Life and Planet

London | 2023 | July 18th – July 19th

Meeting programme

Meeting information

Schedule: July 18th

Schedule: July 19th

Highlight talk abstracts

Oral presentation abstracts

Poster presentation abstracts

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Meeting Information

About the meeting

Life and Planet is the new annual meeting of the **Earth System Science Group** (ESSG) of the **Geological Society of London** which will take place at the historic Burlington House venue in Piccadilly. We aim to provide an exciting, inclusive and supportive yearly event where anybody interested in the co-evolution of life and the Earth can present their work, can build collaborations, and can grow the community. We are dedicated to promoting the work of early career researchers (ECRs) and as such the meeting has free abstract submission, low registration fees and features selected 'highlight' talks from our submissions rather than invited talks from senior colleagues. We hope that attendance will comprise researchers at all career stages as well as other interested parties and individuals.

Scientific focus and sessions

The theme of co-evolution is broad and cross-disciplinary, and we welcome work that spans the fields of (in no particular order) palaeontology, (bio)geochemistry, sedimentology, geobiology, palaeoclimate, geodynamics, tectonics, astrobiology and any scientific work that aims to understand how life has shaped the global environment and/or how the global environment has shaped life on Earth. We welcome equally work from the field, the laboratory or from numerical simulation. The meeting will run over two days and will use a single series of consecutive sessions taking place in the 172-seater main lecture theatre.

Conference venue and travel

Life and Planet 2023 will be held at the Geological Society at Burlington House in Piccadilly, London. From London mainline train stations take the Underground to either Piccadilly Circus (Piccadilly and Bakerloo lines) or Green Park (Victoria, Jubilee, and Piccadilly lines) and walk along the main road. We cannot offer accommodation as part or the conference, but London has a wide range of hotels and very good transport links. Poster boards are provided by the conference venue, and presenters should prepare posters no larger than A0 paper size (84.1 cm x 118.9 cm).

Life and Planet meeting code of conduct

All attendees are expected to behave in a professional manner and to treat each other with respect. The Conference organizers reserve the right to remove any attendee who violates this code of conduct without a refund. If you believe another attendee is in violation of the code of contact, please contact the organizing committee at info@lifeandplanet.com.

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Life and Planet 2023 organizing committee

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Toby Tyrrell
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Rachel Wood
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Ying Zhou
University of Leeds

Meeting schedule

(all times given in BST)

*Highlight talks selected by the organizing committee

Tuesday, July 18th

9:30 – 10:45 Arrivals, icebreaker, and coffee

10:45 – 10:50 Introductory remarks

Session 1

11:00 – 11:15 **Modelling climate change over 500 million years – a community resource for ecological and biodiversity modelling**
Dan Lunt, Paul Valdes, Alex Farnsworth

11:15 – 11:30 **Ocean redox and nutrient cycling in the ~1.64 Ga Chuanlinggou Formation, North China Craton**
Chong He, Benjamin J.W. Mills, Fred T. Bowyer, Xiuqing Yang, Yafang Song, Simon W. Poulton

11:30 – 11:45 **Radiations and extinctions in early Paleozoic oceans: understanding the dynamics of the early marine biosphere**
Alexandre Pohl

11:45 – 12:00* **Prevailing views on the coevolution of life and oxygen**
Lewis J. Alcott, Fred Bowyer, Heda Agić

12:00 – 12:45 Break for lunch (*not catered*)

Session 2

13:00 – 13:15 **Calibrating the diversification of early animals during Ediacaran–Cambrian interval using a newly proposed** beta ichnodiversity
Zekun Wang, Imran Rahman

13:15 – 13:30 **Constraining the onset and environmental setting of Ediacaran metazoan biomineralization: The Nama Group of the Tsaus Mountains, Namibia**
Fred Bowyer, Collen Issia-Uahengo, Kavevaza Kaputuaza, Junias Ndeunyema, Mariana Yilales, Ruaridh Alexander, Andrew Curtis, Rachel Wood

13:30 – 13:45 **Shifting sands: Are late Ediacaran fossil assemblages reliable records of original ecosystems?**
Brennan O'Connell, William J. McMahon, Alexander G. Liu

13:45 – 14:00* **A Great late Ediacaran ice age**
Ruimin Wang, Bing Shen, Xianguo Lang, Bin Wen, Ross N. Mitchell, Haoran Ma, Zongjun Yin, Yongbo Peng, Yonggang Liu, Chuanming Zhou

14:00 – 14:15 Break

Session 3

14:15 – 14:30 **The (bacterio-)chlorophyll biosynthetic pathway provides Bayesian insights into the evolution of photosynthesis**
Giorgio Bianchini, Patricia Sánchez-Baracaldo, Tom Williams, Tanai Cardona

14:30 – 14:45 **Patterns of floral dominance-diversity architecture across the Pennsylvanian-Permian boundary of western equatorial Pangea**
Rebecca A. Koll, William A. DiMichele

14:45 – 15:00 **Testing for a signal of solar irradiance in fern spores from the K/Pg boundary**
Hendrik Nowak, Barry H. Lomax, Wesley T. Fraser, Philllip E. Jardine, Luke Mander

15:00 – 15:15* **Plant adaptation and dispersal shape climatic shifts following massive degassing events**
Julian Rogger, Yves Goddéris, Benjamin Mills, Taras Gerya, Loïc Pellissier

15:15 – 15:30 Break

Session 4

15:30 – 15:45 **The nature of LUCA and its impact on the early Earth system**
Edmund R. R. Moody, Holly Betts, James Clark, Nina Dombrowski, Stuart Daines, Richard Boyle, Xi Chen, Graham A. Shields, Gergely Szöllősi, Anja Spang, Davide Pisani, Tom A. Williams, Timothy M. Lenton, Philip J. Donoghue

15:45 – 16:00 **Dormant Arctic thermophiles point to cellular life histories operating over geologic timescales**
Margaret Cramm, Matteo Selci, Donato Giovannelli, Anne Jungblut, James Bradley

16:00 – 16:15 **Sulfate concentrations in the global ocean through Phanerozoic time**
Alexander J. Krause, Benjamin J. W. Mills

16:15 – 16:30* **The history of atmospheric oxygen: Towards an understanding of oxygen-vegetation feedbacks**
Rayanne Vitali, Claire M. Belcher, Benjamin J.W. Mills, Andrew J. Watson

16:30 – 18:00 Poster session

Wednesday, July 19th

9:30 – 9:45 Coffee

Session 5

9:45 – 10:00 **No evidence for falling marine sulfate levels after the Great Oxidation Event in Fennoscandia**
Roger Bryant, Jordan Todes, Jocelyn Richardson, Tara Kalia, Anthony Prave, Aivo Lepland, Kalle Kirsimäe, Clara Blättler

10:00 – 10:15 **Heterogeneous sulfide reoxidation buffered oxygen release in the Ediacaran Shuram ocean**
Wei Shi, Benjamin Mills, Thomas Algeo, Simon W. Poulton, Robert J. Newton, Matthew S. Dodd, Zihu Zhang, Lei Zheng, Tianchen He, Mingcai Hou, Chao Li

10:15 – 10:30 **Exploring belemnite calcite as an archive of water column phosphorus**
Ailsa C. Roper, Clemens Ullmann, Crispin T.S. Little, Simon Poulton, Paul Wignall, Tianchen He, Robert Newton

10:30 – 10:45* **What triggered the calcification of coccolithophores? Tracing upper ocean oxygenation trends through the Triassic using I/Ca ratios**
Mariana Yilales A., Rachel Wood, Rosalind Rickaby, Sylvain Richoz, Matthew Clarkson, Tianchen He, Stephen Reid, Fred Bowyer

10:45 – 11:00 Break

Session 6

11:00 – 11:15 **Climate homeostasis by and for active inference in the biosphere**
Sergio Rubin

11:15 – 11:30 **Reconstructing levels of volcanic ashfall through geological time**
Jack Longman

11:30 – 11:45 **Disentangling the effects of seasonality from average conditions on modeled forest distribution during the Pennsylvanian**
William J. Matthaeus, Sophia I. Macarewich, Jon D. Richey, Jonathan P. Wilson, Joseph D. White, Jennifer C. McElwain

11:45 – 12:00* **Exploring the rise of oxygen and fall of carbon dioxide over the Paleozoic Era using a deep time dynamic vegetation model**
Khushboo Gurung

12:00 – 12:45 Break for lunch (*not catered*)

Session 7

13:00 – 13:15 **Phosphorus controls on the formation of vivianite versus green rust under anoxic conditions**
Yijun Xiong

13:15 – 13:30 **A Mesoproterozoic weathering event and its possible link to oxygenation**
Xi (Helen) Chen, Ying Zhou, Graham Shields

13:30 – 13:45 **Enhanced continental silicate weathering linked to the Karoo-Ferrar LIPs in the lacustrine Sichuan Basin during the Jenkyns Event**
Jinchao Liu, Jian Cao, Simon W. Poulton, Tianchen He, Wang Zheng

13:45 – 14:00* **Devonian afforestation significant altered the global silicate weathering regime: Evidence from lithium isotopes**
Xianyi Liu, Alexander J. Krause, David J. Wilson, Wesley T. Fraser, Michael M. Joachimski, Uwe Brand, Alycia L. Stigall, Wenkun Qie, Bo Chen, Xiangrong Yang, Philip A.E. Pogge von Strandmann

14:00 – 14:15 Break

Session 8

14:15 – 14:30 **Are widespread ^{13}C-depleted microbial mats a source of more negative $\delta^{13}C$ composition of organic matter in Proterozoic mudrocks?"**
Heda Agić, Susannah Porter, Phoebe Cohen, Christopher Junium

14:30 – 14:45 **Constraining the redox landscape in Mesoproterozoic mat grounds: A possible oxygen oasis in the 'Boring Billion' seafloor**
Tianyi Jia, Ruimin Wang, Tianzheng Huang, Xianguo Lang, Haoran Ma, Bing Shen

14:45 – 15:00 **Micro-elemental analysis of stromatolites reveal Fe as potential biosignature and remnant of a lithification mechanism**
Victoria Cassady, Dylan R. Levene, Aaron Celestian, Victoria Petryshyn, William M. Berelson, Kalen Rasmussen, Bradley S. Stevenson, John R. Spear, Frank A. Corsetti

15:00 – 15:15* **Photochemical modeling of atmospheric oxygen over Earth's middle history and co-evolution with the biosphere**
Bethan Gregory, Mark Claire, Sarah Rugheimer

15:15 – 15:30 Break

Session 9

15:30 – 15:45 **Solid Earth forcing of oceanic anoxic events**
Thomas Gernon, Benjamin Mills, Thea Hincks, Andrew Merdith, Lewis Alcott, Eelco Rohling, Martin Palmer

15:45 – 16:00 **Mass extinctions and close calls: Using experimental Earth system and ecophysiological modelling to understand what makes a catastrophic extinction**
Richard G. Stockey, Erin E. Saupe, Benjamin J. W. Mills, Alexandre Pohl

16:00 – 16:15 **Dynamics of ocean oxygenation and anoxic events**
Stuart Daines, Ziheng Li

16:15 – 16:30* **Instability in the geologic regulation of Earth's climate**
Dominik Hülse, Andy Ridgwell

16:30 Closing remarks

Highlight Talk Abstracts

Prevailing views on the coevolution of life and oxygen

Lewis J. Aclott[1,2], Fred Bowyer[3], Heda Agić[4]

[1]Yale University; [2]University of Waterloo; [3]University of Edinburgh; [4]Durham University

Our current community's understanding of the coevolution of Earth's surface and the biosphere is built on 50+ years of interpretations, which makes it necessary to critically review and continually assess the status quo of our field. Here we provide results of an expert elicitation study, addressing the current paradigm of the evolution of oxygen, the interplay between the evolution of both microscopic and macroscopic life with environmental oxygen concentrations, as well as the most sought-after avenues for future research. With over 130 individual responses from our community including: geochemists, palaeontologists, Earth system modellers, field-based geologists, and geobiologists, we take note of the current disciplinary diversity and inclusion within the field, as well as the promising active participation of early career researchers. Nuances such as the nature of oxygenation events and their principally defining proxies, the predominantly viewed evidence for first occurrences, and the driving mechanisms for evolution, are all considered as part of our community's collective opinion. We also actively discuss the role various uncertainties play in our understanding and the degree to which each of these impact our interpretations. While cohesion of some survey results within and between subdisciplines is apparent, there is a clear lack of discussion and interdisciplinary conversation when regarding the role oxygen did, or did not, play on the evolution of the biosphere.

Photochemical modelling of atmospheric oxygen over Earth's middle history and co-evolution with the biosphere

Bethan Gregory[1], other authors[2]

[1]University of Colorado Boulder; [2]University of St. Andrews

Oxygen makes up 21% of the present-day atmosphere of Earth, but this has not always been the case, and life has played a key role in shaping the composition of the atmosphere over the planet's history. There is compelling evidence for a step increase in atmospheric O_2 around 2.4 billion years ago—the Great Oxidation Event—but, while various models and geological and geochemical proxies have been applied to understand oxygen concentrations during the following Proterozoic eon, uncertainty regarding Proterozoic atmospheric composition remains. Here, we use a photochemical model to simulate the effect of varying biological O_2 and methane fluxes on oxygen levels in the atmosphere, confirming that there is a critical O_2 flux or tipping point above which the model atmosphere transitions from reducing, low-O_2 conditions to oxic conditions with a UV-shielding ozone layer across a very narrow flux range. We then incorporate the three isotopes of oxygen into the model, demonstrating that mass-independent fractionation of oxygen isotopes, a signal observed in the geological record throughout the Proterozoic and Phanerozoic, only occurs with O_2 levels greater than 0.5% of present atmospheric levels (PAL). Our combined results suggest a lower limit for O_2 concentrations of 0.5% PAL for at least some of the mid-Proterozoic, and they show that an ozone layer sufficient to protect surface-dwelling life is likely to have persisted since the Great Oxidation Event. They also imply that an early Earth biosphere with photosynthetic O_2 fluxes of less than 10% of the modern flux would not have sufficient O_2 or O_3 for these species to be remotely detected with our current technology for observing potential exoplanet biosignatures. Improved constraints on the evolution of the atmosphere's composition and how it responds to biological fluxes can help us to understand both how our own

planet’s atmosphere has co-evolved with life and how the atmospheres of exoplanets with and without biospheres might develop.

