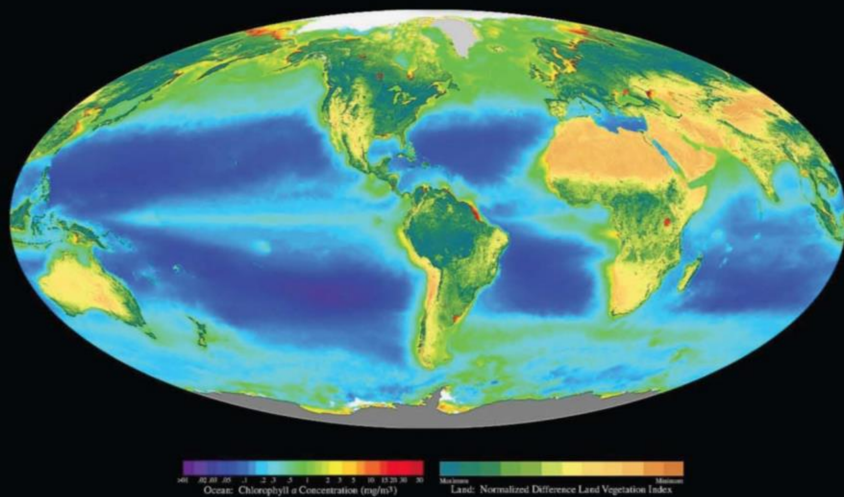
Earth System transitions

How resilient is the biosphere?

17-18 January 2019 | The Geological Society, London



The Geological Society, London

Earth System Science special interest group

Biosphere Evolution, Transitions & Resilience (NERC research programme)

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The four main themes of this meeting are:

- Earth system transitions: the Precambrian
- Earth system transitions: the Paleozoic Era
- Earth system transitions: the Mesozoic and Cenozoic eras
- How resilient is the biosphere – key notes and discussion.

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Deep roots of the Cambrian Explosion

Maoyan Zhu[1]

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The explosive appearance of animals during the early Cambrian ('Cambrian explosion') is evidenced by extraordinarily well preserved fossils from numerous Cambrian fossil-lagerstätten worldwide, such as the Chengjiang deposit of southwestern China, and is regarded as one of the most puzzling evolutionary events in the history of life. However, molecular clocks suggest an earlier appearance of major animal clades during the late Neoproterozoic. The present talk aims to review briefly recent advances and problems in Ediacaran fossil studies, particularly from South China, in an effort to reconcile fossil and molecular records.

In general, the Cambrian explosion is marked by contrasting Ediacaran and Cambrian biotas, exemplified by the abrupt appearance of skeletal animal fossils and the approximately contemporaneous disappearance of macroscopic Ediacara soft-bodied fossils. The latter have traditionally been treated as extinct clades unrelated to animals. New mixed skeletal assemblages from the terminal Ediacaran and basal Cambrian demonstrate that there is a deep root to the Cambrian explosion. Furthermore, recent investigations, through various approaches, suggest that some of the iconic Ediacara fossils are related to known animal phyla. These new insights are further supported by the record of late Ediacaran complex burrows and bilaterian trackways.

Exciting novel insights into the early evolution of animals, based largely on exciting fossil information from the early Ediacaran Doushantuo Formation of South China, include (1) macroscopic animal-like carbonaceous compressions from the Doushantuo black shale, (2) silicified diapause embryos from the Doushantuo chert nodules, and (3) various phosphatized embryos and juvenile animals from the Doushantuo phosphorites. These unique early Ediacaran fossils preserved in distinct taphonomic windows provide biological details of cellular to subcellular resolution that are invaluable for unraveling the puzzle of early animal evolution. Although there is no consensus on whether these Doushantuo fossils represent crown- or stem group animals, new data increasingly suggest a rapid development in complexity accompanying the rise of animals in the immediate aftermath of the Marinoan ice age. However, these putative early animals largely remain cryptic until the late Ediacaran, their appearance coinciding with an increase in ocean oxygenation. All Ediacaran and early Cambrian fossil records suggest that the Cambrian explosion of animals was deeply rooted in the Ediacaran and exhibited an episodic pattern that was closely related to dynamic ocean oxygenation during the Proterozoic-Phanerozoic transition.

Notes

Incorporating Fossil Occurrence Data For The Estimation Divergence Times Can Result In Impossibly Young Age Estimates

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To test evolutionary hypotheses regarding the interaction of the earliest organisms and the environmental systems to which they belonged an accurate timescale of the first appearances and diversification of such organisms is required. The construction of such timescales must utilise the fossil record to determine the age by which different species or groupings of taxa must have appeared by. A literal reading of the fossil record in this manner can be misleading, as groups must have appeared before the age of their oldest member in the fossil record. To account for this, palaeontologists have turned to the molecular clock to estimate divergence times. Analyses which utilise this approach must be constrained so that estimated divergence times are congruent with the fossil record. Such analyses reduce the full complement of available palaeontological data down to little more than the ages of the oldest unequivocal members of clades. A recent methodological development called the Fossilised Birth-Death Process (FBD) allows for the incorporation of all available fossil occurrence data when estimating divergence times, drastically increasing the quantity of applicable data for such analyses. Through the inclusion of an increased quantity of palaeontological data, the FBD is expected to redefine timescales for many taxonomic groups.

