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PROGRAMME

A joint meeting with the NERC Long-term Co-evolution of Life and the Planet Programme

Thursday 05 May 2011	
09.00	**Registration & coffee**
09.25	**Welcome Address**
9.30	**KEYNOTE ADDRESS** Jim Lovelock
SESSION 1: Origins and the oxygen revolution ***Chair:*** *Tim Lenton, University of Exeter*	
10.00	**Energy at the Origin of Life** Nick Lane, University College London
10.30	**Was the Archean climate hot or cold?: Implications to biospheric evolution** David Schwartzman, Howard University
11.00	**Tea & coffee**
11.30	**Origins of (oxygenic) photosynthesis** Euan Nisbet, Royal Holloway University of London
12.00	**Causes and Consequences of the Great Oxidation Event** David Catling, University of Washington
12.30	**Paleoproterozoic fluctuations in biospheric oxygenation** Simon Poulton, University of Newcastle
13.00	**Lunch (provided for all delegates)**
14.00	**KEYNOTE – Evolutionary novelty in the Proterozoic eon: Symbiogenesis in Gaia** Lynn Margulis, University of Massachusetts
SESSION 2: The complexity revolution ***Chair:*** *Andrew Watson, University of East Anglia*	
14.45	**Multicellularity in deep time** Nick Butterfield, University of Cambridge
15.15	**Neoproterozoic glaciations: microbes at work in terrestrial oases** Ian Fairchild, University of Birmingham
15.45	**Tea & coffee**
16.15	**The Neoproterozoic Oxygenation Event** Graham Shields-Zhou, University College London **Life and the Planet I: Reinventing the Planet: The Neoproterozic revolution in oxygenation, biochemistry and biological complexity** Tim Lenton, University of Exeter
16.45	**Evolution and revolution in marine (carbonate) carbon cycling** Andy Ridgwell, University of Bristol
17.15	**Poster session and drinks reception**

Friday 06 May 2011	
Session 3: Life and the Planet during the Phanerozoic ***Chair:*** *Sir Crispin Tickell*	
09.00	**The first plants and their effects on the planet** Liam Dolan, University of Oxford
09.30	**Life and the Planet II: Evolution of modern marine ecosystems** Richard Twitchett, University of Plymouth
10.00	**Biodiversity change through the Early Cenozoic: an introduction to the PALEOPOLAR project** Alistair Crame, British Antarctic Survey **The Maastrichtian – Eocene of Seymour Island, Antarctica: a key PALEOPOLAR reference section** Jon Ineson, Geological Survey of Denmark and Greenland **Paleogene fossil plants and climates of Antarctica** Jane Francis, University of Leeds
11.00	**Tea & coffee**
11.30	**Life and the Planet IV: Descent into the icehouse** Gavin Foster, National Oceanography Centre
12.30	**Discussion – Long-term Co-evolution of Life and the Planet (NERC programme 2011-2015)**
13.30	**Lunch (provided for all delegates)**
Session 4: The Anthropocene – a new revolution? ***Chair:*** *Graham Shields-Zhou, University College London*	
14.30	**Human evolution, environment and climate** Robert Foley, University of Cambridge
15.00	**Matter and mind: Human societies and the way forward** Wolfgang Lucht, Potsdam Institute for Climate Impact Research
15.30	**Looking back from the future at the Anthropocene** Jan Zalasiewicz, University of Leicester
16.00	**Discussion – Earth system education**
16.15	**Close of meeting**

POSTER PROGRAMME

The importance of animals with respect to ecological integrity **What part do animals play within the broader connected ecosystem and to what degree might this currently be under threat?** Julian Ashbourn
The Evolution of Biocalcification in the Context of Water Temperature Uwe Balthasar, University of Glasgow
Symbiotic physiologies bias towards a stable life-environment interaction? Richard Boyle, University of East Anglia
Impact of global disturbances on the evolution of life in the polar regions during the early Cenozoic Alistair Crame, British Antarctic Survey
Rhenium-osmium geochronology of the lacustrine Green River Formation: Insights into Cenozoic ocean osmium evolution Vivien M. Cumming, Durham University
Time, space, and Gaia: Darwinian, sequential, and anthropic selection for multiscale regulation Stuart Daines, University of East Anglia
Descent into the Ice House - methodologies Gavin Foster, National Oceanography Centre
The Maastrichtian–Eocene of Seymour Island, Antarctica: stratigraphy, facies and palaeoenvironments Jon Ineson, Geological Survey of Denmark and Greenland
High-resolution redox cycles during OAE 3 (Demerara Rise, ODP Leg 207) and their implications for ocean chemistry C. März, Bremen University
Climate amelioration in the latest Ordovician - Did weathering of exposed carbonate shelf bring the Hirnantian Glacial Episode to a close? Keith Nicholls, University of Chester
On the Origin and Evolution of the Atmosphere Graham Oram
Mesoproterozoic oxygenation favoured evolution in surface environments John Parnell, University of Aberdeen
Global glaciations and Os seawater chemistry: Implications from Re-Os geochronology of the Neoproterozoic Windermere Supergroup, Canada Alan Rooney, Durham University
Characterization of water column redox conditions at the onset of the Toarcian Oceanic Anoxic Event: a high-resolution multi proxy study from North Yorkshire Najm Salem, University of Newcastle
Gaia or Good Luck? Dave Waltham, Royal Holloway University of London

POSTER PROGRAMME CONTINUED

What are Gaia's Cognitive Capabilities? Symbiosis Causes Associative Learning at the Ecosystem Scale Richard Watson, University of Southampton
Impact of global disturbances on the evolution of life in the polar regions during the Early Cenozoic: a combined biological and palaeobiological approach Rowan Whittle, British Antarctic Survey
Evolutionary regime shifts in simulated ecosystems Hywel Williams, University of East Anglia

Energy at the Origin of Life

Nick Lane, Department of Genetics, Evolution and Environment University College London

The early Earth was analogous to an autotrophic cell, with the outside (volatisphere) oxidised relative to the inside (core and mantle), and the crust acting as a semipermeable membrane. The redox and proton gradients across this membrane were dissipated by alkaline hydrothermal vents, which satisfied many, if not all, of the thermodynamic conditions required for life. In particular, I shall argue that proton gradients were key to the substoichiometric conservation of energy, necessary to power all forms of chemolithotrophic metabolism in the absence of oxygen. This explains why chemiosmotic coupling - once described as the most counterintuitive idea in biology since Darwin - should be as universal the genetic code itself.

Natural proton gradients in alkaline hydrothermal vents provide possibly the only simple solution to an energy gap on the early Earth. The process giving rise to such vents - serpentinization - is likely to be common on all wet, rocky, sunlit planets. It is then likely that life elsewhere in the universe will also be chemiosmotic.

Was the Archean climate hot or cold? Implications to biospheric evolution

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I will make the case for a much warmer climate on the early Earth than now. Both oxygen and silicon isotopes in sedimentary chert and the compelling case for a near constant isotopic oxygen composition of seawater over geologic time support thermophilic surface temperatures until about 1.5- 2 billion years ago, aside from glacial episodes at 2.1-2.4 Ga and possibly one at 2.9 Ga. Further, measurement of melting temperatures of proteins resurrected from sequences inferred from robust molecular phylogenies gave paleotemperatures at emergence consistent with a very warm early climate. I will critique recently published papers supporting a cool Archean climate. A hot Archean/early Proterozoic (aside from the glacial interval) has important implications to biospheric evolution, including a temperature constraint that held back the emergence of major organismal groups, starting with phototrophs. Conversely, a cold Archean is hard to explain taking into account the higher outgassing rates of carbon dioxide, smaller land areas and weaker biotic enhancement of weathering than present in the context of the long term carbon cycle. A geophysiology of biospheric evolution raises the potential of similar coevolutionary relationships of life and its environment on Earth-like planets around Sun-like stars. Reference: Schwartzman, D.W. and L. P. Knauth, 2009, A hot climate on early Earth: implications to biospheric evolution. In: K.J. Meech, J.V. Keane, M.J. Mumma, J.L. Siefert and D.J. Werthimer (eds.) Bioastronomy 2007: Molecules, Microbes, and Extraterrestrial Life, Astronomical Society of the Pacific Conference Series Vol. 420, San Francisco, pp. 221-228. (pdf available upon request).

Origins of (oxygenic) photosynthesis

Euan G. Nisbet, Dept. of Earth Sciences, Royal Holloway, University of London

The evolutionary history of oxygenesis is controversial. Isotopic evidence from ~2.9 Ga stromatolites from Steep Rock, Ontario, Canada, ~2.9 Ga stromatolites from Mushandike, Zimbabwe, and ~2.7 Ga stromatolites in the Belingwe belt, Zimbabwe implies that in all three localities the reef-building autotrophs included organisms using Form I Rubisco. This inference, though not conclusive, is supported by other geochemical evidence that these stromatolites formed in oxic conditions. Collectively, the implication is that oxygenic photosynthesisers first appeared ~2.9 Ga ago, and were abundant 2.7-2.65 Ga ago, long prior to the Great Oxidation Event in the early Proterozoic.

It is possible that natural selection, acting on the specificity of rubisco for carbon dioxide over oxygen, has controlled the CO_2:O_2 ratio of the atmosphere since the evolution of oxygenic photosynthesis, and thereby has also sustained the Earth's greenhouse-set surface temperature. Nitrogenase, which works in partnership with rubisco, may similarly control N_2 and hence atmospheric pressure. Co-evolution of these two enzymes may have allowed natural selection to maintain clement conditions on the Earth's surface, allowing life to be sustained over the aeons.

Causes and Consequences of the Great Oxidation Event

David C. Catling, Dept. of Earth and Space Sciences/ Astrobiology Program, University of Washington, Seattle WA 98195, USA.