Exploring the rise of oxygen and fall of carbon dioxide over the Paleozoic Era using a deep time dynamic vegetation model

Khushboo Gurung[1]

[1]University of Leeds

The evolution and emergence of plants were key events in the Phanerozoic that helped shape Earth's climate and the composition of the atmosphere. Land plants are a major contributor of global biomass and primary productivity, which influences atmospheric oxygen and carbon dioxide levels. Interaction between adaptive plant physiology and the carbon cycle likely exerted some degree of control over the Phanerozoic oxygenation and climate via enhanced weathering and carbon burial. The inclusion of spatially-resolved vegetation within models that predict paleo-oxygen and -carbon dioxide levels is essential, but evolution of plant physiology over time and the subsequent interactions with the carbon cycle are yet to be explored within this framework. Building upon the existing deep-time vegetation model FLORA and coupling this to a climate-chemical model SCION, we observe the impact of productivity of rudimentary verses complex plants on weathering and biomass, and therefore the carbon fluxes, atmospheric oxygen and climate. By integrating evolution and competition into the model, we are also able to postulate whether geographical spread, productivity or plant complexity is the influential factor controlling long-term Earth system change.

Instability in the geological regulation of Earth's climate

Dominik Hülse[1], Andy Ridgwell[1]

[1]University of California, Riverside

Negative feedback between climate and atmospheric CO_2, as mediated via weathering of silicate minerals, is thought to provide the dominant regulation of Earth's climate on geological timescales. In contrast, we show here that faster feedbacks involving organic matter are critical and create unexpected instability in the system. Specifically, using an Earth system model, we show how organic carbon burial, amplified by climate-sensitive phosphorus feedbacks, can dominate over silicate weathering, inducing a cooling 'over-shoot' and, paradoxically, an ice age in response to massive CO_2 release. This instability in the Earth system is most strongly expressed in the model at intermediate redox states of the ocean and atmosphere, offering a novel explanation for the occurrence of past 'snowball' climates as the Earth's surface became appreciably oxygenated.

Devonian afforestation significantly altered the global silicate weathering regime: Evidence from lithium isotopes

Xianyi Liu[1], Alexander J. Krause[1], David J. Wilson[1], Wesley T. Fraser[2], Michael M. Joachimski[3], Uwe Brand[4], Alycia L. Stigall[5], Wenkun Qie[6], Bo Chen[6], Xiangrong Yang[7], Philip A.E. Pogge von Strandmann[1,8]

[1]University College London; [2]Oxford Brookes University; [3]Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU); [4]Brock University; [5]University of Tennessee Knoxville; [6]Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences; [7]Chinese University of Geosciences; [8]Johannes Gutenberg University

The Devonian period (359-419 Ma) documents significant environmental changes and marine species turnover, but whether these changes were linked to terrestrial weathering is unknown. Here, we use lithium isotopes in brachiopods and bulk marine carbonates (δ^7Li_{carb}) from the Devonian period to investigate changes in silicate weathering, which represents the primary long-term atmospheric CO_2 sink. A rise of ~10‰ in δ^7Li_{carb} values (from ~8‰ to ~18‰) is observed across the Mid-Devonian (378-385 Ma), suggesting a major change in the seawater Li budget. We attribute the rise in δ^7Li_{carb} values to an increase in the dissolved riverine Li fluxes and δ^7Li_{river} values, which were likely related to increases in both weathering intensity and regolith thickness, as a result of the expansion of deep-rooted plants and the establishment of mature forest ecosystems. However, the presence of complex terrestrial ecosystems would also have restricted the continuous weathering of silicates. Therefore, to maintain such high $\delta^7Li_{seawater}$ values in the Late Devonian, we propose that cyclic destruction and regeneration of forest ecosystems must have occurred in order to avoid a supply-limited weathering regime being established. This process would potentially have caused oscillations in marine nutrient availability, redox conditions, and organic carbon burial, thereby contributing to the prolonged marine biodiversity loss in the Late Devonian.

Plant adaptation and dispersal shape climatic shifts following massive degassing events

Julian Rogger[1], Yves Goddéris[2], Benjamin J.W. Mills[3], Taras Gerya[1], Loïc Pellissier[1,4]

[1]ETH Zurich; [2]CNRS-Observatoir Midi-Pyrénees; [3]University of Leeds; [4]Swiss Federal Institute for Forest, Snow and Landscape Research

Earth's long-term climate is driven by the cycling of carbon between geologic reservoirs and the surface system of the atmosphere, oceans, and the biosphere. The sustained presence of life and liquid water depends on efficient feedback mechanisms that keep carbon inputs to the surface system by magmatic or metamorphic degassing in balance with carbon sink fluxes, such as silicate mineral weathering and organic carbon burial. Imbalances in the carbon cycle, for example due to the release of carbon during the emplacement of Large Igneous Provinces (LIP), potentially result in catastrophic climatic disruptions, biotic crises, and mass extinctions in the oceans as well as on land. However, it remains enigmatic what climatic, geologic, and biologic variables determine the resilience of Earth's compartments to such a degassing event. Here, we evaluate how the evolutionary adaptation and dispersal capacity of the biosphere affect the temperature anomaly following a massive release of CO_2 to Earth's atmosphere and oceans. To do so, we develop an eco-evolutionary vegetation model in which the biosphere's potential for organic carbon production and plant-mediated enhancement of mineral weathering on land depends on the degree of adaptation to local environmental conditions and couple it to a deep-time carbon cycle and an intermediate complexity climate model. We observe a strong sensitivity of both, the intensity and duration of climatic changes following a LIP emplacement to the capacity of the biosphere to adapt its temperature niche by evolutionary processes as well as to disperse in geographic space. The interaction between the continental configuration (e.g., supercontinent vs. distributed continents)

and the distribution of dispersal barriers for the terrestrial vegetation further result in the emergence of novel long-term climatic steady states. A better understanding of biologically driven climate regulation mechanisms in a spatial context may help to explain unresolved changes in temperature over Earth's history.

The history of atmospheric oxygen: Towards an understanding of oxygen-vegetation feedbacks

Rayanne Vitali[1], Claire M. Belcher[1], Bejamin J.W. Mills[2], Andrew J. Watson[1]

[1]University of Exeter; [2]University of Leeds

Since the emergence of land plants ~420 million years ago, atmospheric oxygen is thought to have been dynamically stable between roughly 17-40% vol. O_2. Such stability suggests mechanisms have been in place to prevent oxygen rising or falling out of these bounds. Amongst processes proposed, negative fire feedbacks are assumed to play a central role due to the sensitivity of fire to varying oxygen concentrations, controlling oxygen levels through suppressing terrestrial vegetation productivity and lowering organic carbon burial: a main source of atmospheric oxygen over geological timescales. Yet despite being prevalent in discussions of oxygen regulation and incorporated into many biogeochemical models, fire and other vegetation-based feedbacks on atmospheric oxygen remain largely untested and debated.

Here we update the LPJ-LMfire Dynamic Global Vegetation Model to include oxygen impacts on global vegetation through oxygen-fire and oxygen-photorespiration effects. Whilst previous work has suggested both photorespiration and fire could have a role in oxygen regulation, work presented here is the first to include both mechanisms and their interactions on a global scale. Through running a series of simulations over a range of oxygen concentrations we investigate the response of global terrestrial vegetation to rising oxygen concentrations through separate and joint effects of fire and photorespiration. Subsequently improving our understanding of the strength that fire and photorespiration has in providing negative feedbacks to atmospheric oxygen and hence its regulation throughout the Phanerozoic. As such, work here has widespread implications including the evolution of land plants and biomes, the development of biogeochemical models (touched on here) and ultimately providing a better understanding of the oxygen cycle – a major part of the Earth system

A great late Ediacaran ice age

Ruimin Wang[1], Bing Shen[1], Xianguo Lang[2], Bin Wen[3], Ross N. Mitchell[4,5], Haoran Ma[6], Zongjun Yin[7], Yongbo Peng[6], Yonggang Liu[8], Chuanming Zhou[7]

[1] Key Laboratory of Orogenic Belts and Crustal Evolution, MOE & School of Earth and Space Sciences, Peking University; [2]State Key Laboratory of Oil and Gas Reservoir geology and Exploitation & Institute of Sedimentary Geology, Chengdu University of Technology; [3]State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan; [4]Institute of Geology and Geophysics, Chinese Academic of Sciences, Beijing; [5]University of Chinese Academy of Sciences; [6]School of Earth Sciences and Engineering, Nanjing University; [7]State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, and Center for Excellence in Life and Paleoenvironment, Chinese Academy of Sciences; [8]School of Physics, Peking University

The emergence of the Ediacara biota soon after the Gaskiers glaciation ca. 580 million years ago (Ma) implies a possible glacial fuse for the evolution of animals. However, the timing of Ediacaran glaciation remains controversial because of poor age constraints on the ~30 Ediacaran glacial deposits known worldwide. In addition, paleomagnetic constraints and a lack of convincing Snowball-like cap carbonates indicate that Ediacaran glaciations likely did not occur at low latitudes. Thus, reconciling the global occurrences without

global glaciation remains a paradox. Here, we report that the large amplitude, globally synchronous ca. 571–562 Ma Shuram carbon isotope excursion occurs below the Ediacaran Hankalchough glacial deposit in Tarim, confirming a post-Shuram glaciation. Leveraging paleomagnetic evidence for a ~90˚ reorientation of all continents due to true polar wander (TPW), and a non-Snowball condition ruling out low-latitude glaciations, we use paleogeographic reconstructions to further constrain glacial ages. Our results depict a "Great Ediacaran Glaciation (GEG)" occurring diachronously but continuously from ca. 580–560 Ma as different continents migrated through polar–temperate latitudes. The succession of radiation, turnover, and extinction of the Ediacara biota strongly reflects glacial-deglacial dynamics.

What triggered the calcification of coccolithophores? Tracing upper ocean oxygenation trends through the Triassic using I/Ca ratios

Mariana Yilales A.[1], Rachel Wood[1], Rosalind Rickaby[2], Sylvain Richoz[3], Matthew Clarkson[4], Tianchen He[5], Stephen Reid[6], Fred Bowyer[1]

[1]University of Edinburgh; [2]University of Oxford; [3]Lund University; [4]InPlanet; [5]Hohai University; [6]University of Leeds

Coccolithophores are single-celled calcifying nannoplankton from the upper ocean that have greatly influenced the environment and marine ecosystems since their appearance in the Late Triassic, ~215 million years ago. By means of their photosynthesis and calcification processes, they became crucial in establishing modern ocean biochemical conditions and carbon cycling dynamics. The possible causes, however, that may have triggered biomineralization in these organisms remain unknown. Oxygen availability has been proposed as a driver for macroevolutionary novelty and innovation, but the relationship between coccolithophore evolution and ocean oxygenation has not been addressed. This project built a high-

resolution record of upper-ocean redox conditions from carbonate samples deposited during the Early (Musandam Peninsula), Middle and Late Triassic (Oman, Sicily and Austrian Alps) using iodine-to-calcium-magnesium ratios (I/(Ca+Mg)) and trace elemental analysis to assess how changes in oxygen concentration might relate to the evolution of biomineralization in coccolithophores. Marine carbonate I/(Ca+Mg) analysis is a relatively novel and reliable proxy to trace oxygen variation in the upper ocean and can track redox dynamics during the period coccolithophores first evolved. I/(Ca+Mg) and Uranium measurements yield evidence of local oxygenation increase immediately prior to the first appearance of coccolithophores in the Late Triassic.

Oral Presentation Abstracts

Are widespread ^{13}C-depleted microbial mats a source of more negative $\delta^{13}C$ composition of organic matter in Proterozoic mudrocks?

Heda Agić[1], Susannah Porter[2], Phoebe Cohen[3], Christopher Junium[4]

[1]Durham University; [2]University of California, Santa Barbara; [3]Williams College; [4]Syracuse University

Proterozoic rocks record significant fluctuations in isotopic composition of sedimentary carbon, and are generally ^{13}C-depleted depleted relative to the Phanerozoic. Potential explanations for the source of isotopically depleted organic matter (OM) in the Proterozoic is that a high proportion was produced by the fixation of inorganic carbon by benthic microbial mats or eukaryotic early plankton operating with large isotope fractionations during carbon acquisition. Is a greater contribution of C-depleted OM from widespread benthic microbial mats during the Proterozoic a source of more negative $\delta^{13}C$ composition of organic matter in mudrocks? Here we probe this question by measuring the organic carbon isotopic composition of individual mat-builder, as well as early eukaryote microfossils.

Mat-building prokaryotes are a common component of Proterozoic organic-walled microfossil (OWM) assemblages. Abundant and widespread form-species include filamentous Siphonophycus and Polytrichoides, and cell-aggregates Synsphaeridium, long interpreted to be cyanobacterial based on similarity to extant microorganisms. We measured the C-isotopic composition of a broad array of individual OWM from multiple Proterozoic units, using nano-EA-IRMS. This approach provides a window into short-term environmental variability and reveals palaeoecological information about Proterozoic microbial life. Studied assemblages derive from the Paleoproterozoic Changcheng Group (China), the end-Mesoproterozoic lower Bylot Supergroup (Canada), the Tonian Chuar Group (USA), and the

Ediacaran Pertatataka Formation (Australia). In general, within-sample $\delta^{13}C_{OWM}$ showed a wide range, in some cases with spreads >15‰. The most consistent values among OWM were of filamentous and cell-aggregate mat-builder taxa, which averaged -29.3‰ (N=10) in the Changcheng, -30.5‰ (N=20) in the Bylot, -27.8‰ (N=45) in the Chuar, and -29.9‰ (N=9) in the Pertatataka assemblage. Mat-builders were on average more depleted than the average assemblage $\delta^{13}C_{OWM}$ within a single sample by 3.7‰ in the Changcheng, 4.8‰ in the Bylot, 3.5‰ in the Chuar, and 2.6‰ in the Pertatataka. Additionally, mat-builders were more depleted than bulk $\delta^{13}C_{org}$ in 37 of 43 samples, including in the strata recording positive C-isotope excursions in the Chuar Group where $\delta^{13}C_{org}$ averaged at -18.3‰.

The consistently light C-isotopic values of OM derived from widespread microbial mats in the Proterozoic likely drove more depleted values of whole rock δ13C during this time. Benthic mat organisms were likely more prevalent contributors to Proterozoic OM than other OWM, including planktonic organisms.

