturbation through time, between facies and across depositional environments. These data highlight that bioturbation intensity varied substantially through this interval and as indicated by change point analyses did not unidirectionally increase over this interval. We find that bioturbation intensities are commonly higher in finer-grained carbonate facies. However, we observe regional differences in correlation between bioturbation and environmental settings. In the Arrow Canyon Range, we observe higher bioturbation intensities in muddy peritidal and shallow subtidal settings. These findings may reflect heightened preservation potential in muddy carbonate lithologies or, alternatively, organismal preferences for more oxygenated shallow ocean waters in the interval leading up to the expansion of ecospace of the Great Ordovician Biodiversification Event.

Impacts of Pleistocene Climate Change on Bioturbation at Willapa Bay, Washington

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Biological reworking and mixing of sediments (i.e., bioturbation) plays a key role in the decomposition of organic matter and the exchange of nutrients between seawater and marine sediments. Still, the effects of climate change on the behaviours and physiologies of bioturbating animals remain poorly understood. Experimental studies have focused on the short-term impacts of marine heat waves, but little is known about the effects of long-term warming or shifts in climate on animal-sediment interactions. To address these longstanding questions, we investigated Willapa Bay in western Washington (USA) as a “natural laboratory” for the study of bioturbation in warmer- and cooler-than-present climates in Earth’s recent past. We compare the style, intensity, and scale of bioturbation in modern intertidal sediments to bioturbation recorded in sedimentary strata that formed in this same region of coastline (and in a similar bay setting) during three previous interglacials. Preliminary findings suggest that intertidal flat deposits from the warmer-than-present Last Interglacial are often characterized by larger animal burrows relative to similar deposits from cooler interglacials. Moreover, a greater abundance of decapod crustacean burrows in modern and Last Interglacial sediments, in contrast to a higher proportion of bivalve traces in units from previous, cooler interglacials, highlights striking shifts through time and across climate states in dominant bioturbators. This work enhances our understanding of how changing global temperatures influenced coastal bioturbation in the Earth’s recent past and how rising temperatures may continue to shape bioturbation in the future.

Bioturbation shapes high-latitude marine biogeochemical cycling following the end-Permian mass extinction

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During the end-Permian mass extinction (EPME), a global decline in bioturbation provides critical evidence for the collapse of marine ecosystems, likely triggered by rapid ocean warming and deoxygenation. However, the decline and subsequent recovery of bioturbation after the EPME may not only have been a symptom of environmental change but also its driver, influencing nutrient exchange and reductant burial across the sediment-water interface and thus water column oxygen availability and seafloor habitability more broadly. Here we test this hypothesis through combined analyses of bioturbation and sediment geochemistry, focusing on shallow-marine siliciclastic records of the Permian–Triassic transition in Svalbard, Arctic Norway. We find that total organic carbon, total sulfur, and organic phosphorus decrease with increasing bioturbation intensity, whereas inorganic reactive phosphorus (authigenic and iron oxide-bound phases) increase. These differences are most strongly associated with biodiffusion (particle mixing) rather than bioirrigation (solute exchange). Our findings suggest that bioturbation primarily influenced sediment chemistry within these settings by enhancing organic matter oxidation, in contrast to some modern settings where downward mixing may promote organic matter preservation within the anoxic portion of the sediment pile. The early return of shallow tier bioturbators in Svalbard <200 kyr after the EPME likely promoted a rapid restoration of efficient carbon and sulfur cycling within benthic ecosystems. In contrast, efficient phosphorus burial via sink-switching may not have resumed until deeper-tier bioturbators achieved pre-extinction levels of sediment mixing >1 Myr after the EPME. Our findings provide important context for understanding how future shifts in bioturbation in response to ocean warming may impact marine biogeochemical cycling and ecosystem health, particularly across high-latitude continental shelves.

Impact of Continental Greening on the Paleozoic Marine Biosphere from a Lipid Biomarker Perspective

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During the Paleozoic Era, the planet underwent significant environmental and ecological changes caused by a progressive continental greening due to the radiation of early land plants alongside a hypothesized rise in atmospheric and marine dissolved oxygen (O2) concentrations [1,2]. Prior to the Silurian Period, atmospheric O2 concentrations were low, but these rose to near-modern atmospheric concentrations by the Middle-Late Devonian [3]. Amidst this rise in oxygen concentrations, ...

... enhanced weathering and delivery to the oceans of terrestrial organic carbon and biologically essential nutrients may have transformed marine biogeochemical cycles and productivity [2,4]. Notably, however, the extent, timing and global influence of such a terrestrial chemical flux on biological productivity and ocean chemistry remains poorly constrained.

Lipid biomarker studies yield valuable and unique insights for identifying fundamental shifts in ancient ocean redox structure and marine biospheric evolution. A suite of thermally well-preserved Silurian-Devonian sedimentary rocks from the Cape Phillips and Bathurst Island formations, Nunavut (Canada), and from the McCann Hill Chert and Road River Formation, Alaska (USA) were collected for detailed lipid biomarker analysis. We are examining: i) the composition of ancient marine organic matter deposited on the northern margin of Laurentia to track secular changes in marine community structures, and ii) the magnitude of terrestrial organic carbon delivered to these local marine settings, which may, in turn, record changes in the relative and absolute abundances of organic matter inputs from early land plants (bryophytes and early tracheophytes). Early land plant contributions to ancient sedimentary organic matter can be assessed through comparison of the abundances of waxy n-alkanes (C23-C33), relative to marine-derived organic matter, and/or detection of a suite of aliphatic and aromatic plant terpenoids [5,6]. The expected Paleozoic preference for C29 steranes, sourced from green algae, was routinely found in samples recording open marine settings. However, some first-order secular variations in the sterane distributions were observed, including a Silurian-Devonian rise in the ubiquity of C30 steranes, specifically 24-n-propylcholestane (24-npc), a sterane indicator of marine pelagophytes [7] and their agal ancestors. Through this study, we can better constrain how the composition of paleotropical marine communities evolved through the Ordovician–Devonian transition, which will help to unravel the influence of progressive continental greening on nutrient delivery and the evolution of the Paleozoic marine biosphere.

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Carbon recycling rates on the Phanerozoic biosphere

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Land plants are a major contributor towards global terrestrial biomass which influences atmospheric carbon dioxide and oxygen levels however the amplitude of their contribution has fluctuated throughout the Phanerozoic; partly due to the evolution of various plant features and strategies. Here we present a coupled model to assess the importance of the evolution of roots and plant strategies (i.e., high net primary productivity and turnover of the lycophyte paleotropical trees) in the rise of ...

... the late Palaeozoic oxygen level. Along with the increase in biomass and weathering rates as plants complexify, the recycling of carbon trapped as 'living' biomass - a key strategy of the now extinct lycophyte trees - appears to be key in the large increase of oxygen levels and the formation of coal forests.

