Presentation Abstracts

for

Life and Planet 2024

Burlington House, London
July 2024

Talks

Listed in order of presentation slot

Day 1 - Wednesday, July 10th

10.00

Sea-level controls on Ediacaran-Cambrian animal radiations

Fred Bowyer[1,2]*, Rachel A. Wood [2], Mariana Yilales [2]*

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The drivers of Ediacaran-Cambrian metazoan radiations remain unclear, as does the fidelity of the record. We use an updated global age framework (ca. 580-510 Ma) to estimate changes in marine sedimentary rock volume, and mean generic reconstructed biodiversity and sampling intensity. This approach reveals that sampling intensity and not total marine sedimentary volume flux correlates with overall mean reconstructed biodiversity, whilst second-order (107 Myr) global transgressive-regressive cycles governed the distribution of different marine sedimentary rocks. The temporal distributions of specific Ediacaran assemblages were controlled, in part, by the temporally and spatially limited record of their host lithofacies. While reconstructed biodiversity changes are biased by sampling, the appearance of the successive metazoan morphogroups that define the Avalon, White Sea and Cambrian palaeocommunities coincide with global oxygenation events inferred from calibrated multi-proxy data (carbonate carbon and uranium isotopes), which also coincide with major sea-level changes. In sum, despite a biased record, the drivers of the appearance of successive early metazoan evolutionary assemblages appear to be related to oxygenation events that were often linked to major sea-level changes, where sea-level further controlled the distribution of diverse habitable settings.

10.15

Microbial ecosystem during the late Ediacaran biotic crisis – insights from the Mohyliv-Podilsky Group, Moldova

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The Moldova-Podillya Basin (Baltica palaeocontinent), exposed in Moldova, Romania, and Ukraine, contains a nearly continuous succession of Ediacaran siliciclastic rocks and hosts Ediacara-type macrofossils. The Moldovan sequence comprises Volyn, Mohyliv-Podilsky, and Kanyliv groups. Recently, the maximum depositional age for of the Mohyliv-Podilsky Group was constrained to c. 556.8 to

551.2 Ma. Here we report a moderately diverse assemblage of soft-bodied macrofossils, trace fossils, and organic-walled microfossils (OWM) from the latter two units exposed in northeastern Republic of Moldova. The macrofossil biota is dominated by Nemiana (likely benthic bacteria) and problematica previously interpreted as possible sponges. The microfossil assemblages include filaments of microbial-mat building bacteria, vesicles with branching hyphae-like structures, budding vesicles similar to yeast, and unicellular morphotypes commonly interpreted as prasinophyte algae. While the mat-builder taxa are common throughout the sequence, the strata following a sharp decline in macrofossil occurrence host abundant fungal analogue OWM, in Zinkiv and Kalyus members. These intervals are also characterized by onset of anoxic conditions. The overlying strata contain prasinophyte OWM including Tasmanites, often termed 'disaster taxa' which occur in abundance during/following intervals of biotic/environmental crises. The fossil distribution in the Mohyliv-Podilsky Group offers an insight into a complex microbial community of primary producers and decomposers, and paints a picture of an ecosystem decline and successive recovery over ~5 million years.

10.30

Earth's first mass extinction? Palaeo-environmental controls on the rise and fall of the Ediacaran biota

Brennan O'Connell [1]*, William J. McMahon [1] Alexander G. Liu [1]*

University of Cambridge

Observed shifts in taxonomic diversity between three biotic assemblages of the Ediacaran biota–the Avalon (~575–560 Ma), White Sea (~560–550 Ma), and Nama (~550-539 Ma)–strongly influence current understanding of early animal evolution, and are considered to evidence biological radiation and extinction events. However, the influence of local palaeo-environmental controls on Ediacaran taxonomic diversity is not adequately accounted for in existing datasets. Brief or highly generalised palaeo-environmental descriptions for key localities, limited study of non-fossiliferous units, and differences in interpretation of strata by various research teams complicate palaeo-environmental reconstructions and global site comparisons. Here, we apply consistent field-based sedimentological and stratigraphic methods to reconstruct the palaeo-environmental context of key sites representing each Ediacaran biotic assemblage (from Canada, Australia, and Namibia), considering both fossiliferous and non-fossiliferous intervals. Our approach permits direct comparison of similar palaeo-environments between assemblages, and recognition of potential palaeo-environmental controls on the observed distribution of Ediacaran macrobiota. Preliminary findings suggest broad overlap in palaeo-environments between key sites, with deltaic, shoreface, and offshore shelves represented in all studied basins. However, subtle but important differences between sites have the potential to influence interpretation of true organismal diversity and community structure. For example, a higher prevalence of transported biota in the Nama assemblage compared to the White Sea or Avalon, and far more extensive deltaic deposits in the Avalon (100s of meters thick) than in

the White Sea or Nama (10s of meters thick) may account for variation in community composition, ecosystem maturity, and organism size. Comparisons of taxonomic diversity through time that rely on comparisons between biotic assemblages must account for facies-scale palaeo-environmental variability, to distinguish ecological or environmental controls from evolutionary patterns. Macrofossils are strongly facies and environment-dependant in all studied sections, which impacts interpretation of late Ediacaran extinction events.

10.45

Giant treptichnids from the Ediacaran-Cambrian boundary of Namibia

Simon Darroch [1]*, Alison Cribb [2], Kat Turk [3], Luis Buatois [4], Helke Mocke [5] and Lyle Nelson [6]*

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Treptichnids are a group of trace fossils formed by vermiform metazoans that range from the late Ediacaran to the Recent, characterized by a subhorizontal burrow system with repeated arcuate probes that reach up towards the sediment-water interface. Among treptichnids, Treptichnus pedum is currently recognized as the global biostrigraphic marker for the base of the Cambrian. As arguably the first bed-penetrative trace fossils to appear in the geological record, treptichnids preserve crucial evidence not only for the appearance of new invertebrate body plans and behaviors through the Ediacaran-Cambrian boundary ('ECB'), but also of ecosystem engineering processes that continue to influence benthic communities in the present day. Here, we describe an assemblage of 'giant' treptichnids from the Nomtsas Formation, in the Ediacaran to Cambrian-aged Nama Group of southern Namibia. Burrow systems are large (commonly up to 1.5 cm diameter) but relatively shallow – extending <1 cm below the sediment surface – and preserved both as exposed burrows and circlets of probes on the top of a channel-filled coarse-grained sandstone. This trace fossil assemblage occurs ~10 m above an ash bed dated at 538.58 ± 0.19 Ma, and apparently below the regional FAD of T. pedum, thus suggesting a latest Ediacaran age.

We discuss several aspects of these trace fossils that have broad implications for understanding both the character and timing of the ECB. First, these burrows illustrate a rapid five-fold increase in the maximum body size of treptichnid tracemakers over <4 million years of the late Ediacaran, with minimal changes in burrow architecture. We discuss possible controls on the evolution of motile invertebrate body size over the ECB, as well as the evolution of behavioral complexity. Second, we use geochemical modeling techniques to quantify the ecosystem engineering impact of these burrows, and the extent to which they may have been involved in altering late Ediacaran shallow marine environments and impacting the structure of benthic communities. Third, we discuss its presence in an unusual setting (i.e. channel), and what this may reveal about the evolving ecology of treptichnid tracmakers. Lastly, we discuss the significance of these trace fossils for recognizing the position of the ECB in Namibia, and, more broadly, correlating this challenging stratigraphic boundary worldwide.

11.30

How did the Permian-Triassic hot house climate shape the vegetation landscape and how did the land plant fight back?

Zhen Xu [1], *Jianxin Yu [2], Jason Hilton [3], Barry H. Lomax [4], Paul B. Wignall [1], Benjamin Mills [1]*

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During the Permian-Triassic Mass Extinction (PTME) ~252Ma, diverse lowland forests were replaced by low diversity pioneer herbaceous lycopod communities that proceeded to dominate the Early and Middle Triassic landscape. The flourishing of Early-Middle Triassic herbaceous lycopods was coincident with data that suggests lethally warm surface temperatures (>40°C) occurred across large regions of the planet. To explore how these plants were able to thrive during this interval of enhanced climatic stress, we collected data from over 400 fossil plant specimens from South China, supplemented by additional data from literature reviews from other regions and geological ages. Our studies on their morphology indicate that among all Phanerozoic lycopods the transitional Permian-Triassic genus Tomiostrobus (=Annalepis) has the closest morphological relationship with the recent lycopod Isoetes.

Extant Isoetes are renowned for their flexibility with regard to the photosynthetic pathway they use and their capacity to absorb CO_2 through their roots. To evaluate whether this photosynthetic flexibility was linked to their Early-Middle Triassic ecosystem dominance, we undertook carbon isotope and sedimentary facies analysis including plant taphonomy to test for the presence of the Crassulacean Acid Metabolism (CAM) photosynthetic pathway. Plants capable of CAM pathway growing in stressful environment typically have heavier isotopic signatures while show typical C3 plant signatures in hospitable environment. Our carbon isotope data shows that Permian Triassic Transition Tomiostrobus isotopic signature is on average ~2‰ less negative when compared to contemporary non lycophyte vegetation. Furthermore, the carbon isotope of the Middle Triassic lycopods ~1.07‰ heavier than the other plants, while Late Permian Lepidodendron exhibits a similar $\delta^{13}C$ value with other contemporary plants. These findings suggest that CAM photosynthesis may have played a role in the dominance of the Triassic herbaceous lycopods. The dominance of CAM plants following the PTME has implications from an Earth Systems standpoint due to their diminished productivity and a lower capacity for biotic weathering, features that likely suppressed negative feedback loops important in driving climate stabilization during the ~5Ma PTME recovery phase.

11.45

Tracing the coevolution of plants and the environment in Paleozoic Era ecosystems through plant paleoecophysiology

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Plants have been a key interface in the global carbon and water cycles for nearly 475 million years. Because the core of plant physiology—including photosynthesis and water transport—is biophysical and has remained consistent over this time, key aspects of plant function can be interpreted from fossilized anatomy in a quantitative way. Applying mathematical modeling to anatomically preserved specimens of land plants from the early terrestrial ecosystems of the Rhynie Chert (~405 Ma) through the polar forests of the Late Permian shows a number of significant evolutionary patterns, from the role of drought resistance shaping the early evolution of vascular complexity to novel adaptations to resist extreme drought and frost. Novel adaptations appeared in plants within Paleozoic Era ecosystems that are rare or absent in modern ecosystems, including individual xylem cells that approach the functional capacity of extant multicellular vessels. These adaptations responded to, and drove, vegetation-climate feedbacks that altered plant community composition and Earth surface environments in complex ways, and implementing these adaptations in Earth system models will yield greater insight into these interactions in deep time.

12.00

Exploring root evolution in an Earth System Model

Khushboo Gurung, *Ben Mills*

University of Leeds, University of Leeds

Land plants are a major contributor to global photosynthetic biomass which in turn influences atmospheric CO2 and O2 levels. Their emergence on land has been hypothesised to significantly amplify continental weathering processes, which are a critical component of many global biogeochemical cycles. Here, we attempt to include a spatially resolved vegetation and a rudimentary form of rooting evolution within the climate-biogeochemical model (SCION), to explore the impact of plant colonisation over the Paleozoic. By integrating simplified evolutionary and competition dynamics into the model, we can compare the effects on weathering, carbon burial, and climate to help us better understand the dynamics that influence the expansion of land plants and the resulting long-term Earth system changes.