The (bacterio-)chlorophyll biosynthetic pathway provides Bayesian insights into the evolution of photosynthesis

Giorgio Bianchini[1], Patricia Sánchez-Baracaldo[1], Tom Williams[1], Tanai Cardona[2]

[1]University of Bristol; [2]Imperial College London

Primary production through photosynthesis is a key factor for life on Earth, as it allows the conversion of the light energy input from the sun into chemical energy that is available to living organisms. Photosynthetic and phototrophic bacteria have been identified in evolutionarily unrelated groups; it is therefore unclear when and in which bacterial group photosynthesis first appeared.

For photosynthesis to occur, a number of different cellular components need to be present and to interact in a carefully concerted way; two of these are reaction centre core proteins and chlorophylls. Chlorophylls capture the light energy from the sun, while the reaction centre core ensures that all the components required for photosynthesis are arranged in an effective manner.

In this talk, I will present some preliminary analyses on the evolution of reaction centre core proteins and chlorophyll biosynthesis, using a Bayesian approach (stochastic mapping). Based on the inferred presence of most of these components in the last common ancestors of all bacteria (LBCA), I hypothesise that photosynthesis originated before the LBCA. The ability to perform photosynthesis was then preserved in an uninterrupted lineage leading to Cyanobacteria, as it evolved and incorporated "modern" features. Based on current estimates of the age of the LBCA and the divergence between Cyanobacteria and other bacterial phyla, these analyses highlight that organisms capable of oxygenic and/or anoxygenic photosynthesis may have been living on Earth since the early Archean.

Constraining the onset and environmental setting of Ediacaran metazoan biomineralization: The Nama Group of the Tsaus Mountains, Namibia

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The advent of animal (metazoan) biomineralization marks a fundamental transition in Earth's history, facilitating the diversification of novel body plans as well as biological control of carbonate sediment production, thereby permanently restructuring the global carbon cycle. The terminal Ediacaran fossil record hosts a number of tubular organisms, the cloudinids, some of which (e.g., *Cloudina*) may represent the earliest biomineralizing metazoans. Current chronostratigraphic schemes suggest that the oldest cloudinids are recorded in shallow marine sediments of the Nama Group, Namibia, but precisely when, where, and why metazoans first acquired the ability to biomineralize and their timing relative to the regional $\delta^{13}C_{carb}$ profile is undocumented. Assessing possible environmental triggers for this key event therefore requires accurate constraint of the age, paleoenvironmental setting and the geochemical context of the earliest cloudinids.

Here we present new stratigraphic, sedimentological, and geochemical ($\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$) data from the oldest strata (Dabis Formation) of the Nama Group from the Witputs Sub-basin, exposed in the Tsaus Mountains of southwest Namibia. This outcrop lies within the former 'Sperrgebiet', an area of the remote Namib Desert owned by a diamond mining corsortium where site access has historically been strictly prohibited, but which has since been designated the Tsau Khaeb National Park. New insights from the Tsaus Mountains constrain the first appearance of *Cloudina* to limestones of the lower Kliphoek Member, ca. 551–550 Ma, that were deposited laterally-

equivalent to the more proximal fossiliferous Kliphoek quartzite, from which the earliest publications of Ediacaran fossils were described in the 1930s. Host limestones of the lower Kliphoek Member have dominantly negative $\delta^{13}C_{carb}$ values that immediately precede recovery from the basal Nama negative $\delta^{13}C_{carb}$ excursion (BANE), and were deposited in shallow waters after a transition from semi-restricted, evaporitive-dolomitic to open marine carbonate settings. Regional correlation shows that *Cloudina* first appeared during an interval of dominantly low oxygen and unstable, regional marine redox conditions, and colonised the sea floor during short-lived oxic intervals. We conclude that data do not support a long-term shift towards more stable, oxygenated conditions as a driver for the first appearance of skeletonization in metazoans, but do suggest that open marine carbonate settings were required to support the calcifying *Cloudina*.

No evidence for falling marine sulfate levels after the Great Oxidation Event in Fennoscandia

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Biotic evolution is thought to have been intimately linked to evolution of Earth's surface oxidant budget. The marine sulfate reservoir is a key component of Earth's modern oxidant budget, but its evolution in deep time is uncertain. For example, the concentration of marine sulfate is thought to have fluctuated widely during and after the Great Oxidation Event (GOE), reaching >10 mM around 2.0 Ga before undergoing a purported decline. The evidence for post-GOE sulfate reservoir 'collapse' is based on sulfur and

carbon isotope ratios in carbonates, which more recent research suggests can be influenced by their depositional setting and subsequent diagenetic alteration. To assess the effects of depositional environment and early marine diagenesis on post-GOE carbonate sulfur and carbon isotope records, we present facies-specific carbonate δ34S, $\delta^{13}C$, $\delta^{26}Mg$, and $\delta^{44/40}Ca$ data from the Onega Basin (Karelia, Russia). Our analyses focus on the ca. 2.1-1.9 Ga Tulomozero Formation carbonates and the gradationally overlying shales of the Zaonega Formation, which collectively host the end of the GOE-linked Lomagundi-Jatuli positive carbon isotope excursion. Over this transitional interval, δ34S values increase whereas $\delta^{13}C$, $\delta^{26}Mg$, and $\delta^{44/40}Ca$ values become more negative. Synchrotron methods show that the dominant form of sulfur changed concomitantly, shifting from more mineralized sulfate and carbonate-associated sulfate (CAS) to variable mixtures of sulfide, organic sulfur, and dolomite CAS. Those changes map directly onto the facies change from shallow-marine evaporitic/nearshore settings to deeper-marine (below storm wave base) slope settings. The $\delta^{44/40}Ca$ data indicate that the geochemical and isotopic shifts correspond to changes in the local diagenetic environment, as shown by a shift from more seawater-buffered (open system) to more sediment-buffered (closed system) carbonate precipitation. While the resultant $\delta^{34}S$ trends closely match previous studies, they cannot provide evidence for an increase in marine sulfate $\delta^{34}S$ values and a decrease in sulfate concentration in the aftermath of the Great Oxidation Event, given the observed paleoenvironmental and diagenetic effects. More work deconvolving the effects of diagenesis on carbonate $\delta^{34}S$ is required to accurately reconstruct the Paleoproterozoic sulfur cycle.

Micro-elemental analysis of stromatolites reveal Fe as potential biosignature and remnant of a lithification mechanism

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Stromatolites—lithified, laminated organosedimentary structures typically built by microbes—are found in geological settings spanning at least the last 3.5 billion years, and act as the major record of life for 7/8ths of Earth's history, yet the details of their formation and lithification remain poorly understood. Additionally, the history of stromatolite abundance and diversity remains difficult to explain, with stromatolites increasing in abundance toward their peak in the Mesoproterozoic followed by dramatic decline after 1 Ga into the Phanerozoic, after which they remain rare. The leading hypothesis explaining stromatolite decline implicated burrowing/grazing metazoans in microbial mat destruction; however, metazoans arose after stromatolite decline began. Here, we hypothesize that dissimilatory iron reduction—a metabolism not previously recognized as important in stromatolites—may have a central role in microbial mat lithification and throughout the Precambrian. Within stromatolite laminae, iron oxides may form in the presence of oxygen produced via cyanobacterial photosynthesis during daylight hours. During local anoxia at night, iron reducing bacteria may use iron oxides as electron acceptors producing Fe^{2+}. This metabolic process increases local alkalinity more than other common metabolisms and favors CaCO3 precipitation. Since Fe^{2+} can substitute for Ca^{2+} in the CaCO3 crystal lattice, evidence of iron reduction may be preserved within stromatolite laminae. To test this, we examined the distribution of Fe, Ca, Mg, S, Si, Al, Ti, and Sr in several stromatolites with ages spanning their historic rise, peak, and decline using micro X-ray Fluorescence

Spectrometry and Raman Spectroscopy. We find that stromatolites with presumed biogenic origin show a heterogeneous distribution of iron inextricably linked to stromatolite laminae and the presence of Ca and not S, indicating that the iron is located within $CaCO_3$ and not pyrite. Additionally, background levels of detrital input gleaned by Si, Al, Ti, and Sr are insufficient to explain cyclic increases in iron corresponding to laminations. An abiogenic stromatolite sample displayed a homogenous iron distribution and no association with laminae. This indicates that iron association with laminae in biogenic stromatolites may be a genuine biosignature of microbial iron reduction and Fe-cycling and suggest the presence of a critical stromatolite lithification mechanism.

A Mesoproterozoic weathering event and its possible link to oxygenation

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The mid-Proterozoic interval (approximately 1.8–0.8 Ga) is characterized by low atmospheric oxygen levels and widespread oceanic anoxia, punctuated by intermittent oxygenation events. Previous studies have revealed a notable oxygenation event recorded in shallow marine carbonates of the middle Gaoyuzhuang Formation (~ 1.57 Ga, North China). This event is associated with a negative carbon isotope excursion and coincides with the presence of some of the earliest known multicellular eukaryotic fossils, some of which are exceptionally large. However, weathering conditions during this period and the underlying cause of this oxygenation event have received limited attention and remain uncertain. In this study, we present isotopic records of strontium (133 samples) and lithium (57 samples), as well as paired carbon and oxygen isotopes (240 samples) derived from carbonate rocks from four different sections of the Gaoyuzhuang Formation. Following a section-by-section diagenetic screening process, the selected high-quality samples exhibit positive shifts in both Sr and Li isotopes, by approximately 0.0007 and 6 ‰, respectively, just below the carbon isotope negative excursion (i.e., the oxygenation event). The observed increases in seawater Sr and Li isotopes contradict the previously proposed hypothesis of enhanced weathering of Large Igneous Provinces (LIPs) during this period, as LIPs typically exhibit less radiogenic and more congruent isotopic signatures. Instead, it is possible that an enhanced incongruent weathering of radiogenic, K-rich rocks (indicated by the presence of A-type granite and felsic rock peaks) generated through the partial melting of ancient continental crust, triggered the simultaneous increases in seawater Li and Sr isotope ratios. In the meantime, increased CO_2 degassing from LIPs extruded during breakup of the supercontinent Nuna would have favoured enhanced weathering by maintaining high CO_2 during this period. Such a change in weathering conditions preceding the ~1.57 Ga carbon isotope anomaly suggests that increased input of nutrients via weathering may have led to enhanced oceanic primary productivity and ultimately transient ocean oxygenation.

Dormant Arctic thermophiles point to cellular life histories operating over geologic timescales

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Thermophilic organisms, life that can only grow at high temperatures, are often found in permanently cold environments, such as the Arctic, where temperatures are too cold for their growth and activity. The presence of thermophiles in cold environments suggests there are transportation vectors between the cold environments in which they are found and hot ecosystems, such as hydrothermal vent systems, tectonic spreading centres, or deep subsurface biospheres. Transportation vectors may include ocean or air currents or rising hydrothermal fluids. Their presence in cold regions also suggests that some thermophiles have strategies for surviving inhospitable environments long enough to allow this transportation to occur. Dormancy through specialized structures called endospores allows organisms to be resistant to conditions that would otherwise kill the growing and active organism. Endospores allow the dormant organism to remain viable for thousands to millions of years suggesting thermophilic endospores could survive cold and inhospitable environments on geologic timescales. We used high-temperature laboratory incubation and genomics to identify thermophilic endospore-forming organisms in geothermal spring water from Greenland. We suggest that rising fluids carry thermophilic life from the deep hot biosphere to the cold Arctic surface and that these dormant thermophiles remain viable, able to begin growth and activity upon encountering hot environments again. This work illuminates a cellular life history that may operate over geologic timescales and points to strategies that could confer survival during extra-planetary dispersal or panspermia.

Dynamics of ocean oxygenation and anoxic events

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The atmosphere and ocean have become progressively oxygenated over Earth history. Ocean redox state is decoupled from atmospheric oxygen and is also controlled by oxygen demand from decay of organic matter and hence by marine nutrient level and productivity. Previous work has linked Phanerozoic Ocean Anoxic Events (OAE) and Neoproterozoic-Paleozoic Ocean Oxygenation Events (OOE) to nonlinear feedbacks generated by the redox-sensitivity of phosphorus burial. However, an overall understanding of controls on stability and dynamics has been lacking.

We introduce a dynamical systems framework that exploits timescale separation in the Earth system to provide qualitative insights into the dynamics of global marine phosphorus and atmospheric oxygen. The Earth system may be in a highly nonlinear "excitable" regime where stochastic forcing by small tectonic events can produce a large transient response (an OOE or OAE), or may show stable or oscillatory behaviours. We use a hierarchy of models in the PALEO framework to show that the primary control on stability is the spatial heterogeneity of ocean floor marine carbon and phosphorus burial environments. This heterogeneity mediates the link between globally integrated marine burial fluxes and atmospheric oxygen and total marine phosphorus. Local marine shelf and slope environments (which dominate organic carbon and phosphorus burial) are thereby linked to global Earth system dynamics.

Preliminary comparisons of model predictions to Neoproterozoic-Paleozoic datasets demonstrate that considering both stability and stochastically

forced excitability can explain observed patterns in carbon and uranium isotopes. Our approach connects qualitative insights from low-dimensional dynamical systems at a global scale to spatially resolved process models at the local scale and can be applied to other areas in Earth system dynamics.

Solid Earth forcing of oceanic anoxic events

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Oceanic anoxic events (OAEs) are geologically rapid phases of extreme oxygen depletion in the oceans that caused mass extinctions of marine biota. The main phase of OAEs in the Mesozoic Era, occurring from about 180–85 million years ago, coincided with extensive volcanism that accompanied a global reorganization of the continental landmasses. However, whether the OAEs were ultimately the result of changes in carbon dioxide emission from volcanoes or enhanced chemical weathering of Earth's surface in the greenhouse world, is unclear. Here we combine plate tectonic reconstructions, tectonic-geochemical analysis, and global biogeochemical modelling to show that OAEs can be explained by enhanced weathering of reactive mafic lithologies during continental breakup and nascent seafloor spreading. Weathering pulses collectively gave rise to massive releases of the nutrient phosphorus to the oceans, stimulating biological primary production, which enhanced organic carbon burial and caused widespread ocean deoxygenation on a scale sufficient to drive recurrent OAEs. Our results implicate strong feedbacks between the solid Earth, oceans, and atmosphere, reshaping our understanding of how the first-order reorganization of Earth's surface environment sets the tempo of climate and biotic change over geological time.