The paleobiology of Galeaspids from the Silurian-Devonian of China

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Galeaspids are an extinct group of jawless armored vertebrates (stem-gnathostomes) that thrived with about 100 species during the Silurian and Devonian periods, but only endemic in Silurian-Devonian strata of China and North Vietnam. As important members of early vertebrate faunas, galeaspids provide critical insights into vertebrate evolution, and bear important paleoecological, biostratigraphic and biopaleogeographic significance.

Although jawless, galeaspids show evidence of a nascent cranial structure that prefigures the development of jaws. Their internal anatomy, inferred through CT scanning and digital reconstructions, reveals complex endocranial features, including an independent hypophysial duct and separated paired nasal sacs, supporting the hypothesis that galeaspids are closely related to jawed vertebrates (gnathostomes). Recent studies also suggest that the evolution of paired fins and body segmentation in vertebrates may have roots in galeaspid anatomy, although this remains a subject of active debate.

Galeaspids lived a benthic life in the lagoon, beach, and submarine–deltaic to shallow shelf environments. They had developed at least three different kinds of lifestyles: semi-infaunal benthic (half buried), epibenthic, and suprabenthic (nek-tonic) habits to accommodate to differentiated ecological niches, and reached the peak of their diversity by the Pragian of the Early Devonian. Their widely distributed fossil records and advances in the systematic taxonomy make galeaspid fossil play a more and more important role in the biostratigraphic correlation of Silurian-Devonian Strata. A large number of galeaspids fossils have been found on the South China and Tarim Block, which has allowed a consideration of the close association between Tarim and South China at 438 mya.

In summary, galeaspids occupy a pivotal phylogenetic position in early vertebrate evolution. Their unique morphology, ecological adaptations, and well-preserved fossils provide invaluable data for reconstructing the transition from jawless to jawed vertebrates. Continued research into galeaspid paleobiology promises to shed further light on the evolutionary innovations that shaped the vertebrate body plan.

Origin of Ancient Phosphorites: Potential Roles of Alkalinity, Evaporation, and Hydrological Conditions

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The evolution of the phosphorus (P) cycle may have shaped ocean-atmosphere oxygen levels along with biospheric innovation across Earth's four-billion-year history. Reconstructing past marine P cycling is therefore critical, and often relies on an end-member sedimentary archive—phosphorites, rocks exceptionally rich in P. However, the origin of ancient phosphorites remains debated—specifically, whether their occurrences reflect changes in the global seawater nutrient inventory or are instead tied to local depositional conditions. To shed light on this question, we focus on the Permian Phosphoria Formation, a P-rich shale sequence deposited in a subtropical epicontinental sea along western Pangaea. While previous models attribute the extensive phosphogenesis to upwelling as in modern analogs, our data—specifically the low concentrations of redox-sensitive trace elements even within anoxic intervals—suggest that these environments were instead (semi)-restricted. Interestingly, we find exceptionally high $\delta^{15}N$ values (> 15‰) from both the bulk sediments and associated kerogen. These signatures may result from NH_3 volatilization in a redox-stratified, NH_4^+-enriched water column, which can imply a unique local water mass chemistry with elevated pH and alkalinity. Elevated salinity, as indicated by the presence of evaporative minerals and previously reported gammacerane, might have inhibited nitrification and thus facilitated the accumulation of NH_4^+ that enabled NH_3 loss.

Given that the P-rich intervals correspond to marine transgressions, we propose that incursions of seawater from the open ocean might have replenished phosphate into the basin, despite its semi-restricted nature. Alkaline conditions could have promoted phosphate accumulation in the water column, which would be further enhanced by strong evaporation. Notably, the P-rich sediments exhibit pronounced negative cerium anomalies together with low concentrations of total organic carbon (TOC), both indicating deposition under oxic conditions. In contrast, sediments lacking P enrichment show elevated TOC, suggesting anoxic deposition. Based on these patterns, we propose a two-phase, P–redox cycle: during phases of P accumulation in the water column, the resulting elevation in primary productivity would drive marine anoxia and enhanced TOC burial. As organic-bound P settled and was buried, productivity would have declined, leading to a more ventilated water column. Meanwhile, P bound to previously buried organic matter could have been recycled and reprecipitated as apatite, forming phosphorites. This model helps explain the episodic nature of P enrichments observed in our sediments. Taken together, our study emphasizes the potential roles of alkalinity, evaporation, and basin restriction in driving phosphogenesis within and possibly beyond the Phosphoria Formation.

Unsteady gypsum cycling may decouple ocean and atmosphere carbon reservoirs

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The ocean-atmosphere carbon system is stabilized by the silicate weathering feedback and by homeostasis of the saturation state of marine $CaCO_3$. However, imbalances between gypsum weathering and burial, i.e. unsteady gypsum cycling, may drive changes in the ocean-atmosphere carbon reservoirs by changing [Ca^{2+}] with no direct effect on alkalinity. These changes could be geologically rapid given the episodic nature of gypsum deposition and weathering through Earth history. Here we develop an ocean-atmosphere box model to investigate the influence of unsteady gypsum cycling on the ocean-atmosphere carbon reservoirs. Model results indicate that unsteady gypsum cycling can induce changes in ocean pH, alkalinity, and dissolved inorganic carbon (DIC) with relatively minimal effects on atmospheric pCO_2. The size of the perturbation to the oceanic carbon reservoir is primarily a function of the relative change in oceanic [Ca^{2+}], while the timescale of the ocean's return to baseline depends on the degree to which background gypsum burial responds to changes in the Ca^{2+}-SO_4^{2-} ion product. A system responsive to this ion product restabilizes over the timescale of sulfate's residence time in the ocean (~10 Myr), while a system responsive only to tectonic forcing effectively shifts to a new steady state until an equal and opposite gypsum flux is applied. Monte Carlo simulations across a range of Phanerozoic boundary conditions indicate that a doubling or halving of [Ca^{2+}] via this mechanism roughly doubles or halves deep-sea [H^+], respectively. The same doubling or halving of [Ca^{2+}] respectively decreases alkalinity by ~30% or increases it by ~35%, with similar changes seen in DIC. Thus, unsteady gypsum cycling may drive changes in ocean pH and in the size of the oceanic carbon reservoir independently of the atmospheric carbon reservoir. This mechanism could complicate the conversion of pH proxy data to pCO_2 values from intervals of rapid weathering or burial of gypsum. More broadly, the effects of unsteady gypsum cycling on pH may be relevant to interpretations of marine isotopic records and to changes in nutrient speciation in deep time.

Mapping strontium in modern Shark Bay stromatolites: A biogeochemical window into these historic organosedimentary structures

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Stromatolites found in Shark Bay, Australia provide modern day analogues for their ancient counterparts that have persisted on Earth since the Archean. These organosedimentary structures are classical examples of shallow marine biogeochemistry, forming through a combination of microbial mat growth, sediment trapping and binding, and carbonate cement precipitation. In this study, the structure and chemistry of a fully preserved, resin-embedded subtidal stromatolite from Hamelin Pool is characterized using electron and X-ray microscopy and spectroscopy. The ...