Before 2.4 Ga, O_2 concentrations in Earth's atmosphere were <1 ppmv, and by 2.32 Ga, a transition to 0.2-2% by volume had occurred. The O_2 level after this *Great Oxidation Event* (GOE) was apparently insufficient for supporting macroscopic animals but enough to dominate the redox chemistry of the atmosphere and establish a stratospheric ozone layer. What caused the GOE is less obvious than it might first appear. It was not the appearance of oxygenic photosynthesis because several lines of evidence show that cyanobacteria were established several hundred million years before the GOE. The important consideration is that the Earth's overall chemical composition is reducing, so that reactions of O_2 with geothermal gases in the Archaean atmosphere or reducing cations in the ocean must have acted as a powerful chemical buffer opposing the accumulation of atmospheric O_2. In the pre-GOE atmosphere, methane had a lifetime of ~10^4 years and likely attained levels of 10^2-10^3 ppmv. Such abundant methane, along with its hydrocarbon products and CO_2, could provide sufficient greenhouse warming to counteract an early Sun that was 25-30% fainter. Mass independent fractionation (MIF) of Archaean sulphur isotopes provides evidence for high methane because photochemical models show that <1 ppmv O_2 and a sufficiently high abundance of methane are required for sulphur MIF. An inevitable consequence of abundant methane was rapid escape of hydrogen to space leading to irreversible oxidation of the Earth, and a secular decline of methane atmospheric levels. Consequently, the disappearance of sulfur MIF at 2.4 Ga is best explained by the collapse of atmospheric methane as oceanic sulphate became more abundant, which allowed increasing anaerobic methanotrophy. The collapse of methane was followed by glaciations and a substantial rise of O_2. Thus, the GOE can equally be considered a great collapse of methane.

The consequences of the GOE were increased sulphate production from weathering, leading to increasingly oxic oceans. Evidence from molybdenum isotopes suggests a much greater proportion of euxinic seafloor than today in the Mesoproterozoic oceans. Under such conditions, methane could re-establish itself as an important greenhouse gas, albeit at a lesser abundance than in pre-GOE air. Hydrogen escape and irreversible oxidation of the Earth therefore likely continued. In addition, subduction of sulphides on the seafloor was another likely source of secular oxidation. The combination of sulphide subduction and methane-induced hydrogen escape set the scene for a second rise of O_2 at the end of the Proterozoic.

Paleoproterozoic fluctuations in biospheric oxygenation

Simon W. Poulton, University of Newcastle

The Palaeoproterozoic was characterised by three major (potentially global) glaciations that coincided with the transition from a dominantly anoxic to a well-oxygenated atmosphere (the Great Oxidation Event; GOE). This transition has been dated at 2.32 Gyr ago, based on a loss of S isotope mass-independent fractionations (MIF) in sediments from the Transvaal Supergroup, South Africa. These South African sediments are considered to correlate with the second of three glaciations recorded in the Huronian Supergroup, Canada. Oxidation of atmospheric methane following biogenic oxygen production has been suggested as a driver for the onset of glaciation, with fluctuations in oxygen production potentially leading to multiple glacial episodes. However, the drivers, dynamics and consequences of oxygenation during the GOE remain poorly understood.

This presentation will focus on detailed geochemical records through the Huronian glacial succession and elsewhere. We see evidence for a stepwise increase in oxygenation across the three glaciations, that led to fundamental changes in ocean chemistry. After the first glaciation, the deep ocean remained anoxic and rich in dissolved Fe (ferruginous). After the second glaciation, however, the ocean became transiently euxinic, consistent with increased oxidative weathering of the continents. We find evidence from multiple S isotopes for a transient, early loss of mass-independent S isotope fractionations (MIF) in the lower part of the second glacial cycle. In contrast to the South African records, the second Huronian glacial succession shows no evidence for a permanent loss of the S isotope MIF signal. After the third glaciation, we see no evidence for anoxic oceanic conditions, suggesting the development of widespread (potentially global) oxic oceanic conditions for the first time in Earth history. These data highlight complex interactions between oxygen production, glaciations and ocean chemistry, and suggest that atmospheric oxygen levels fluctuated considerably across Earth's first Great Oxidation Event.

Evolutionary novelty in the Proterozoic eon: Symbiogenesis in Gaia

Lynn Margulis, UMASS

Speciation by accumulation of "random DNA mutations" has not been adequately documented in the field, laboratory or fossil record. However many first-rate scientific studies have unequivocally shown symbiogenesis underlies the origin of eukaryotic species and more inclusive higher taxa. Speciation itself, a process that evolved in the earliest anaerobic eukaryotes, is absent in prokaryotes. In "eukaryosis" (origin of nucleated cells) members of at least two prokaryotic subkingdoms ("domains") permanently merged. A sulfidogenic archaebacterium and a sulfide-oxidizing motile eubacterium (a *Perfielevia* spirochete) formed a motile sulfur syntrophy that emerged as the ancestral first eukaryotes. By the neo-Proterozoic eon (c. 800 million years ago as documented in the fossil record of acritarchs e.g., *Vandalosphaeridium)* they generated the earliest nucleated organisms. Heterotrophic, phagocytotic motile protoctists, I suggest, were ancestral to mitotic cells: late Proterozoic and Phanerozoic eon eukaryotes. Our 14 minute film "*Eukaryosis*" documents plausible cell origins that led to other protoctists and to animals, fungi and plants. The origins of the highest taxa are inferred by study of extant co-descendants. *Thermoplasma* or *Sulfolobus*-like "eocytes" (=crenarchaetoa) archaebacteria and *Spirochaeta perfielevia* symbiogenetically formed a plethora of amitochondriate early eukaryotes. **LECA**, the ***Last Eukaryotic Common Ancestor***, evolved well before the Marinoan glaciation c. 650 million years ago.

There are no missing links in our evolutionary scenario: our saga is bolstered by the Canfield-Knoll concept of some sulfidic deep ocean basins until the late Proterozoic and by acritarchs. Our recent investigation of contemporary symbiotic associations includes studies of the statoblasts of *Pectinatella magnifica,* a local freshwater bryozoan. Certain phototrophic-heterotrophic symbiogenetic analyses make us virtually certain that symbiogenesis was and still is the major source of evolutionary novelty. Young Boris Mikhaylovich Kozo-Polyansky (1890-1957) boldly and correctly asserted this idea (1921) at the first All-Russian Botanical Congress. His brilliant book, ignored, rejected and forgotten***, Symbiogenesis: A New Principle of Evolution*** (1924), finally translated into a foreign language (English by Victor Fet, edited by Fet and Margulis) was published by Harvard University Press, Cambridge Massachusetts (2010).

Multicellularity in deep time

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Multicellularity is considered one of the 'major transitions in evolution,' but it is also enormously convergent. In addition to its independent appearance in plants, animals and fungi, it has been readily adopted by most groups of protists and prokaryotes. As such, it is not surprising to find it richly represented in the early fossil record. Prior to the Phanerozoic, most instances of multicellularity are represented by microfossils of unknown affiliation. Even so, that can be loosely classified on the basis of their 'grade of organization,' which range from simple clonal colonies to integrated coenobia, unbranched and branched filaments, filaments exhibiting cellular differentiation, vesicles exhibiting 'hyphal fusion' and a variety of problematic forms. Taphonomic processes have of course obscured much of this early record, and in certain instances have led to fossils being classified above their true grade. The more fundamental concern, however, is the down-grading of multicellular fossils due to fragmentation.

Of those Proterozoic fossils that have been taxonomically resolved, the majority are recognized on the basis of diagnostic cell-division patterns preserved in multicellular forms. To date, there is a significant Proterozoic record of multicellular cyanobacteria, filamentous red algae, coenobial and filamentous green algae, filamentous chromalveolates and possible fungi. Biomarker evidence for the presence of pre-Cambrian 'demosponges' remains equivocal in the absence of morphologically preserved fossils. It is increasingly clear, however, that neither eumetazoans nor embyrophytes had put in an appearance prior to the Ediacaran.

Given the ease with which multicellularity is adopted, the belated (Ediacaran) appearance of eumetazoans has been widely ascribed to external constraints, especially the availability of diatomic oxygen. But this is to confuse the myriad quick and easy routes leading to sub-tissue-grade multicellularity with the fundamentally more complex business of developing integrated systems of functionally specialized tissues and organs. Organ-grade multicellularity has evolved only twice on this planet – once in animals and once in plants – a pattern that points strongly in the direction of internal developmental constraints. In view of the enormous geobiological impact of eumetazoans and embryophytes, it is hardly surprising that their arrival was accompanied major biogeochemical perturbation.

Neoproterozoic glaciation: microbes at work in terrestrial oases

Ian Fairchild, University of Birmingham

In the ongoing debate concerning the causes, severity, and history of Neoproterozoic glaciation, the concept of a biosphere under great environmental stress repeatedly emerges. The continuity of life through the Cryogenian demonstrates the constant presence of a range of life-supporting environments, but there is little direct evidence of life during a glaciation. Theoretically, even under the most severe Snowball Earth environments that have been proposed, localized surface open water would be present, in addition to sub-ice marine environments, and oases in localized regions of high heat flow. However, the most specific evidence of biological activity under extreme cold arid conditions consistent with panglaciation is found in ancient fluvilacustrine environments from Svalbard that bear close comparison with modern Antarctic oases, such as those in the McMurdo Dry Valleys.

The Svalbard occurrences are within the Wilsonbreen Formation, which represents the younger of two discrete glacigenic stratigraphic units in the Neoproterozoic succession of NE Svalbard. In this region, and the former basin continuation in E Greenland, occur Tonian carbonate platform sediments, succeeded by dominantly mixed shale-carbonate facies which are interrupted by the glacial units, with deposition continuing into the Ediacaran Period. The Wilsonbreen Formation consists dominantly of diamictites, displaying evidence of a range of depositional conditions from waterlain, to subglacial, but along the central tens of km of its outcrop strip, the diamictites are interrupted by one to several units of sandstones, rhythmites and carbonates with specific evidence of glacifluvial and glacilacustrine origin.