Ocean redox and nutrient cycling in the ~1.64 Ga Chuanlinggou Formation, North China Craton

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While the Earth system remained poised at a low oxygen state across Earth's 'middle age' (~1.8-0.8 Ga) , it is increasingly apparent that oxygenation levels fluctuated, with considerably temporal and spatial heterogeneity in the redox chemistry of the oceans. However, the evolution of global and local ocean redox conditions across this interval remain poorly constrained, as do the underlying controls on apparent variability in ocean redox conditions. Here, we have focused on the ~1.64 Ga Chuanlinggou Formation on the North China Craton, to investigate temporal and spatial variability in oceanic redox conditions and associated nutrient cycling. High resolution samples from two drill cores have been analysed, with a focus on redox controls on phosphorus phase partitioning and cycling. The two drill cores, which were deposited in a shallow shelf setting only 2 kilometres apart, surprisingly show diverse features. For example, the succession begins with the deposition of an iron formation in the shallowest setting, while this iron formation is absent in the slightly deeper water setting. Nevertheless, multiple independent redox proxy data reveal that the deeper water Chuanlinggou Formation samples were generally deposited under ferruginous conditions, with periodic development of oxic intervals, and the iron formation is interpreted to have formed during upwelling of anoxic ferruginous waters in oxic shallow waters. Our focus on high resolution P

phase partitioning analyses reveals new insight into the nature of biogeochemical P cycling and its control on planetary oxygenation in the late Paleoproterozoic.

Constraining the redox landscape in Mesoproterozoic mat grounds: A possible oxygen oasis in the 'Boring Billion' seafloor

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The Earth's middle age or the 'Boring Billion' (~1.8 to ~ 0.8 Ga, billion years ago) represents one of the most enigmatic intervals in Earth's history, characterized by the absence of significant carbonate carbon isotope excursions and the sluggish evolution of eukaryotes. It is widely accepted that the atmospheric O_2 level was low (<1% PAL or < 10% PAL) and the ocean remained predominantly anoxic with the development of sulfidic (H_2S rich) continental margins. It is suggested that 2–10% of seafloor euxinia was sufficient to deplete some micro- nutrients in the ocean inventory, such as Mo and Cu, which are essential for nitrogen-fixation for eukaryotes. However, recent studies report multicellular fossils and episodic/sporadic inception of oceanic oxidation in Mesoproterozoic. These findings imply the possible occurrences of oxygen oasis that provided habitable niches for eukaryote evolution. Such oxygen oasis likely developed at shallow marine seafloor covered with microbial mat, where O_2 produced by benthic cyanobacteria resulted in the oxygenation of seafloor. Therefore, in order to constrain the habitability of Mesoproterozoic oxygen oasis, it is essential to reconstruct the O_2 fugacity in the seafloor. In this study, we analyzed pyrite

sulfur isotopes and pyrite contents of the Mesoproterozoic Wumishan Formation (~1.4 Ga). The Wumishan Formation is composed of cyclic deposition of, in a shoaling upward sequence, the subtidal calcareous shale, massive thrombolitic dolostone, and microbial laminated dolostone. Both microbial laminated dolostone and thrombolytic dolostone precipitation involved with microbial activities, and thus might record the redox condition of putative oxygen oasis in the Mesoproterozoic oceans. We apply the One-Dimensional Diffusion-Advection-Reaction (1D-DAR) model to simulate diagenetic pyrite formation in sediments. Sedimentation rate can be well constrained by the depositional cycles of the Wumishan Formation. The modelling results indicate that more than 60 ~ 80% of H2S that was generated in microbial sulfate reduction (MSR) was reoxidized, and that organic matter supply, both from surface water and seafloor, was limited. Thus, our study indicates that the seafloor could be substantially oxygenated in Mesoproterozoic, even when the atmospheric O_2 level was extremely low. Shallow marine seafloor covered with microbial mat may function as the oxygen oasis, providing habitable niches for the evolution of eukaryotes.

Patterns of floral dominance-diversity architecture across the Pennsylvanian-Permian boundary of western equatorial Pangea

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The late Palaeozoic was a time of major global change, shaped by the formation of the supercontinent Pangea and the transition from a deep icehouse (Cisuralian) to greenhouse (Lopingian) global climate coupled with dramatic oscillations in the extent of southern hemisphere ice during the Late Palaeozoic Ice Age (360-255 million years ago). These pronounced tectonic and climatic shifts helped drive compositional changes in lowland vegetation throughout the western and central regions of the Pangean equatorial belt, propelling spatial and temporal swings in the relative abundance and proportional dominance of mesomorphic-to-hygromorphic floras to those typifying xeromorphic, or seasonally dry habitats, beginning in the late Middle Pennsylvanian and becoming prominent around the Pennsylvanian-Permian boundary. This expansion of lower diversity floras of seasonally dry habitats may also suggest a net reduction of biodiversity in the fossil record accompanying the rapid environmental warming characterising the Pennsylvanian-Permian boundary and into the early Middle Permian. However, the relationship between wetland and seasonally dry elements of this region remains coarsely understood due to variability in their patterns of occurrence within mixed floras. In this study, we explore the dominance-diversity profiles of nearly fifty localities throughout western equatorial Pangea, modern north-central Texas, spanning the Late Pennsylvanian Markley Formation (Wolfcampian) through the early Permian Waggoner Ranch Formation (Leonardian). Based on plant macrofossil census collections housed at the US National Museum of Natural History, preliminary analysis of the structure and diversity of these plant communities indicates that mosaic landscapes, meaning a mix of wetland elements, dominated by marattialean tree ferns, lycopsids, medullosan pteridosperms, callipterids, and sphenopsids and seasonally dry elements, dominated by conifers, taeniopterids, cordaitaleans, and noeggerathialeans, may hold greater significance than previously thought in our understanding of the ecological dynamics of the Pennsylvanian-Permian boundary.

Sulfate concentrations in the global ocean through Phanerozoic time

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Understanding the long-term variance of seawater sulfate concentrations ($[SO_4^{2-}]_{sw}$) is of great importance due to the dynamic relationship between the sulfur and carbon cycles on Earth, leading to the eventual oxygenation of the surface environment and an Earth capable of supporting large eukaryotic life forms. In this study we explored how $[SO_4^{2-}]_{sw}$ has changed throughout the course of the Phanerozoic and its possible relationship to atmospheric oxygen and the climate, by utilising the biogeochemical box model: GEOCARBSULFOR. We reveal that $[SO_4^{2-}]_{sw}$ rose throughout the Paleozoic, declined during the Mesozoic and then rose once more in the Cenozoic, generally matching the currently available geochemical proxies. Atmospheric oxygen mirrors $[SO_4^{2-}]_{sw}$ during the Paleozoic and Mesozoic, but intriguingly, decouples during the Cenozoic, possibly due to increasing rates of uplift of mountainous regions exposing pyrite to oxidation during this time. We explored $[SO_4^{2-}]_{sw}$ further by introducing scalings to the sulfur fluxes, finding that pyrite burial during the Carboniferous needs to be significantly increased in order for the model to match proxy records. Separately, we modelled the effect of excluding calcium concentrations as a constraint on gypsum burial, finding that calcium holds a dominant control on $[SO_4^{2-}]_{sw}$ through the Phanerozoic, but its effect on atmospheric oxygen and climate, in the model, is muted.

Enhanced continental silicate weathering linked to the Karoo-Ferrar LIPs in the lacustrine Sichuan Basin during the Jenkyns Event

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The Early Jurassic Jenkyns Event (ca. 183 Ma) represents a major environment perturbation, characterized by a negative carbon isotope excursion during the early Toarcian. Currently, the activity of the Karoo–Ferrar LIPs (183 ± 1 Ma) is considered to have driven this event, with enhanced continental silicate weathering providing an important link between the Karoo-Ferrar LIPs and the Jenkyns Event. However, previous studies have focused only on western Tethys, while the response of the eastern Tethys realm, which is relatively distant from the Karoo–Ferrar LIPs, has not yet been reported. These issues have limited understanding of the impact of the Karoo–Ferrar LIPs and the mechanisms driving the Jenkyns Event. Here, we report multi-proxy analyses (including organic carbon isotopes, iron speciation, mercury (Hg) concentrations and isotopes, and detrital lithium (Li) concentrations and isotopes) for two drill cores (proximal X3 core and distal LQ104X core) from different depositional environments in the lacustrine Sichuan Basin of SW China, with the aim to explore the global impact of the Karoo–Ferrar LIPs activity on silicate weathering (weathering congruency) in the eastern Tethys realm. The results show synergistic fluctuations between the redox proxies, and Hg and Li geochemical and isotopic signatures in the Sichuan Basin during the Jenkyns Event. Specifically, significantly elevated Fe_{HR}/Fe_{T} and Fe_{Py}/Fe_{HR} ratios alongside Mo_{EF} and U_{EF} systematics indicate that anoxic-ferruginous conditions were occasionally interspersed with euxinic episodes. In addition, an apparent Hg enrichment, particularly in the distal LQ104X core, combined with fluctuations in the Hg isotope system ($\Delta^{199}Hg$ and $\Delta^{200}Hg$ values) suggest that the Sichuan Basin records the activity of the Karoo-Ferrar LIPs. Furthermore, a decrease in detrital $\delta^{7}Li$ suggests that continental silicate weathering was significantly enhanced (more congruent silicate weathering) at the periphery of the Sichuan Basin during the Jenkyns Event, and did not develop into extremely high-intensity congruent weathering, which may be related to the relatively arid climate of the eastern Tethys. Taken together, we infer that the enhanced continental silicate weathering associated with the activity of the Karoo-Ferrar LIPs was the triggering mechanism for the Jenkyns Event. This is the first combined study of Hg isotopes and detrital Li isotopes during the Jenkyns Event, and provides important insight to unravel the global drivers of the T-OAE.

Reconstructing levels of volcanic ashfall through geological time

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Volcanic ash is known to influence a range of biogeochemical processes once deposited in the oceans. These processes include the fertilisation of phytoplankton, and the enhancement of organic carbon burial, and the impact typically scales with the volume of ash. It has been shown that during periods of intense volcanic ash deposition, the impact on the ocean carbon cycle can be significant enough to cause global cooling. As a result, knowing the volume of ash entering the world's oceans through time is vital to understanding the role explosive volcanism plays in setting global climate states. However, records of ash deposition consist of a small number of individual archives of ash input estimated via either layer counting or from multivariate statistical partitioning. Here, we compile the discontinuous and patchy records of volcanic ash deposition in the Pacific Ocean over the past 70 million years and synthesise all available data to produce a coherent record of ash accumulation rates. We show how the development of certain provinces, such as the Izu-Bonin Arc led to considerable upticks in ash input, and discuss how changing levels of ash deposition may have impacted Cenozoic climate change. Further to this work, we present and discuss preliminary efforts to extend this estimate of Pacific Cenozoic volcanic ashfall to global estimates across the Phanerozoic.

Modelling climate change over 500 million years - a community resource for ecological and biodiversity modelling

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During the Phanerozoic (the last ~0.5 billion years), the Earth has experienced massive changes in climate, spanning the extensive glaciations of the Permo-Carboniferous (~300 million years ago), to the mid-Cretaceous super-greenhouse (~100 million years ago). Recently, several studies have used geological data to reconstruct global mean temperatures through this period, as a way of characterising the zeroth-order response of the Earth system to its primary forcings. However, there has been little modelling work that has focused on these long timescales, due to uncertainties in the associated boundary conditions (e,g., CO_2 and paleogeography) and to the computational expense of carrying simulations spanning these long timescales. Recently, paleogeographic (Scotese and Wright, 2018) and CO_2 reconstructions (Foster et al, 2017) have emerged, and model and computational developments mean that we can now run large ensembles of relatively complex model simulations. In particular, here we present an ensemble of 109 simulations through the Phanerozoic, with a tuned version of HadCM3L that performs comparably with CMIP5 models for the modern, and is also able to produce meridional temperature gradients in warm climates such as the Eocene in good agreement with proxy data. We show that the model produces global mean temperatures in good agreement with

proxy records. The resulting model fields can (and indeed have) be used as input to ecological and biodiversity modelling studies, and some of the results of such studies are presented here, but the main aim is to provide this exciting resource to the community.

Disentangling the effects of seasonality from average conditions on modeled forest distribution during the Pennsylvanian

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Iconic Carboniferous arborescent lycophytes (lycopsids) are thought to have been relegated to refugia by moisture seasonality based on evidence from fossil and geological records. Lycopsids were replaced across much of their range by Marratialean tree ferns and early diverging conifers (cordaitaleans), which may have been dry-adapted. We simulate global arboreal vegetation in the late Paleozoic ice age by combining climate modeling and ecosystem-process modeling for two end-member conditions representing glacial and interglacial extremes of the late Paleozoic ice age (LPIA). Extinct plants are represented by fossil-derived leaf C:N, maximum stomatal conductance, specific conductivity, and stem physiological limitations for several major Carboniferous plant groups. We simulated global ecosystem processes at a 2-degree resolution with Paleo-BGC. We use a unified statistical modeling framework to disentangle moisture seasonality (i.e., the skew of precipitation) from other abiotic factors—simulation average temperature and precipitation from National Center for Atmospheric Research's Community Earth System Model version 1.2 (CESM) simulations parameterized for the Pennsylvanian, varying pCO_2 and

continental configuration and ice extent for glacial-interglacial cycles—in their effect on plant performance of four major late Paleozoic plant taxa. Based on preliminary statistical analysis, we hypothesize that moisture seasonality will have an impact on simulated plant performance as strong as average precipitation or temperature. Ecosystem simulations parameterized using era-appropriate stem and leaf trait combinations may provide an objective measure of non-analog plant and ecosystem function using methods that are applicable across deep time.