... stromatolite sample consisted of a cemented internal column overlain by a 5–7 mm thick external layer. The external layer, interpreted to be the remnants of the cyanobacteria microbial mat, consisted of copious 'empty' space that would have been occupied by hydrated microbial exopolymer while in the subtidal growth environment. Microbial exopolymer would have played a key role in trapping and binding detrital grains during sedimentation and accretion. The internal lithified column was composed primarily of aragonite ($CaCO_3$) cement. Synchrotron based X-ray fluorescence microscopy (XFM) revealed the cement to be enriched in strontium compared to collocated detrital grains. XFM mapping revealed a clear structural and chemical boundary between the internal and external portions of the stromatolite. The depth of this interface below the structure's surface corresponds with what was likely the location of maximum sulfate reducing bacteria activity, just below the cyanobacteria mat layer. This result suggests that this anaerobic metabolism played a key role in cementation. The identified interface marks a biogeochemical boundary delineating the transition from net carbonate precipitation in the internal column, to net carbonate dissolution in the external layer. The presented findings highlight that mapping the chemical composition of stromatolite cements can reveal details about their internal architecture, and provide insights into the past and present growth of these iconic structures.

Microbial Mats as Time Capsules: Lessons from Modern Hydrothermal Systems

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Shallow-water hydrothermal vents (SWHVs) offer a unique window into microbial life shaped by dynamic environmental forces. At the interface of reduced hydrothermal fluids and oxidized seawater, diverse microbial mats thrive. Due to their shallow depths and coastal proximity, these systems are strongly influenced by episodic disturbances such as storms and tides, providing a real-time model of environmental change and microbial resilience.

While SWHV microbial communities have been studied extensively, their responses to sudden environmental shifts remain underexplored. In this study, we investigated white microbial mats from the sulfide-rich vents of Paleochori Bay, Milos Island (Greece), using a combined approach of 16S rRNA sequencing, transcriptomics, and metagenomics. Our results show that storm events and hydrodynamic forcing lead to rapid microbial community restructuring and succession—highlighting the role of disturbance in shaping both taxonomic and functional diversity.

Dominated by chemolithoautotrophic Campylobacterota and rich in viral signatures and mobile genetic elements, these mats reveal strategies for adaptation and ecosystem rebuilding following disruption. The interactions between microbial communities and the benthic boundary layer suggest that physical processes are key drivers of microbial spatial dynamics.

By studying how modern mats respond to disturbance, we gain insights into how microbial ...

… ecosystems may have recovered from global perturbations. This work provides a framework for considering how microbial communities might respond to environmental change, both today and in Earth's past.

Connecting Microbial Communities to Deep Earth Processes

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Convergent margins are the main conduits transferring material between Earth's surface and deep subsurface. Subducting plates at these margins bring carbon from the surface to earth's interior and geothermal processes subsequently bring volatiles—including carbon—back to the surface. In conjunction, the subsurface is one of the largest chemolithoautotrophic ecosystems on earth. These chemolithoautotrophic microbial communities have the ability to fix CO_2 and may play a critical role in the subsurface carbon cycle: analogous to photosynthesizing organisms influencing the atmosphere. Despite both of these processes' effects on earth's carbon cycle, very little is known about the connection of these subsurface microbial communities to geological processes. Previous studies have given light to this connection, showing shifts in microbial community composition along a convergent margin in Costa Rica. This study takes this work a step further by investigating this connection in the Southern Convergent Zone (SCZ) of the Andean Convergent Margin (ACM) in Chile. Samples were collected from natural seeps and springs across the ACM. These seeps act like windows into the subsurface. By collecting material coming up to the surface—and using mantle gas ratios to deconvolute surface vs. subsurface fluid—we acquired a sample of the subsurface microbial communities residing there. Furthermore, using bioinformatics, we will determine what organisms make up these communities, how these communities vary with geochemical parameters, and what metabolisms they are capable of carrying out: providing a greater understanding of their interrelatedness to deep earth processes and earth's carbon cycle.

Potential-Correlated Enrichment Identifies Candidate Electroactive Bacteria in a Meromictic Lake Using a Multi-Level Electrode Array

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Electroactive bacteria (EAB) are capable of transferring electrons to or from solid substrates via extracellular electron transfer (EET), playing essential roles in biogeochemical cycles and bioelectrochemical systems. These bacteria have been discovered in diverse environments, both natural and man-made. Anode-respiring bacteria (electrogens) typically inhabit anaerobic environments rich in organic matter, where they oxidize organic compounds with the reduction of Fe(III) or Mn(IV) oxides. In contrast, cathode-oxidizing bacteria (electrotrophs) have been found in oligotrophic environments, such as certain marine sediments and industrial settings, where electrons derived from cathodes are used to reduce inorganic compounds like nitrate, sulfate, and metals. …

… Although there have been no reports of EAB isolated from meromictic lakes to date, these environments offer thermodynamically favorable conditions for the isolation of both electrogenic and electrotrophic bacteria.

Here, we report the enrichment of candidate EAB on graphite electrodes deployed in Green Lake (Fayetteville, NY) using a multi-level electrode array (MLEA). The MLEA leveraged the stable redox potential of the euxinic monimolimnion as a reference "anchor" potential, enabling the maintenance of poised potentials (+0, +200, +400, +600, and +800 mV relative to the anchor electrode) using a self-contained, battery-powered circuit, without the need for potentiostat control. Arrays were deployed at three depths—10 m (mixolimnion), 20.5 m (redoxcline), and 35 m (monimolimnion)—and left in place for 30 days. After recovery, DNA was extracted from each electrode, and amplicon sequencing of the 16S rRNA V3–V4 region was performed to assess microbial community composition. Distinct assemblages of amplicon sequence variants (ASVs) were observed across both depth and electrode potential, including taxa previously identified as electroactive. Notably, the relative abundances of several taxa showed consistent positive or negative correlations with electrode potential, supporting the selective enrichment of electrogens and electrotrophs, respectively. These findings indicate meromictic lakes are promising natural laboratories for the discovery and enrichment of novel electroactive microorganisms.

Magnetoreception in an anaerobic ciliate via tripartite symbiosis

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Magnetotactic bacteria (MTB) use biomineralized, intracellular structures called magnetosomes as built-in compasses to navigate along Earth's magnetic field. Magnetosomes guide MTB toward optimal redox conditions along dissolved O_2 gradients. While magnetosensing has been well studied in MTB, recent findings indicate that this ability extends to microbial eukaryotes (protists) as well. Some protists exhibit magnetoreception, through predation or symbiosis with MTB, and it has been proposed that some protists can directly biomineralize magnetosomes. Here we report the discovery of a novel magnetic protist with endosymbiotic MTB and methanogens. Through a combination of light and electron microscopy, we observed that this holobiont possesses bullet-shaped magnetosome crystals and responds to magnetic fields. 18S rRNA gene phylogenetic analyses revealed that the protist is a ciliate from the novel family Tropidoatractidae and transcriptomes show that it expresses an Fe-Fe hydrogenosomal hydrogenase gene - indicating an anaerobic lifestyle and H_2 production through fermentative hydrogenosomes. Transcriptomes of the magnetic holobiont revealed the *mamA* gene, which is expressed in magnetosome formation, as well as *dsrA*, which is closely associated with magnetotactic sulfate-reducing bacteria (*Desulfobacteria*). Expression of the methyl-coenzyme M reductase gene (mcrA) involved in methanogenesis from the magnetic holobiont were derived from endosymbiotic H_2-oxidizing methanogenic archaea (*Methanoregula*). These results indicate that a bacterial endosymbiont produces the magnetosomes inside the …