There are numerous points of sedimentological similarity between the ancient facies and the modern Dry Valleys, but differences in tectonic setting and in carbonate abundance. The Neoproterozoic examples formed within carbonate-rich terrains which facilitated the reprecipitation of carbonate from terrestrial waters. Glacifluvial facies consist of sandstone units, locally cross-stratified, up to 3 m thick, with numerous thin beds of limestone, often demonstrably stromatolitic, and which are laterally equivalent to zones of intraclasts. Analogous facies in modern Antarctica are microbial mats in ephemeral stream courses which become broken up and deflated when the bed is dry. Rhythmites often display a characteristically lacustrine motif of mm-scale couplets of detrital sediment and precipitated carbonate (probably from seasonal microbial blooms), may contain thin mass flows, and commonly exhibit dropstones indicative of floating ice. A structureless 3 m sandstone unit, consisting of well-rounded (aeolian-transported) grains is interpreted as an analogue of modern ice conveyor deposits – important in demonstrating a year-round ice-cover of lake centres, found only in the modern McMurdo cold, hyperarid conditions. Saline lake facies in the Svalbard examples contain a variety of dolocrete precipitates, stromatolites locally with textured mat surfaces, and evaporite relics and dissolution-breccias; in the modern environment subtle variations in the degree of hyperaridity lead to profound water level and salinity changes.

In addition to the mat-building cyanobacteria, microbes had important roles to play in redox cycling in these cold-arid terrestrial environments. Mn-enrichment is a notable feature of the carbonates and specialized Mn-cycling, including reduction of Mn oxides in aerobic conditions is a feature of the modern oligotrophic lakes. The isotope systematics of sulphate within the carbonates has revealed values that have stretched the envelope of known values in nature and demonstrated the importance of microbial redox cycling. Limestones with highly negative $\Delta^{17}O_{SO4}$ is attributed to oxidation of sulphides on the land surface by atmospheric oxygen with a strongly depleted $\Delta^{17}O$ signal, created by stratospheric processes, and consistent with high atmospheric carbon dioxide concentrations (Bao et al., 2009). Evaporative dolostones on the other hand have their sulphate oxygen isotope systematics re-set: the $\Delta^{17}O_{SO4}$ anomaly is lost, whilst δ^{18}_{SO4} evolved to very high values indicative of extreme hyperaridity. Thus, microbes generated the geochemical signals of environmental stress that represent a completely independent line of evidence for panglaciation.

I acknowledge the varied contributions of colleagues on the current NERC-supported project GAINS (Glacial Activity in Neoproterozoic Svalbard).
http://www.gees.bham.ac.uk/research/clusters/geosystems/gains2010.shtml

Bao, H., Fairchild, I.J., Wynn, P.M. and Spötl, C. 2009 Stretching the envelope of past surface environments: Neoproterozoic glacial lakes from Svalbard. *Science*, 323, 119-122.

The Neoproterozoic Oxygenation Event

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The Neoproterozoic era marked a turning point in the development of the modern earth system. The irreversible environmental changes of that time are viewed as being rooted in tectonic upheavals that drove chain reactions between the oceans, atmosphere, climate, and life. Key biological innovations took place amid carbon cycle instability that pushed climate to unprecedented extremes and resulted in the ventilation of the deep ocean. Despite a dearth of supporting evidence, it is commonly presumed that a rise in oxygen triggered the evolution of animals. Although geochemical evidence for oxygenation is now convincing, our understanding of the Neoproterozoic earth system and of early animal evolution has changed apace. New geochemical evidence (Isotopic, iron speciation, redox-sensitive elements) reveals an altogether more complicated picture in which the spread of anoxia played an important role during the nascent stages of animal evolution, and questioning assumed cause-and-effect relationships between oxygenation and biological evolution. The challenge to future researchers lies in unraveling the complex entanglement of earth system changes during this pivotal episode in earth history. The Neoproterozoic Earth System is the focus of a new UK-based multidisciplinary project (Reinventing the Planet…). Marine and terrestrial strata from the UK and China will form the basis of new geochemical and palaeontological studies which along with existing datasets will be integrated and interrogated through the development of heuristic, spatial and evolutionary models.

Life and the Planet 1: Reinventing the Planet: The Neoproterozoic revolution in oxygenation, biogeochemistry and biological complexity

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The Earth is truly a remarkable planet. In addition to the physical processes driving plate tectonics, climate and ocean-atmospheric exchange, it supports an extraordinary diversity of living organisms, from microbes to mammals and everything in between. Such wasn't always the case, however, and it is clear that both the planet and its biosphere have evolved – indeed, co-evolved – over deep time. In the past two billion years, by far the most fundamental shift in this co-evolutionary process occurred during the Neoproterozoic (1000 – 542 million years ago), a planetary revolution that culminated in the modern Earth System. The Neoproterozoic begins with a biosphere populated almost exclusively by microbes, and ends in the midst of its greatest ever evolutionary radiation – including the diverse macroscopic and biomineralizing organisms that define the modern biosphere. At the same time, it witnessed the greatest climatic and biogeochemical perturbations that the planet has ever experienced, alongside major palaeogeographic reconfigurations and a deep ocean that is becoming oxygenated for the first time. There is no question that these phenomena are broadly interlinked, but the tangle of causes, consequences and co-evolutionary feedbacks has yet to be convincingly teased apart. In order to reconstruct the Neoproterozoic revolution, we propose a multidisciplinary programme of research that will capture its evolving geochemical and biological signatures in unprecedented detail. Most significantly, these collated data will be assessed and modeled in the context of a co-evolutionary Earth system., whereby developments in one compartment potentially facilitate and escalate those in another, sometimes to the extent of deriving entirely novel phenomena and co-evolutionary opportunities.

Our newly launched collaborative project will be guided by three general hypotheses, testable against accruing data and theory: H1) that the enhanced weathering associated with land-dwelling eukaryotes was initiated in the early Neoproterozoic leading to major environmental change, including extreme glaciations and stepwise increase(s) in atmospheric oxygen concentration; H2) that major environmental changes in the mid-Neoproterozic triggered the emergence of animals; and H3) that the late Neoproterozoic-Cambrian radiations of animals and biomineralization were themselves responsible for much of the accompanying biogeochemical perturbations. Primary data for this project will be assembled from field studies of key geological sections in the UK and North China, along with contributed sample sets from Namibia, Spitsbergen and various archived collections. Together, these offer close to comprehensive coverage of the Neoproterozoic, and highlight the sometimes overlooked British Neoproterozoic heritage of well preserved non-marine successions of the Torridonian in Scotland and spectacular new surfaces of Ediacaran macrofossils from Charnwood Forest. Collected samples will be analysed to assess associated weathering and climate (Sr, C, O and S isotopes), oceanic redox conditions (Fe speciation and trace metals), nutrient dynamics (P speciation and trace metals) and biological constituents (microfossils, macrofossils and biomarker molecules). These data will be integrated and interrogated through the development of heuristic, spatial and evolutionary models. Beyond its integrative approach, the potential of this project lies in the diversity of the contributing researchers from the fields of Neoproterozoic stratigraphy, geochronology, biogeochemistry, palaeobiology, Earth system modeling and biomarker analysis. Further insight will come from our contingent of two PDRA's and three PhD students working across a range of topics and linked via a schedule of regular team meetings. We anticipate an improved understanding of the Neoproterozoic Earth system and the co-evolutionary interplay between the biosphere and planet.

Evolution and revolution in marine (carbonate) carbon cycling

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The Phanerozoic has seen fundamental changes in the global biogeochemical cycling of calcium carbonate ($CaCO_3$), particularly the advent of biomineralization during the early Cambrian when the products of weathering could first be removed through metabolic expenditure (by e.g. corals and benthic shelly animals). The subsequent ecological success of planktic calcifiers (e.g., coccolithophores and foraminifera) during the Mesozoic further shifted the locus of deposition from the continental shelves to the deep open ocean. These biologically-driven $CaCO_3$ depositional 'mode' changes along with geochemical and tectonic variations in boundary conditions such as sea-level and calcium ion concentrations affected the carbonate chemistry of the ocean. The evolutionary success of planktic calcifiers during the Phanerozoic has also enhanced the stability of the climate system by introducing a new mechanism that acts to buffer ocean carbonate-ion concentration on multi-millennial time-scales: the saturation-dependent preservation of carbonate in sea-floor sediments.

The first land plants and their effect on the planet

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The growth of plants requires elements including phosphorus, potassium, calcium and magnesium, which are extracted from the substrate by rooting systems. Rooting systems may be specialised axial organs with a surface network of filamentous cells (root hairs) that extend into the soil. These are the true roots found in vascular plants. Non-vascular plants on the other hand develop a system of filamentous cells called rhizoids that are likely to serve a similar function. An ancient network of *RSL* basic helix loop helix transcription factors controls the development of these filamentous cells at the land-plant soil interface. The majority of land plant rooting systems have evolved a variety of symbiotic relationships with fungi that accelerate the release of these essential nutrients from rocks and facilitate their transfer to the plant. Therefore many of the processes that occur in extant land plants are likely to have occurred in the earliest land plants that colonized the continental surfaces.

Land plants (and their associated symbionts) accelerate silicate weathering compared to background levels by secreting organic acids that act as powerful chelators in the mineral substrate. Vascular plants enhance silicate weathering by 2-10 fold compared to non-vascular plants. Since silicate weathering removes atmospheric CO_2, the step change in silicate weathering rates caused by the radiation of vascular plants is widely thought to have caused a drawdown of atmospheric CO_2 between 400 and 360 million years ago. This in turn led to a period of global cooling and glaciation. Nevertheless the presence of fossilized plant spores in ~470 million year old sediments indicates that non-vascular land plants were growing on continental surfaces approximately 100 million years before this vascular plant induced cooling event. Given their need to access rock-bound minerals, we set out to determine if the radiation of the first land plants – non vascular plants – might have also have caused a step change (increase) in silicate weathering rates. We determined the impacts of non-vascular plants on silicate weathering and will be present these results and their impacts on global change in the Ordovician discussed.

Early Evolution of Modern Marine Ecosystems

Richard J. Twitchett[1], Clive N. Trueman[2], M. Friedman[3], Gregory D. Price[1]

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Currently, our marine ecosystems are threatened by a number of environmental changes, including rising global temperatures and changes in ocean circulation patterns. Recent surveys have shown that parts of the world's oceans are becoming anoxic 'dead zones' where no marine animals can live. As these dead zones continue to expand significant numbers of marine species may become extinct.