The nature of LUCA and its impact on the early Earth system

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The nature of the Last Universal Common Ancestor (LUCA), its age and its impact on the Earth system have been the subject of vigorous debate among diverse disciplines based on disparate data. Age estimates for LUCA are usually based on the fossil record, varying with every reinterpretation. The nature of LUCA's metabolism has proven equally contentious, with some attributing all core metabolisms to LUCA, while others infer it to have been half alive, subsisting only with the aid of geochemistry. Here we use a set of pre-LUCA gene duplications, calibrated with eukaryote fossils to infer that LUCA was older than 3.9 Ga, thus predating the end of the Late Heavy Bombardment. We use phylogenomics to estimate a species tree of Archaea and Bacteria, confirm its root to be on the branch separating these lineages and reconstruct the evolution of key metabolic gene families through gene

tree-species tree reconciliation. We found LUCA was similar to modern prokaryotes in complexity: and infer it was an anaerobic, cellular acetogen that possessed UV damage repair enzymes and a CRISPR-cas anti-viral defense system. We infer a much larger genome (1297 genes) than previous estimates, hallmark enzymes of which hint at a cooler ecology, closer to the surface of the water. Our results support a hydrogen-fuelled early ecosystem powered by the reactions of the WLP/Acetyl-CoA pathway enhanced by the photochemical breakdown of the waste product CH4 in the atmosphere where air-sea exchange of H2 and HCN could provide global supplies of free energy and nitrogen respectively.

Testing for a signal of solar irradiance in fern spores from the K/Pg boundary

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The K/Pg boundary is famously marked by one of the most prominent mass extinction events. It is generally accepted nowadays that the main cause was an extraterrestrial impact and its subsequent effects on the global climate. The model proposed by Alvarez et al. (1980, Science 208) involves an "impact winter" caused by a dust cloud formed by ejecta in the stratosphere. This is thought to have hindered photosynthesis in plants. Our study aims to test this theory. In many sections preserving the boundary, palynofloras right above it are dominated by fern spores. The sporopollenin making up the spore walls is chemically complex and variable, including UV-B absorbing compounds. The concentration of these compounds can be measured using Fourier-transform infrared (FTIR) spectroscopy. It has previously been

shown with this method that the relative abundance of UV-B absorbing compounds correlates with the UV irradiance during plant growth. We are now analysing fern spores obtained from dense sampling around the K/Pg boundary in North America to show whether they document a drastically reduced irradiance immediately above the boundary consistent with the influence of a dust cloud.

Shifting sands: Are late Ediacaran fossil assemblages reliable records of original ecosystems?

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Recent research into the bed-scale spatial ecology, functional traits, and metabolisms of Ediacaran macro-organisms has revealed information on their feeding habits, reproduction and life history, and their response to fluctuating redox conditions of terminal Precambrian oceans. However, such studies assume that the fossilised organisms are preserved in, or very close to, the environments in which they lived.

The latest Ediacaran Nama Group of southern Namibia (~549–539 Ma) preserves both soft-bodied and biomineralized macrofossils, providing insight into the early evolutionary history of metazoans. We present sedimentological evidence from over 40 fossil-bearing beds in the Witputs Sub-basin of southern Namibia that demonstrates ubiquitous transport of both soft-bodied and biomineralizing macro-organisms in cohesive debris flows, turbidites, and linked debris flow-turbidite 'hybrid' event beds. Event beds have been sourced from up-slope shallower environments, with transport placing preserved macrofossils, including all 'classic' Namibian taxa of the Ediacaran biota, in environments potentially far removed from

their original life habitat and geochemical environment. Individual fossil specimens act as clasts within beds, and can be horizontal, imbricated, or chaotic in orientation, reflecting different sediment transport modes (laminar, transitional, or turbulent flow) rather than life position or feeding behaviours. Rare storm event beds, conversely, are recognised to smother and preserve in-situ assemblages of entirely different taxa, including tubes, *Beltanelliformis*, and simple horizontal burrows, in relatively deep-water depositional environments. The distinct in-situ and transported fossil assemblages are preserved in close stratigraphic proximity, but may not have been in close environmental proximity or interacted in terminal Precambrian ecosystems. Transport also complicates other common analyses, in that geochemical signatures recorded in proximal beds may have limited relevance to the geochemical requirements of associated macro-organisms preserved within those same beds.

Recognition of widespread specimen transport within the Witputs Sub-basin has implications for research into bed-scale ecologies, species interactions, and feeding behaviours of taxa in this region. Furthermore, the discovery of distinctive new fossil assemblages on rare in situ matground horizons offers opportunities to directly compare terminal Ediacaran shallow marine ecosystems from Namibia with those in older Ediacaran settings such as Russia and South Australia, to determine the role of environment in shaping the global distribution of Ediacaran early animals.

Radiations and extinctions in early Paleozoic oceans: understanding the dynamics of the early marine biosphere

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The early Paleozoic (Cambrian and Ordovician – 541-444 million years ago, Ma) represents a key interval for the establishment of marine communities. Following the appearance of most animal phyla that we know today during the "Cambrian Explosion", the Early and the Middle Ordovician reflect their rapid diversification at lower taxonomic levels during the "Great Ordovician Biodiversification Event" (GOBE). This protracted phase of net biodiversification, already identified in the seminal compilation of Sepkoski, stands in recent paleontological compilations, and constitutes the most prominent increase in the diversity of marine organisms during the entire Phanerozoic. Yet, Cambrian-Ordovician extinction rates derived from the paleontological databases are an order of magnitude higher than during the rest of the Phanerozoic. Taken together, these analyses suggest that the early Paleozoic marine biosphere exhibited specific dynamics that would not show up again later during the Phanerozoic.

However, paleontological databases, often due to incomplete and heterogeneous sampling, are necessarily biased and the veracity of the reported global temporal trends in diversity and extinction are increasingly often questioned. Recent work suggests that the pause in biodiversification separating the Cambrian Explosion and the GOBE ("Furongian Gap") may be an artifact of geological sampling and that instead, a long-term early Paleozoic biodiversification may exist, consisting in a series of local radiations with biodiversification hotspots moving through space and time. Concomitantly, the deleterious impact of sampling bias on the calculation of background extinction rates has long been discussed and mathematical models show that decreasing background extinction rates are an expected outcome of increasing sampling of faunas during the Phanerozoic. Therefore, reassessing the dynamics of marine Life at the dawn of the animal-rich biosphere today constitutes both an urging question and a scientific challenge. Although geological proxy data permit documenting deep-time environmental changes with continuously improving robustness and temporal resolution, they can only be used to establish temporal correlations and thus bring no firm response.

Here, we propose an alternative, innovative approach to mark a step change in our understanding of the dynamics of marine Life during the early Paleozoic. We go beyond temporal correlations and interrogate the causal relationships governing the co-evolution of Life and the physical environment in the Cambrian and Ordovician using a physically-consistent coupled climate-biodiversity numerical simulation framework. Our numerical simulations, guided by the abundant geochemical database and compared with the paleontological record, allow us to quantify the impact of changes in key environmental variables on speciation and extinction rates, and standing marine biodiversity.

Exploring belemnite calcite as an archive of water column phosphorus

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Determining changes in marine nutrient cycling throughout Earth's history is key to understanding periods of environmental change, as well as the functioning of Earth's systems. Phosphorus is considered to be the limiting marine nutrient over geological timescales and has also been identified as a potential driver of oxygen depletion in ancient oceans. Despite its importance, obtaining direct information on spatial and temporal variations in phosphorus concentration has proved challenging. Recent work has determined that analysing phosphorus in biogenic carbonates can be used to investigate changes in water-column phosphorus concentration (Dodd et al. 2021, GCA). Building on this approach, we have explored using belemnites, an extinct group of nektic molluscs with an internal calcite skeletal structure called the rostrum, as a monitor of water-column phosphorus concentration.

We have developed a method to quantify phosphorus in belemnite rostra and applied this method to samples from multiple sites in the European Epicontinental Seaway (EES) from the upper Sinemurian to the Toarcian in the Lower Jurassic, a time period likely to contain a range of water column phosphorus concentrations. We present carbonate-associated phosphorus records from three different locations in the EES, and comparisons between these records of redox and temperature proxies for the same basins. Data from each basin demonstrates coherent coincident changes in P/Ca ratios within different sites in the EES. The data also show covariation in P/Ca and Mg/Ca from all sections studied. This suggests that incorporation of phosphorus into belemnite calcite is either (i) mineralogically controlled by the concentration of magnesium in the calcite, or (ii) both Mg and P incorporation are controlled separately but respond similarly to another palaeoenvironmental factor such as temperature or salinity. We make an argument for the need for a careful, holistic view of belemnite chemistry and biology in the synthesis and interpretation of stratigraphic records.

Climate homeostasis by and for active inference in the biosphere

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In this work we prove that a biosphere-climate dynamical system maintains stationary climate dynamics by active inference. We partition a simple dynamical model of the biosphere-climate system into internal states–the biosphere– and external states–the net incoming solar radiation, separated by a boundary comprising sensory (surface temperature) and active states (greenhouse gases concentration). We then numerically identify a synchronisation function that maps internal states to a probability distribution (posterior belief) over external states. Our results suggest that the biosphere can be seen as inferring changes in incoming net solar radiation via changes in greenhouse gas concentrations that result in the maintenance of stationary surface temperature dynamics. When the surface temperature is perturbed away from its expected state, the biosphere-climatic system acts on the external states to restore climate stationarity, in a way that could be interpreted as an active correction of sensory prediction errors. Modifying system parameters that relate to energy balance changes the properties of the synchronisation map and therefore affect the quality of inference. When the solar constant reaches levels below those of 4 Gyr ago or more than 1.5 Gyr from the present, inference fails. The historical early microbial biosphere or the future biosphere's lifespan roughly corresponds to solar constant within those limits where climate homeostasis is at play by and for active inference in the biosphere.

Heterogeneous sulfide reoxidation buffered oxygen release in the Ediacaran Shuram ocean

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Ediacaran (~635-539 Ma) carbonate rocks record the largest negative carbonate-carbon isotope excursion in Earth history, termed the Shuram Excursion (SE). This event has been attributed to anaerobic oxidation of dissolved organic carbon as a result of enhanced weathering inputs of sulfate to the ocean during the amalgamation of Gondwana. However, the effect of carbon-sulfur cycle interplay on the net redox state of the ocean-atmosphere system remains unclear, impeding our understanding of the co-evolution of life and the environment during the Ediacaran. Here, we generate high-resolution records of paired sulfate sulfur and oxygen isotopes, in addition to phosphorus concentrations, for the SE interval in South Australia (Parachilna Gorge) and South China (Jiulongwan and Xiang'erwan sections, Three Gorges), and we evaluate these data in the context of COPSE biogeochemical model simulations to assess net long-term redox changes. Our results support widespread H_2S reoxidation in shelf areas during the SE, which would have buffered the net release of oxygen sourced from the burial of organic carbon and pyrite. Varying degrees of H_2S reoxidation on different cratons likely contributed significantly to high spatial heterogeneity in both local oceanic redox state and nutrient availability, which characterized local oxygen-deficient conditions in an overall oxygenated SE shelf ocean, and likely affected the distribution of the Ediacaran Biota. Our study highlights the important role of H_2S reoxidation

in the coevolution of marine redox conditions and complex life during the critical Ediacaran period.

Mass extinctions and close calls: Using experimental Earth system and ecophysiological modelling to understand what makes a catastrophic extinction

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Ancient warming events are commonly proposed as deep-time analogues for modern climate change. However, ancient hyperthermals are complicated by potentially critical differences in the rate and magnitude of warming, and changes in key Earth system boundary conditions such as continental configuration. These differences make it difficult to compare ancient extinctions to the modern biodiversity crisis, and to mechanistically understand why some ancient warming events resulted in more severe marine extinctions than others. The synergistic effects of ocean warming and deoxygenation have been proposed as key physiological mechanisms for driving extinction in marine animals across hyperthermals through time, emphasising the importance of spatially explicit palaeoceanography to provide direct links between climate and animal physiology.

We first address how oxygen minimum zones respond to different rates and magnitudes of global warming under different Mesozoic–Cenozoic continental configurations using the cGENIE Earth system model. Then, we use ecophysiological modelling approaches to simulate how the combined physiological impacts of marine oxygen, temperature, and productivity dynamics control the ability of marine organisms to track their physiological niches in response to warming. Using these modelling approaches, we investigate why well-characterized Mesozoic–Cenozoic hyperthermal events resulted in markedly different marine biodiversity responses. In so doing, we evaluate how well approaches to modern global change predict ancient mass extinctions. This enables us to contextualise how ancient mass extinctions can inform us about both modern climate change and each other, for instance aiding comparisons between the Permian-Triassic extinction and the current extinction crisis. Despite informative correlations between ancient warming and catastrophic extinctions through time, many classic examples of warm climates over the last 300 million years do not correlate with major marine extinctions. Our approach therefore also allows for the evaluation of specific 'close calls' in Earth history – such as addressing why marine extinction at OAE-2 was less severe than at the Permian-Triassic.

Calibrating the diversification of early animals during Ediacaran–Cambrian interval using a newly proposed beta ichnodiversity

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Trace fossil documents the complex interactions between animal, substrate and the fluid flow, thus provides important insights into the body plan, motility and behaviours of the trace maker. An interval when trace fossil record is especially important is the Ediacaran–Cambrian transition, which records the diversification and evolution of earliest complex animals on the Earth. To quantify the variation in the diversity of trace fossils across this critical interval, a new measure of beta ichnodiversity based on vector calculation is proposed. The obtained results enable us to quantify the diversification rate of traces over this transition, and help calibrate the timings when different behaviors (grazing, foraging, resting, parenting etc.)

first appeared. Deciphering these results in the context of environmental change and advancement of motility and sensibility, we can further precisely pinpoint the advent and sequence of the Fortunian Diversification Event, Cambrian Information Revolution and Agronomic Revolution, shedding light on the diversification of animals' body plans, behaviors and locomotory capabilities during the Ediacaran and Cambrian transition. Applying this newly-proposed metrics to the ichnological records from shallow and marine settings, a more rapid diversification rate in shallow marine settings, and the progressive niche partitioning process during Ediacaran to Cambrian are also identified.