12.15

Extreme chemical weathering during the P-T transition linked to volcanism-driven terrestrial ecosystem collapse: Evidence from potassium isotopes

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The Permian–Triassic (PT) transition witnessed catastrophic terrestrial and marine extinctions, rising temperatures, extensive wildfires and ocean anoxia, likely triggered by intense volcanism. Continental weathering has been invoked as a mechanism linking land and marine environmental changes, and as a moderating influence on the warming climate. However, controversy persists regarding how chemical weathering changed across the end-Permian mass extinction (EPME) interval, casting uncertainty on the mutual interactions among chemical weathering, terrestrial ecosystem collapse, and marine extinction. The emergence of potassium (K) isotopes offers a new perspective on tracing chemical weathering processes. Here, we report K isotope compositions (δ41K) of three continuous terrestrial successions that span the EPMEmely the Guanbachong, Lengqinggou, and Taoshujing sections in Southwest China. We find that the lowest δ41K values across the PT transition coincide with high total organic carbon (TOC) and Hg concentrations, which is best interpreted by intense chemical weathering associated with increased volcanism and destruction of the land ecosystem. Based on the recently established chronostratigraphic framework, the seawater-recorded weathering history shows synchronicity with that of terrestrial records, which offers primary evidence in support of the hypothesis that enhanced continental weathering led to a surplus of nutrients in the ocean, thus catalyzing the oceanic anoxia and subsequent EPME. Our study has important implications for understanding the response of the surficial environment to climate change and the refinement of Early Triassic precipitation pattern.

14.00

Organic-carbon-induced reduction of phosphate and the availability of soluble and reactive phosphorus species for the origin and early evolution of life

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Phosphorus (P) is a key element for the origin and early evolution of life because it is a major constituent of cell walls, ATP, DNA, and RNA. However, the dominant form of P, phosphate (P^{5+}), has a low solubility in natural fluids, particularly in the presence of divalent cations, e.g., Ca, Fe^{2+}, and Mg. Phosphate limitation may have been overcome in some environments on the early Earth, such as alkaline lakes, but their prevalence remains unknown. Furthermore, phosphorylation, a key step for the origin of life, is inefficient with phosphate. In contrast, phosphite (P^{3+}) has ~1000 times higher solubility compared to phosphate in the presence of divalent cations and is more reactive towards organic compounds, facilitating phosphorylation. Polymerized P species such as pyrophosphate ($P_2O_7^{4-}$) may also be better phosphorylating agents compared to phosphate. However, the formation process of phosphite and polymerized P species on the early Earth is not well understood and their presence in the rock record is not well documented. In this contribution, we show that thermal metamorphism of inorganic phosphate in the presence of organic carbon might have provided a wealth of reactive and soluble P species.

We performed laboratory experiments replicating the thermal metamorphism of an organic matter-rich rock containing inorganic phosphate minerals and analysed similar shaly sandstone of Archean age (Moodies Group, 3.2 Ga) to test our hypothesis. We dry-heated four different phosphate precursors (hydroxyapatite-$Ca_5[PO_4]_3(OH)$, vivianite ($Fe_3(PO_4)_2.8H_2O$), amorphous Fe-phosphate ($Fe_3(PO_4)_2.xH_2O$, and magnesium phosphate ($Mg_3(PO_4)_2.xH_2O$) in the presence of laboratory-grown bacterial biomass at 1150 ^{o}C and measured the P species using IC-ICPMS and NMR. We found that a significant part (~10% of total extracted P) of vivianite-hosted phosphate was converted into pyrophosphate and reduced to phosphite and possibly hypophosphite (P^{+}). The amorphous Fe-phosphate experiment produced the largest number of P species including phosphite, hypophosphite, phosphonate, hypophosphate, and several polymerized species containing up to four P atoms converting >50% of initial phosphate into these species. XRD data suggest the possible presence of a phosphide compound (Fe_2P) in these experiments. We did not notice any reduced P species from other experiments using apatite and magnesium phosphate, but minor pyrophosphate might have been produced. We interpret that carbon may reduce phosphate at high temperatures, particularly if transition metals are present. The contact-metamorphic rocks (contact between a basaltic intrusion and organic matter-rich shale) from the Moodies Group contain very minor amounts (0.20 ppb; ~0.01% of total extracted P) of phosphite and a significant amount (up to 0.10 ppm; 15% of total extracted P) of pyrophosphate. Based on these observations, we suggest that C was responsible for the reduction of phosphate while pyrophosphate formed due to thermal effect. Therefore, we propose that in the Hadean and Archean, thermal metamorphism of phosphate- and carbon-bearing sediments may have produced a wealth of soluble, reduced, and reactive P species crucial to the origin and early evolution of life.

14.15

Exploring the role of alternative phosphorus species in Precambrian biogeochemical cycles: A Genomics Approach

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Phosphorus plays a crucial role in controlling biological productivity, but geological estimates of phosphate concentrations during life's early evolution in the Precambrian, vary over several orders of magnitude. Alternative phosphorus compounds, such as phosphite and phosphonates, may have played a role in supplying the phosphorus needed for life, but their bioavailability on the early Earth remains unknown. To address this gap, we use a phylogenetics approach to predict when phosphorus-utilization pathways evolved in microbial communities, based on their DNA. Results of Bayesian molecular clocks and gene-tree-species-tree reconciliatons suggest that Paleoarchean microbes could access phosphate using a low-affinity transporter (pnas) associated with high phosphate concentrations. Toward the GOE, CP-lyases for metabolising alternative phosphorus compounds in low phosphate concentrations (<0.1 µM) appeared. This could indicate reducing phosphate availability throughout the Archean, possibly associated with phosphate-scavenging Fe(III) and expansion of the biosphere at the Paleoarchean-Proterozoic boundary. Small amounts of phosphonacetaldehyde were bioavailable via phnX in the Paleo-/Meso-archean, but life could not draw on phosphite as a phosphorus-source until the Neoarchean, unless other methods of accumulating it have since gone extinct.

14.30

Characterization of Mineral Fabrics, Biofabrics, and Void space architecture in Incipient Microbialites can Explain Texture in Lithified Equivalents

Victoria C. Cassady*, Victoria Petryshyn [3], Joan M. Bernhard [4], Florian Hofmann [5], Aaron Celestian [2], William M. Berelson [1], Emily H.G. Cooperdock [6], David Bottjer [1], Frank A. Corsetti [1]*

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Microbialites–macroscopic organosedimentary structures (rocks) formed by the interaction between microbial communities and detrital or chemical sediments–represent the oldest evidence of life on Earth and remain a target for extraterrestrial investigation on Mars. Microbialites are recognizable as macroscopic manifestations of microbial life because of their texture, which consists of visible remnants of primary mineralogy and cemented void spaces. Despite the importance of texture, little is known about the origin of texture, its evolution, and its dependence on local biofabrics and microbial processes. Here, we investigate incipient CaCO3 microbialites from Little Hot Creek (LHC), a hot spring system in eastern California, where actively-lithifying microbial mats have a dendrolitic (shrub-like) texture strikingly similar to certain ancient microbialites, providing a unique opportunity to examine modern mat lithification in-situ with relevance to ancient structures. We use fluorescently labelled embedded coring to preserve internal textures in life position, and use micro Computed X-ray Tomography (microCT scanning) to render the sample in three dimensions. Petrographic thin sections were also made from FLEC cores, and both petrographic analysis and epifluorescence microscopy were used to characterize mineral and bio-fabrics within the samples in two dimensions. Using Dragonfly software, mineral and void space phases are segmented and textures are reconstructed in three dimensions. Pore network modeling software in Dragonfly is used to map pore spaces and characterize them based on porosity, amount of branching, tortuosity (curvilinear nature), and diameter. By integrating mineral fabrics, biofabrics, and channel architecture in two and three dimensions, we demonstrate not only an unprecedented level of lateral textural heterogeneity within incipient microbialites, but also present mechanisms for how textures preserved in ancient microbialites could have formed under biological influence.

14.45

A novel metric for assessing planetary surface habitability

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Planetary surface habitability has so far been, in the main, considered in its entirety. The increasing popularity of 3-D modelling studies of (exo)planetary climate has highlighted the need for a new measure of surface habitability. Combining the observed thermal limits of Earth-based life with surface water fluxes, we introduce such a measure which can be calculated from the climatological outputs from general circulation model simulations. In particular, we pay attention to not only the bounds of macroscopic complex life, but additionally the thermal limits of microbial and extremophilic life which have been vital to the generation of Earth's own biosignatures. This new metric is validated on Earth, using ERA5 reanalysis data to predict the distribution of surface habitability which is then compared to the observed habitability created from satellite-derived data of photosynthetic life. Additionally, the validation against observed habitability is repeated for a selection of popular metrics of surface habitability, allowing for the first time a comparison of metric performance with respect to Earth-based surface life.

Day 2 - Thursday, July 11th

10.00

Resolving affinities of mysterious fossils using infrared spectroscopy and machine learning.

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The affinities and original composition of extinct organisms are often difficult to resolve using morphology alone. Using molecular analysis provides great complementary results. For example, using infrared spectroscopy, we can access the molecular fingerprints of various fossilization products of organic precursors. These precursors can tell us a lot about the original composition of fossil organisms and their possible biological affinities.

The ca. 407 Devonian Rhynie Chert, one of the most exceptional fossil assemblages from the Palaeozoic, constitute a powerful positive control for such molecular analyses. The assemblage contains morphologically pristine remains of plants, fungi, bacteria, and animals. Using a combination of infrared spectroscopy (both benchtop and synchrotron-based), multivariate statistics and machine learning, we can, for example, differentiate prokaryotes from eukaryotes, discriminate tissue types, and clarify the affinities of morphologically ambiguous taxa; all despite the overwhelming influence of silica (Loron et al., 2022). Here, we show how similar approach can also successfully help resolving the long-debated possible affinities of the first terrestrial giant, Prototaxites, an organism that could reach several meters, as well as other mysterious nematophytes. Recent studies converged at interpreting Prototaxites as a possibly extinct member of higher fungal clades but were only based on morphological similarities with modern mushroom-forming fungi. Our results, coupled with complementary analyses of extracted biomarkers, show that they were molecularly different than contemporaneous fungi in the Rhynie chert. Similarly, the nematophyte Nematoplexus most certainly shared fossilization products with Prototaxites, suggesting they were derived from similar organic precursors.

Beyond the great interest of better understanding early terrestrial ecosystems, this global approach, validated on the Rhynie chert, can now be successfully extended further back in time for the interpretation of older ambiguous, assemblages and fossils, for example in the Precambrian.

10.15

Tracking solar irradiance across the K/Pg boundary with fern spores using FTIR

Hendrik Nowak [1], *Barry H. Lomax [1], Wesley T. Fraser [2], Philllip E. Jardine [3], Luke Mander [4]*

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It is hypothesized that the mass extinction at the Cretaceous–Palaeogene (K/Pg) boundary was caused by dust and soot blocking the sunlight from reaching Earth's surface nearly completely during a so-called impact winter, suppressing photosynthesis and thereby interrupting the food chain. As the dust settled, certain ferns were the first land plants to recover, hence why fern spores are prolific in palynological assemblages directly above the boundary. Sporopollenin, the biopolymer forming the walls of spores and pollen, contains UV-B absorbing compounds (UACs), which have been shown to reflect UV irradiance during plant growth. Their abundance can be measured using Fourier-transform infrared (FTIR) spectroscopy. We used this method to test for a signal of changes in solar irradiance in fern spores from the Cretaceous–Palaeogene boundary in North America that could be related to the end-Cretaceous mass extinction. The FTIR spectra of these spores do not record a reduction of UACs after the event, but rather an increase. This implies that the light regime experienced by the pioneering ferns was less shaded than normal and supports a rather short effective duration for the impact winter. The ferns presumably started to regrow as soon as light levels were sufficient for the most shade-adapted species. By the time the plants had matured and were forming spores, the lack of a tree canopy and potentially damage to the ozone layer caused by the impact and/or the Deccan Traps volcanism then outweighed any residual UV-B blockage.