Although these present-day environmental changes are of great concern, it is not the first time that marine ecosystems have faced such threats. The fossil record shows that at many times in the past global temperatures have risen, ocean circulation has slowed down, and oxygen-starved dead zones have expanded throughout the world's oceans. Modern marine ecosystems are the result of millions of years of evolution. Many of the animal groups that comprise modern marine ecosystems first appeared or radiated during the Mesozoic, in the aftermath of the Late Permian extinction event. This major biotic crisis was associated with rising global temperatures, changes in ocean circulation and expansion of oxygen-poor dead zones - the very same threats facing modern ecosystems today. As early modern-style ecosystems appeared and evolved after the Late Permian and through the Mesozoic, they were struck by a succession of similar environmental catastrophes, with similar combinations of global warming, expanding dead zones and widespread extinction.

The aim of our study is to understand the effect that global warming, changes in ocean circulation, and expansion of the oxygen-starved dead zones had on these early modern-style marine ecosystems of the Mesozoic. We will determine how the structure of these ecosystems changed through time, and in particular how well they functioned, in response to changing environmental conditions. Furthermore, we will evaluate whether there been an improvement in the resistance of marine ecosystems to changes in temperature, ocean circulation and available oxygen over time. In order to address these questions, we will undertake a series of linked studies at two contrasting scales: (a) global-scale analyses of marine ecosystem response to long-term changes in global temperature and atmospheric carbon dioxide and oxygen levels; and (b) local-scale, high-resolution analyses of ecosystem response to local environmental changes in dissolved temperature, oxygen concentration, and ocean circulation. Local-scale analyses will involve field expeditions to various sites that are known to contain a detailed record through four key events in our study interval. Global-scale analyses will involve ecological study of published information and museum collections of all known marine taxa that existed through the Mesozoic. The results from our multidisciplinary study will represent a step-change in our understanding of the role(s) that environmental changes in temperature, ocean circulation and levels of dissolved oxygen had on the structure, function and early evolution of modern marine ecosystems.

Biodiversity change through the Early Cenozoic: an introduction to the PALEOPOLAR project

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The rise to prominence of many modern groups of plants and animals through the Cenozoic era has always proved something of a paradox; why should global biodiversity show such a steep increase just as climates were deteriorating? It is possible that at least part of the answer to this question lies in the regionalisation of biotas, with higher extinction rates towards the poles being balanced, or exceeded, by higher speciation in the tropics. Such a process would in turn be an important mechanism underpinning the formation of polar – equatorial gradients in taxonomic diversity through to the present day.

The PALEOPOLAR project sets out to look at the balance between speciation, extinction and dispersal in both the high- and low-latitude regions at selected time intervals through the Early Cenozoic era. We will concentrate on both polar regions and make comparisons with the lower latitudes using existing archive datasets. Our starting point is the latest Cretaceous (Maastrichtian stage) so that we can plot biological change occurring across high- and low-latitude K-Pg boundary sections. Particular use will be made of a new dataset from Seymour Island, Antarctica which has one of the best-exposed K-Pg sections anywhere in the world. We will plot biotic recovery patterns through the early and mid- Paleocene and link them, where possible, to observed palaeoenvironmental and palaeoclimatic changes. Using the Antarctic stratigraphic sections and hopefully others such as those in West Greenland, we will investigate the response of the polar regions to the PETM and other Early Eocene hyperthermal events.

Our programme will also include molecular phylogenetic investigations of selected polar marine taxa, and GCM modelling of Early Cenozoic climates. By adopting a multidisciplinary approach we hope to throw important new light on how Early Cenozoic biotic and climatic events helped shape some of the major patterns of life on Earth at the present day.

The Maastrichtian–Eocene of Seymour Island, Antarctica: a key PALEOPOLAR reference section

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Seymour Island, at the north-eastern tip of the Antarctic Peninsula, is atypical for the region in being ice-free. The Maastrichtian–Eocene succession is thus fully accessible and in the context of the PALEOPOLAR project provides a unique high-latitude reference section for the southern hemisphere. Seymour Island reveals the youngest deposits of the James Ross Basin, a Jurassic–Paleogene back-arc basin. Four discrete phases of basin evolution are represented on the island: Maastrichtian – earliest Paleocene (Lopez de Bertodano Formation), early Paleocene (Sobral Formation), late Paleocene (Cross Valley Formation) and Eocene (La Meseta Formation).

The Lopez de Bertodano Formation (*c*. 1200 m on Seymour Island) provides an expanded marine record through the Maastrichtian and the earliest Paleocene. Dominated by bioturbated silty muds and very fine sands, this richly fossilferous marine succession is punctuated by glaucony-rich horizons representing periods of sediment starvation; the Cretaceous–Paleogene boundary (K–Pg) is one such composite glaucony-rich interval. A subtle unconformity separates the Lopez de Bertodano Formation from the succeeding lower Paleocene Sobral Formation, a regressive sand-rich marine succession (*c*. 300 m thick) of tide-influenced deltaic origin. The uppermost Lopez de Bertodano Formation and the Sobral Formation together yield a marine record of the post K–Pg biotic recovery.

The Cross Valley and La Meseta Formations record two discrete episodes of deep valley incision in the mid-Paleocene and early Eocene, respectively. The former event created a deep, steep-sided valley that was rapidly plugged by a thick succession (*c*. 200 m) of coarse volcaniclastic detritus. These fluvial sandstones and conglomerates of the Cross Valley Formation are capped by a thin unit of shallow-marine sandstones and mudstones containing oysters and well-preserved leaf fossils. Early Eocene incision resulted in a 6–7 km wide valley cutting several hundreds of metres into the Cretaceous–Paleocene substrata. The valley-fill (La Meseta Formation) is a complex, heterogeneous succession of deltaic, shallow marine and estuarine sediments; commonly highly fossiliferous, this formation provides an important record of Eocene biotic development following the Paleocene–Eocene Thermal Maximum (PETM).

Paleogene fossil plants and climates of Antarctica

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During the Cretaceous and early Cenozoic the Antarctic continent was situated over the South Pole but geological evidence indicates that the land was covered in lush green forests rather than ice sheets, evidence for much warmer global climates than present.

Rocks and fossils of this age are now exposed in the Antarctic Peninsula region, particularly on Seymour Island. Although the sedimentary sequence is marine or estuarine in origin, the strata contain abundant fossil wood and leaves and well preserved pollen and spores. These fossils plants are the remains of forest vegetation that grew on the wooded slopes of the volcanic arc that formed the spine of the Antarctic Peninsula at that time but which were subsequently washed into the adjacent ocean and preserved in basin sediments.

Previous work on leaf beds of Paleocene and Eocene age (Francis, Tosolini, Cantrill, Craggs) shows that the forests were composed of ancestors of the modern Southern Hemisphere vegetation: podocarp and monkey puzzle conifers, southern ferns, and flowering plants of families such as the Nothofagaceae (southern beech), Winteraceae (mountain pepper) and Proteaceae (proteas). Paleocene floras are the most diverse and contain warmth-loving types but Eocene floras are dominated by cool-temperate types of southern beech. This change in diversity and plant type reflects climate cooling from warm Paleocene to cooler Eocene climates. Analysis of leaf characteristics indicates that mean annual temperatures in this region dropped from about 13°C to 10°C during this time but climates were strongly seasonal with hot summers and cool winters.

New work for the PALEOPOLAR project will analyse fossil wood, leaves and pollen to determine the changing nature of terrestrial vegetation and climates from the latest Cretaceous through the Paleogene and its response to global events. There appears to have been little impact from the end-Cretaceous disturbance on terrestrial environments and vegetation in Antarctica but preliminary work suggests that the vegetation may have responded more dramatically to warming at the end of the Paleocene, to local devastation caused by volcanic eruptions and by subsequent global cooling that heralded the onset of glaciation in Antarctica.

Descent into the Ice House

Gavin L. Foster[1], Paul N. Pearson[2], Richard D. Pancost[3], Andy Purvis[4], Philip F. Sexton[5], Caroline H. Lear[2], Toby Tyrell[1], Robert Marsh[1], Dan J. Lunt[6], Samantha J. Gibbs[1], Tom Dunkley-Jones[7], J. Andrew Milton[1], Eleanor John[2]

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For at least as long as the Phanerozoic, the Earth's climate has oscillated between two main modes, a globally warm and humid so-called 'greenhouse state', and periods of significant continental glaciation called an 'icehouse' state. Solid evidence for this grand climatic cycling is relatively scarce and scattered across geological archives of many sorts, becoming ever sparser and more difficult to interpret with increasing age. The relative roles of solar forcing, surface albedo, ocean circulation and greenhouse gas concentrations in controlling the long-term history of surface temperature of the planet are poorly understood, and above all the complex feedbacks exerted by the biosphere in response to global change are only dimly perceived. Reducing these uncertainties has become an urgent priority for Earth system science research given the nature of the uncertainties associated with predicting our future warm climate. This presentation will outline a recently funded proposal by NERC as part of the Life and the Planet theme that focuses on the most recent and best documented major climatic shift on Earth - the Cenozoic climate transition. Understanding of this transition has increased greatly in recent years, stimulated by vigorous debate, providing a platform for new research to better understand the interplay between the physical and biological components in the evolution of the Earth’s climate.

The primary objective of the proposal “Descent into the Icehouse” is to determine what led to the rapid switch at the Eocene/Oligocene boundary from the warm greenhouse state that characterised much of the Mesozoic and early Cenozoic, to the relatively frigid icehouse state that has characterised the last ~34 mys. Although the rapid growth of the Antarctic Ice sheet at ~34 Ma was a threshold event, this was the culmination of a cooling trend that began ~16 million yrs before. The most commonly cited driver of this long-term climate change is a gradual decline in the CO_2 concentration of the atmosphere due to a subtle imbalance between silicate weathering (CO_2 sink) and volcanic outgassing (CO_2 source). Our current proxy records, however, do not support this assertion, suggesting either that factors other than CO_2 control long term climate change or that our records of CO_2 in early Cenozoic are inaccurate.

Our proposal aims to address the following fundamental questions:

1. What drives the evolution of climate on geological timescales?
2. What role do biological feedbacks have on the evolution of pCO_2, and hence climate, on these timescales?