Phosphorus controls on the formation of vivianite versus green rust under anoxic conditions

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The formation of green rust (GR; a mixed ferric/ferrous hydroxide) and vivianite (ferrous phosphate) are likely to have exerted a major control on phosphorus (P) cycling in ancient anoxic oceans. However, the factors that influence the formation of these minerals under different chemical conditions are poorly constrained, which limits understanding of the pathways that ultimately result in P drawdown and retention in anoxic sediments. This, in turn, limits understanding of P cycling in anoxic oceans and hence potential productivity feedbacks. Here we explore the effect of dissolved P concentration on the formation of sulfate GR (FeIII2FeII3(OH)12SO4) versus vivianite (FeII3(PO4)2·8H2O) under anoxic conditions. Our results show that at low dissolved P concentrations and with P:Fe(II) molar ratios <1:30, P drawdown is effectively controlled by interlayer anion exchange and adsorption onto GR species, via the formation

of amorphous Fe-P precursors. Such precursors may delay the precipitation of crystalline GR, but vivianite was not detected under these conditions. At higher dissolved P concentrations and P:Fe(II) ratios, GR also forms. However, the GR formed under these conditions rapidly dissolves, likely forming amorphous ferric hydroxides together with dissolved Fe(II) and phosphate, with the dissolved species subsequently reacting to form crystalline vivianite. Our observations agree with studies showing the water column formation of GR in modern oligotrophic, anoxic Fe-rich (ferruginous) settings, and provide support for a major role for GR in controlling P cycling in ancient oligotrophic ferruginous oceans. By contrast, in more productive ancient anoxic settings, enhanced redox-controlled P recycling and/or increased weathering inputs would have led to higher dissolved P concentrations in the water column and sediments. Our observations show that such conditions ultimately promote the formation of vivianite, which would have exerted a limiting control on the extent of P recycling in ancient, more productive settings, via the long-term fixation of P in the sediments.

Poster Presentation Abstracts

Primary producer dominated environment of the Ediacaran-Cambrian transition in the Mackenzie Mountains, northwest Canada

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The early evolution of macroscopic life, including the Cambrian 'explosion' of animals, took place over more than 100 million years against the backdrop of dynamic environmental changes such as unstable redox conditions and nutrient supply. The transition from the terminal Ediacaran into the early Cambrian is marked by the appearance of macroscopic biomineralizers and burrowing behaviour seen in complex trace fossils, but also a seeming decline in diversity of macroscopic fossils. Occasionally termed the 'Kotlinian crisis', this diversity decline contrasts the rich communities of macroscopic Ediacara-type biota preserved in older units worldwide. Our understanding of this biotic change, as well as its environmental drivers, suffers from stratigraphic incompleteness, as continuous mid and upper Ediacaran, and Cambrian strata are rarely exposed in a continuous sequence in the same area, or represent different depositional settings.

The Mackenzie Mountains in the Northwest Territories, Canada are a home to a nearly continuous sedimentary succession from the Cryogenian to the Cambrian and as such, provide a great target to analyse biotic and environmental changes through time. We have investigated the succession of carbonates and siliciclastics through the Blueflower, Risky, Ingta, Backbone, and Vampire formations. Here we present integrated palaeontological and geochemical data to produce a high resolution biostratigraphic and chemostratigraphic profile for the Ediacaran-Cambrian boundary interval.

The Ediacaran-Cambrian boundary occurs in the Ingta Formation, estimated by the sporadic occurrences of trace fossils Treptichnus. Simple bed-parallel traces *Planolites* occur throughout the formation. Also common are well-preserved bacterial filamentous organic-walled microfossils in mudrocks, and prasinophyte disaster taxa, but the boundary interval lacks complex acritarchs or cuticular animal remains. Macroscopic carbonaceous fossil problematica were also recovered. The first occurrence of complex trace fossils is in the overlying Backbone Ranges Formation, and their abundance increases in the Vampire Formation, but complex traces absent from the lowermost Cambrian strata in the Mackenzie Mountains. This primary producer dominated environment and the absence of organically preserved animal remains in a setting otherwise conducive to organic preservation imply a true decline in diversity through the boundary interval – possibly a result of either phylogeny or ecology.

Oceanic redox conditions during the terminal Cambrian extinction event

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In the late Cambrian period, a number of extinctions have typically been attributed to anoxic events evidenced by positive carbon isotope shifts. In this study, we analysed carbon and uranium isotope ratios ($\delta^{13}C$ and $\delta^{238}U$ values) for carbonate rocks from the Wa’ergang section in South China. Our dataset covers the period that includes the last major negative $\delta^{13}C$ excursion (TOCE) of the Cambrian Period, and the recovery/rising limb of TOCE corresponds to the terminal Cambrian extinction event. We found that the $\delta^{13}C$ and $\delta^{238}U$ values are correlated and shift together throughout the section, initially decreasing to lower values, with $\delta^{238}U$ falling below the modern open-ocean seawater value from the beginning to the middle of the profile, followed by an increase towards the end of the Cambrian. This positive coupling of $\delta^{13}C$ and $\delta^{238}U$ has not been commonly reported before, and it suggests the existence of extensive intermediate reducing settings (from low-O_2 suboxia to intermittent anoxia) during the late Cambrian having relatively low atmospheric pO_2 and a greenhouse climate. We propose that an expansion of intermediate reducing conditions, rather than persistent anoxic euxinia, is consistent with the recovery of $\delta^{13}C$ and $\delta^{238}U$ to higher values, as well as the presence of benthic fauna and the shoreward extension of deeper-water fauna that may have had greater tolerance against hypoxia.

Biogeochemical consequences of benthic extinctions during the end-Permian mass extinction

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The end-Permian mass extinction (EPME) was the most devastating mass extinction that occurred in the Phanerozoic, resulting in severe impacts to benthic ecosystems. In particular, shallow marine bioturbators – animals that burrow into and mix seafloor sediments – were profoundly impacted by the EPME. The Early Triassic trace fossil record indicates a reduction in trace fossil diversity, size, and depth, which are all evidence for a severe reduction in bioturbation intensity. Moreover, it has been proposed that the collapse in bioturbation intensity after the EPME led to a significant reduction in the sedimentary mixed layer. The collapse of the Early Triassic sedimentary mixed layer has been hypothesized to have had various biogeochemical consequences to benthic sulfur cycling, organic carbon burial, and water column oxygen dynamics. However, no hypotheses about the biogeochemical impact of the loss of bioturbation and the collapse of the sedimentary mixed layer in the Early Triassic have been quantitatively tested. Moreover, some complex, large bioturbators persisted regionally and may have maintained the sedimentary mixed layer locally, although the biogeochemical significance of these persisting bioturbators remains unclear. Here, we run a series of biogeochemical modeling experiments to investigate the biogeochemical consequences of the EPME's impacts on bioturbators and the sedimentary mixed layer. First, we use cGENIE to reconstruct environmental conditions in Early Triassic benthic ecosystems and compare these reconstructions to the trace fossil record to understand what ecophysiological variables may have influenced bioturbators' survival and extinction. Second, we use the reconstructions of benthic ecosystem conditions and the trace fossil record to simulate the EPME's impact on sediment biogeochemistry using a sedimentary reaction-transport model. Ultimately, we find that the biogeochemical consequences of the loss of large, complex bioturbators and the collapse of the sedimentary mixed layer in the Early Triassic are locally variable. In particular, the nature and magnitude of biogeochemical changes are a function of local environmental conditions and the ecological strategies of bioturbators which were present in each Early Triassic ecosystem. The results of these biogeochemical modeling experiments provide new insights into the impacts of the EPME on benthic ecosystems, the relationship between bioturbators and biogeochemistry in deep time, and the biogeochemical nature of recovery during the Early Triassic.

A Bayesian approach to stratigraphic correlation and dating

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Reconstructing the evolution of life and environments requires the integration of palaeoenvironmental and fossil data into a common temporal framework. Many geological formations lack radiometric dates, making stratigraphic proxies like stable isotope ratios invaluable for correlating records from different sedimentary sections. Here, we present a Bayesian stratigraphic model that uses the global signature of δ13C excursions to correlate proxy records from multiple locations. The model works by evaluating the fit of Bayesian splines to different alignments of the sections, using Markov Chain Monte Carlo methods to obtain the posterior distributions. Our model also integrates radiometric dates across sections, using ages from well-dated sections to inform age estimates in sections with little or no age information. This results in absolute age estimates with age uncertainties for every data point in each section, while also providing a probabilistic assessment of different alignment possibilities. Additional data, such as prior information on sedimentation rates or unconformities can be easily integrated to further constrain the resulting age model. Our new method is particularly suited for improving the temporal resolution of palaeoenvironmental and palaeobiological datasets from the Neoproterozoic and early Palaeozoic, where reliable index fossils are scarce.

Tilioideae-Anthophila interactions in the Cenozoic of Europe

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Bees of Europe are known to visit Tilia flowers of the subfamily Tilioideae and pollen grains of this plant genus are frequently found on the bee's exterior, especially in their corbiculae and scopae. To unravel the origin and history of Tilioideae-Anthophila relationships through the geological history of Europe, we studied flowers and insects from four Paleogene localities in France and Germany, including Menat (middle-late Paleocene, Selandian-Thanetian, 61–56 Ma), Messel (middle Eocene, early Lutetian, c. 48 Ma), Eckfeld (middle Eocene, middle Lutetian, c. 44 Ma), and Enspel (late Oligocene, late Chattian, c. 24 Ma), focusing on Tilioideae flowers and fossil bees with in-situ and/or adhered Tilioideae type pollen. Additionally, we also investigated living wild bees from different regions of present day Austria and screened them for Tilioideae pollen. Today, the Tilioideae consists of three genera; Craigia (2 spp.), Mortoniodendron (16 spp.), and Tilia (31 spp.). Craigia is restricted to S. China and Vietnam, Mortoniodendron ranges from S. Mexico to Colombia, but Tilia has a wide Northern Hemispheric distribution. All three genera are generally insect pollinated, some taxa are also wind pollinated, and all groups are known to be visited by both Anthophila (e.g., bees, bumblebees) and Diptera (e.g., hoverflies, blowflies).

Our study revealed a close relationship between bees and Tilioideae flowers in Europe already during the Paleocene and spanning more than 55 million years until present day. We have identified bees with adhering Tilioideae pollen from all investigated localities. In addition, we have discovered several fossil flowers from Eckfeld and Enspel with in-situ Tilioideae type pollen enabling a morphological/anatomical comparison with extant flowers of the subfamily. Our findings suggest that in Europe bees visited Mortoniodendron flowers during the Paleocene and Eocene, then Craigia and Tilia from the Oligocene to Miocene, and then continued visiting Tilia until present times.

Earth System dynamics at the dawn of the animal-rich biosphere

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Earth System boundary conditions remain either substantially under-constrained, or contentious in their interpretation, for the late Ediacaran–early Cambrian interval (circa 580 to 510 million years ago), a time of major macroevolutionary innovation. Currently there are a number of plausible continental reconstructions for this interval but generally limited proxy data to constrain environmental context. Modelling studies investigating time slices over this interval are therefore obliged to either make unpalatable choices about boundary conditions, or to incorporate the full range of uncertainty in each parameter, which is computationally expensive. In this presentation, we summarise the current state of knowledge in late Ediacaran and early Cambrian Earth System boundary conditions and outline a framework to reduce current levels of uncertainty. Within this framework, we plan to build on the holistic approach we have previously developed,

whereby we couple a broad spectrum of geological data with high resolution climate model simulations to iteratively assess 'best fit' between data and models. We will apply this approach to six time slices corresponding to major intervals of macroevolutionary innovation during the late Ediacaran–early Cambrian. In parallel, we will develop (a) $\delta^{18}O$ palaeo-temperature proxy dataset based on phosphatic materials, (b) a suite of climatically-sensitive lithological data, and (c) climate simulations exploring the range of plausible boundary conditions. By iterative comparison of climate model simulations and proxy data we will be in a position to produce high-resolution reconstructions of Earth's climate through the late Ediacaran and early Cambrian. This approach is similar to that employed for examining Earth System evolution in geologically younger time intervals. Advances in stratigraphic resolution and palaeoclimate proxy data and models now make it possible to apply this method for the late Ediacaran–early Cambrian interval. We aim over the next three years to provide a robust series of detailed reconstructions of the Earth System across this crucial interval in the history of the biosphere, and to provide a framework for tackling macroevolutionary questions in an environmental context.

Palaeoecology and taphonomy of Archaean photosynthetic ecosystems

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Fossilised traces of photosynthetic organisms have an almost 3.5-billion-year record, the most ancient examples being silicified microbial mats and stromatolites of Palaeoarchaean age (Schopf, 2006, PNAS; Hickman-Lewis & Westall, 2021, SAJG). Establishing the palaeoecologies of these fossilised ecosystems is a key step toward constraining the origins, distribution and early evolution of photosynthetic metabolisms.

Microbial mats, and particularly stromatolites, are most accurately appraised as three-dimensional phenomena. As such, in addition to high-magnification petrography, morphological data provided by X-ray tomography has emerged as a key tool for understanding 3D lateral variability in shape and composition, particularly in stromatolites with high degrees of remineralisation. Achieving sub-micrometre resolutions, we have demonstrated the preservation of numerous micromorphologies diagnostic of biogenic growth processes, including 3D non-isopachous laminae, grain trapping, fenestrae, and oriented fabric elements such as microbial palisade structure (Hickman-Lewis et al., 2017, JGS London; 2023, Geology).

Highly complementary compositional information given by Raman and Fourier Transform infra-red (FTIR) spectroscopy shows that remnant kerogen in Palaeoarchaean microbial mats is syngenetic and includes diverse organic materials (Hickman-Lewis et al., 2018, Precam. Res.; 2020, Palaeontology). FTIR detections of aromatic C–C, aliphatic C–H, carboxylic COOH and other organic groups denotes the former presence of EPS-rich microbial mat communities that underwent extremely rapid and resilient preservation and entombment by silica. Quantifying the CH3/CH2 ratios of microbial mat carbonaceous materials has also enabled the distinction between mats dominated by Bacteria and those dominated by Archaea (Hickman-Lewis et al., 2020, Palaeontology). Scanning transmission electron microscopy (STXM) has further shown that biogeochemical heterogeneities are preserved in these mats.

Finally carbon isotope geochemistry has shown a dominance of remarkably heavy values (–20 to –10‰), consistent with an ecosystem containing abundant anoxygenic photoautotrophs, with relatively minor contributions from other groups (e.g., methane-cyclone organisms) identified by more negative carbon isotope fractionations.

In concert, these complementary approaches provide new insights into the palaeoecology of Archaean microbial ecosystems, constrain their roles in, and influence on, global biogeochemistry at this early period of Earth history, and explain under which conditions such exceptional preservation may endure in the geological record for billions of years.