10.30

Erosion, Chemical Weathering and the Uplift of the New Guinea Highlands

Peter D. Clift [1,2], *Yifan Du [1], Katharina Pahnke [3], Mahyar Mohtadi [4], Philipp Böning [3]*

1: University College London, 2: Louisiana State University, 3: ICBM, University of Oldenburg, 4: MARUM, University of Bremen

Chemical weathering in Southeast Asia is increasingly recognised as being a core control over global climate, particularly the cooling of Earth during the Cenozoic. This is particularly true during the Neogene when chemical weathering fluxes from the Himalayas decreased through time, meaning that silicate weathering in that region was not the primary control over falling CO2 levels in the atmosphere.

Instead, chemical weathering of sediments eroded from the arc and ophiolite terrains in Southeast Asia may be critical. Recent study of marine sedimentary deposits offshore Eastern New Guinea now show that there is a trend towards more intense chemical weathering in that region over the last 20 million years and especially since 6 Ma. Collision between New Guinea and Australia primarily commenced around 15 Ma when erosion from uplifting arc terrains made the sources especially reactive. Since that time uplift has created a large island with increasing erosion from continental Australian sources, reducing the reactivity. We estimate that sediments eroded from New Guinea maybe approximately 2 to 3 times as effective at consuming of CO_2 as their equivalents in South Asia. Over shorter, orbital timescales there is more erosion from accreted Australian crust during interglacial times when the stronger rainfall was able to penetrate deep into the New Guinea Highlands than during glacial times when erosion was more focused on mafic rocks along the coast. Chemical weathering intensity follows global climatic cycles with generally less weathering during interglacial warm periods, likely related to faster transport driven by high fluvial discharge.

10.45

A trade-off linking tectonics, climate, and diversification of Andean flora

Esteban Acevedo-Trejos [1], *Jean Braun [1], Benedikt Ritter [2], Tim Böhnert [3], Adeniyi Mosaku [4,5], and Hannah S. Davies [1]*

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Life, climate, and landforms interact to shape the biodiversity patterns we observe in Earth's Mountain regions. Plausible tectonic and climatic explanations have emerged to explain, for example, the evolutionary patterns of Andean plant groups. However, it remains unclear how different tectonic and climatic histories affect the evolution of Andean flora on geological time scales. Here we present the results of numerical experiments using our coupled speciation and landscape evolution model to investigate how tectonics and climate interact to produce distinct evolutionary histories in the Andes. To address this, we first calibrated our model using a Bayesian inversion approach with observations of present-day topography and precipitation, paleo-elevation reconstructions, and thermochronological data to calibrate three scenarios with different uplift histories, which were designed based on the literature and named as propagating and compound. The propagating scenario considers the west-to-east propagation of a gaussian-shape wave of uplift, which has been shown to adequately approximate evolution of plateaus. The compound scenario divides the landscape into 6 geomorphic regions, each with its own uplift history. Additionally, we tested a third scenario as a control, in which we maintained the present-day topography for the course of the simulation (ca. 80 Myr), which we named static. We ran the eco-evolutionary component of our model in these three distinct uplift scenarios, covering the mountain building of the Andes for the past 80 Myrs, and designed a series of ensemble simulation in which we randomly assigned dispersal and mutation variability to recreate different assemblages with distinct evolutionary histories and evaluate if the different scenarios produce any consistent speciation patterns comparable to reported time-calibrated phylogenies of various plant groups. We found that the uplift scenario with a more complex uplift history, i.e. compound, better agrees with the different observations. This scenario also showed an increase in diversification during the Miocene (23-4.5 Ma), a feature observed in several Andean plant groups. This demonstrates how diversification constraints obtained from phylogenetic studies can be used to discriminate between conflicting uplift scenarios for the Andes/Altiplano that have been suggested by paleo-altimetry estimates and other geological observations. Last, we demonstrate the importance of environment-mediated trade-offs as a mechanism linking tectonics, climate and diversification of Andean flora.

11.30

Oceanic Anoxic Event 2: Can CO2 degassing from Large Igneous Provinces explain the biogeochemical perturbations?

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The Cretaceous was a remarkable time in Earth's history – elevated temperatures caused by high atmospheric CO_2 concentrations shaped a hothouse world. Sources of atmospheric CO_2 have been ascribed to increased mid-ocean ridge activity and high seafloor spreading, but several emplacements of large igneous provinces (LIPs) additionally degassed vast amounts of isotopically light CO_2 into the atmosphere. Oceanic Anoxic Events (OAEs) document major perturbations to biogeochemical cycles on a global scale, and are commonly directly linked to LIP degassing events. For OAE2 (Cenomanian/Turonian, ~94.5 Ma) an increase in organic carbon burial has been recorded, which has been linked to amplified continental weathering[1,2] and increased marine nutrient availability. Despite the event being well studied, a model that directly estimates the combined biogeochemical effects of LIP-derived CO_2 input, and compares this to the combined geological record, is lacking.

Here, we use a climate-sensitive, biogeochemical multi-box model which produces a self-consistent estimate of the global C, O, and P cycles across the ocean. We explore the outputs of this model for carbon isotope excursions in carbonates and organic carbon, as well as for paleo-sea-surface temperatures (SSTs) under different LIP CO_2 degassing scenarios, and compare the results to the geological record of OAE2.

The utilization of this model combined with biogeochemical perturbations and climate responses documented for OAE2 enables us to quantify volcanic CO_2 degassing fluxes during the LIP emplacements. However, in addition to the amount of CO_2 input, the magnitude of the CIE is highly dependent on both the productivity and export of organic matter to the seafloor, and the increased burial of organic matter under oxygen-depleted bottom water conditions. We therefore investigate the bioavailability of nutrients (supplied by increased weathering inputs and recycling from the shelf) and the extent of marine anoxia in more detail.

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2 Nana Yobo et al., 2021, GCA

11.45

A marine mechanism for the origin and recovery of eccentricity paced (hyper)thermals?

Pam Vervoort [1], *Sandra Kirtland Turner [2], Dominik Hulse [3], Sarah Greene [1], Andy Ridgwell [2]*

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Milankovitch cycles in marine sediments demonstrate the influence of astronomical forcing on Earth's climate-carbon dynamics. Proxies suggest that during greenhouse climates, isotopically light carbon is released during episodic warm intervals (at eccentricity maxima) and re-sequestered during the following cooling (at eccentricity minima). However, the dominant carbon sources and sinks across the so-called 'hyperthermal-style' variability that characterizes Mesozoic and early Cenozoic records remain unclear. Methods: In the cGENIE Earth system model, we apply 4-Myr-long transient astronomical forcing to examine how various climate-sensitive physical and (bio)geochemical processes respond and how this forcing is expressed in key oceanographic proxies. Results: Weathering-burial cycles of carbon and nutrients afflict the greatest changes to the global carbon cycle. These processes are driven by local conditions -controlled mainly by precession, but the high-frequency changes are converted to low-frequency eccentricity cycles in pCO_2, benthic $\delta^{13}C$, and wt% $CaCO_3$ as a result of lowpass filtering in the ocean reservoir. While the 'hyperthermal-style' $\delta^{13}C$ variability can be explained by input-burial flux imbalances of marine organic carbon alone, the dominant frequency, magnitude, and relative phasing of proxies highly depend on the distribution of landmasses. Implication: We demonstrate that under favourable paleogeographic configuration, the interplay between nutrient cycling and marine organic matter burial provides a mechanism for the 'hyperthermal-style' events where eccentricity maxima repeatedly coincide with elevated pCO_2, global warming, negative $\delta^{13}C$ excursions, and reduced wt% $CaCO_3$. I will also highlight ongoing efforts to include terrestrial feedbacks in our framework that further affect orbital-scale climate variability, resulting in an increasingly comprehensive representation of the global carbon cycle.

12.00

Evidencing the unique challenges for marine life under rapid warming: changing extinction selectivity trends during hyperthermals

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Marine life is responding to anthropogenic warming but conditions are exceeding the recent evolutionary experience of modern organisms. Models informed solely by recent historical observations may therefore fail to make successful predictions of the future. To understand how marine life may respond in general scenarios of rapid, sustained, and severe warming events that are outside modern experience, fossils record the ecological responses at numerous hyperthermal events, and extinction patterns may have the most robust record. We address how well modern hypotheses of organism vulnerability, often informed by experimental manipulation or projections of niche models, agree with patterns of extinction selectivity in the past. Moreover, we assess whether it is more appropriate to look at raw extinction selectivity (i.e. the differences in extinction rate among groups of organisms) at hyperthermal events, or whether the differences in a group's extinction selectivity between hyperthermal events and non-hyperthermal events may be more informative. That extinction rates vary greatly among clades has long been observed and is a keystone of biostratigraphy. When this variation is accounted for, we show how some extinction patterns of organisms differentiated by clade, ecological trait, and thermal habitat are more unique to hyperthermal events, and correspond better to mechanism-based hypotheses of vulnerability.

12.15

Scaling Biohorizons and scaling Geochronologies

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Life and the planet - macroevolution and the climate - are highly variable over all observed time scales. The simplest framework for understanding and modelling such systems is scaling. This means that big and small, fast and slow fluctuations vary in power law ways; that they are qualitatively the same over potentially wide ranges of scale in space and in time.

Modern “big” paleodata has made it possible to determine the scaling ranges and (multifractal) scaling exponents of paleontological and geological series ranging from extinction and origination rates, biodiversity and as well as numerous climate proxies [Spiridonov and Lovejoy, 2022], substantiating the notion of climate “regimes” and allowing for the development of new model types [Lovejoy and Spiridonov, 2024].

These advances have been facilitated by the application of Haar fluctuation analysis that quantifies fluctuations and uses this to determine scaling regimes and statistical (scaling) exponents. In this report, we use Haar fluctuations to analyze a new paleoindicator: the temporal density of biohorizons and the (related) temporal density of geochronologies (corresponding to the density of samples taken from cores). We study the density of official stratigraphic boundaries as well biohorizon densities from as zone fossils: Calcareous nanoplankton, Conodonts, Ammonoids and Graptolites. We show that they are scaling over ranges spanning ≈ 1Myr to several hundred Myrs and we measure fundamental fluctuation exponents, intermittency exponents and multifractal indices. We exploit the strong intermittency to directly estimate the outer (largest) scale of this "megaclimate" regime [Lovejoy, 2015] finding it to be close to 1 Gyr. We also make similar quantifications of various geochronologies including those from benthic stacks.

Biohorizons and geochronologies inform much of understanding of macroevolution of deep time geology and their (hierarchical) irregularity is quite challenging for conventional statistical and for numerous applications. We discuss ways in which the scaling quantification of this variability opens new doors to our understanding of life and the planet.

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14.00

Animals! Major and unpredictable perturbation of global carbon cycling by complex life

Craig Walton [1], *Oliver Shorttle [2]*

1. ETH Zurich 2. University of Cambridge

Understanding the co-evolution of complex life with Earth's geology is an enduring challenge. The rock record evidences remarkable correlations between changes in biology and the wider Earth system, yet cause and effect remain unclear. Here, we link the evolutionary history of eukaryotes with the rise and fall of carbonate rock fraction within continental crust – a key variable in controlling the efficiency of carbon drawdown during weathering, solid Earth degassing rates, and ultimately nutrient supply to life. We use geospatial database analyses to demonstrate a strongly non-linear growth and then collapse in Earth's continental crust carbonate reservoir. Biomineralisers reshaped Earth's surface in their image, armouring continental margins with carbonate platforms such that the continental carbonate reservoir increased in size by 5-fold in under 100 Myr after the Cambrian Radiation of animal life. This Paleozoic carbonate revolution represents among the most dramatic crustal evolutionary events in Earth's history. The Permo-Triassic extinction event coupled to the rise of open ocean calcifiers initiated a steady decline in continental crustal carbonate content; one that still continues today, which unabated would produce Precambrian-style crustal carbonate distributions in around500–1000 Myr. Our results demonstrate strongly non-linear crustal evolution after the rise of the complexPhanerozoic biosphere. This outcome suggests that complex life may generate unique biogeochemical trajectories on otherwise geologically similar worlds, posing a new challenge in the hunt for life beyond Earth.