Human evolution, environment and climate

Robert Foley, Leverhulme Centre for Human Evolutionary Studies, University of Cambridge

The evolution of the lineage leading to humans occurs over the last five million years or so, a very short and recent part of the earth's history. Despite its brevity as an evolutionary event, human evolution is distinctive because a) humans are a remarkable lineage by any evolutionary standard; b) it occurred against a period of very dramatic climatic change; and c) humans are now having an enormous impact on the biosphere, and even affecting the climate itself. In this paper I shall explore the interaction of ecological and evolutionary patterns during the course of human evolution. I shall focus on the nature of 'climatic determinism' in evolutionary models, and how these apply to human evolution; at the extent to which hominin speciation, extinction and dispersals were influenced by environmental change and biogeographical factors; at the evidence for the first human impact on environments; and finally, at the scale of human influence on ecological structures across evolutionary time. Two broad implications will be discussed: the first is that interactions between the evolution of any lineage, including humans, and the environment are complex and often very local; and second, that human evolution offers a remarkable opportunity to study evolutionary processes, in detail.

Matter and mind: Human societies and the way forward

Wolfgang Lucht, Potsdam Institute for Climate Impact Research

Human societies are entering the critical global change phase of their long co-evolution with the environment. It is likely that a transition to more sustainability will require what has been called a Grand Transformation in societies that will alter the way they relate to the environment and will have to consist of a cascade of interlinked co-transitions in order to avoid detrimental co-evolution paths. A transition to low-carbon societies alone, currently at the center of political negotiations, will not be sufficient as it neglects the effects of energy use, habitat loss and globalisation. What, then, will the nature of the greater transition be? The core topic to be tackled concerns the material flows between societies and their environment because the volume of societal material extractions from and emissions into the environment strongly shapes the potential future co-evolution pathways and therefore of the whole of the Earth system. Societies support maintenance, reproduction and growth of their social structures through these material flows, fueled by the amount of energy available, currently from fossil fuels. The other important element is language, which is entering a phase of increasingly networked world communication. As a look back into Earth's history may inform about potential future developments, so a look back into human history is instructive about the deeper nature of material relations of human existence to the world and the role of languages, a primary constituent of human existence. I will argue that before the language of words there was a language of material artifacts that reaches back to the beginnings of humans on Earth. It links the later transition to symbolic, categorical thought to earlier self-expression through artifacts, two dimensions that now are transitioning into a phase where they produce global change. Today, both material expressions of human social organisation and the expansion of increasingly networked thought through languages are processes that will determine the future co-evolutionary future of human societies. What is needed are new cosmologies describing the human position in the world that are in resonance both with latest science and the streams of cultural narrative and material reproduction. The sustainability challenge emerging from this suggests three forms of (self-) engineering that are relevant: technological engineering, (bio-) geoengineering, and social self-engineering. None of these are unproblematic. All of them could be exciting.

Looking back from the future at the Anthropocene

Jan Zalasiewicz, University of Leicester

The deep time history of the Earth, and of its biota, is decipherable mainly from evidence contained within strata. The formal organisation of that history, in the Geological Time Scale, is pragmatic and essentially dynastic. The almost infinite - to human perceptions - duration and complexity of that history is rendered manageable by recognition of major reorganisations of the Earth system. These reorganisations – as, for instance at the Cretaceous/Tertiary boundary - enable subdivision of the stratal record into segments that are recognisable by particular combinations of physical, chemical and (especially) biological characteristics.

The concept of the Anthropocene (Paul Crutzen's term, which has rapidly become a vivid and commonly used, albeit still informal, geological time term) involves, in effect, a thought experiment: it considers how the effects of ongoing global change might be preserved into a far future geological record, by considering anthropogenic phenomena in terms of their closest ancient geological analogues. A measure of the scale, distinctiveness and relative permanence of human effects on Earth can thus be glimpsed; ultimately, this might translate into, say, the appropriate hierarchical scale (e.g. Age, Epoch, Period) for the term, were it to become formalized.

A key measure of stratigraphic change is biological, in its guise as palaeontology. Thus, a direct, preserveable biostratigraphic signal of the Anthropocene on Earth is the geologically novel and highly distinctive human trace fossil assemblage – that is, our towns, cities and roads. This may comprise a short-lived event layer, but indirect effects of human action (species invasions, the scale of which is equally novel in Earth history; and ongoing extinctions) have already caused what is effectively permanent biotic, and therefore biostratigraphic, change. Most biological change to date has reflected habitat loss and human predation. The effects of warming and acidification are in their early stages; as these intensify, consideration of the Anthropocene as merely an epoch may come to be seen as conservative.

The importance of animals with respect to ecological integrity

What part do animals play within the broader connected ecosystem and to what degree might this currently be under threat?

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The importance of biodiversity is generally acknowledged, but from what perspective? Naturally we do not like to see the disappearance of species and are consequently becoming more adept at identifying species which are threatened and endangered and, in many cases, establishing remedial programmes for their ongoing protection.

In the natural world, species evolution, including, where applicable, extinction might be considered an integral factor of the broader evolution of change. It is postulated that unnatural species extinction, prompted by anthropological activities for example, will similarly have an ecological impact, the broader scope of which might not be fully understood.

Consequently, it is argued that ecological integrity should include the natural presence of animals and the part they play within both local and connected habitats. Reference will additionally be made to the concept of ecological integrity, as promoted and managed by Parks Canada within a variety of environments

The Evolution of Biocalcification in the Context of Water Temperature

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Sitting at the interface between biogeochemical cycling and evolution, biocalcification is intimately linked to the evolution of the planet. Aragonite and calcite are the two main polymorphs of calcium carbonate exploited by calcifying organisms and precipitated as inorganic marine cements. While in today's oceans, aragonite is the most stable inorganic precipitate, calcite was the primary calcium carbonate mineral during the Middle Cambrian – Lower Carboniferous and the Middle Jurassic – Palaeocene. It is a long-standing question whether ocean chemistry influences the choice of calcium carbonate polymorph in calcifying organisms. Currently the strongest link between the aragonite/calcite sea conditions and carbonate skeletal composition is recognised for organisms that evolved calcification for the first time from a non-mineralised ancestor (Porter 2010), while the ratio of aragonite/calcite skeletal components gradually increases throughout the Phanerozoic with more pronounced shifts during mass extinctions and no apparent relation to shifts in aragonite/calcite ocean states (Kiessling et al. 2008).

The shifts between aragonite and calcite seas have been mainly attributed to oscillations in the marine Mg/Ca ratio and pCO_2 (Stanley & Hardie 1998; Zhuravlev and Wood 2009). However, in the context of the influence of ocean chemistry on the evolution of calcification it has commonly been overlooked that Mg/Ca controls calcium carbonate polymorph formation as a function of temperature (Morse et al. 1997). Applying the experimentally derived Mg/Ca and temperature dependent precipitation fields of aragonite and calcite (Morse et al. 1997) shows that at the commonly used threshold of Mg/Ca = 2 (with Mg/Ca < 2 = calcite seas and Mg/Ca > 2 = aragonite seas) aragonite would have been the favoured polymorph in waters warmer than 18° C.

By implication shallow tropical marine waters would have remained aragonite facilitating even during calcite sea intervals. Considering that in the marine realm shallow tropical environments appear to have the highest evolutionary origination rates (Krug et al. 2009), permanent aragonite-facilitating conditions in these environments suggest a strong link between the aragonite/calcite ocean state that goes beyond the time of origin of any given clade. Geological evidence for this phenomenon is likely to be obscure as eventual sea level fluctuations would have either exposed the shallow marine aragonite to corrosive meteoric waters or to the deeper and cooler marine waters facilitating the formation of calcite. Both these situations probably would have resulted in the well documented early diagenetic aragonite dissolution during calcite sea intervals (Palmer & Wilson 2004). However, the recent discovery of the common occurrence of relic aragonite in Ordovician and Silurian brachiopods (Balthasar et al. in review) shows that relic aragonite inclusions in secondary calcite represent a yet unexplored geological archive with the potential to resolve the aragonite environments of calcite seas.

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Symbiotic physiologies bias towards a stable life-environment interaction?

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A connection is hypothesized between the physiological consequences of mutualistic symbiosis and life's average long-term impact on certain highly biologically conserved environmental variables. This hypothesis is developed analytically and with a variant of the Daisyworld model.

Biological homeostasis is frequently effective due to co-ordination between opposing physiological "rein" functions, which buffer an organism in response to an external (often environmental) perturbation. It is proposed that during evolutionary history the pooling of different species' physiological functions in mutualistic symbioses increased the range of suboptimal environmental conditions that could be buffered against—a mutual tolerance benefit sometimes sufficient to outweigh the cost of cooperation. A related argument is that for a small number of biologically-crucial physical variables (i) the difference between organism interiors and the life-environment interface is relatively low, and (ii) the biologically optimum level of that variable is relatively highly conserved across different species. For such variables, symbiosis tends to cause (at a cost) an increase in the number of environmental buffering functions per unit of selection, which in turn biases the overall impact of the biota on the state of the variable towards the biological optimum. When a costly but more temperature-tolerant and physiologically versatile symbiosis between one black (warming) and one white (cooling) "daisy" is added to the (otherwise unaltered) Daisyworld parable, four new results emerge: (1) The extension of habitability to a wider luminosity range, (2) resistance to the impact of "cheater" white daisies with cold optima, that derive short-term benefit from environmental destabilisation, (3) the capacity to maintain residual, oscillatory regulation in response to forcings that change more rapidly than allele frequencies and (crucially) (4) "succession"-type dynamics in which the tolerant symbiosis colonises and to an extent makes habitable an otherwise lifeless environment, but is later displaced by free-living genotypes that have higher local fitness once conditions improve. The final result is arguably analogous to lichen colonisation of the Neoproterozoic land surface, followed by the Phanerozoic rise of vascular plants. Caution is necessary in extrapolating from the Daisyworld parable to real ecology/geochemistry, but sufficiently conserved variables may be water potential, macronutrient stoichiometry and (to a lesser extent) the temperature window for metabolic activity.