Controls on the termination of OAE2 in the Tarfaya Basin, Morocco

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Black shales deposited during Cretaceous oceanic anoxic event 2 (OAE2, ~94 million years ago) record major perturbations to biogeochemical cycling (e.g., Fe, S and C). The subtropical shelf of the Tarfaya basin, located on the NW margin of Africa, documents anoxic water column conditions before the onset and after the end of OAE2, as indicated by multiple, independent redox proxies. During the onset, euxinic conditions dominated but were

periodically interrupted by the development of ferruginous episodes linked to orbitally-driven changes in weathering inputs of reactive Fe and sulfate. Extensive recycling of phosphorus (P) from the sediments back to water column maintained strongly reducing conditions by promoting primary productivity in the surface waters, which resulted in an enhanced export of organic matter to the sea floor (Poulton et al. 2015, Geology).

To understand the controls behind the termination of the event, we have performed a high resolution study of the recovery phase, utilising a combination of multiple redox-proxies, carbon isotopes ($\delta^{13}Corg$) and phosphorus phase partitioning. Iron-sulphur systematics and high uranium enrichments point to prevailing anoxia during the recovery phase. However, the redox chemistry fluctuated between ferruginous/weakly euxinic and strongly euxinic conditions on short time scales, as indicated by variations in molybdenum enrichments linked to the availability of dissolved sulphide. Towards the end of the recovery phase, however, redox proxies point to the progressive development of less reducing conditions, which is further reflected by a decrease in P recycling. Temporal variations in nutrient availability coupled to trade wind-induced changes in upwelling intensities along Tarfaya's coast may have exerted the overall control over the termination with intervals of extensive P drawdown aiding the recovery from water column anoxia. These dynamics emphasise a high degree of instability during the recovery phase on a local scale. However, global instability during the recovery is also indicated by the occurrence of the Holywell Event, a $\delta^{13}C$ excursion, representing a short-lived episode during which strongly reducing conditions and increased P recycling transiently returned.

The formation of carbon-sulphur biomorphs as potential protocells in earth Earth environments

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The origin of life (OoL) is thought to require three key ingredients for propagation: (1) a metabolic system, (2) a replication mechanism and (3) compartmentalisation. Here we investigate a possible mechanism of compartmentalisation in the OoL, offering insight into candidates for membrane structures the earliest life on Earth may have utilised. Using a 'bottom-up' experimental approach, early Earth sulphidic environments are laboratory synthesised to investigate the self-assembly of carbon-sulphur biomorphs (CSBs) and assess their role in potential protocell formation during abiogenesis. It is shown that anoxic, euxinic and ferruginous high and low salinity aqueous environments can facilitate CSB formation with select prebiotic organics and that Fe3+ may act as a viable oxidising agent in an anoxic ocean world. CSBs candidacy as a false biosignature in Earth's geological record is questioned, and a preservation mechanism using iron-oxides and iron-sulphides is suggested.

Widespread chemically oscillating reactions during oxidative diagenesis and fossilization recorded in the Ediacaran Doushantuo Formation

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The Neoproterozoic oxygenation event co-occurred with widespread phosphate deposition in sediments, the formation of concretionary structures, and the rise of animals, all well-recorded in South China. However, all these remain enigmatic and the presence of purported animal embryos and other fossils inside phosphate granules is poorly explained by rounding through sediment reworking and ultimately brought from elsewhere. The latter popular explanation also does not predict that such spheroids should contain any mineral patterns or fossils. Here we show that diagenetic spheroids such as botryoids, rosettes, granules, nodules, and concretions are widespread in the Ediacaran Doushantuo Formation and we document evidence that they indicate chemically oscillating reactions (COR) during oxidative organic diagenesis. The distinct radial and concentric geometry in diagenetic spheroids spans several orders of dimension sizes, as do fractal patterns from COR. Their mineral assemblages include apatite, carbonates, organic matter (OM), sulfides, sulfates, and metal oxides, such that their precursor compounds are analogues of COR reactants and products. Additionally, OM within diagenetic spheroids is compositionally variable, suggesting out-of-equilibrium conditions during biomass oxidation in seafloor sediments or low-grade metamorphism. Hence, COR elegantly explains the exceptional preservation of fossils within diagenetic spheroids as a major consequence of oxidative diagenesis.

The Boring Billion: Hurdle or stepping stone for life on Earth? A geodynamic perspective

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Earth's 'Boring Billion' or 'Middle Age' (~1.8 – 0.8 Ga) clearly played an important role in the evolution of the biosphere, but did ocean and atmospheric conditions delay the evolution of complex life, or were evolutionary pressures a trigger for biological diversification? A comprehensive understanding of the life and planet requires integration of data from the geosphere, atmosphere, hydrosphere and biosphere. Although much has been postulated about the tectonic and geodynamic evolution of the Boring Billion in the last decade, through the arm-waving one can find little quantification, and an abundance of untested claims. Therefore, even our understanding of the geosphere during the Proterozoic remains a box of unknowns.

So what do we know, what don't we know, and what do we need to better quantify? This study reviews the knowns and known unknowns of the tectonics and geodynamics of the mid-Proterozoic, so that future models of bio-geochemical cycling can be better informed, and to pave a clearer path to a better integrated understanding of this enigmatic period of Earth history.

Through paleomagnetic records combined with geological records of magmatism and metamorphism, a geodynamic framework can be established that comprises the formation and break-up of the Columbia and Rodinia supercontinents, with diverse orogenesis that had subtle but critical differences to modern orogenic belts. Contrary to some claims, plate tectonics with long-lived subduction and arc magmatism was maintained throughout these supercontinent cycles. The abundance of LIPS was not abnormal, and atypical magmatic suites common to this time, such as anorthosites, can be explained by the effects of secular mantle cooling. Evidence for sub-continental thermal blanketing due to the long-lived Columbia supercontinent is lacking.

Why do the above matter to the biosphere? Because topography, emergence and the composition of the continents have a key role in chemical cycles. Although it has been claimed that continental emergence occurred in the Neoproterozoic, there are no independent data to support this claim. However, the extent of sub-aerial continents during the Proterozoic lacks precise quantification. A variety of proxies and models for both continental thickness and continental elevation have been proposed in the last decade, but it can be demonstrated how these are flawed, and in some cases contradictive. Thus, topographic evolution of both the stable continental areas, and in particular, of active continental margins, remains a priority area for further research and quantification. Rather than relying on geochemical proxies taken in isolation, integration of detailed geological records such as sedimentology, the pressure-temperature evolution of specific orogens, and magmatic composition, are likely to be more fruitful.

The Garbh Eileach Formation, SW Scotland: A strengthened case for the Tonian–Cryogenian GSSP

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The boundary between the Tonian and Cryogenian periods (c. 720 Ma) represents a transition into one of Earth's longest and most extensive ice ages, the Sturtian glaciation. Owing to major global glacioeustatic sea level fall and the action of glacial erosion, the sedimentary record of this transition has commonly been erased. Missing strata at such a key juncture presents a significant challenge to both stratigraphic correlation of pre-glacial successions, and the establishment of a formal Global Stratotype Section and Point (GSSP) for the basal Cryogenian.

The Garbh Eileach Formation (GEF) is a >75 m succession of Tonian carbonates that directly underlies the 1.1 km thick glaciogenic Port Askaig Formation of Sturtian affinity. Fairchild et al. (2018) argued for a possibly unique transitional contact between Tonian and Cryogenian sediments on the largest of the Garvellach islands (Garbh Eileach) where the formation is best exposed. Amongst several lithostratigraphic observations for the gradual onset of ice (e.g. ice rafted sediment, gypsum pseudomorphs), their argument is poised on the preservation of the Garvellach carbon isotope ($\delta^{13}C$) anomaly and associated $\delta^{13}C$ values of clasts in the overlying diamictite. The carbonate $\delta^{13}C$ values defining the 'Garvellach anomaly' in the GEF, descend from -4‰ to -7‰, before recovering to +1‰ immediately beneath the overlying glaciogenic Port Askaig Formation. The GEF hosts the most complete known record of this global signal, where it is somewhat anchored chronologically by late Tonian 87Sr/86Sr signatures of 0.7066–0.7069 (Sawaki et al., 2010); however, the Garvellach anomaly is evidenced in at least two further global sections (Lamothe et al., 2019). In the absence of a reliable biostratigraphic framework for the Tonian, the point at which the δ13C values of the Garvellach anomaly become positive, 4 m below the first evidence for ice-rafted sediment, may offer a chronostratigraphic horizon suitable for the basal Cryogenian GSSP (Fairchild et al., 2018).

In 2013, Garbh Eileach was visited by the Cryogenian Subcommission to review its suitability for the placement of the basal Cryogenian GSSP within the GEF. The Scottish succession boasts a relatively thick and complete record of Sturtian glaciation as well as 100% exposure across the proposed Tonian-Cryogenian transition (Ali et al., 2018). Furthermore, the island of Garbh Eileach is relatively accessible and open to further research, all of which address criteria set out by the International Commission on Stratigraphy for future GSSPs. Although Garbh Eileach is considered to be a highly promising GSSP candidate due to its suitability as a chemostratigraphic type section, the lack of a direct radiometric age constraint still needs to be addressed (Shields et al., 2018). For this reason, we are focussing our attention on producing a more robust geochronological constraint for the GEF, while increasing the resolution of the Garvellach anomaly.

Here we present preliminary attempts at deriving a radiometric age constraint for the GEF by directly dating calcite using the U-Pb geochronometer. In-situ U-Pb carbonate geochronology has had recent success for Tonian carbonate successions to within 2.5% uncertainty (Lan et al., 2022) and it is hoped that further investigation will produce a meaningful age for this succession. These findings are coupled with a new high resolution δ13C curve (>200 data points) across the c. 75 m of exposed GEF on the island of Garbh Eileach. The new curve displays a similar form to that of Fairchild et al. (2018) and further refines the proposed chronostratigraphic horizon at which the GSSP could be placed.

Interrogating the links between coeval Earth system perturbations, climatic forcings, and the onset of the Sturtian glaciation, remains challenging. However, we consider that our high resolution, multiproxy study of the demonstrably transitional succession at Garbh Eileach will help to maximise the geological significance of any future Cryogenian GSSP, while shedding light on a remarkable episode in Earth's history.

Modelling the life-environment interface in ancient shelf seas

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The co-evolution of life and environment is a dynamic system of feedbacks. Yet studying events through a series of stratigraphic horizons reduces dynamic feedback loops to proxy correlations and invites speculation as to the cause and effect relationships. Models can suggest hypotheses to test ecosystem dynamics and the effects of changes to life or the environment on the other. Much of the evolution of life took place in localized shelf sea environments. Evolving biota and redox conditions created feedbacks which are hypothesized to have increased the ecospace for life to radiate - and sometimes perhaps brought about its own demise. A particular modelling challenge is to connect these localized environments to global Earth system dynamics over long timescales. A hierarchy of models is needed to separate spatial and temporal scales and allow for the construction of models specific enough to be supported by limited geological data. We introduce a 1D column model of an ocean shelf sea in the PALEO framework to represent the ecological dynamics of important early life forms such as plankton, sponges and early burrowers and their effects on redox conditions, sediment burial and diagenesis. This model demonstrates that ecological dynamics and nutrient cycling can be modelled at the finest scales, while being computationally viable over geological timescales. Ongoing work

integrating this model with data from critical time intervals in the Ediacaran and Cambrian can provide specific hypotheses for the local behavior of the life-environment interface and can be connected to broader models for global investigations.

Sedimentary processes in an active floodplain produce wide ranges in sediment Hg contents: Implications for the "Hg anomaly" paleo-proxy

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Mercury (Hg) anomalies in sedimentary deposits are frequently used as proxies for environmental perturbations in Earth's past, including as evidence linking massive volcanism with mass extinction. However sedimentary archives also integrate a range of materials and processes that can complicate interpretation of stratigraphic changes in Hg concentrations. Resolving how Hg is cycled in sediment routing systems is critical for assessing Hg variations in sedimentary records. To better understand how sedimentary deposits acquire and store Hg, we have been studying deposits from a large alluvial river—the Koyukuk River, a major tributary of the Yukon draining the southern Brooks range—near Huslia, Alaska. The river deposits sit within Pleistocene eolian deposits up to 11,600 years old. We characterized the organic carbon stocks and ages of sediment from contrasting geomorphic units across the floodplain, and then investigated how Hg is distributed within the deposits. We find very large ranges in Hg contents and ratios of Hg to Total Organic Carbon (TOC), which vary by ~2 orders of magnitude across this active floodplain. These results point to the need for more work to characterize how sedimentary processes

influence the Hg contents and Hg/TOC ratios of sedimentary archives, potentially independently of large changes in external Hg sources such as volcanism.

How did Earth's climate remain conducive to life? Examining the role of chance using an energy balance model

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The climate of our planet has remained suitable for habitability over a timeframe of 3 to 4 billion years. Should Earth’s climate have failed catastrophically just once throughout this significant period of evolution, development of life would have ceased and humanity would not exist now. The faint young sun paradox describes a puzzle in Earth’s climate history, where solar luminosity of our sun has increased by 30% since life first evolved; if this had not been counteracted somehow, Earth would have become sterile due to climate becoming incompatible with life. Moreover, Earth’s climate is fragile, as seen in climate records and also in current anthropogenic climate change (~1°C temperature change within only a couple of centuries). Taken together, uninterrupted habitability across several billion years is surprising and requires explanation. This study builds on an earlier one (Tyrrell, 2020), to investigate whether similar results are found with a zero-dimensional (global) energy balance model (this study) as were found with a simpler model (the earlier study). A large number of planets were each assigned a variety of random climate feedbacks. These planetary arrangements were each tested to check whether they remained habitable over a period of 3 billion years. Whilst the accepted view suggests that Earth’s long period of habitability is due to stabilising mechanisms only, results collected with the original version of this model suggested chance played a role in the outcome of planets, in addition to mechanism. The

results from this study agree very closely with those from the simpler model, cementing the suggestion that chance played a role in Earth's persistent long-term habitability.