14.15

SCION 2.0: A new biogeochemical model for investigating atmosphere and ocean oxygenation across the Phanerozoic

Alexander J. Krause [1]*, Andrew S. Merdith [1,2], Khushboo Gurung [1], Zhen Xu [1], Stephen J. Hunter [1] and Benjamin J. W. Mills [1]*

[1] University of Leeds, [2] University of Adelaide

The chemical composition of Earth's atmosphere and oceans has changed significantly throughout its 4.5-billion-year history, in the process affecting its capability to host complex life [1]. However, the main drivers behind the various chemical changes and their relative importance to eliciting fluctuations in, for example, oxygen concentrations and climate, are still widely contested.

Numerical model simulations have enhanced our understanding of the evolution of the Earth system, but because of their computational expense trade-offs between spatial and temporal resolution must be made. While 0D box models can explore changes to the Earth over multi-million-year timescales, typically their atmosphere and oceans are combined into a single reservoir [2]. Furthermore, spatially heterogeneous processes (e.g., silicate weathering [3]) are denoted as global averages, thus the extent of their impact on the evolution of Earth's environment and life remains inconclusive. At the other end of the scale, 3D models can explore fine scale Earth system processes, but the computing power and wall time required to run such models means that they are limited to investigating geologically shorter timescales (~ <= 10 million years) [4,5].

Here, we present a spatially-resolved model capable of exploring the various hypothesized mechanisms behind Earth system changes over multi-million-year timeframes. The work here substantially updates the SCION model [6] by adding a new biogeochemistry framework [7], with terrestrial reservoirs, an atmosphere reservoir and a separate ocean split into five reservoirs, allowing us to explore: abiotic and biotic influences on nutrient cycling in the ocean; the consequent impact on Earth's climate; and both atmosphere and ocean oxygenation during the Phanerozoic.

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14.30

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. In Neoproterozoic and Cambrian ocean shelf seas, evolving biota and redox conditions created biogeochemical feedbacks which are hypothesized to have permanently shifted the redox state of the ocean and sediment and enabled complex ecosystems to emerge. Models can explore these feedbacks and allow hypotheses on the effects of changes to life or the environment on the other to be tested. But connecting localized, short timescale matter and energy fluxes through ecosystem components to global Earth system cycles over geological timescales is a particular modelling challenge. When modelling processes and cycles over geological timescales, smaller scale processes are often taken to be in steady state and abstracted out. However, when the small-scale feedbacks at the life-environment interface compound directionally, the assumption of steady state is violated, and the very dynamics leading to long-term ecosystem evolution can be left out of models. We introduce a 1D biogeochemical column model of a shelf sea in the PALEO modelling framework to explore the compounding interactions between biology and the physical and chemical environment. The model consists of a coupled ocean-sediment system with key components of early ecological networks, such as size-structured plankton communities, benthic microorganisms, early filter feeders and simple burrowers, represented by ecological functions. Representing the biological populations explicitly presents an alternative to standard approaches in biogeochemical models, where the biological pump in the ocean or bioturbation in the sediment are parameterized from modern data, and the water column and sediment column are often explored separately without the biological link between organic reservoirs and fluxes. Our approach allows the redox profile in the ocean and sediment to be formed directly

by modelled biological activity, and nutrient cycling to be linked to this activity. The model is being used to explore hypotheses on the effects of evolving filter feeders and burrowers on redox conditions and phosphorus cycling, but can be adapted for a range of time periods where there is interest in life-environment feedbacks, such as mass-extinction events.

14.45

Dust variations over the half billion years and their role in iron fertilization of the ancient oceans

Yixuan Xie[1], *Dan Lunt [1], Fanny Monteiro [1], Richard Stockey [2], Paul Valdes [1]*

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Desert dust is a vital component of the Earth's climate system. The climate system regulates dust emission processes, such as sediment availability and wind entrainment, in various ways. Dust modulates the Earth's radiation balance, and wind-carried dust deposition provides essential nutrient iron to land and marine ecosystems. While dust science is well-developed for the modern and the Quaternary, little investigation has been done for the Earth's deep time.

Here, we present continuous simulations of dust emissions, depositions, and bioavailable iron for the first time throughout the Phanerozoic era (since 540 Ma ago). Results are derived from multiple schemes based on the paleoclimate fields output produced by the General Circulation Model HadCM3L. Our results show how dust emissions fluctuated over time with a stage-level resolution (approximately 5 Ma). We then diagnosed the controls of these fluctuations, and identified that paleogeography changes are the dominant control, whereas CO2 plays a marginal role. Our ongoing research explores the influence of deposited dust on oceanic productivity and oxygen levels across various geological time periods, as modelled by cGENIE. This study aims to quantify the historical iron fertilization effect on Earth's oceans and offers insights into the variability of marine biodiversity through the lens of iron.

15.00

Marine biodiversity and the niche-environment interaction through deep time

Alexis Balembois [1], *Bertrand Lefebvre [2], Alexandre Pohl [3], Thomas Servais [4], Paul J. Valdes [5], Dan J. Lunt [5], Grégory Beaugrand [1]*

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Although ~30 hypotheses or theories have been proposed to explain global species richness and its large-scale spatial arrangement in the marine and terrestrial realms, a scientific consensus has not been reached yet. Here we use a multidisciplinary approach coupling a paleoclimatic and a macroecological model to show that the niche-environment interaction is fundamental to explain how global species richness has varied during the Phanerozoic Eon and how the resulting large-scale biodiversity patterns have been shaped through time. Although our model identifies a major mechanism, it also suggests that the niche-environment interaction is itself modulated by global climate, a mid-domain effect in the niche space, the position of the land masses, the global area available around continents and habitat fragmentation that affect environmental heterogeneity, which in turn promotes allopatric speciation that controls the global pool of species. Our study therefore demonstrates that any unifying theory on global biodiversity should consider a large number of factors that controls not only biogeographic biodiversity patterns but also their changes through deep time.

15.15

Climate Modelling of the late Neoproterozoic Era.

Stephen J. Hunter [1], *Benjamin J. W. Mills [1] and Andrew S. Merdith [2]*

School of Earth and Environment, University of Leeds [1], School of Physics, Chemistry and Earth Sciences, University of Adelaide [2]

The late Neoproterozoic Era saw deep glaciation and possible rises in atmospheric and marine oxygen levels. It has been suggested that both of these environmental changes could be the consequence of supercontinent breakup and amplified continental weathering rates, which could have drawn down CO2 and liberated nutrients. But this idea has not been tested using high resolution paleoclimate models and recent paleogeographic reconstructions. Here we present a suite of HadCM3L climate model simulations covering the late Neoproterozoic Era (800 – 600 Ma) based upon a new full-plate model and palaeogeographic framework. We outline the boundary conditions and modelling strategy including the representation of continental-scale ice-sheets, and discuss initial results. To assess the implications for the carbon cycle, the resulting suite of climatologies will be incorporated into the SCION climate-chemical model to produce a self-consistent reconstruction of biogeochemistry (including chemical weathering and atmospheric O2 and CO2) and climate. The ROCKE-3D planetary climate model will be implemented for comparison against HadCM3L and to investigate sensitivities such as atmospheric composition (e.g. reduced-O2) and reduced day-length.

Day 3 - Friday, July 12th

10.00

Records of Phosphorus and Sodium in biogenic calcite through 30 Myrs of the early Jurassic

Ailsa Roper [1], *Clemens Ullmann [2], Crispin T.S. Little [1], Simon Poulton [1], Paul Wignall [1], Tianchen He [1], Robert Newton [1]*

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Elemental records from biogenic calcium carbonates have long been used for palaeo-environmental reconstruction. Surprisingly, several elements which are incorporated in relatively high abundance have received relatively little attention. Here we focus on P and Na, which are both incorporated in millimolar quantities per mole of calcium, similar to more widely researched elements such as Mg and Sr. P is an essential nutrient for life, the limiting marine nutrient over geological timescales and a potential driver of oxygen depletion in ancient oceans. Despite its importance, obtaining direct information on spatial and temporal variations in P concentration has proved challenging. Recent work has suggested that P in biogenic carbonates can be used to investigate changes in water-column P concentration [1]. Na in carbonates has received only scant attention but recent work on foraminiferal tests suggests that, in these organisms at least, it is likely to represent some combination of Ca concentration and saturation state [2]. Presently there are limited direct proxies for seawater calcium concentration and saturation state, yet both are crucial for reconstructing seawater chemistry and the carbon cycle.

We have developed a single extraction method for P and Na in carbonates and tested it in belemnites, an extinct group of nektic molluscs with an internal calcite structure. These tests show that both P and Na have good reproducibility on a range of scales (after screening for diagenesis), with Na being more reproducible than P.

We analysed belemnites and calcitic bivalves from multiple sites in the European Epicontinental Seaway (EES), comprising a 30 Myr interval from the Hettangian to Toarcian in the Early Jurassic, and compare these data to existing records of environmental change. This time period contains both icehouse and greenhouse climates, the latter associated with the global expansion of anoxic conditions during the early Toarcian. Both P/Ca and Na/Ca demonstrate coherent change across different sites in the EES and between bivalves and belemnites. P/Ca, Mg/Ca and Sr/Ca all show strong covariation, but are not correlated with Na/Ca, which has its own distinct pattern of change.

We suggest that P/Ca could be controlled either by (i) a mineralogical control during magnesium incorporation into the calcite, or (ii) an external unidentified palaeoenvironmental factor that controls both Mg and P incorporation. Records of Na/Ca are close to the range present in Cenozoic foraminifera, and a marked change in the early Toarcian is broadly consistent with a proposed ocean

acidification event at this time. Further work is necessary to fully understand the degree to which these records represent primary environmental information versus biological controls during mineral formation.

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10.15

Continental Weathering Dynamics and Early Biomineralization in the Late Ediacaran.

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Continental weathering is essential for climate control and significantly influences seawater chemistry and thus also the biochemical record. The late Ediacaran period (~555 to 545 Ma) marked the emergence of complex organisms, including the first biomineralizers, likely associated with enhanced alkalinity and carbonate supersaturation of the marine realm. Our study aims to investigate the relationship between weathering, ocean chemistry, and the rise of early biomineralizers using elemental and isotope geochemical information preserved in late Ediacaran (~551 to 547 Ma) carbonate rocks within the Kuibis Subgroup, southern Namibia, obtained from ICDP GRIND-ECT core 1G. This subgroup possibly records the first appearance of Cloudina, one of the earliest organisms to secrete calcium carbonate. Our data reveal periodic variations in lithium ($\delta 7Li$), magnesium ($\delta 26Mg$) and strontium (87Sr/86Sr) isotope composition, across the upper Mara, lower Kliphoek, and lower Mooifontain members, reflecting distinct weathering cycles. Notably, intervals with negative $\delta 7Li$ excursions coincide with positive $\delta 26Mg$ and 87Sr/86Sr and high Sr/Ca ratios, suggesting enhanced chemical weathering associated with increased seawater alkalinity. This may have induced an aragonitic state with high carbonate supersaturation from a previous dolomite-aragonite state that allowed the onset of biomineralization.

10.30

Rhenium isotopes as a tool for tracing oxidative weathering intensity in Earth's ancient past

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Rhenium is strongly coupled with organic matter in sedimentary rocks. CO_2 is released to the atmosphere during oxidative weathering of fossil sedimentary carbon and this flux has been quantified in modern river catchments by measuring the riverine Re flux and coupling this to the Re:C ratio of the unweathered rocks. This approach cannot be used to trace oxidative weathering in the geological past, however, which has led to an interest in stable Re isotopes ($\delta^{187}Re$) due to the potential for differences in oxidative weathering intensity to alter the composition of the weathered input flux of Re to the oceans. We present stable Re isotope measurements of weathered and unweathered samples of the Eagle Ford shale to quantify this effect. We show firstly that the $\delta^{187}Re$ composition of rocks decreases with increasing oxidative weathering intensity, and secondly that this effect can be empirically modelled using open-system Rayleigh fractionation. The range of $\delta^{187}Re$ variation observed in the calculated weathered flux of Re is sufficient to generate measurable differences in whole-ocean isotope compositions, with a possible application for tracing ancient CO_2 emissions.