Impact of global disturbances on the evolution of life in the polar regions during the early Cenozoic

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This new project will investigate the impact of major global disturbances on marine and terrestrial ecosystems during the latest Cretaceous–early Cenozoic period of global warming, with particular emphasis on the evolution of life in the environmentally-sensitive polar regions. We will test the hypothesis that a range of major disturbances reset the global evolutionary clock in this climatically-sensitive period, and had a pronounced effect on polar biotas long before the onset of global cooling that led to Cenozoic glaciation.

This period includes the Cretaceous-Paleogene (K–Pg) mass extinction event and the Paleocene Eocene Thermal Maximum, as well as other hyperthermal climate events. A newly studied sequence on Seymour Island, Antarctica, is now recognised as having one of the best exposed and most complete high latitude sedimentary sections through this interval anywhere in the world and has long been recognised as a palaeontological locality of global importance.

Using new sediment and faunal and floral fossil collections we will construct a palaeotemperature record for the latest Cretaceous–early Paleogene using a variety of geochemical and palaeontological proxies, which will allow us to establish the occurrence and magnitude of global climatic events in southern high latitudes. This new temperature data will allow us to determine global latitudinal temperature gradients and assess how diversity in Antarctic biotas related to changes in environmental conditions (e.g. changes in temperature, seasonality, carbon cycling). We will determine the scale of the K–Pg mass extinction and nature and timing of biotic recovery in Antarctica during the Paleocene and assess the impact on polar biotas of climatic events of shorter duration. Using comparisons with Arctic and low latitude data, we will determine whether there was a specific polar response to environmental perturbations, and whether high latitude warming caused both extinctions and radiations in polar biotas.

Rhenium-osmium geochronology of the lacustrine Green River Formation: Insights into Cenozoic ocean osmium evolution

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Lacustrine sedimentary rocks provide an invaluable archive of continental geological processes responding to tectonic, climatic and magmatic influences. Correlating these rocks to global geological phenomena requires accurate geochronological frameworks. The rhenium-osmium (Re-Os) geochronometer is a widely used tool for determining precise depositional ages of marine organic-rich sedimentary rocks (ORS). We demonstrate the application of the Re-Os geochronometer to lacustrine ORS of the Eocene Green River Formation (GRF). Our results provide a precise depositional age of 49.2 ± 1.0 Ma, which is in excellent agreement with Ar-Ar and U-Pb ages of interbedded tuff beds within the GRF. In addition, the isotope data reveals an initial $^{187}Os/^{188}Os$ composition of 1.52 ± 0.01, which represents the $^{187}Os/^{188}Os$ composition of lake water at the time of deposition. Lake water is primarily derived from continental runoff, thus the initial $^{187}Os/^{188}Os$ composition provides the first record of the $^{187}Os/^{188}Os$ composition of continental runoff during the Early Eocene Climatic Optimum (EECO) prior to the decent into an icehouse world. This $^{187}Os/^{188}Os$ composition of continental runoff is comparable to that of global riverine input into the ocean today (1.54). Global ocean $^{187}Os/^{188}Os$ has evolved from ~0.54 during the EECO to a modern day value of 1.06. The causes of this increase are contentious, relating to variations in unradiogenic inputs such cosmic dust and hydrothermal alteration versus radiogenic continental weathering. We propose that the evolution of seawater $^{187}Os/^{188}Os$ during the last 50 Ma has been principally driven by a decrease of unradiogenic Os inputs into the oceans rather than an increase in radiogenic Os from continental runoff. Future application of the Re-Os system to ancient lacustrine ORS will aid in the understanding of global ocean Os fluctuations, and also evaluation of past climate and tectonic processes.

Time, space, and Gaia: Darwinian, sequential, and anthropic selection for multiscale regulation

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Biological regulation of the environment is present at scales from individuals, to ecosystems, to the global biosphere. However, different mechanisms are required to explain regulation at different temporal and spatial scales. At the level of the individual organism, it is well understood how Darwinian natural selection creates robust homeostatic mechanisms. At local ecosystem scales, co-evolution and the assembly of emergent ecological structures, which as ``niche construction'' (Odling-Smee etal 1996) are beginning to be understood as a consequence of Darwinian evolution, are known to regulate the environment. Recent work (Williams & Lenton 2008) has demonstrated emergence of global regulation from local selection in a metapopulation model with (rapid) diffusive mixing. However, at global scale, biosphere regulation must also be reconciled with geochemical feedbacks, often with time delays comparable to or longer than biological evolution, as well as with selection on an anthropically-biased sample of one planet. Sequential selection (Betts & Lenton 2007) and anthropic selection (Watson 2004, 2008) mechanisms, operating alongside natural selection, have been proposed to explain regulation with geological timescale separation. In both these cases, the limited information input and their ``satisficing'' (rather than optimising) nature make it probable that: (i) regulation at the global level involves only simple configurations of multiple (individually local and Darwinian) physiologically limited ``biotic plunder'' mechanisms (Tyrell 2004) combined with abiotic feedbacks, and (ii) regulation of Earth's environment need have been only sufficiently stable for the continued existence of complex life. An intelligent observer is therefore most likely to find themselves inhabiting a complex body highly optimised by natural selection, in a fragile ecosystem structured by coevolution, on a planet with a simple system of biospheric regulation.

Descent into the Ice House - methodologies

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The primary objective of the proposal “Descent into the Icehouse” is to determine what led to the long term cooling of the planet that culminated in the rapid switch at the Eocene/Oligocene boundary from the warm greenhouse state, that characterised much of the Mesozoic and early Cenozoic, to the relatively frigid icehouse state that has characterised the last ~34 mys. The most commonly cited driver of this long-term climate change is a gradual decline in the CO_2 concentration of the atmosphere due to a subtle imbalance between silicate weathering (CO_2 sink) and volcanic outgassing (CO_2 source). Our current proxy records, however, do not support this assertion, suggesting either that factors other than CO_2 control long term climate change or that our records of CO_2 in early Cenozoic are inaccurate.

Our proposal aims to address the following fundamental questions:

1. What drives the evolution of climate on geological timescales?

2. What role do biological feedbacks have on the evolution of pCO_2, and hence climate, on these timescales?

In a series of posters we will outline how this improved understanding of the Earth system will be achieved. We will focus on the following approaches:

A. We will use state of the art techniques and understanding of the boron isotope paleo-pH proxy to determine the global evolution of the water column pH (deep to surface) over the time period 54 to 34 Ma. This will provide a global picture of how the carbonate system evolved and allow a new robust estimate of long term pCO_2 change associated with this switch in climate state.

B. We will use a multiproxy approach to reconstruct the latitudinal gradient in temperature over the time period 54 to 34 Ma. This will provide a comprehensive test of the various mechanisms proposed for the climate switch (ocean circulation, pCO_2) and a thorough documentation of the changes in climate accompanying the transition in climate state.

C. We will reconstruct the nutrient and temperature distribution of the water column over the time period 54 to 34 Ma to better determine the influence of these parameters on phytoplankton evolution and the rate of organic carbon respiration in the water column over this time period.

D. We will use a fully coupled ocean-atmosphere general circulation model (GCM; HadCM3L) to simulate a number of time slices in the Cenozoic during the run up to the Eocene/Oligocene boundary. Employing sensitivity tests associated with various gateway configurations we will use a modelling approach, combined with new data, to better assesses the role of ocean circulation and pCO_2 in early Cenozoic climate evolution. This will also provide a key test of the ability of HadCM3L to accurate simulate a warm high-CO_2 world.

E. We will use a hierarchy of modelling approaches (box models and Earth System Models of Intermediate Complexity) to tease apart the roles of various feedbacks and drivers in generating the evolution of pCO_2 during the course of the Cenozoic. These range from the purely abiotic (weathering, outgassing, ocean circulation) to the biotic (changing community structure and rain rate ratio due to the diversification of diatoms, and enhanced water column carbon respiration).

The Maastrichtian–Eocene of Seymour Island, Antarctica: stratigraphy, facies and palaeoenvironments

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The Maastrichtian–Eocene succession of Seymour Island is well-exposed and fully accessible, the island being ice-free in the summer months, and is a key reference section for this period at southern high latitudes. This succession represents the youngest-known fill of the James Ross Basin, a Jurassic–Paleogene back-arc basin that developed east of a volcanic arc, the roots of which form the present-day Antarctic Peninsula. Four discrete phases of basin evolution are represented on the island: Maastrichtian – earliest Paleocene (Lopez de Bertodano Formation), early Paleocene (Sobral Formation), late Paleocene (Cross Valley Formation) and Eocene (La Meseta Formation).

The Lopez de Bertodano Formation (*c*. 1200 m on Seymour Island) provides an expanded marine record spanning the Maastrichtian and the earliest Paleocene. Dominated by bioturbated silty muds and very fine sands, this richly fossilferous marine succession is punctuated by glaucony-rich horizons representing periods of sediment starvation; the Cretaceous–Paleogene boundary (K–Pg) is one such composite glaucony-rich interval. A subtle unconformity separates the Lopez de Bertodano Formation from the succeeding lower Paleocene Sobral Formation, a regressive sand-rich marine succession (*c*. 300 m thick) of deltaic origin. Though commonly thoroughly bioturbated, the marine sands locally display mud-draped cross-bedding, testifying to a marked tidal influence in proximal environments. The uppermost Sobral Formation records a discrete influx of volcanic detritus, possibly heralding the mid-Paleocene uplift and volcanism recorded by the succeeding Cross Valley Formation.

The Cross Valley and La Meseta Formations record two discrete episodes of deep valley incision in the mid-Paleocene and early Eocene, respectively. The former event created a deep, steep-sided valley that was rapidly plugged by a thick succession (*c*. 200 m) of coarse volcaniclastic sediment, possibly the result of catastrophic drainage of ash-dammed lakes. These fluvial sandstones and conglomerates of the Cross Valley Formation are capped by a thin unit of shallow-marine sandstones and mudstones containing oysters and well-preserved leaf fossils. Early Eocene incision resulted in a 6–7 km wide valley cutting several hundreds of metres into the Cretaceous–Paleocene substrata. The valley-fill (La Meseta Formation) is a complex, heterogeneous succession of deltaic, shallow marine and estuarine sediments which are commonly highly fossiliferous and provide an important record of Eocene biotic development.