... ciliate, and reduces sulfate using molecular hydrogen produced by hydrogenosome-like organelles of the eukaryote host. A second archaeal symbiont also appears to use the host derived hydrogenosomal H_2 for methanogenesis. A time-calibrated phylogenetic analysis suggests that the lineage leading to the ciliate host emerged at ~172 Ma, about 10 Ma after the Pliensbachian–Toarcian extinction event marked by widespread anoxia. The evolution of magnetoreception in the holobiont may have been shaped by this event. Overall, these findings expand the diversity of magnetotactic microbes to include anaerobic ciliates, suggesting that magnetotaxis in eukaryotes may be wider distributed than previously thought.

Changing organic matter variability and sulfur isotope signals: implications for Earth history

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Microbial sulfate reduction is the dominant reaction that affects the sulfur isotope composition ($\delta^{34}S$) of sedimentary sulfide, one of our longest-lived geochemical records preserving information about past sulfur, carbon, and oxygen cycling. In the sulfate-replete oceans that have dominated over the last ~600 Myr, organic matter speciation is the primary environmental factor influencing the magnitude of sulfur isotope fractionations ($^{34}\varepsilon MSR$) between sulfate and sulfide. Here we investigate how the release of labile substrates during organic matter degradation impacts sulfate reduction rates and sulfur isotope fractionations.

We used sediment slurries from Tuckerton Marsh, NJ to enrich natural sulfate-reducing communities on a variety of carbon sources. Enrichments grown on cyanobacterial and eukaryotic biomass exhibit similar sulfide accumulation rates and $^{34}\varepsilon MSR$ magnitudes despite preliminary chromatography indicating different distributions of important organic degradation products. These results indicate that changing organic carbon delivery may not be sufficient to explain major excursions in the sedimentary sulfide $\delta^{34}S$ record. Enrichments on simple carbon sources reveal vastly different sulfate consumption rates. Additionally, a porewater sulfide $\delta^{34}S$ profile implies stronger $^{34}\varepsilon MSR$ magnitudes in deeper, peat-rich sediment relative to the peat-poor overlying sediment, implying that differences in $\delta^{34}S$ patterns may be due to the presence of organic matter from plants. Sediment incubations reveal slower sulfate-reduction rates in the deeper peat-rich sediment, implying that the important organic substrates deeper may be associated with slower sulfate reduction rates. These results provide important constraints on the microbial processes in sediment that link variations in organic carbon availability to environmental change in the past.

Deciphering the geobiological formation of isotopically superheavy pyrites in the modern to understand their environmental relevance in oceans past

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Based on the current understanding of the mechanisms underlying sulfur isotope fractionation, a major biogeochemical tenet in both ancient and modern marine sediments is that the sulfur isotope ($\delta^{34}S$) signature of seawater sulfate ($\delta^{34}S_{SO4}$) is always larger than or equal to that of contemporaneous pyrite ($\delta^{34}S_{pyrite}$). However, throughout Earth's $\delta^{34}S$ record, there are isolated time intervals when $\delta^{34}S_{pyrite}$ values appear to be larger than coeval $\delta^{34}S_{SO4}$ values. These pyrites with "superheavy" $\delta^{34}S$ values seem to co-occur with major evolutionary transitions and extinction events in the past. It is unclear what causes these ancient deviations from the $\delta^{34}S$ paradigm, which hampers our ability to discern what environmental or ecological information that they may reflect. We used geochemistry and metagenomics to evaluate the major factors that promote the deposition of superheavy pyrites in the seasonally anoxic Chesapeake Bay. Our preliminary findings implicate iron speciation, sedimentation rates, and anaerobic methane oxidation as having possible connections to superheavy pyrite formation. The long-term goal of this ongoing work is to build an interpretative framework for the environmental signals encoded in ancient superheavy pyrites.

Castle Room

Exploring the impact of ecosystem engineers using evolutionary simulations

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Through modulating resource availability or modifying physical and biological aspects of the environment organisms can act as ecosystem engineers, providing feedback between life and the environment it inhabits. The introduction or removal of ecosystem engineers from stable ecosystems can impact co-occurring species, such as driving local extinctions or promoting biodiversity. While ecosystem engineering has been invoked as a driver for several major transitions in Earth history, such as the appearance of extensive bioturbation and faunal turnover during the Cambrian substrate revolution and the Great Oxygenation Event, the macroevolutionary impacts of such novel behaviours at their onset are less clear. If ecosystem engineers are frequently associated with turnover and extinction in deep time is not known. Here we investigate the general outcomes of phenotype-environment feedback by assigning lineages the ability to impact the fitness of co-occurring taxa in an eco-evolutionary simulation framework using TREvoSim 3.0. We explore numerous conditions, including the frequency of engineering behaviours (one-shot or pulsed), and whether ecosystem engineers modify existing niches or create new ones. While there is no general expected outcome from the introduction of ecosystem engineers, in a minority of runs, ecosystem engineering ...

… lineages completely dominate, rendering all others extinct. Our results suggest that ecosystem engineers have complex impacts, but possess the capacity to profoundly shape diversity, and it is appropriate to consider them alongside other exogenous extinction drivers in deep time.

Selection by differential survival among marine animals in the Phanerozoic

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The Gaia hypothesis posits that the Earth and its biosphere function as a single self-stabilizing system, but a key challenge is explaining how this could have arisen through Darwinian evolution. One theory is that of "selection by differential survival," in which a clade's extinction probability decreases with age as it accumulates adaptations resisting environmental disturbances. While this is hard to assess during early Earth history, we can assess whether this process operated among marine animal genera throughout the Phanerozoic. To that end, we analyzed time ranges of 36,117 extinct animal genera using fossil occurrence data from the Paleobiology Database in order to study marine metazoan extinction age selectivity, extinction rates, and speciation rates over the Phanerozoic. We identify four signatures of selection by differential survival: lower extinction rates among older lineages, heritability and taxonomically nested propagation of extinction resistance, reduced age selectivity during rare environmental perturbations, and differential extinction rather than speciation as the primary driver of the phenomenon. Evidence for this process at lower taxonomic levels also implies its possibility for life as a whole – indeed, the possibility of Gaia.

Bacteria-mineral interactions; a career in 3 min.