10.45

Mineralogical controls on climate and oxygenation

Caroline L Peacock [1], *Lisa Curti [1], Oliver W Moore [1,2], Peyman Babakhani [1,3], Ke-Qing Xiao [1,4], Mingyu Zhao [1,5], Clare Woulds [1], Ben J W Mills [1], Will B Homoky [1]*

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The preservation of organic carbon in marine sediments is fundamentally important for Earth's carbon and oxygen cycles, but the controls on carbon preservation remain unclear. Preservation can be enhanced by limiting exposure of carbon to oxygen, but on continental margins, where the majority of carbon preservation occurs, the relationship between oxygen exposure and burial efficiency is weak. In these environments in particular, additional preservation mechanisms are proposed, including the protection and preservation of carbon with sediment minerals. We show that the sorption of carboxyl-rich carbon [1] and its chemical transformation [2] with iron and manganese minerals provides a hitherto unrecognised mechanism for the stabilisation and preservation of carbon in sediments, such that the flux of iron and manganese into the oceans may provide a new control on planetary climate and oxygenation [2,3].

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11.30

The Rise of Algae promoted eukaryotic predation in the Neoproterozoic benthos

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The Neoproterozoic rock record documents the oldest unequivocal evidence for crown-eukaryote steranes, extant lineages of predatory eukaryotes, and animal life. More specifically, the sedimentary sterane record suggests an increase in the relative abundance of rhodophyte algae in the Tonian Period, followed by an increase in chlorophyte algae by the Ediacaran Period. The establishment of abundant eukaryote primary producers in the Neoproterozoic (generally referred to as the 'Rise of Algae') is predicted to have stimulated the ecology of predatory eukaryotes, such as Amoebozoans, and the earliest benthic metazoans. To test the idea that the input of algal matter to benthic ecosystems would have stimulated the activity of predatory microbial eukaryotes in the Neoproterozoic, we added algal cells and organic matter – specifically particulate diatom extracellular polymeric substances (dEPS) – to marine sediments underlying the Benguela Upwelling System (BUS) of Namibia. Using community gene expression data (metatranscriptomics), we show that the addition of dEPS significantly stimulates gene expression among microbial single-celled eukaryotes (protists) with corresponding decreases in gene expression across bacteria and archaea. The genes overexpressed by protists in our dEPS treatments include those encoding key enzymes in anaerobic energy metabolism and phagocytosis ('cell swallowing,' by which eukaryotes internalize prey cells via invaginations of the plasma membrane). Expressed 18S rRNA shows that dEPS increased the relative abundance of protists belonging to phagotrophic clades with known Proterozoic origins, including the Amoebozoans, Ciliates, and Excavata. As a test of reproduction under these conditions, cell counts of benthic foraminifera across our treatments and controls revealed that dEPS stimulates the growth of the phagotrophic foram Bolivina spp.

under anoxia. Together, our results suggest that the effective transfer of algal-derived organic matter from marine surface waters to benthic ecosystems in the Neoproterozoic would have effectively promoted the activity and growth of anaerobic, phagotrophic protists living just beneath the seafloor. As key linkages between the 'microbial loop' and classical, animal-containing food chains, increasingly abundant predatory protists in the Neoproterozoic benthos would have effectively created more modern food webs by mediating the transfer of fixed carbon and energy to higher trophic levels, including the earliest animals.

11.45

Fossil taphonomy in a mid-Proterozoic siliciclastic succession

Johnson, B. R., [1],*, Tostevin, R., [2], Lara, Y., [1], Clayton, K. E., [3], Robinson, S. A., [3], Tosca, N. J., [4], Javaux, E. J., [1]*

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Fine-grained siliciclastic sedimentary rocks are a rich archive of early life on Earth. In particular, phyllosilicate-rich rocks such as mudstones have proven to be effective in the preservation of organic walled microfossils (OWM). Recent work has suggested that phyllosilicate composition is less important than phyllosilicate abundance in determining the preservation quality of OWM. However, it is currently unclear how phyllosilicate composition and abundance impact OWM preservation on a basinal scale. To investigate this question, we conducted an extensive investigation of OWM preservation quality, and the associated clay mineralogy in the exquisitely preserved ~1.4 Ga Greater McArthur Basin (GMB), northern Australia. The GMB was a long lived stable cratonic marine basin, with clastic dominated sedimentation. Thanks to abundant drill core material, the GMB provides an easily accessible archive of Proterozoic life and environments. We examined an extensive sample set of lithologies which represents the full range of temporally and spatially adjacent depositional environments from across the GMB. Our data suggest that there is no clear link between OWM preservation and any specific phyllosilicate species, or an assemblages of specific phyllosilicate species. However, the preservation quality and species richness of OWM are positively correlated, while both preservation quality and species richness negatively correlate with the increasing abundance and diversity of benthic microbial mats and microbially induced sedimentary structures. Further, the preservation quality, and species richness of OWM, and the abundance and diversity of benthic microbial mats, vary with depositional facies. Finally, we also observe a number of mineralised fossils and organo-mineral structures previously undescribed from this succession that indicate rapid seafloor authigenic mineral growth associated with organic matter was common across the basin. We combine these observations in a tapho-facies model where the chemical and physical conditions of the depositional environment exert a major control on the preservational quality of OWM within the basin.

12.00

Multicellular eukaryotes from the late Paleoproterozoic Chuanlinggou Formation in North China

Lanyun Miao [1]*, Zongjun Yin [1], Andrew H. Knoll [2], Yuangao Qu [3], Maoyan Zhu [1]*

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Multicellularity is crucial for eukaryotes to acquire organismal complexity and large size, yet when eukaryotes first evolved this innovation in their deep evolutionary history is still poorly understood. Early fossil records claimed to be multicellular eukaryotes can be traced back to Paleoproterozoic Era, but most of them are controversial due to simple morphology and/or lack of cellular structure. These include the uniseriate filaments of Qingshania magnifica Yan, 1989, initially described from thin sections of shales from the ca. 1.64 Ga Chuanlinggou Formation in North China. Here we document abundant filaments of Qingshania isolated from enclosing shales from Chuanlinggou Formation by acid maceration. Using combined techniques of TLM, SEM, Raman and Infrared spectroscopy, we revealed conspicuois morphological details of these filaments, and that their wall kerogen is different from those of co-occuring cyanobacterial fossils. The fossils are unbranched, with large cell diameters up to 190 µm and show a certain degree of morphological variability. The intracellular spheroidal structures in some cells probably represent spores, adding another layer of biological complexity. The combination of these features permits the interpretation of these large filaments to be eukaryotic, based on comparisons with extant organisms. The occurrence of multicellular eukaryotes in Paleoproterozoic rocks not much younger than those containing the oldest unambiguous evidence of eukaryotes as a whole supports the hypothesis that simple multicellularity arose early in eukaryotic history, as much as a billion years before complex multicellular organisms diversified in the oceans.

12.15

Building the eukaryotic planet: a view from marginal marine settings

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Marginal marine settings – the deltaic, estuarine, and mudflat habitats at the interface of land and sea – offer exceptional taphonomic windows on the rise of eukaryotic ecologies. Organic microfossils from tidally influenced horizons point to pre-Cryogenian origins for major eukaryotic groups, including red algae (Butterfield 2000), putative fungi (Butterfield 2003, 2005), and amoebae (Porter et al. 2003; Dehler et al. 2012). Meanwhile, an absence of comparable records even in those supratidal settings offering exceptional preservation conditions (e.g., in early diagenetic silica) suggests that Precambrian eukaryotes were essentially confined to subaqueous environments. Yet, these windows onto early eukaryotic history are vanishingly rare and temporally restricted. Efforts to place them within a broader record, spanning the Precambrian-Cambrian transition and its Phanerozoic aftermath, have been frustrated by a lack of similar organically preserved biotas from Cambrian marginal marine settings. New ichnofossils and Small Carbonaceous Fossils (SCFs; Butterfield & Harvey, 2012) from mudcracked horizons of the Middle Cambrian Pika Formation (Western Canada) offer a comprehensive view on an early Palaeozoic fauna from a periodically emergent mudflat. The wiwaxiids, priapulids, stem- and crown-annelids, and burrow traces of the Pika biota show that classic Burgess Shale-type metazoans ventured into tidally influenced settings, where they coexisted with members of derived living orders. This attests to an early influence of animal 'pioneer taxa' on dysoxic, intermittently desiccating marginal habitats. These findings push the limits of metazoan ecological tolerance to dehydration, UV exposure, and salinity and redox fluctuations (e.g. Sagasti et al., 2001; Blewett et al., 2022), complementing the Precambrian record to suggest shallow-marine settings as cradles of eukaryotic innovation across the Neoproterozoic-Cambrian boundary.

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Posters

Wednesday

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

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Ediacaran macrofossils (580-539 Ma) reveal critical insight into the evolution of life and include representatives of the earliest-known complex animals. In this study, we focus on Charniodiscus – a group of upright, sessile frondose organisms that are exceptionally well-preserved under volcanic ash deposits in Newfoundland, Canada and Charnwood Forest, UK. They are relatively understudied and are morphologically simpler than the iconic rangeomorphs, and so provide a perfect test case for the development of new quantitative techniques. One of the largest in situ census populations of Charniodiscus occurs within the Main E Surface community in the UNESCO Mistaken Point Ecological Reserve. With over 120 specimens, this population provides an opportunity to explore physical variation across different specimens, as well as the spatial distributions of those variations. To do this, a photogrammetric map of E Surface was generated, and a 3D surface mesh was created by combining LiDAR (mean resolution of 1mm) with 0.05mm laser-line probe data. Then, the branching architecture of 116 well-preserved Charniodiscus specimens was marked up on Inkscape. Quantified morphological traits included the disc width, frond length, frond-to-stem angle, number of primary branches, average primary branch angle and branch lengths. Multivariate cluster techniques were used to identify different morphotaxa groups present within the Charniodiscus specimens on the surface, and to constrain the key morphological traits that defined them. Subsequently, random labelling analyses were used to investigate how the spatial patterns of specific characteristics varied across the population, and to identify the spatial patterns of the different morphogroups identified. Traits that show distinctive spatial patterns and defined morphogroups are likely to be more ecologically and therefore evolutionarily important than those which vary randomly within the population. Therefore, this novel approach is the first step in elucidating which morphological traits – or combinations of traits - are the key drivers of ecological dynamics in the Ediacaran.

Natural sampling and aliasing of marine geochemical signals

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It is well known that the sedimentary rock record is both incomplete and biased. Without absolute age constraints the temporal correlation of spatially distinct records is therefore problematic and uncertain, but these effects have rarely been analysed quantitatively using signal processing methods. Here we use a computational geological process model to illustrate and analyse how spatial and temporal geochemical records are biased by the inherent, heterogenous processes of marine sedimentation and preservation. This confirms that sedimentary hiatuses can span a substantial proportion of geological time, but, more importantly, that even in geochemical records that are essentially spatially continuous and complete, the signal is irreversibly disguised as lower frequency signals by an aliasing effect, caused by inherent natural geological processes. We demonstrate that Nyquist's theorem correctly predicts these biased signatures, proving that aliasing is caused by cyclical and multiscale relative sea-level changes. Our combined results show that deeper marine records are significantly more likely to provide unaliased environmental signatures, and careful sedimentological field observations can indicate possible aliasing. We propose that spatially separated aliased records may still be correctly correlated in age and correct geochemical cycles inferred if a paired-sampling strategy adjusted to local stratigraphy is applied.