Taphonomic variation in vase-shaped microfossils from dolomite nodules of the Late Tonian Chuar Group, Grand Canyon, Arizona, USA

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Vase-shaped microfossils (VSMs), found in middle Neoproterozoic rocks worldwide, are interpreted as testate amoebae in the Amoebozoa, thus providing the earliest direct evidence for predatory eukaryotes in the fossil record. In addition to their palaeobiological significance, some VSM species are regarded as potential Tonian biostratigraphic index fossils due to well constrained stratigraphic ranges, global distribution, and a variety of preservation modes in numerous lithologies. In the Chuar Group of the Grand Canyon (Arizona, USA), VSMs are reported in cherts, carbonates, and black shales as siliceous and calcareous casts and molds (sometimes coated with organic matter, pyrite, or iron oxide), as casts of pyrite and iron sulfate minerals such as jarosite, and as original organic tests. VSMs are found in great numbers (up to 4000/mm3) in dolomite nodules in black shales of the Walcott Member, uppermost Chuar Group. For this study, we sampled fossiliferous dolomite nodules at ~5 m intervals spanning ~50 m of stratigraphy on Nankoweap Butte to study VSM taphonomy within a stratigraphic and sedimentological framework. We used scanning electron microscopy to document mineral phases and patterns of preservation in 57 VSM specimens from three nodule samples (15–25 specimens per nodule). A majority (60%) of VSMs are preserved as siliceous casts with calcareous—likely dolomite or Mg-rich calcite—internal molds, with most remaining

(32%) specimens preserved as calcareous internal molds. Very few are preserved as (4%) siliceous casts with siliceous internal molds and as (4%) internal molds of amalgamated pyrite framboids, a taphonomic mode not previously documented from the Chuar Group. Elemental mapping reveals that more than half of the VSMs (n=33), independent of preservation mode, show patterns of aluminum- and/or potassium- enrichment adjacent to test walls, where sometimes it is clear that clay minerals are coating microfossil material. Finally, we report the presence of phosphatic scale microfossils in two of three nodule samples. These phosphatic scales may be found tangential to or within VSMs that are primarily siliceous casts with calcareous internal molds.

Redox and biotic response to the early Silurian Ireviken Event, Welsh Basin, UK

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The Llandovery-Wenlock boundary interval in the early Silurian was a pivotal period marked by significant marine environmental evolution and biotic turnover, culminating in the Ireviken Extinction Event (IEE), which coincided with the Early Sheinwoodian Carbon Isotope Excursion (ESCIE)1. The Ireviken carbon cycle perturbation coincided with a proposed expansion of euxinic waters along continental margins, according to geochemical evidence. The ensuing oceanic hypoxia caused a crisis in marine ecosystems, a typical and recurrent scenario during the Silurian era. However, previous studies have focused on carbonate strata deposited in shallow water platforms2, with a lack of crucial geochemical data for siliciclastic successions deposited across the continental shelf-slope. To address this gap, we applied multiple independent redox proxies to three sections deposited across a bathymetric transect in the Welsh basin, UK. Our findings suggest that oxic depositional conditions progressively gave way to anoxia, with the specific development of euxinia in mid-depth waters, across the Llandovery-Wenlock boundary. However, in the shallowest water setting, an oscillating redox state between ferruginous-oxic or ferruginous-euxinic conditions is documented, with intervals of more persistent and intense bottom water anoxia exerting a particularly strong impact on the benthic biota. Our study highlights the importance of deeper marine sections for understanding the complex dynamics of the IEE and providing crucial insight into the role of marine anoxia in shaping the evolution of marine ecosystems during the Silurian era.

Trace elements, carbon and sulfur isotopes constraints on redox environments and origin of P accumulation in the earliest Cambrian

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The Earliest Cambrian recorded the emergence and extinction of Cambrian-type small shelly fauna (SSF), and their intimate association with phosphorites. To place better constraints on the oceanic redox conditions and the origin of the extreme P enrichment, a series of geochemical analyses are conducted, including trace elements, total organic carbon, carbon isotopes, and sulfur isotopes of organic matter ($\delta^{34}S_{kero}$) and pyrite ($\delta^{34}S_{pyrite}$) at the outcrop section, North China. A gradual evolution of redox conditions is identified, from euxinic (interval I) to suboxic-oxic (interval II and III), and further back to euxinic conditions (interval VI). High primary productivity coincided with euxinic interval period. The relatively low $\delta^{34}S_{kero}$ and $\delta^{34}S_{pyrite}$ values, with former slightly lighter than the latter corresponds with interval I period euxinia, suggesting organic matter sulfurization occurs more

quicklier than reactive Fe in pervasively sulfidic water column. The $\delta^{34}S_{pyrite}$ values shift positively to around 27‰ upwards whilst $\delta^{34}S_{kero}$ remains stably low values during suboxic-oxic interval II and III period, indicating organic matter was sulfurized mainly in shallow sediment or at the water-sediment surface, while pyrite was formed within the deeper sediment with limited sulfate supply. The invariable and high $\delta^{34}S_{kero}$ and $\delta^{34}S_{pyrite}$ values recorded in the interval VI sediments suggest that BSR occurred both in larger sinking organic particles in the context of stable euxinic water columns and sediments. The P enrichment in the association with the most negative carbon, sulfur isotopic compositions of kerogen in the lower Yurtus Formation suggests that phosphate was released by decomposition of dissolved organic carbon through BSR in the water column and then upwelled to the surface water, which enhanced bloom of small shelly fauna and thus deposition of black shales with phosphatic SSF at the base of Yurtus Formation.

Using Gaussian Processes to reconstruct seawater calcium, magnesium, and sulphate concentrations over the last 100Myr

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The seawater concentrations of calcium, magnesium, and sulphate are linked to many biogeochemical processes, including: skeletal mineralogy of calcifiers, seafloor spreading rate, and determination of palaeo temperature, pH, and CO_2 from oceanic proxies. Our current understanding of how the concentrations of calcium, magnesium, and sulphate evolved over the last 100Myr comes mainly from fluid inclusions, but the seawater magnesium/calcium ratio is independently estimated by other archives (such as corals and carbonate veins), and the seawater calcium concentration is independently estimated by the sodium/calcium ratio of foraminifera. Combining the estimates from these techniques creates an overdetermined system, where datapoints are relatively sparse, somewhat clustered, and often have substantial uncertainty – meaning interpolation is not straightforward. Here we illustrate using a Gaussian Process approach to perform a joint reconstruction of all available data. This approach allows us to integrate the information on the residence time of each element, the uncertainty on the data, and the data density of each signal to reconstruct the non-linear history of seawater calcium, magnesium, and sulphate concentrations.

Decline and fall? Examining Late Cretaceous ammonoid diversity patterns and their drivers using a Bayesian framework

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Ammonoid cephalopod molluscs were integral components of marine ecosystems for over 300 million years. Their evolutionary success is often considered to have waned through the Late Cretaceous prior to their final extinction at the end of the Mesozoic. The pattern of this hypothesised decline and its drivers (abiotic or biotic) are unresolved, and require disentanglement from the pervasive spatial and geographical sampling biases that affect the fossil record. We compiled data from the published literature, new and unpublished museum collections, and the Paleobiology Database (PBDB), to generate a large database (>20,000 occurrences) of Late Cretaceous (Cenomanian – Turonian) ammonoids, employing statistical methods to detect and resolve stratigraphically and taxonomically spurious occurrences. We divide our database into spatially-standardised

subsamples, eliminating geographic sampling bias and providing a regionalised perspective on the apparent global decline of ammonoids. We then infer regionalised diversification dynamics in a Bayesian framework that corrects for uneven sampling through time (PyRate). We uncover a mosaic of ammonoid diversity patterns, demonstrating that a global trend of ammonoid decline is not regionally pervasive. Preliminary analyses suggest that spatially varied palaeogeographic and environmental drivers are responsible for this mosaic, highlighting strong biogeographic nuances in the history of this iconic and well-sampled fossil group prior to the end-Cretaceous (K-Pg) mass extinction.

The Earth Science Box Modeling Toolkit (ESBMTK)

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Box modeling is a versatile tool to explore earth systems processes, ranging from transient changes in the marine carbonate system to the long-term evolution of biogeochemical cycles. The Earth Science Box Modeling Toolkit is a python based toolkit that allows for the rapid creation and deployment of box models. It abstracts typical modeling tasks, e.g., air-sea gas exchange, weathering, seafloor carbonate precipitation/dissolution, kinetic isotope fractionation, etc., to python classes. Class instances can then simply be combined to build a model. While there is no graphical interface, this approach significantly reduces coding complexity and model development time. Crucially, the model structure is independent of the numerical implementation. Instead the model is parsed to dynamically create the necessary equation systems that can be passed to ode solver libraries like ODEPACK. Separating model description from numerical implementation results in well-documented model code, and combines the computational efficiency of state-of-the-art numerical libraries with the ease of use of

python. The efficiency of this process is demonstrated by a 12-box model with air-sea gas exchange, tracers for carbon isotopes, and water column carbonate chemistry that requires about 1 CPU second to calculate the model evolution over 30 million years.

Carbonate precipitation versus sapropelic events in the Sea of Marmara

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The factors controlling methane emission dynamics at ocean margins are essential to the Earth's global carbon cycle. Significant uncertainties on how cold seepage may have responded to environmental changes in the geological past are still poorly understood. In the Sea of Marmara, we found a sapropel layer that may reflect major anoxic events and paleo-environmental changes over the last deglaciation period. Below the deposition of sapropel, the absence of carbonate concretions in the lacustrine sediment indicates that low sulfate concentrations in pore waters during the glacial time and so the processes of anaerobic methane oxidation (AOM) in sediments were prevented. However, sulfate input by Mediterranean waters incursion allowed AOM, and as a result, aragonite-rich concretions occur above the regional sapropel. Thus, cold seeps have strongly influenced the local environment through variations of dissolved sulfate and oxygen contents in the water column which vice versa may have impacted the marine carbon cycle in past and modern oceans.

Climate changes in the non–glaciation epoch of Cryogenian, global synthesizing with new findings from the Datangpo Formation in south China

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Cryogenian non–glaciation epoch (CNE) is a period from the termination of the Sturtian snowball Earth to the initiation of the Marinoan snowball Earth in ca. 9.8 myr. Carbonate sequences in low latitudes and siliciclastic deposition of south China in middle latitudes record characteristics of climate variations in CNE. Three carbon isotope (δ13C) negative excursions, named Rasthof, Tayshir and Trezona excursions from bottom to top, bracket two $\delta^{13}C$ stable stages forming CNE in carbonate sequence, however, time of the subdivision has not been calibrated in the absence of chronologic or cyclostratigraphic constraints in carbonate sequences. Datangpo Formation (Fm) in south China is mudstone and siltstone dominated strata, preserving complete siliciclastic deposition in CNE. A high–resolution magnetic susceptibility (MS) profile of the Datangpo Fm has been used to establish the astronomical scale of CNE. Here statistical methods including smooth curve, boxplot and Mann–Kendall mutation test on the MS profile are performed and environmental magnetism measurements of high–temperature-dependence of MS, isothermal remanent magnetization, anhysteretic remanent magnetization and saturation isothermal remanent magnetization in the samples from the Datangpo Fm are carried out. The results reveal four segments of the Datangpo Fm, in ascending order, ascent segment (Da), low stable segment (Db), transition segment (Dc) and high stable segment (Dd). The time and the duration of the segments are calculated in 659–655.6 Ma, 655.6–653.3 Ma, 653.3–652.3 Ma and 652.3–649.2 Ma, respectively. Environmental magnetism analyses from Db to Dd segments imply that Dd

has more concentration and larger size of terrigenous magnetite than Db. Sea–level's dropping in Dc well explains the magnetic difference between Db and Dd. As no tectonic event is reported, climate cooling induced continental ice sheet expansion contributes to the decline of the sea–level. Furthermore, the ocean conditions variation of the Datangpo Fm is comparable with the ocean conditions variation revealed in the $\delta^{13}C$ records of carbonate sequences. Da corresponds to Rasthof excursion representing anoxic deep ocean condition and the transition to oxygenation. Both Tayshir excursion and Dc reveal a climate transition event between two stable stages, causing deep ocean translate to anoxic condition in Mongolia and sea-level dropping in south China, so we propose that Dc corresponds to Tayshir excursion at ca. 653 Ma, and Db and Dd correspond to the two $\delta^{13}C$ stable stages, respectively. Our results suggest that the climate became cooling ~ 4 myr before the onset of the Marinoan snowball Earth.

Biogeochemical cycling in the aftermath of the Sturtian Snowball glaciation: Insights from integrated sulfur, uranium, zinc isotopes from the Taishir Formation, Mongolia

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The Cryogenian Period (ca. 717–635 Ma) is bookended by the Sturtian and Marinoan Snowball glaciations with a nonglacial interlude that possibly witnessed important ecosystem transformation. However, the atmospheric-oceanic redox variation and nutrient availability during the nonglacial interval remain controversial. For this study, we present integrated rare earth elements and sulfur ($\delta^{34}S_{CAS}$), uranium ($\delta^{238}U$), and zinc ($\delta^{66}Zn$) isotopes in carbonate rocks mainly from the lowest member (T1) of the Taishir Formation, which were deposited in the aftermath of the Sturtian glaciation on an open-marine carbonate ramp in western Mongolia. Our $\delta^{34}S_{CAS}$ data (up to 68.09‰) are among the highest values during the nonglacial interlude of the Cryogenian and possibly throughout the Earth's history. The value is ~30–40‰ higher than previous estimates of open-ocean sulfate $\delta^{34}S$, consistent with the hypothesis of a ^{34}S-enriched low sulfate deep seawater, possibly relict from the Sturtian glaciation. Additionally, the coupled decreasing of $\delta^{238}U$ and $\delta^{66}Zn$ and increasing $^{87}Sr/^{86}Sr$ in the lower part of T1 member suggest that elevated weathering-derived nutrient input after the glaciation may have increased oxygen consumption in the ocean, leading to intense anoxia and possibly euxinia in locally productive margins. Upsection, the $\delta^{238}U$ and $\delta^{66}Zn$ show a covaried increasing trend with a further slight increase of $^{87}Sr/^{86}Sr$, accompanied by an increase in $\delta^{13}C_{carb}$ to >+5‰. This could potentially be explained by enhanced organic export in a less reducing ocean (suboxic to ferruginous). Due to the massive pyrite and organic carbon burial, the nonglacial atmosphere could have been oxygenated while the deep ocean remained anoxic. Nevertheless, surface seawater could have been well oxygenated due to exchange with the atmosphere and increased oxygen solubility, which is partly supported by decreasing Ce anomalies to values as low as ~0.5. Shallow oxygenated oceans could have paved the way for ecological evolution during the Cryogenian nonglacial interval.