Gordon Southam*[1]

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Bacteria play an important role in catalysing a wide array of biogeochemical processes that affect the dissolution of minerals, the aqueous geochemistry of their surroundings and secondary mineral formation. Processes that take place at the bacteria-mineral interface, occurring in nanoenvironments and can extend to kilometre-scale when the active growth of bacteria is supported. In any bacterially influenced system, we need to focus on the scale of the bacteria themselves to appreciate the chemistry of their surroundings and the kinds of reactions they catalyse. The colonisation of mineral substrates depends on the physico-chemistry of the mineral surface, which will be influenced by the presence (or absence) of secondary mineral phases and on the ability of mineral substrates to support redox reactions, i.e., energy generating processes, and to provide nutrients. The use of minerals as substrates, lithotrophy, is typically considered to represent life in extreme environments.

These bacterial-mineral interactions are of industrial and environmental importance with biotechnology and mining making contributions to earth system science. The growth of iron and sulphur oxidising bacteria on metal sulphide minerals in outcrop and in mine tailings environments can contribute to the formation of acid mine drainage (catalysed by bad bacteria) or to copper …

... recovery via bioleaching (good bacteria) depending on our ability to control these ecosystems. Elemental gold is considered to be an inert element, i.e., it doesn't corrode, yet a biogeochemical cycle of gold exists, which contributes to mineral exploration programs and to the growth of gold nuggets. Mineral weathering of mafic and ultramafic materials releases divalent cations that contribute to mineral carbonation. This natural biogeochemical process can combat climate change / produce a carbon neutral mine. In addition to these secondary gold and carbonate cements, bacteria can make iron cements, canga, in Brazilian banded iron formation systems, enhancing geotechnical stability.

Lipid Biomarkers and Earth System Models Reveal Enhanced Ocean Methane Cycling During the early Phanerozoic

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By producing and consuming methane (CH_4), microbial ecosystems play a critical role in the Earth's carbon cycle and climate. In modern aquatic systems, the oxidation of methane is all most entirely facilitated through the process of anaerobic oxidation of methane (AOM) via microbial sulfate reduction (MSR) [1]. This raises the question of how the global methane cycle operated during the Ordovician and Silurian Periods, particularly under conditions of lower oxygen concentrations in the atmosphere and lower dissolved sulphate in the oceans [2,3]. Diminished dissolved oxidant availability in the oceans (i.e. oxygen and sulfate) may have altered how the global CH_4 cycle operated during this key time interval in Earth history.

To explore this, we extracted and analyzed lipid biomarker assemblages in a large suite of over 580 well-preserved sedimentary rocks from over 20 localities deposited in offshore environments. All study sites and analyzed samples have escaped significant thermal alteration as independently constrained from Rock-Eval pyrolysis. Rock extracts were analyzed for a suite of branched and polycyclic hydrocarbon biomarkers utilizing the sensitivity and selectivity of Metastable Reaction Monitoring-Gas Chromatography-Mass Spectrometry (MRM-GC-MS). Compound-specific stable carbon isotopic analyses of Ordovician-age hopanes using Gas Chromatography-Isotope Ratio Mass Spectrometry (GC-IRMS) were analyzed and compared with marine hopanes sourced from other Phanerozoic intervals.

Anomalously high relative and absolute abundances of lipid biomarkers derived from certain groups of methanotrophic bacteria and archaea suggest that strong and pervasive marine methane cycling was sustained in Ordovician and Silurian oceans, spanning at least 80 million years of geologic time. We consistently find elevated 3-methylhopane index values (3-20%, an order of magnitude above Phanerozoic baselines) for Ordovician, Silurian and Early to Middle Devonian successions from marine shelf environments. The high 3-methylhopane index values demonstrate no covariation with the lithofacies, mode of productivity (bacterial versus algal), or total organic carbon content of the host rocks analyzed. Additionally, compound-specific $\delta^{13}C$ ratios reveal significant ^{13}C-depletion of hopanes and acyclic isoprenoids in samples. Lastly, simulations with an Earth system model of intermediate complexity (cGENIE); configured under appropriate Paleozoic climatic, environmental and ...

… paleogeographical conditions, predict very high global average methane oxidation rates in the surface ocean compared with other intervals of Earth history.

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New insights into early vascular land plants as geobiological agents of phosphorus weathering

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The emergence of vascular land plants with deep rooting systems during the late Silurian and Early Devonian periods is suggested to be one of the most profound changes to the Earth system. Previous work has suggested that this evolutionary event ushered in prominent changes to marine biogeochemical cycling. This view arises from the fact that land plants with roots can increase both physical and chemical weathering rates. As weathering on land dictates nutrient and trace element transport to the oceans, vascular land plants may have modified ocean chemistry by impacting weathering. Because the nutrient phosphorus (P) is ultimately derived from the continents, the radiation of vascular land plants may have played an important role in altering P delivery to the ocean. However, P can enter the ocean as either unreactive detrital apatite, or as bioavailable dissolved P. Apatite dissolution can be enhanced by physical weathering from plant roots that increases mineral surface area, as well as by organic acids secreted from plant roots that lower soil pH. This study tests the hypothesis that early vascular plants increased bioavailable P delivery to the oceans through increased continental apatite weathering intensity during the Silurian-Devonian transition.

Here we present new P geochemistry data from a >700-meter succession of lower–middle Paleozoic marine shales from the Cape Phillips and Bathurst Island Formations from Bathurst Island, Nunavut, Canada. We highlight stratigraphic patterns contemporaneous with a shift from a baseline in the mid-upper Silurian, before vascular plants developed deeper rooting systems, to the Lower Devonian when vascular plants radiated. We report P speciation data and P/Al to track detrital apatite fluxes, as well as Chemical Index of Alteration data to constrain trends in chemical weathering intensity through this critical interval. Phosphorus speciation data in particular separates detrital and authigenic apatite, and brings new insights to the longstanding question of the extent to which the radiation of vascular land plants impacted continental nutrient fluxes or marine P cycling.

Lichen biogeochemistry in the Atacama Desert, Chile: Adaptation to the driest place on Earth

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Lichens are a diverse group of symbiotic organisms that colonize all biomes on Earth. They typically consist of at least one mycobiont and often multiple photobionts, such as cyanobacteria and/or green algae. Well-adapted to harsh environments, lichens frequently function as terrestrial pioneers, colonizing a variety of surfaces. Despite their widespread occurrence, there are still major knowledge gaps regarding how their formation depends on environmental conditions, as well as their survival strategies and interactions with surrounding substrates. Although their presence since the Neoproterozoic is highly likely, their contributions to early terrestrialization and biogeochemical cycles remain poorly understood. The overall desert biodiversity in connection to the surface evolution of the Atacama Desert over geological time scales is currently investigated as part of the Collaborative Research Centre (CRC 1211 - Evolution at the dry limit).

To improve our understanding of the ecological and geochemical functions of lichens in an extreme, early Earth-like environment, we investigated lichens growing on evaporitic crusts in the hyperarid core of the Atacama Desert. Lichens and other microbial communities appear to play a critical role as primary producers in this harsh environment, which is characterized by extremely low precipitation (<2 mm/year), intense UV radiation, and low nutrient availability.