Quantification of MISS textures to untangle the relationships between matgrounds and Ediacaran macrofossils

Katie M. Delahooke [1], *Alexander G. Liu [1], Nile P. Stephenson [1], Charlotte G. Kenchington [1], Emily G. Mitchell [1]*

1: University of Cambridge

The existence of Ediacaran matgrounds is reflected by a disparate range of microbially-induced sedimentary structures (MISS) preserved alongside the fossilized remains of the first animal communities. Such matgrounds have been implicated in exceptional fossil preservation, as well as playing several palaeoecological roles. Quantification may help resolve MISS classification issues, as well as permitting the incorporation of mat features into statistical models that assess the ecological role of matgrounds. However, quantitative description of MISS is challenging, as they often lack discrete or homologous features. Here, we propose the novel application of two forms of texture analyses to quantify MISSmely surface metrology and persistent homology, permitting characterisation of textural types as well as investigation of the relationship between matgrounds and macrofossils. Surface metrology involves calculating a suite of parameters, each describing a

certain aspect of surface topography, such as mean height deviation and fractal dimension. Persistent homology is instead a topological method that describes shape through changes in connectivity of structures across scales.

These techniques were applied to topographic maps derived from high-resolution (~25 µm) 3D scans of 6.0 m2 of the ~574 Ma Pigeon Cove fossil surface in Mistaken Point Ecological Reserve, Canada. The techniques were able to successfully recover textural distinctions that have previously only been recognised qualitatively: “Ivesheadiomorphs” were separated from other surface textures following ordination of surface metrics and persistence diagrams calculated from isolated topography maps. A MaxEnt species distribution model was also able to predict the location of ivesheadiomophs with high accuracy, using maps of surface metrics calculated over the entire surface by a moving window. Species distribution modelling of the spatial position of associated small frondose fossils (n = 68) and maps of surface metrics, identified an association between frond presence and locally more complex textures. Application of surface metrology and persistent homology therefore provides a promising new tool to classify problematic structures and understand ecological interactions between organisms and their environment.

Modelling the microbial to metazoan transition

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During the Ediacaran (635-538.8 Ma), the fossil record records a unique evolutionary shift from microbial-dominated ecosystems to ecosystems dominated by large, multicellular metazoans. However, these first metazoan ecosystems were very different from modern ecosystems, or even the ecosystems of the Cambrian (538.8-485.4 Ma). Various modern ecological features such as motility, predation, and bioturbation were absent from these ecosystems, and evolved over the course of the Ediacaran, culminating with the radiation of recognisably modern body plans and ecologies in the Cambrian. Consequently, while a wide range of taxa are known from these early ecosystems, the ecological functioning of these ecosystems is not well understood. We tackle this problem using biomass-explicit ecological network models, where nodes in the network represent ecologically distinct groups of organisms, and edges (i.e. connections between nodes) are modelled as pairs of Lotka-Volterra equations, describing nodes’ effects on one another. These models allow for the assessment of the biological plausibility of different sets of potential inter-species interactions and species biomasses, and can identify potential responses of ecosystems to changes in biotic and abiotic conditions.

A current view and evaluation of global diversity in the Proterozoic: insights from the fossil record

Sanaa Mughal [1], *Kurt O. Konhauser [1]*

1: University of Alberta

Environmental change and the evolution of the biosphere through geologic time is intimately linked. For the Phanerozoic (538 Ma – present), mapping macroevolutionary patterns using the rich fossil record has allowed scientists to deconvolve these complex relationships between biological innovation, rates of evolution, extinction, ecosystem structure and the dynamic changes in the Earth's atmosphere, oceans, and land through deep time. However, despite Earth's extensive and dynamic history, the paucity and poor quality of the Precambrian (>538 Ma) fossil record – likely the most tangible evidence of early life - pose significant challenges for palaeobiologists in reconstructing the earliest trajectory of life. These challenges can be broken into four main categories: (1) geological record, (2) taphonomy, (3) taxonomy, and (4) reporting and analysis of data. Here, I present these limitations and consider future approaches for mitigation. I highlight the key discoveries from both fossil and molecular data and evaluate Proterozoic diversity by compiling and analysing a comprehensive dataset of over 300 organic walled microfossil taxa, drawing from the current understanding of the fossil record to elucidate insights into global taxonomic richness.

The Boring Billion: hurdle or stepping stone for life on Earth?

Nick M W Roberts [1]

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Understanding Earth's 'Boring Billion' or 'Middle Age' (ca. 1.8 – 0.8 Ga) is crucial for building comprehensive models of Earth history. This period of Earth history is becoming more data rich, although still remains poorly understood. The view of static biosphere, atmosphere and hydrosphere evolution is being destroyed by recent studies that point to a more dynamic history. Generating models of bio-geochemical evolution require inputs from geodynamics; however, although much has been postulated about the tectonic and geodynamic evolution of the Boring Billion in the last decade, there is an abundance of arm-waving and little quantification. Here, I review the knowns and known unknowns of mid-Proterozoic geodynamics, with the aim 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. I focus on the question: what are the similarities and differences between the mid-Proterozoic and younger periods of Earth history. With these answers, we can speculate on questions such as: did ocean and atmospheric conditions delay the evolution of complex life, or were evolutionary pressures a trigger for biological diversification?

Statistical detection of microtopographic signatures of bacterial weathering

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The detection of biosignatures of microbe-mineral interactions plays a crucial role in the search for traces of life in the geological record and, more generally, for paleoenvironmental reconstruction. Among these biosignatures, microtopographic imprints of bacterial weathering, such as etching features resembling cells in 'size, shape and distribution', detected on naturally-weathered samples, have been proposed as evidence of past presence of life [1]. However, it has been showed that qualitatively similar microtopographic features can equally be produced through purely abiotic processes [2]. Therefore, shifting towards mechanistically supported quantitative criteria appears necessary to overcome such ambiguities. In the present study, we addressed this problem through a combination of experimental and modelling approaches. We conducted calcite dissolution experiments at room temperature and at various solution saturation states with respect to calcite (i.e., Ω = 0.00, 0.10, 0.30, 0.55, 0.65, 0.80) in alkaline conditions (pH = 7.9), either under sterile conditions or with a cyanobacterial biofilm of Chroococcidiopsis thermalis PCC 7203 cells covering the calcite surface. While nanoscale chemical and crystallographic characterizations failed to detect any distinctive biogenicity feature, at far-from-equilibrium conditions (i.e., $\Omega \leq 0.30$), statistical analyses of the microtopography allowed to detect the presence of high-elevation regions at the calcite surface, making microbially-weathered surfaces quantitatively distinguishable from their abiotic counterparts. Kinetic Monte Carlo (kMC) modelling of crystal dissolution suggested that these microtopographic signatures resulted from a local increase in fluid saturation state at the biofilm-mineral contact, which led to a localized reduction in dissolution rates. The formation of these biosignatures was then additionally monitored in real-time through dissolution experiments performed using in situ vertical scanning interferometry, which further supported the ex situ findings, suggesting that the calcite microtopography resulting from cyanobacteria-mediated dissolution may preserve a record of the interplay between biofilm coverage, metabolic activity, and calcite reactivity.

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Phanerozoic ocean biogeochemistry and marine biodiversity in space and time

Richard G. Stockey [1], *Benjamin J. W. Mills [2], Erin E. Saupe [3], Pedro Monarrez [4], Alison T. Cribb [1], Przemyslaw Gruszka [1], Alexandre Pohl [5], Fanny Montiero [6], Yixuan Xie [6], Pam Vervoort [7], Gordon Inglis [1], Thomas Gernon [1], Dominik Hulse [8], Andy Ridgwell [9], Daniel Lunt [6]*

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The spatial and temporal distributions of dissolved oxygen and organic carbon through Earth's oceans have far reaching implications for the evolution of marine ecosystems and the broader Earth system. Reconstructing regional variation in ancient ocean biogeochemistry has underexplored potential for understanding the impacts of environmental change on marine ecosystem dynamics and for linking geochemical proxy records to oceanographic processes. In particular, spatially resolved oceanographic reconstructions enable us to directly link fossil occurrences to regional marine environmental conditions, facilitating a range of new approaches to mechanistically test environmental drivers of ancient extinction and biodiversification events.

We present preliminary results for a new series of stage-by-stage simulations of 3D ocean biogeochemistry through the Phanerozoic. Our intermediate complexity Earth system modelling framework builds on global circulation and long-term carbon cycle modelling by coupling cGENIE to SCION and HADCM3L reconstructions of atmospheric composition, marine nutrient inventories and atmospheric circulation. This enables us to present a new oceanographic perspective on global ocean oxygenation over the last ~540 million years, illustrating linkages and non-linearities between dissolved oxygen in shelf environments, global volume of oxygen minimum zones and global seafloor redox, and similar spatial decouplings in organic carbon burial. With this approach, we move towards a new quantitative framework for evaluating climatic, continental, and long-term carbon cycle controls on ocean oxygenation and organic carbon cycling through geologic time.

Our 3D reconstructions of Phanerozoic oceans further provide a new platform for exploring the role of environmental change in the evolution of marine ecosystems through the Phanerozoic. We illustrate the potential of this approach to test mechanistic drivers of marine biodiversity dynamics in space and time by presenting preliminary results investigating the role of dissolved oxygen supply in the evolution of animal body size through the Phanerozoic.

Earth's first Phanerozoic-style glaciation?

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The Ediacaran Period (635 Ma to 538.8 Ma) was a crucial transition interval for the Earth System between the Proterozoic and Phanerozoic worlds. Rocks of mid- to late Ediacaran age (c. 600 Ma to 538.8 Ma) preserve profound changes to the global carbon cycle, via the stable carbon isotope record, and reveal through body and trace fossil records the emergence of ecosystems with complex macroscopic organisms that include early animals. There is also abundant geological evidence for at least one mid- to late Ediacaran glaciation that, whilst challenging to correlate in detail, appears to break the 'Snowball Earth' mould of globally distributed low altitude ice seen during the preceding Cryogenian Period (720 Ma to 635 Ma). In particular, a cluster of glacial deposits on Avalonia and Gondwana have been associated with the 'Gaskiers glaciation', which terminated at about 579 Ma, just prior to the emergence of the Ediacaran biota.

Here, we re-evaluate the geological evidence associated with the Gaskiers glaciation, which encompasses a wide range of potentially mid- to late Ediacaran glaciogenic deposits. From this re-evaluated dataset we provide an updated perspective on the duration and extent of the Gaskiers glaciation in the rock record. We use this updated understanding of the Gaskiers glaciation to combine well-correlated geological data with general circulation model simulations of global climate to determine the possible extent of the Gaskiers glaciation, and the nature of the climate system through this interval. This re-evaluation supports a Phanerozoic-style icehouse interpretation for the mid-Ediacaran climate, with low altitude ice confined to the high latitudes, in contrast to a Cryogenian-style 'Snowball Earth'.

Using U-Pb dating of early marine cements to constrain the base of the Nama Groupmibia

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The Nama Group (≥550.5 to <538 million years ago, Ma), located in the southernmost region of Namibia, hosts some of the most diverse fossil assemblages of the terminal Ediacaran period. To understand the evolution of the first animals and the Ediacaran-Cambrian faunal transition, it is crucial that we can accurately date the rocks hosting this fossil record. The lack of datable ashbeds and an unconformity at the base of the Nama Group, however, hinders our ability to know the age of the oldest part of this key geological unit. Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) can be used to measure the uranium and lead composition of distinct mineral phases of carbonate cements, and use their ratios (U-Pb) to date each carbonate mineral with reasonable precision (3 % –10 %, 2σ). We performed in situ U-Pb dating on early marine carbonate cements from the lower Nama Group, immediately overlain by a radiometrically dated ashbed, and whose depositional paragenetic sequence had been previously characterized. Our results show a broad coincidence between the age of early pseudomorphed aragonite botryoidal cements and the age yielded by the overlaying ash bed, and revealed at least two phases of later dolomitization. Overall, these results support the use of this method as an alternative approach to radiometrically date geologic units without readily available volcanic deposits, and suggest it is a suitable method to better constraint the base of the Nama Group and contextualize the appearance of the first biomineralized animal, Cloudina.