High-resolution redox cycles during OAE 3 (Demerara Rise, ODP Leg 207) and their implications for ocean chemistry

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A continuous Mid-Cretaceous black shale section of around 90 m thickness was recovered during ODP Leg 207 from Demerara Rise (Equatorial Atlantic), documenting high organic matter deposition under oxygen-depleted bottom water conditions from the Cenomanian through the Santonian (including Oceanic Anoxic Events (OAEs) 2 and 3[1]). However, despite continuous oxygen deficiency, even finely laminated black shale deposits can record a much more variable redox history than commonly suggested. We conducted a high-resolution geochemical study of a selected interval from OAE 3 (Coniacian-Santonian boundary) that revealed cyclic dynamics of trace metals, Fe, S and P cycling in response to alternations between sulfidic and anoxic, non-sulfidic conditions[2]. A typical redox cycle started with weakly sulfidic conditions where fast reaction kinetics promoted rapid precipitation of Cd and Zn sulfides, depleting these metals from bottom waters. Thereafter, increasingly sulfidic conditions triggered enhanced Mo sequestration from the water column ("thiomolybdate switch"). In parallel, excess H_2S concentrations in sediment pore waters reacted with organic matter, enhancing carbon preservation through sulfurization. Eventually, sulfidic conditions in the water column ceased as documented by strongly decreased burial of TOC, S and trace metals. Still, lower but notable trace metal enrichments and the lack of sediment bioturbation argue against persistent oxic to suboxic bottom water conditions. Suboxic conditions may have periodically occurred, allowing for limited growth of benthic foraminifera[3], but were too short-termed to be recorded by trace metal records. We suggest that these least reducing intervals dominantly represent anoxic, non-sulfidic redox conditions, which have rarely been described for Phanerozoic black shales, but were likely the dominant state of the ocean over long periods of Earth's history[4]. On Demerara Rise, these intervals are characterized by sharp P peaks probably related to deposition of Fe-P phases (supported by the recent discovery of anoxic Fe-P coupling below the Baltic Sea redoxcline[5]), but the exact process of P enrichment and its preservation in the sediment record is still unclear. Another pending question concerns the cyclic termination of sulfidic bottom water conditions on Demerara Rise during OAE 3. Based on pyrite S isotope data, we consider that sea water in the Cretaceous contained less sulphate than today, and was thus sensitive to further depletion by widespread intense sulphate reduction in organic-rich sediments, eventually leading to strongly reduced H_2S production. This idea is in line with a recent study of OAE 2 that reports similar shifts in the Cretaceous marine sulphate pool[6], while other explanations like repeated influx of oxygenated water masses, changes in the organic substrate, or shifts in the ecology of oceanic and sediment microbes might be considered as well. This work exeplifies how our understanding of biogeochemical cycles and their variability during anoxic events can be advanced by high-resolution studies of black shale deposits throughout Earth's history.

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Climate amelioration in the latest Ordovician – Did weathering of exposed carbonate shelf bring the Hirnantian Glacial Episode to a close?

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Evidence for eustatic sea-level drawdown associated with the Hirnantian Glacial Episode (HGE) is widespread. Rocks in the east of the Welsh Basin record the results of sea-level drawdown on shallow shelf sediments along the Avalonian Shelf, whilst further west the rocks record the effects in deep water of the shelf denudation occurring nearer shore.

A particular effect in shallow waters is the exposure of carbonate shelf deposits, not so widespread in Wales where clastic sequences predominate, but much more prevalent in, for example, Balto-Scandinavia and the Laurentian Platform. It is postulated that exposure of the bio-clastic Ordovician carbonate sediments to meteoric water, and consequent development of karst weathering processes, may have contributed a significant pulse of carbon dioxide to the atmosphere. This increase in greenhouse gases may have played a part in bringing the climate out of its Hirnantian ice-house condition.

Some of the key outcrops of Hirnantian rocks in the Welsh Basin are described, and the evidence they offer in respect of the hypothesis discussed.

On the Origin and Evolution of the Atmosphere

Graham Oram

The poster first reviews and contrasts the 1950s proposals from astronomers and geologists for the origin of the atmosphere, which concluded with the dominance of the geological view that volcanoes supply the gases to the air. New information from Plate Tectonics, the Apollo missions to the Moon and more recent geological advances suggest this conclusion may not be the correct solution.

The poster then reviews the influence of Plate Tectonics Theory for a more structured view of volcanoes and support for the observation that most volcanic gases are recycled from subducted wet oceanic crust while only a few volcanoes on the mid ocean rifts might supply some new gas from the interior of the Earth to the air.

Information on the lunar magma ocean and more recently on early core formation on the Earth suggests a hot planetary origin and rapid differentiation of the primordial carbonaceous chondrite material into a molten iron core, hot stony mantle and gaseous atmosphere. Any free gas trapped inside the Earth was released to the air soon after planetary formation. Any gas now inside the Earth must have been taken in through subduction zones.

Ices delivered to the inner solar system by comets add to this early massive atmosphere making its composition very different from today. Its evolution is written in the sedimentary minerals and rocks. The rise of oxygen is well documented but the loss of carbon dioxide is not.

Since the Earth didn't begin with any sedimentary rocks on its surface, after 4,560 million years, weathering has locked most of the original carbon dioxide resource into carbonate sediments; very little of the original resource remains in the air. The key question is whether the current supply of carbon dioxide to the air is sufficient to meet the demand. This poster suggests that the current evidence indicates that there isn't an independent carbon dioxide reservoir inside the Earth and all the weathering demand must be met by carbon dioxide from the air. Therefore the amount of carbon dioxide in the air naturally reduces over geological time.

Sedimentary evidence from the Archaen and Proterozoic eons suggests the Earth may have had an atmosphere comparable to Venus today at the start of the Proterozoic eon. Over the last 2,000 million years, water and life on Earth have moved calcium and magnesium from silicate minerals into carbonate minerals and have consumed most of the carbon dioxide resource.

This conclusion is so different from the current assumption of stability that if proved true would radically alter future strategies.

Mesoproterozoic oxygenation favoured evolution in surface environments

John Parnell, Sam Spinks, Stephen Bowden, Malcolm Hole (University of Aberdeen), Adrian Boyce and Darren Mark (SUERC, Glasgow)

The Mesoproterozoic is often seen as part of the 'boring billion' period (~1.8-0.8 Ga), when there were supposedly only minor changes in atmospheric oxygenation, ocean chemistry and biological evolution. However, there is growing evidence for increasing oxygenation during the Mesoproterozoic, with implications for the evolution of life, long before the second oxygenation 'event' in the Neoproterozoic.

One measure of oxygenation is the degree of fractionation of sulphur isotopes in diagenetic pyrite. Large fractionations indicative of disproportionation (reflecting coupled microbial sulphate reduction and sulphide oxidation) have recently been identified in the 1.2 Ga Stoer Group, Scotland (Parnell et al. 2010), several hundred million years earlier than the previous oldest record. Similar data have been recorded in the 1.0 Ga Torridon Group, Scotland. Both Stoer and Torridon Groups were deposited in terrestrial (lacustrine, fluvial) environments, in contrast to the marine environments of this age which do not exhibit the same fractionation. This selective occurrence of disproportionation indicates oxygenation of the terrestrial environment, and the potential to support an advanced biota, at a time when the deep ocean was anoxic.

The Stoer Group, Torridon Group and other Mesoproterozoic terrestrial/restricted marine successions also contain syngenetic/early diagenetic copper sulphides, each with a microbial sulphur isotope signature. High concentrations of copper (and other metals) are toxic to microbes, who remove it from the environment by precipitation of copper sulphides. This implies that surface environments in the Mesoproterozoic were sufficiently rich in copper and other metals to allow their bio-utilization, while an anoxic/euxinic deep ocean sequestered metals to restrict their bioavailability. Thus, differential bioavailability of metals favoured evolutionary diversification in the terrestrial environment during the Mesoproterozoic.

Parnell, J., Boyce, A., Mark, D., Bowden, S. & Spinks, S. 2010. Early oxygenation of the terrestrial environment in the Mesoproterozoic. Nature, 468, 290-293.

Global glaciations and Os seawater chemistry: Implications from Re-Os geochronology of the Neoproterozoic Windermere Supergroup, Canada

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The Late Proterozoic Rapitan Group of NW Canada is a ~1.5 km thick succession of mudstones, diamictites and sandstones believed to represent low-latitude glaciation with the onset of glaciation constrained by U-Pb zircon ages at ca. 717 Ma. The Rapitan Group has been correlated with the glaciogenic Areyonga Formation of the Amadeus Basin of Central Australia which is overlain by the deepwater siliciclastics of the Aralka Formation.

The organic-rich (TOC >0.5 wt%) Coppercap and Twitya Formations which lie uncomfortably below and conformably above, respectively, the Rapitan Group provide an ideal opportunity to constrain the duration of the glaciation. In addition, these units are an ideal natural laboratory to evaluate the evolution of Os seawater composition through a Cryogenian glaciation.

The Re-Os geochronology data from the Coppercap Formation yield a Model 1 depositional age of 733 ± 4 Ma with an unradiogenic initial Os isotope composition (Os_i) of 0.14. This unradiogenic value for Os seawater may be related to the erosion of basalts of the underlying Little Dal Group as well as the Gunbarrel magmatic events, and hydrothermal vents associated with rifting during the break-up of Rodinia.

Preliminary Re-Os geochronology data from the Twitya Formation yields a Model 1 depositional age of 655 ± 26 Ma with a radiogenic Os_i value of 0.83 suggesting that post-glaciation; the crustal Os flux from rivers exerted a stronger influence on ocean Os composition. Coupled with the Re-Os geochronology of the Twitya Formation the existing U-Pb zircon ages strongly suggests that the Rapitan glaciation lasted a minimum of 36 Myrs.

Both the Re-Os isochron age and the Os_i data for the Twitya Formation are identical, within uncertainty, with values from the Aralka Formation, Central Australia. Together, these data suggest that de-glaciation was broadly penecontemporaneous, and that the Sturtian and Rapitan glaciations are correlative. Furthermore, the data presented here support the hypothesis that increased weathering caused by the glaciation resulted in an shift to more radiogenic Os values as is seen with the Sr isotope record.