For our initial study, three sites within the coastal mountain range (Coastal Cordillera), differing in aridity and salinity, were selected. Biogeochemical characterization was done using GC-MS and SEM-EDX. Sample preparation techniques and analytical protocols were optimized to enhance separation and resolution of substances allowing a better identification and quantification of the present lipids. Among a high ratio of unsaturated and saturated fatty acids as well as sterols, fatty acid profiles varied across the sites. Whereas methyl-branched C15:0 and C17:0 fatty acids predominated in samples in the north of the Atacama Desert (Pisagua region), reflecting a greater abundance of bacteria as symbionts, a higher diversity of unsaturated fatty acids dominated in lichens growing in the central part (Salar Grande region East), suggesting green algae and cyanobacteria acting as photobionts here. The lowest fatty acid diversity was observed in lichens growing directly in the Salar Grande valley which may be attributed to a reduced abundance of symbionts presumably due to the local hypersaline environment.

Carbon isotope fractionation by the fern-cyanobacteria symbiosis Azolla disentangles photosynthesis by host and symbiont

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The evolution of mitochondria and chloroplasts were major leaps in biologic complexity: eukaryogenesis and eukaryotic photosynthesis. Both of these organelles are descended from ancient bacteria that became obligate endosymbionts. Recently, it was proposed that an obligate endosymbiont nitrogen-fixing (diazotrophic) cyanobacteria, UCYN-A, has crossed the thresholds of ...

… integration with its host haptophyte alga, including *Braarudosphaera bigelowii*, to be considered an organelle ("nitroplast"), representing another leap in biologic complexity: eukaryotic nitrogen fixation. While there is no independently evolved mitochondrial analog, and there is only one independently evolved analog of chloroplasts (the chromatophore in the amoeba *Paulinella* spp.), there are at least four independent examples of diazotrophic cyanobacteria forming obligate symbioses with algae or plant hosts. These "diazo-cyanobionts", therefore, offer a unique opportunity to study the process of evolution from symbiont to organelle. Two diazo-cyanobionts have evolved to lose the ancestral cyanobacterial trait of photosynthetic carbon fixation, living heterotrophically on host-derived photosynthate, while two diazo-cyanobionts remain photosynthetic. One of the diazo-cyanobionts that remains photosynthetic is *Trichormus azollae*, which lives extracellularly in the leaves of Azolla ferns. Our recent comparative genomic investigation of molecular evolutionary signatures of natural selection revealed that strong purifying selection maintains photosynthesis in T. azollae. However, the ratio of photosynthesis by Azolla and *T. azollae* is uncertain. Here, we measure the rate of carbon fixation and the resultant isotopic fractionation of the unfixed CO_2 by the Azolla-*T. azollae* symbiosis and by Azolla that has had *T. azollae* removed. By varying CO_2, we leverage the relative sensitivity of C3 plants, and relative insensitivity of cyanobacteria, to changing concentrations of CO_2, in terms of carbon fixation rate and isotopic fractionation of CO_2 by carbon fixation, to determine the ratio of photosynthesis by Azolla and *T. azollae*.

Experimental Diagenesis of Soil Fossilizing in Tree Resin

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Because microbes do not often leave behind informative body fossils, identifying individual microbial taxa in the fossil record is a difficult task, entire communities or microbiomes even more so. For microbes, molecular fossils – cellular biochemical constituents preserved (but also chemically altered by diagenesis) in a range of geologic archives – can be our best set of clues to the biological past. Amber (fossil tree resin), is a geologically-durable archive that can preserve delicate biological structures, and potentially also biopolymers from microbial biomass trapped within. While sequenceable DNA is unlikely to be preserved in amber for long time periods, the preservation of proteins might be better due to isolation from many kinds of diagenetic alteration. Like DNA, proteins can preserve taxonomic and metabolic information, but proteins are more durable over geologic time in a variety of depositional contexts. However, the use of protein molecular fossils as recorders of microbial evolution and as environmental proxies is in its infancy. There is an outstanding need in the field for methods to discriminate truly ancient proteins from modern contamination, which hinges on a clearer molecular-level understanding of protein diagenesis in a wider array of preservational settings. In this project, we performed diagenetic experiments with soil in tree resin to understand protein diagenesis in fossil resins. In diagenetic experiments, the total number of identified peptides decreases over time, while the average length does not change. This suggests that diagenetic covalent modifications to the peptide structures could be making them unidentifiable, or cross-linking peptides to the resin matrix and inhibiting extraction.

Tracing Oxygen's Role in Early Animal Evolution: Non-traditional Isotope Insights from the Cambrian Wheeler Formation

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Reconstructions of Earth's oxygenation history during the Cambrian Period provide insight into the role of O_2 in early animal evolution. Many Cambrian oxygenation reconstructions are formed from sedimentary successions with no material evidence of animals. While there are benefits of this approach, it requires indirect and oftentimes imperfect correlations to fossil-bearing strata, complicating temporal animal-O_2 connections.

Here, we will present our ongoing efforts to reconstruct Cambrian ocean oxygenation levels from fossil-bearing shale of the <505 million year old Wheeler Formation from western Utah recovered from drill core DM-15-1. Wheeler Formation sediments were deposited on a distal, mixed siliciclastic-carbonate ramp in the House Range Embayment along the Laurentian margin. This formation hosts a well-studied soft-bodied ('Burgess Shale-Type') animal fauna and is an as-yet underutilized archive for paleoenvironmental reconstruction. Our ultimate goal is to generate a full suite of geochemical data for siliciclastic-dominated sedimentary rocks in the Wheeler Formation, including Fe speciation, redox-sensitive trace metals, light stable isotopes, and thallium (Tl) isotopes.

Geochemical data generated to date provide important paleoenvironmental information about Cambrian redox conditions. Iron speciation and trace element data used to constrain ancient local-scale redox conditions provide evidence of a weakly oxygenated to anoxic-euxinic environment. These local redox results provide novel information about the environmental conditions of Cambrian fauna habitation and fossil taphonomy. Evidence of generally reducing conditions bodes well for the application of stable Tl isotopes, a "paleoredox proxy" ideally applied to such environments and capable of providing information about ocean oxygenation beyond a local scale.

Calibrating stable Sr isotope proxy (d88/86Sr) in modern coastal marine system: A 'new tool' to constrain past oceanic carbonate cycling and seawater saturation state through time?

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Ocean water yields an integrated global signal of complex geological and biological processes operating on our planet, which in turn control oceanic elemental cycles, marine carbonate system (saturation state, pH, etc.) and thus the atmospheric CO_2 levels. Past changes in marine carbonate cycling and seawater $CaCO_3$ saturation state through time have been inferred by geochemical models, sedimentary rock record, and recently also by the stable Sr isotope ($d^{88/86}Sr$) variations documented in ancient marine carbonate archives [1].

To further test and validate the above application of the $d^{88/86}Sr$ proxy for palaeo-studies, we investigated or calibrated stable and radiogenic Sr isotope variations ($d^{88/86}Sr$ and $^{87}Sr/^{86}Sr$) in recent waters and carbonates from a coastal marine/lagoon system in South Australia, which is connected to the Southern Ocean, thus exhibiting large spatial and temporal gradients in water chemistry, ...