Uncovering the origin of an early Tonian carbon isotope excursion: evidence of sulfur isotope from North China Craton

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The Neoproterozoic Era (1000–ca. 539 million years ago) witnessed several negative carbon isotope excursions including the oldest one during the early Tonian Period, the ca. 940 Ma 'Majiatun' or MJT anomaly, where δ13C went as low as -6‰. However, since very few studies have focused on the earlier Neoproterozoic carbon cycle, the origin of this excursion remains enigmatic. Nevertheless, by analogy to other such excursions, changes to the global sulfur cycle, the other major player in Earth's exogenic oxygen budget, may have played an important role. Here, we report carbonate-associated sulfate (CAS) isotope data from three sections on the North China Craton that span the Yingchengzi, Majiatun and Cuijiatun formations of the Jinxian Group. Our results highlight a significant increase in CAS concentrations (up to 380 ppm) and decrease in δ34S values to as low as +16.4‰ during the δ13C excursion. Alongside a new compilation of published δ34S data from the Tonian Period, we find that C and S isotopic fluctuations remain coupled through the MJT anomaly. Published 87Sr/86Sr data indicate enhanced continental weathering through this interval, which would potentially have supplied additional sulfate to the ocean. In light of these observations, we propose a conceptual model to explain the origin of the MJT anomaly that invokes a similar driver to the Ediacaran Shuram anomaly. An increased oceanic sulfate flux may have oxidised a marine dissolved organic carbon (DOC) pool directly through microbial sulfate

reduction (MSR), generating a 13C-depleted dissolved inorganic carbon ocean reservoir.

A tiny Cambrian fossil resolves the problematic evolutionary affinity of trilobites

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Trilobites existed for ~270 million years during the Palaeozoic and represented a major extinct clade among Euarthropoda. However, it has long been a conundrum whether trilobites and their closest relatives (together forming Artiopoda) were stem-lineage Mandibulata or Chelicerata on the arthropod tree of life. With X-ray microtomography, here we investigate the fine-scale soft-bodied morphoanatomy of Primicaris larvaformis, a millimeters-sized, trilobite-like euarthropod (Acercostraca) from the ~518-million-year-old early Cambrian Chengjiang fauna, China. Primicaris possesses an artiopodan body plan featuring morphologically similar post-antennular biramous appendages, but also mandibulate characteristics including a well-differentiated hypostome-labrum complex, multi-segmented exopodites, and a pancrustacean configuration of anteriormost three pairs of appendages. Phylogenetic analysis resolves Artiopoda, Acercostraca and Marrellida constituting a monophyletic stem-mandibulate lineage. Therefore, Primicaris provides a morphological and evolutionary link between Artiopoda and crown-Mandibulata, supporting a mandibulate affinity of trilobites. Primicaris suggests that a mandibulate configuration of head appendages was established in stem-mandibulates with undifferentiated post-antennular appendages, preceding their morphological specialization in the later cephalization of Mandibulata.

Oxygenation of a Mesoproterozoic ocean: Geochemical clues from the c. 1.45 Ga Tieling Formation

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The Mesoproterozoic oceans were previously thought to be characterized by low oxygen content, which has been invoked to explain the apparent relative stasis in biological evolution. However, recent studies reveal several potential pulses of oxygenation during the time interval, although detailed constraints on oxygen dynamics remain limited. In this study, we report a new set of Ce anomaly and carbonate-associated iodine (CAI) data from the c. 1.45 Ga Tieling Formation at Jixian section, North China Craton. The coupled stratigraphic variation of these two redox proxies indicates that trends relate more to changing lithology rather than to changing redox conditions. Nevertheless, carbonate samples characterized by seawater-like rare earth element patterns contain Ce anomalies as low as 0.6, while CAI values are significantly higher than the Precambrian background value of 0.5

μmol/mol. Together with other published geochemical data from the North China Craton, our results confirm that oxygen levels were significantly elevated at least locally to regionally in shallow seawater at c. 1.45 Ga. The global extent of this oxygenation event and its implications for biological evolution await further study.

Posters

Thursday

PALEOECOLOGY AND PHYSIOLOGY INFERRED FROM OXYGEN AND CARBON ISOTOPES OF FOSSIL FISH AND CEPHALOPODS

Emily Ball

University of Southampton and Natural History Museum London

Understanding the relationship between environmental perturbations, physiological traits of organisms, and their evolutionary consequences is important because it allows us to predict the impact of anthropogenic climate change on current ecosystems, and to better quantify the role of climate change in deep time evolutionary trends.

Physiology provides the link between physical and biotic changes in the environment and their effects on an individual animal. Field metabolic rate (the energetic cost of living) integrates a wide range of potential physiological and behavioural responses to environmental change. Monitoring how individual field metabolic rate varies in response to environmental change within and across species can therefore provide a sensitive test of climate-organism interactions.

In my PhD, I am using a novel proxy based on the stable carbon isotope compositions of carbonate biominerals, to reconstruct field metabolic rates in modern and fossil marine animals. We aim to use our proxy to determine relative metabolic rates across taxa and to quantify how sensitive animal physiology is to temperature change

Initially I have applied the proxy to modern fish otoliths, successfully demonstrating among-species differences in metabolic level and thermal sensitivity of metabolic rate. Next we extend analyses to fossil otoliths from the London Clay, exploring metabolic rates of fish taxa currently confined to cold, deep waters in the shallow, warm waters during the Eocene Thermal Maximum. Finally, I will extend the proxy from fishes to ammonite cephalopods, aiming to compare relative metabolic rates across body morphologies, ecological and environmental contexts.

Distribution of plant-sediment interactions in the late Palaeozoic

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A key revolution in the shaping of planet Earth and its landscapes was the evolution of vascular plants, which today exert a significant biogeomorphic influence through controls on substrate stability, sediment accumulation and hydrodynamics. The near-synchronous stratigraphic correlation of sedimentary evidence for geomorphic diversification of fluvial environments with fossil evidence for the expansion of Palaeozoic vegetation attests to the importance of this influence in deep time. Many sedimentary facies (and, by extension, landforms) do not exist until certain milestones of plant evolution are passed. On the smallest spatial scale, discernible at outcrop, vegetation-induced sedimentary structures (VISS) provide tangible evidence of plants mediating sediment deposition and erosion in ancient environments, because they represent primary sedimentary structures formed from in situ plant-sediment or plant-hydrodynamic interactions. Yet, despite the ubiquity of VISS in modern river systems and their capacity to represent volumetrically significant accumulations of sediment, descriptions from the geological record remain sporadic. This poster highlights several newly discovered examples of VISS and other vegetation-deendent sedimentary structures dating to a crucial interval of plant evolutionary reorganization. Pennsylvanian and Early Permian strata record major changes in climate and plant assemblages, from lycopsid-dominated tropical 'coal swamps' to conifer-dominated dryland environments: the so-called 'Carboniferous rainforest collapse'. VISS from pre-'collapse' strata are typically found in association with abundant in situ plants, preserved in coal swamp environments. In later oxidising red-bed facies, where taphonomic conditions encouraged plant decay, vegetation falsely appears less abundant. By identifying VISS geometries in the older facies, we have been able to identify similar examples in younger strata where plant remains are absent, and successfully used these sedimentological signatures to prospect for new fossil occurrences. The VISS we have identified in latest Carboniferous and Permian strata demonstrate that plants such as early conifers persisted as fundamentally important sculptors of sedimentation and erosion, even after the demise of the coal forests.

Phanerozoic marine biodiversity increased in presence of ecosystem engineers
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Much of the structure of biodiversity throughout the Phanerozoic is the result of interactions between life and the environment. Ecosystem engineers – animals whose behaviours impact resource availability and can change community structure – may be an important driver of the spatial and temporal structure of biodiversity. Here, we focus on bioturbators and reef-builders, two of the most important groups of modern marine ecosystem engineers, and investigated how they may have driven changes in biodiversity over the Phanerozoic. We conducted an effect-size analysis over the Phanerozoic using marine fossil occurrences from the Paleobiology Database (PBDB) to determine how strongly associated bioturbators and reef-builders are with greater biodiversity. We compared generic richness and Shannon's Diversity in fossiliferous formations with and without ecosystem engineers to calculate Hedges' g statistics for the effect of the presence of ecosystem engineers in each stage. We find that bioturbators have moderate (Hedges' $g > 0.5$) to strong (Hedges' $g > 0.8$) positive effects on both generic richness and Shannon's Diversity, which arise in the Cambrian and persist throughout most of the Phanerozoic. Reef-builders have similarly moderate to strong effect sizes on both generic richness and Shannon's Diversity, with a shift to more commonly strong positive effect sizes when Scleractinia evolved. Finally, we find that intervals of climatic stress during the Mesozoic tend to be associated with weak (Hedges' $g < 0.5$) to insignificant (Hedges' $g < 0.2$) effects for both bioturbators and reef-builders. Overall, these results highlight the role that ecosystem engineers play in impacting local biodiversity, as well as the role that the Earth systems play in modulating the effects of key biotic interactions on community structure.

Slimehead size through time: testing the temperature-size relationship in Trachichthyidae
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As global temperatures have increased due to Anthropogenic climate change, some fish species have decreased in size. Smaller body sizes may negatively impact reproductive success and lead to population declines in slow reproducing, economically important families like Trachichthyidae (also known as 'Slimeheads'). However, testing the temperature-size relationship in extant Trachichthyidae is challenging and research in this area is limited. An extinct Trachichthyidae genus, Hoplopteryx, survived millions of years of climate instability through the Cenomanian to Campanian stages (100 - ~72 Ma) of the Late Cretaceous. This study used the extensive collections of well-preserved fossils of this genus from the English Chalk, housed in the Natural History Museum, London, and other UK institutions, to investigate Hoplopteryx body size changes through the Late Cretaceous. These size data were then compared to palaeotemperature estimates from oxygen isotope analysis of bulk chalk matrix attached to each specimen. Results showed a significant negative relationship between $\delta18O$-derived palaeotemperature estimates and body size in the species Hoplopteryx lewesiensis, but a similar relationship at the genus level was not significant. These findings support the prediction that fish shrink in size in warmer seas and are the first evidence of this effect in Trachichthyidae. However, the influence of ontological and sexual variation in body size on the observed temperature-size relationship in Hoplopteryx lewesiensis remains unclear. Further research should address these influences to strengthen the insight into the temperature-size relationship in Trachichthyidae.

Evaluating the mechanistic importance of ocean deoxygenation in regional biodiversity dynamics during the Permian-Triassic mass extinction
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Ocean deoxygenation poses a severe threat to present day marine ecosystems in a warming world. Globally widespread episodes of enhanced ocean anoxia are commonly linked with hyperthermal events and have been recognised as potential drivers of ancient marine extinctions. The concentration of dissolved oxygen in modern ocean and 3D models of ancient ocean oxygenation varies spatially, and localised oxygen minimum zones (OMZs) have dramatically lower oxygen concentrations than global averages. The ecophysiological impact of ocean deoxygenation is therefore expected to be regionally variable, but the direct control of expanding oxygen minimum zones on regional biodiversity remains underexplored.

In this project, our goal is to evaluate the hypothesis that the expanding oxygen minimum zones were a key driver of marine extinctions during ancient hyperthermal events and to examine how marine ecosystems were affected at varying degrees of spatial resolution. Using the Permian-Triassic mass extinction as a case study, we present a new methodological approach integrating 3D Earth system model simulations of the marine redox environment with reconstructions of marine animal biodiversity in areas corresponding to different regimes of hypoxic stress. Our analyses of spatio-temporal changes in diversity trends in different physiological stress regimes provide new quantitative constraints on the role of warming driven ocean deoxygenation on marine biodiversity, evaluating the impact of expanding OMZs and extent of euxinia on the spatial distribution of marine ecosystems and regional diversity dynamics.