Characterization of water column redox conditions at the onset of the Toarcian OceanicAnoxic Event: a high-resolution multi proxy study from North Yorkshire

Najm Salem, Simon Poulton, Richard Tyson, Thomas Wagner, University of Newcastle

The lower Whitby Mudstone Formation of the Cleveland Basin in North Yorkshire (UK) is a world renowned location for the Early Toarcian OAE (Jenkyns 1988, 2003). Detailed climate records of the event have been reported from this location (McArthur et al., 2008) that shed new light on the forcing and timing of climate perturbations and associated development of ocean anoxia. Despite this extensive previous work, few studies have explored the well-preserved sediments below the event that document different phases finally leading to large-scale (global) anoxia, which is the focus of this project. We resampled the underlying Grey Shale Member at cm-scale resolution and conducted a detailed multi-proxy geochemical approach to reconstruct the redox history prior to the Toarcian OAE.

The lower Whitby Mudstone Formation, subdivided into the Grey Shale Member overlain by the Jet Rock (Toarcian OAE), is a cyclic transgressive succession that evolved from the relatively shallow water sediments of the Cleveland Ironstone Formation. The Grey Shale Member is characterised by three distinct layers of organic rich shales (~10-60 cm thick), locally named as the sulphur bands. Directly above and below these conspicuous beds, the sediments represent more normal marine mudstones. Further upwards the sequence sediments become increasingly laminated and organic carbon rich (up to 14 wt %) representing a period of maximum flooding that culminated in the deposition of the Jet Rock (representing the Toarcian OAE). Detailed analyses of the Grey Shale Member, with a focus on the sulphur bands, for TOC and total sulfur concentrations, iron speciation (FeHR/FeT, FePyrite/FeHR), trace element concentrations, photic zone euxinia biomarkers, and bulk carbon and sulphur isotopes confirm highly variable redox conditions prior to the Toarcian OAE, with repeated anoxia/euxinia during periods of sulphur band deposition. Cm-scale geochemical records from the lower sulphur band actually suggest significant, short term variations in redox, with one full cycle from anoxia/euxinia to oxic conditions and back. We speculate that these cyclic variations in redox during sulphur band formation were driven by orbital forcing, however better chronological information is necessary to validate this interpretation. The bioturbated mudstones between and below the sulphur bands show less enrichment of TOC, reactive iron and trace elements, but still suggest conditions close to the Fe-proxy threshold characteristic of anoxia (FeHR/FeT = 0.38). Further up the section in the bioturbated mudstones, highly reactive iron and trace elements are significantly depleted, indicating a return to more oxic conditions, which persisted up the top laminated unit of the Grey Shale. This observation challenges the general concept that anoxia/euxinia was limited to the Toarcian OAE, at least in the Cleveland Basin of North Yorkshire. This presentation will discuss the detailed dynamics of redox variations and biogeochemical elemental cycling in the run-up to this major event in Earth history.

Gaia or Good Luck?

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The Gaia hypothesis may have confused cause and effect. Perhaps a stable environment is a precondition for a complex biosphere rather than the other way around. This poster presents evidence that this “anthropic selection” effect has influenced Earth properties. Gaian proposals must therefore be treated with caution since apparent planetary homeostasis may result from coincidence.

Given the large number of planets (~10^{22} in the observable Universe and, if inflationary cosmology is correct, vastly more beyond the cosmic horizon), it is almost inevitable that a few worlds will experience chance cancellations between the astronomical and biogeochemical processes controlling the global environment. If the resulting stable environments are a necessary precondition for the emergence of complex organisms, the Earth must be one of those rare, lucky planets. Under these circumstances, potentially dangerous excursions in environmental variables (e.g. temperature) due to, say, astronomical factors (e.g. a slowly warming Sun) will always have been cancelled by an excursion in another factor (e.g. greenhouse gas concentration) but this cancellation will have resulted from coincidence rather than a biologically mediated negative feedback. This is not a new idea but is there any evidence to support it?

Any such evidence will take the form of apparent fine-tuning, i.e. control factors with just the right value to ensure a stable environment. As an example, the conductivity of the Earth’s core has just the right value to ensure the strongest possible magnetic field (higher conductivity suppresses convection, lower conductivity suppresses electrical currents) and this high field strength plays a key role in preventing erosion of the Earth’s atmosphere by the solar wind. Any search for more fine-tuning effects should initially concentrate on astronomical controls since a positive result cannot then be easily explained as resulting from negative feedback. Furthermore, astronomical phenomena are more conducive to calculations than messy and complex biogeochemical processes.

As an example, this poster looks at the influence of the Moon upon Earth’s axial stability. It is shown that a smaller moon (and/or higher angular momentum) results in an Earth with a higher rate of obliquity change whereas a larger moon (and/or smaller angular momentum) produces an Earth with a chaotically unstable axis. Hence, small changes in the outcome of the moon-forming collision at 4.5 Ga would result in a present-day Earth with a much less stable climate. In more detail, only 0.7% of alternate Earth-Moon systems produce a “better” climate than the one we actually enjoy. This is strong evidence that at least one of our planet’s Earth-friendly properties is the result of good luck. The suggestion that apparent planetary homeostasis results from coincidences that were necessary preconditions for our existence, rather than from feedback, should therefore be taken seriously.

What are Gaia's Cognitive Capabilities? Symbiosis Causes Associative Learning at the Ecosystem Scale

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Models of planetary homeostasis illustrate that simple ecosystems can exhibit self-sustaining regulation of environmental conditions. Since neither ecosystems nor planets are evolutionary units, such 'organismic' properties seem surprising. But in fact, the purpose of such models it to show that these homeostatic or ultra-stable properties come 'for free' in dynamical systems of the appropriate form. Here we show that more surprising capabilities also come for free in ecosystems. Neural network theory shows us that networks of simple units with simple local rules of interaction can exhibit "collective computation" without centralised control if they have the appropriate organisation. Since metazoan nervous systems are (part of) an evolutionary unit, we are not so surprised that they might exhibit such capabilities. But actually, an incredibly simple fully-decentralised learning mechanism is sufficient to transform a random recurrent network into one with appropriate organisation to exhibit capabilities such as memory, generalisation, classification and constraint optimisation. Specifically, Hebbian learning is simply a process that changes synaptic connections in the direction that reinforces the status quo. We show that this too is something that comes for free, via a process we call 'associative induction', in dynamical systems made of the 'right stuff'. Specifically, in adaptive networks, like ecosystems, where species adapt their symbiotic relationships with others to maximise their individual fitness, the system level consequence of this 'ecological re-wiring' is functionally identical to the application of Hebbian learning in a neural network. There is, in fact, a deep homology between species seeking to stabilise their selective environment by forming symbiotic relationships with other species and associative learning in neural networks. This does require that each of the species involved is modified by natural selection, but it does not require that the ecosystem as a whole is a selective unit. Nonetheless, the implications are that Gaia is capable of the recalling past ecological states, generalising responses to environmental conditions, and 'solving' distributed constraint optimisation problems over a set of resources in the same sense, and by the same mechanism, as organismic learning.

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Impact of global disturbances on the evolution of life in the polar regions during the Early Cenozoic: a combined biological and palaeobiological approach

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PALEOPOLAR will study the impact of major global disturbances on marine and terrestrial ecosystems during the latest Cretaceous to early Cenozoic period of global warming, with particular emphasis on the evolution of life in the environmentally-sensitive polar regions. A major part of the study will focus on biological change in Antarctica through the Paleocene, and what effect this had on the composition of the modern polar biota.

The modern Antarctic marine fauna arose following the Cretaceous-Paleogene (K-Pg) mass extinction event and biotic recovery occurred through much of the Early Cenozoic Era. Seymour Island comprises one of the most prolific fossil sites in Antarctica, with assemblages including marine invertebrates and vertebrates, as well as terrestrial plant material washed in from the nearby Antarctic Peninsula. Newly identified fossil material will be used to estimate species richness and diversity from the Cretaceous to the Eocene. Using this comprehensive 20 million year time span, the scale of the K-Pg extinction plus the nature and timing of biotic recovery in the Paleocene of Antarctica will be re-assessed. The impact of climatic events of shorter duration such as the PETM (Paleocene-Eocene Thermal Maximum) and early Eocene hyperthermals on polar biotas will also be evaluated. Total diversity in different units from Seymour Island will be fed into global databases for the relevant time intervals, to see how they relate to global patterns for these periods.

Combined molecular and palaeontological studies will be carried out on groups such as the superfamily Buccinoidea (Gastropoda), which are common in Seymour Island collections and may be related to certain modern Antarctic clades. Fossils will be used to calibrate molecular trees to identify the timings of major radiations of Antarctic marine taxa as an independent test of fossil analyses. Using these data large scale patterns of Cenozoic biodiversity change in the polar regions and their relationship to the distribution and diversity of organisms at the present day will be identified.

Evolutionary regime shifts in simulated ecosystems

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Earth history has included periods of stability interspersed with major transitions where evolutionary changes in the biota were coupled through feedback loops to changes in the physical environment. Theoretical models for the evolution of the Earth system must account for both the periods of stability and the punctuating transitions between them, yet many theoretical models have focused on explaining how regulation can arise. Here we use a conceptual model of evolution and environmental feedbacks in a system of linked ecosystems to explore evolutionary triggers for transitions between periods of environmental regulation. Catastrophic regime shifts in ecosystems occur when the system is tipped into a new attractor state under some external forcing. In our model, evolutionary adaptations can trigger such transitions when new traits arise that allow exploitation of under-utilized resources. Subsequent rapid growth of the population carrying the new trait causes abrupt environmental change that drives incumbent species extinct. We call these transitions ‘evolutionary regime shifts’. These internally generated perturbations can result in global ecosystem collapse, followed by recovery to an alternate stable state, or occasionally system-wide extinction. While these disruptions may have a negative impact on ecosystem productivity in individual simulation runs, mean results over many simulations show a trend for increasing ecosystem productivity and stability over time. Feedback between life and the abiotic environment in the model creates a ‘long-tailed’ distribution of extinction sizes without any external trigger for large extinction events. We speculate that similar processes may have been relevant for transitions in the Earth system.