… including $CaCO_3$ saturation state. The measured parameters analysed in our system include water salinity, temperature, pH, alkalinity (DIC) and carbonate/$CaCO_3$ saturation state (calculated via PHREEQC), which were monitored seasonally throughout the year (in spring, summer, fall and winter), along with the $d^{88/86}Sr$ and $^{87}Sr/^{86}Sr$ isotope proxies. These time-series data allowed us to assess and calibrate the sensitivity of stable Sr isotope proxy to changes in key physico-chemical properties of the coastal/marine waters, which in turn has implications for palaeo-oceanographic studies, including possible reconstruction of past changes in $CaCO_3$ saturation state of seawater through time [2]. We will speculate how the $d^{88/86}Sr$ proxy could be applied to 'deep time' marine carbonate archives to reconstruct past changes in seawater saturation, marine carbonate chemistry, and the oceanic C and $CaCO_3$ cycling.

1. Wang J., *et al.* (2023) The evolution of the marine carbonate factory. *Nature*; 2. Farkas J., *et al.* (2025) Alkalinity and elemental cycles in present and past ocean: Insight from geochemical modelling and alkali and alkaline earth metal isotopes. *Treatise on Geochemistry, Third Edition*

Local and diagenetic constraints on the structure and interpretation of Early Triassic chemostratigraphic records

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The Early Triassic (252–247 Ma) reflects the prolonged scars of the end-Permian mass extinction, captured in depauperate marine communities, a persistent metazoan reef gap, and a record of unusual, anachronistic carbonate facies. Furthermore, it is characterized by substantial fluctuations in the geological carbon cycle, with $\delta^{13}C_{carb}$ values ranging from -5‰ to 8‰, among the most extreme instability recognized throughout the Phanerozoic. As conventionally interpreted, these unusually large and rapid excursions reflect changes in seawater $\delta^{13}C_{DIC}$ values, potentially linked to patterns of volcanogenic and thermogenic carbon release, organic carbon burial, methanogenesis, carbonate saturation state, seafloor anoxia, and/or authigenic carbonate precipitation. These varied interpretations fundamentally rely on the faithful preservation of $\delta^{13}C_{carb}$ values – or, more broadly, carbonate-bound geochemical records – that accurately reflect the chemical composition of global oceanic reservoirs. However, local variations in seawater chemistry and the ubiquity of early marine diagenesis in shallow-water carbonates may appreciably impact preserved carbonate geochemistry, often overprinting global and/or primary signals and obscuring inferred palaeoceanographic patterns. Here, we leverage a multi-proxy carbonate geochemical framework to decipher potential local and diagenetic constraints on $\delta^{13}C_{carb}$ records from the Great Bank of Guizhou of southern China, an iconic succession that forms the backbone of Early to Middle Triassic chemostratigraphy.

Consistent with previous studies, we observe facies-dependent $\delta^{13}C_{carb}$ trends in Guizhou. During the Induan Stage, $\delta^{13}C$ values decline by ca. 5‰ from the platform top to the basinal margin, although this gradient largely disappears by the Olenekian Stage. Calcium isotope records reveal comparable patterns: $\delta^{44/40}Ca$ values in the platform vary by ca. 0.8 ‰ in the Induan, consistent with the preservation of a primary carbonate mineralogy gradient (from aragonite to calcite) throughout the Great Bank of Guizhou. Subsequently, $\delta^{44/40}Ca$ values generally increase towards inferred Triassic …

… seawater $\delta^{44/40}Ca$ values in the Olenekian, suggestive of early marine diagenetic resetting that would have likely influenced associated $\delta^{13}C_{carb}$ records. Collectively, we suggest that at least some aspects of the Great Bank of Guizhou $\delta^{13}C_{carb}$ records may partially reflect a combination of local, facies-related mineralogical controls (Induan), and diagenetic resetting (Olenekian). This revised interpretation may help to resolve some of the difficulties with our current understanding of the Early Triassic carbon cycle, but does present further challenges that remain targets of ongoing research. In light of these findings, we encourage the careful reconsideration of Early Triassic geochemical records to examine the potential implications of facies-specific and diagenetic influences.

Stable Carbon Isotope Fractionation During Steady-State Methanogenesis as a Function of DIC Concentration

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Autotrophic methanogenesis, or the biological conversion of carbon dioxide (CO_2) to methane, is an ancestral metabolism found in a specific group of anaerobic archaea called methanogens. Methanogens live in a wide range of chemical systems and are often found in extreme environments. One such extreme environment is a serpentinizing system, where water-rock reactions create (hyper)alkaline, hydrogen-replete, and carbon-limited conditions. Although carbon-limitation is prevalent in these astrobiologically and early Earth relevant extreme environments, most experiments investigating carbon isotope fractionation have focused on carbon-replete systems and have not tested the impact of carbon-limitation on microbial biosignatures. Additionally, most isotope fractionation studies use closed-system laboratory experimental set-ups that do not mimic open-systems that are more common in the natural environment. Here we test the impact of carbon-limitation on the carbon isotope fractionation between CO_2 and methanogenesis products produced during steady-state through chemically static (chemostat) continuous culture experiments. We varied the amount of CO_2, the limiting nutrient, available to the methanogen species Methanococcus maripaludis while keeping a constant slow growth rate to create conditions ranging from carbon-replete to carbon-limited. The data show that carbon isotope fractionation between methanogenesis products and aqueous CO_2 is a factor of carbon availability, with decreasing carbon availability causing greater fractionation between the two pools. Additionally, we see that the energetic state of the system is not heavily impacted by carbon-availability and that methanogenesis is a thermodynamically favorable reaction in carbon-limited conditions if there is sufficient H_2 present. We created an isotope flux model to explain the differences in carbon isotope fractionation that shows how the flux of CO_2 between the gaseous and aqueous pools, the diffusion of CO_2 in and out of the cell, and the kinetic fractionation of methanogenesis steps all impact the fractionation of methanogenesis products from source CO_2. Specifically, the model shows that forward carbon fluxes in the system need to be higher than reverse carbon fluxes, that the net kinetic carbon isotope fractionation factor of the first five steps of methanogenesis needs to be greater than previously inferred, and that the net kinetic carbon isotope fractionation factor of the last two steps of …

... methanogenesis needs to be lower than previously inferred in order to encompass the range of fractionation trends we observe from the chemostat data. Overall, this study shows that carbon isotope fractionation during methanogenesis varies as a function of carbon availability.

Mitigating Methane Emissions from Municipal Sewage Treatment Facilities by Phosphogypsum Bioconversion

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Over 200 million tons of phosphogypsum, a byproduct of global fertilizer production, are stacked or discharged annually, posing long-term environmental challenges. We explore the potential of sustainable conversion of sulfate from phosphogypsum into alkaline solutions and sulfide by microbial sulfate reduction (MSR) coupled to sewage sludge digestion, which is typically dominated by methanogenesis. The new process can reduce methane emissions and generates solutions that can be used for the subsequent precipitation of calcium carbonate and recovery of elemental sulfur. We have enriched a microbial community that couples gypsum reduction with the oxidation of organic matter from sewage, reducing sulfate and yielding alkalinity with negligible methane emissions. Nearly all generated alkalinity can be recovered as solid carbonate with minimal carbon dioxide loss during drying. Lab-scale bioreactor studies suggest that this process can be scaled up for typical municipal sewage treatment.