By integrating oceanographic and ecophysiological models with regional biodiversity reconstructions, we will enhance our mechanistic understanding of the environmental drivers responsible for the end-Permian mass extinction and other ancient extinction events. By deploying this approach more widely, we hope to add to a growing body of evidence describing the impact of ancient climate change on marine biodiversity.

Bayesian network analysis reveals the assembly drivers and emergent stability of Pleistocene large mammal communities
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The nature of community assembly is one of the oldest questions in ecology. The observed fossil community structure is a result of a number of environmental, biogeographic, ecological and taphonomic factors.

Using Bayesian network inference methods we determined the degrees of association between 12 large mammal families and their local environment, global temperature, locality age and large-scale geographical extent.

A Bayesian network is a directed acyclic graph that specifies a joint probability distribution between the entities of interest (nodes) in a modular way, as a product of local conditional distributions at each node. The graph structure determines the qualitative dependences between the variables, whereas the local conditional distributions allow quantitative inference of relationships.

With an exception of Hominidae, we do not find significant associations between external variables (latitude, age, mean surface temperature) and the families analysed here, demonstrating that the majority of families showed remarkable resilience to extreme climatic variability of the Pleistocene. The associations between the mammal families themselves seem to be structured by the degree of generalism in carnivores and omnivores, and by similar environmental preferences in herbivores.

We are currently conducting research on biotic interactions at the taxonomic levels of genera and species.

To our knowledge, this is the first Bayesian network inference study of motile land animal palaeocommunities. The results of this study may be useful for further research into the influence of biotic and environmental factors on palaeocommunities.

Impacts of Phanerozoic climate change on life - a community resource for paleobiogeography studies.
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Changes in climate are a key (but not the only) driver of biogeography, biodiversity, and evolutionary change on Phanerozoic timescales. In order to understand and evaluate this driver on regional to global spatial scales, detailed knowledge of climate is required. Here we present a new set of climate model simulations through the Phanerozoic, which have been tuned to best represent the processes which drive temperature and precipitation change over long timescales. In particular, modifications to cloud properties mean that polar amplification is represented in such a way that there is good agreement between model and proxy temperature gradients during super-warm periods of the Phanerozoic, such as the mid-Cretaceous and PETM. Furthermore, atmospheric CO2 has been prescribed in such a way that the global mean temperature is also in good agreement with proxy temperature records. The resulting predicted paleoclimate is presented, along with the results from several recent studies which have applied the model simulations so paleobiogeographic applications.

Tiny tracheid traits, big effects: a case study on the impact of pit area per tracheid on ecosystem processes during the Pennsylvanian using Paleo-BGC
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In some cases, key trait differences may scale up to meaningful differences in global ecosystem function and vegetation distribution. The late Paleozoic ice age ultimately saw the permanent replacement of iconic Carboniferous wetland biomes with more modern dryland biomes across much of Pangea. Two carboniferous dominants, arborescent lycophytes (lycopsids) and Marratialean tree ferns, were each successively replaced by conifers. The ‘losers’ of this race are distinct in many ways but share some common characteristics. Among these is the predominance of xylem water transport through scalariform-walled tracheids, as compared to tracheids bearing circular-bordered pits in conifers (the ‘winners’). To test the hypothesis that this difference was critical to the demise of Carboniferous dominant arborescent plants, we use a process-based ecosystem model (Paleo-BGC), which is modified to use fossil-derived ecophysiological parameters for era-appropriate plants and driven by daily output from the National Center for Atmospheric Research’s Community Earth System Model version 1.2 (CESM). Ecosystem process models provide the flexibility to test translational hypotheses about the biosphere at a mesoscale that is relevant to both plant characteristics and Earth system processes.

No evidence the Columbia River Flood Basalts drove the Miocene Climatic Optimum in sedimentary mercury records.

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Throughout the Phanerozoic, the emplacement of large igneous provinces (LIPs) was often associated with significant palaeoclimatic perturbations. Based on coincident timing, the smallest and most recent known LIP in the geological record, the Columbia River Flood Basalts (CRFB), has been linked to the Miocene Climatic Optimum (MCO). The MCO was ~4–8 °C warmer than present-day, with pCO2 estimates around 400–600 ppm, and serves as an analogue for future climate projections. Despite the temporal correlation between this event and major volcanic phases in the CRFB, remarkably few studies have sought direct volcanic signatures in Miocene-age successions. Mercury (Hg) is emitted in large quantities during volcanic eruptions, and repeated and prolonged eruptions, such as those occurring during LIP emplacement, can perturb the global Hg cycle. In recent years, Hg has become a widely used proxy for LIP volcanism. Here, the connection between the CRFB and MCO is explored by analysing trends in sedimentary mercury from four globally widespread successions, across various lithologies, depositional systems, and diagenetic conditions. Detailed analysis of relationships between Hg and total

organic carbon (TOC) and total sulphur (TS) – proxies for organic matter and sulphide host phases, respectively – is undertaken. With the use of novel analytical (thermal desorption profiles) and statistical techniques we account for non-volcanic influences on the recorded signals. We find no evidence that the Columbia River Flood Basalts caused a significant perturbation in the Hg-cycle; therefore, our data do not provide positive support for the hypothesis that CRFB volcanism played a role in the MCO. All sedimentary Hg anomalies recorded in individual successions can be attributed to local environmental factors, including depositional, lithological and diagenetic characteristics, sedimentation rate, and potential variability in terrestrial input. The emplacement style of the CRFB, its relatively small size, and lower eruption rates may explain the limited impact on the Hg cycle, when comparing the signals attributed to massive volcanism across other past oceanic anoxic events, carbon isotope excursions and mass extinctions.

Long-term Phanerozoic global mean sea level: Insights from strontium isotope variations and estimates of continental glaciation

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Global mean sea level is a key component within the fields of climate and oceanographic modelling in the Anthropocene. Hence, an improved understanding of eustatic sea level in deep time aids in our understanding of Earth's paleoclimate and may help predict future climatological and sea level changes. However, long-term eustatic sea level reconstructions are hampered because of ambiguity in stratigraphic interpretations of the rock record and limitations in plate tectonic modelling. Hence the amplitude and timescales of Phanerozoic eustasy remains poorly constrained. A novel, independent method from stratigraphic or plate modelling methods, based on estimating the effect of plate tectonics (i.e., mid-ocean ridge spreading) from the 87Sr/86Sr record led to a long-term eustatic sea level curve, but did not include glacio-eustatic drivers. Here, we incorporate changes in sea level resulting from variations in seawater volume from continental glaciations at time steps of 1 Myr. Based on a recent compilation of global average paleotemperature derived from δ18O data, paleo-Köppen zones and paleogeographic reconstructions, we estimate ice distribution on land and continental shelf margins. Ice thickness is calibrated with a recent paleoclimate model for the late Cenozoic icehouse, yielding an average ~1.4 km thickness for land ice, ultimately providing global ice volume estimates. Eustatic sea level variations associated with long-term glaciations (>1 Myr) reach up to ~90 m, similar to, and is at times dominant in amplitude over plate tectonic-derived eustasy. We

superimpose the long-term sea level effects of land ice on the plate tectonically driven sea level record. This results in a Tectono-Glacio-Eustatic (TGE) curve for which we describe the main long-term (>50 Myr) and residual trends in detail.

Oceanic deoxygenation during the mid-Silurian Ireviken Extinction Event
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The Llandovery-Wenlock transition during the Silurian Period was a pivotal phase marked by significant marine environmental evolution and biotic turnover, culminating in the Ireviken Extinction Event (IEE) and the Early Sheinwoodian Carbon Isotope Excursion (ESCIE). Published geochemical evidence suggests a simultaneous expansion of euxinic waters along continental margins, consistent with the observed carbon cycle perturbation during the IEE. The development of oceanic anoxia precipitated a crisis in marine ecosystems, reflecting a recurrent scenario during the Silurian.

Here, we present an investigation of a major Silurian anoxic event associated with the IEE, employing a diverse geochemical dataset and modeling approach. Four field sections across the Llandovery-Wenlock boundary in England and Wales, representing varying water depths, were selected. Utilizing C-S-Fe systematics, redox-sensitive trace metals, and elemental weathering proxies, alongside sedimentological and stratigraphic paleontological evidence, we reconstructed the regional redox evolution of this basin. We then utilized U and Mo isotopes, in conjunction with a newly developed U-Mo isotope fractionation model, to reconstruct global redox variability during this period.

Our findings suggest that the Silurian Telychian ocean experienced significant oxygenation under warm climatic conditions after the Hirnantian glaciation, approaching the degree of oxygenation of modern oceans. However, a subsequent shift to colder climatic conditions likely intensified ocean circulation, resulting in the upwelling of deeper nutrient-rich waters onto the shelf. Consequently, the global ocean transitioned to an expanded state of ferruginous anoxia. This process particularly facilitated regional anoxia in shallower shelf settings during the IEE, which triggered the global carbon and sulfur isotope excursion and biotic crisis. Our study highlights the complex interplay between climate dynamics, ocean circulation, and biogeochemical processes during the Silurian, shedding light on the mechanisms driving major environmental and biotic change in the mid-Palaeozoic.

New Tonian microfossils provide insights into the evolution of filamentous symmetry
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The Tonian diversification of eukaryotes marks a pivotal turning point for life on Earth, with the bulk of primary production shifting from cyanobacteria to eukaryotic algae and complex ecological interactions occurring for the first time. Here we document new exceptionally-preserved microfossils from the c. 915–820-million-year-old Veteranen Group of northeastern Svalbard (Norway). This sedimentary succession is c. 4.5 km thick and records deposition largely in marginal marine environments. Preservation quality within a limited number of horizons within the Veteranen Group is high; several new multicellular eukaryotes are preserved in addition to the known green alga Proterocladus. Molecular fingerprints from FTIR spectroscopy of Palaeosummetria brachiata n.gen. n.sp. and Multicapsula circumamicta n.gen. n.sp. reveal fossilisation products that point to an original, possibly cellulosic or xylanosic, polysaccharide component. These results are consistent with a red algal affinity for these taxa (modern red algal cell walls are characterised by cellulose and polysaccharide constituents of agar). This affinity is further supported in P. brachiata by a branching pattern that can be compared to some modern florideophytes. The regularity and symmetry of the opposite branching pattern, indicates algae already had access to developmental pathways that gave significant control over their morphology by the middle of the Tonian period. It is the oldest example of symmetrical branching in a filamentous eukaryotic organism in the fossil record.

Integrating Ice Sheet Dynamics into Phanerozoic Climate Simulations
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The role of large-scale glaciations in driving evolutionary leaps in Earth's history is well-established (e.g. Vincent et al. 2004). Yet considering ice sheet dynamics in non-transient climate simulations across the Phanerozoic remains challenging, mainly due to discrepancies in the temporal and spatial resolution among the model components. However, determining land areas affected by ice sheets is crucial for estimates of silicate weathering, primary productivity, freshwater inputs and general circulation.

Recent work by Vérard (2024) shows significant short-term variations in sea level of about 60 m across the Phanerozoic, which are attributed to water stored in land ice. Based on these sea-level variations, Vérard (2024) proposes estimates of potential

land ice volume. However, since reconstructions of land distribution and in particular orography are still highly uncertain, using state-of-the-art ice sheet models might be inappropriate since they are strongly dependent on boundary conditions such as subglacial topography.

Here, we propose a framework to address the challenges of integrating ice sheet dynamics into intermediate complexity climate simulations for the Phanerozoic. Using the PANALESIS paleogeographic reconstruction and associated ice volume estimates, we estimate ice sheet extent and topography as initial conditions for the PlaSim-GENIE climate model. We present a simple coupling framework between PlaSim-GENIE and a shallow-ice approximation model, incorporating key climatic forcings such as temperature, precipitation, and solar radiation. Feedbacks from the ice sheet to PlaSim-GENIE include albedo, topographic boundary conditions and, potentially, fresh water influx into the ocean. This is work in progress and meant to foster on-site discussions.

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