Investigating the sedimentological and chemical feedbacks recorded in carbonate mounds across the early Carboniferous

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To better predict future global warming scenarios, we must study historical Earth events that more closely resemble our modern climate regime. The Early Carboniferous (~359 Ma) is one such time frame that records rapid climatic and biological change, including a major carbon isotope excursion (TICE, ~352 Ma). Recent work suggests global ocean deoxygenation covered ~30% of the seafloor, vastly limiting ecospace, and marine strata record abundant deep water carbonate mounds, indicating a shift in carbonate sedimentation and carbon burial. Despite their ubiquity, uncertainties remain about the origin and timing of these carbonate mounds relative to the development of anoxia and carbon cycling. In this talk I will highlight our work investigating how the mounds relate temporally to the TICE and whether they are precursors to, or responses of, anoxia across the TICE. This work aims to clarify key feedbacks within the Earth System to better understand future climatic responses.

Reconstructing Fluvial Planform Morphology

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Planform morphology of rivers encodes the combined signatures of climate, tectonics, vegetation, and hydrology, yet it is notoriously difficult to retrieve from the stratigraphic record. We introduce a field-ready, quantitative workflow that reconstructs paleo-planform style and sinuosity directly from paleocurrent measurements. Center-line azimuths from 78 meandering, 29 wandering, and 26 braided rivers form the modern training set. Each dataset is first corrected for the empirically derived "transport anomaly" that offsets bed-form migration from channel trend, then summarized by the circular variance (V) of the adjusted orientations. In meandering systems V scales with channel sinuosity, yielding a simple equation that converts any paleo-V to paleo-sinuosity and provides sample-size–dependent uncertainty. Two validation cases—Cretaceous and Eocene inverted channels—show that V extracted from dune cross-strata reproduces both known planform style and measured sinuosity. Application to fluvial successions that span the Paleocene–Eocene Thermal Maximum in the Bighorn Basin (Wyoming, USA) reveals that, although sand bodies widened during peak warming, V remained constant. The transient width increase therefore reflects heightened lateral mobility rather than a shift from meandering to braided flow. This methodology transforms routine paleocurrent datasets into quantitative constraints on river behavior, enabling sharper tests of how Earth-surface systems respond to climatic and tectonic perturbations across deep time.

Lithium isotopes of the Peace River Arch in the Western Canada Sedimentary Basin: A framework for resolving deep basin lithium sources

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Lithium (Li) enrichment in the formational brines of deep sedimentary basins has emerged as a crucial component of global Li inventories. However, the processes driving the formation of Li-brines remain poorly understood. Here we use lithofacies analysis and Li isotope geochemistry to investigate the sources and emplacement mechanisms within weathered subcropping units and overlying detrital sediments of the Peace River Arch (PRA) in the Western Canada Sedimentary Basin (WCSB). We analyze data from three drill cores that traverse Precambrian basement and five of its overlying siliciclastic and carbonate units. These cores reside both within and outside of the fault zone proposed as a migration pathway for hydrothermal emplacement. Lithofacies analysis revealed that these sediments were weathered directly from crystalline basement of the cratonic uplift and transported via a fluvial-deltaic system into the surrounding shallow marine basin. Like modern weathering regimes, we find Li concentrations are strongly lithofacies dependant, ranging from 0.4 to 167.3 ppm, with δ^7Li values ranging from 1.5 to 23.5‰. Our results show that superficially weathered, coarse-grained lithologies and carbonate facies are Li-depleted and δ^7Li-enriched, whereas fine-grained facies characterized by the formation of secondary clay minerals are δ^7Li depleted and ...

... exhibit the highest Li concentrations. Contrary to the prevailing model of hydrothermal emplacement, we find no visual, mineralogical or geochemical evidence of hydrothermal alteration. Instead, Li enrichment is attributed to weathering of the crystalline basement and syndepositional emplacement during basin evolution. Sedimentation continued throughout the overall transgression of the Devonian, resulting in the interfingering of these clastics with every onlapping unit until the PRA was buried at the end of the Devonian. This study is the first to directly trace Li from source to sink in an ancient sedimentary basin and we show that the modern distribution of Li brine concentrations can be explained by their proximity and intercalation with weathered subcropping units. Moreover, our results provide a source and mechanism of transporting dissolved Li into the restricted basin, supporting previous suggestions that Li brines towards the southeastern portion of the WCSB are the result of basin scale evaporation-concentration of paleoseawater. Our results underscore the link between the nature and distribution of basin fill sediments and the formation of Li enriched brines. As formational brines gain prominence as future Li resources, the methodology presented here establishes a framework for characterizing Li genesis, with applications for sedimentary basins worldwide.

PhreeFit: a tool to estimate the surface reactivity of biogeochemical surfaces

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The surface reactivity of clays, oxides, organic matter, and microorganisms controls the bioavailability and fate of metals and nutrients in most aqueous environments. Adsorption models are a widely used tool in predicting the adsorption of solutes under varying environmental conditions. Compared to empirical adsorption models, surface complexation models (SCMs) more accurately depict adsorption mechanisms because they account for element speciation, the surface electrical properties of sorbents, and the structures of adsorbed species. Solving for SCM parameters, including site densities, intrinsic formation constants, capacitances, and charge distribution coefficients, usually relies on optimization routines encoded in programs such as FITEQL, ProtoFit, MINFIT, and ECOSAT-FIT. However, existing SCM optimization programs often fail to converge due to flaws in their local optimization algorithms. Furthermore, they also lack universality in optimizing SCM parameters and unfortunately often do not have user-friendly interfaces. In this study, several common optimization algorithms were tested on five typical proton and metal adsorption data sets, to test nonelectrostatic, generalized diffuse double layer, constant capacitance, and charge-distribution multisite SCM model approaches. The efficiency in estimating all types of SCM parameters, including intrinsic equilibrium constants, site densities, capacitances, and charge distribution coefficients, was evaluated. Global optimization algorithms consistently produced better fits than local optimization algorithms, and were not susceptible to the values of initial parameter guesses and the number of fitted parameters. Among the global optimization algorithms, the differential evolution algorithm was the most efficient in achieving convergence and most consistent in reproducing a good fit. Based on these tests, an open-source program named “PhreeFit” was developed. Subsequent software tests on data from ...

… metal adsorption experiments to biochar, minerals, and mineral-microbe aggregates consistently demonstrated the capability of PhreeFit to accurately and rapidly estimate SCM parameters. This program limits time spent on adjusting initial guesses and program settings to arrive at an optimal solution, and facilitates the development of an accurate system of reactions and an understanding of the underlying mechanisms of adsorption. PhreeFit is designed with a graphical user interface for ease of use, allowing SCM approaches to be more broadly employed in the biogeochemical community.

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