Despite the obvious potential presented by the FBD method, when it is applied to the estimation of divergence times in some of the most ancient and speciose clades the amount of fossil occurrence data now applicable is simply impossible to analyse. In such cases a subsample of the available fossil occurrence data must be obtained and analysed instead. Through the use of simulated datasets we have demonstrated that analysing such subsamples will lead to age estimates that are impossibly young and therefore incompatible with the fossil record. We have also demonstrated that if this effect is controlled for by constraining FBD analyses to only consider ages compatible with the fossil record then the resulting age estimates are overly ancient. These results draw the applicability of such methods for the estimation of divergence times in occurrence-rich clades into question.

Notes

Advances in the geochronological framework of Ediacaran System

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The Ediacaran (635-539 Ma) follows the ‘Snowball Earth’ glaciations in the Cryogenian and precedes the rapid radiation of complex animals in the Cambrian. It is a critical transitional time interval when the Earth transferred from a microbial-dominated world to a metazoan world. To decipher how life and environment co-evolved, and what caused these fundamental changes during this time interval, a geochronological framework of Ediacaran System is essential. A growing database of radio-isotopic dates are being published from the Ediacaran strata worldwide and a first order chronology of events, however a resolved framework still remains ambiguous limiting our ability to integrate data from disparate stratigraphic sections. This is due in part to a lack of radio-isotopic dates for some critical horizons, large uncertainties of some dates, difficulties in stratigraphic correlation, and different interpretations. Here we present several new CA-ID-TIMS zircon U-Pb dates from Ediacaran strata, in the context of the global radio-isotopic dataset, and also assess the variable quality of the existing geochronological database. Integrating absolute dating results with other forms of temporal stratigraphic information, we start to build the geochronological framework of the Ediacaran System (especially in South China) and begin to discuss approaches to quantifying uncertainty across the stratigraphic record. This framework provides preliminary time scale of the Ediacaran System, with uncertainties and subject to further changes, and provides a mechanism to test correlation models and integrate data from disparate stratigraphic sections.

Notes

Microscopic comb jelly fossils in the Ediacaran Doushantuo Formation, South China

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Evidence for the earliest metazoans, including putative embryos, larva and adults, have been previously reported from the Ediacaran Doushantuo Formation (635–551 Myr ago), south China. These interpretations, however, have long been debated due to limited occurrences of morphologically complex fossils. Here we report new soft-bodied microfossils from black granular phosphorites of the Doushantuo Formation at Weng'an, South China, with detailed morphological and anatomical features. The microfossils share some features with previously published large acanthomorphic acritarch *Tianzhushania*, which has been interpreted as diapause egg cysts, but also have their distinct features including flakes likely representing degraded remains of digestive cells, gonad-like spheroids, and muscle-like multi-laminated membrane. In addition to these new observations, we interpret their medusoid shape, diploblasty, epidermal mucous layer, and microstructures akin to ciliated combs (ctenes), digestive cells, myofibrils and nerve nets to represent an affinity to the ctenophora. These microfossils shed new light on the origin of complex metazoans as evidence of resilience in the aftermath of the Marinoan glaciations and are probably related to the rise of atmospheric and oceanic oxygen in the late Neoproteozoic.

Notes

Ediacaran-Cambrian Place and Pace are Interpretably Inseparable

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The Ediacaran-Cambrian transition posed a number of challenges and irreversible shifts to Earth's evolving biosphere: these include Snowball Earth glaciations, progressive environmental oxygenation, and True Polar Wander. Each of these phenomena are hypothesised credibly to affect the timing, pattern, and scale of evolving ecosystem complexity. Alternative arguments hold that the biosphere was insensitive to mid-Ediacaran glaciation, that enabling oxygen levels preceded the Neoproterozoic Oxidation Event, and that True Polar Wander promoted artefactual preservation of mid-Cambrian fossils rather than any significant biological innovation. We show that the hypothesised ~522-515 Ma True Polar Wander event passes new, independent, geochronological and palaeomagnetic tests from Grand Canyon, USA. We expand upon the ways that Cambrian True Polar Wander would have artifactually emphasised the apparent mid-Cambrian restriction of the classic "Cambrian Explosion" but also articulate ways that True Polar Wander could have promoted real ecosystem complexity and locked in new bodyplan innovations. Finally, we demonstrate that it is difficult to frame or test hypotheses of biological resilience and response to the Neoproterozoic transitions without specific and precise constraints upon both age and geography: understanding of the Gaskiers severe glaciation and biospheric response exemplifies this current ambiguity acutely.

Notes

Constraining the impact of bioturbation on substrate properties across the Ediacaran–Cambrian transition

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The Ediacaran–Cambrian transition records the rise to prominence of metazoans in marine environments, and the development of the metazoan-dominated ecosystems that epitomize the Phanerozoic. The geological record across this interval documents several significant evolutionary, ecological and geochemical events, which have been hypothesised to be causally linked via a variety of feedback pathways. Potentially one of the most influential biological events is the evolution and radiation of burrowing animals. Such organisms, through their mixing of sedimentary substrates, are considered to have fundamentally changed sedimentary redox conditions, with implications for substrate habitability, fossil preservation, and nutrient cycling: all of which play a role in shaping either biosphere resilience, or our view of it.

Ichnofossils represent our primary record of organismal behaviour through time, and offer a key line of evidence for understanding both biological evolution, and changes in the impact of organisms on sedimentary substrates. The origin of burrowing is argued to coincide with changes to the physical and chemical properties of substrates across the Ediacaran–Cambrian transition, but the majority of our knowledge of ichnofossils is built on the study of macroscopic trace fossils. Such traces extend back into the Ediacaran Period, with abundant simple shallow infaunal burrows present at ~555 Ma in certain settings, followed by a marked diversification across the Ediacaran–Cambrian boundary. Our understanding of the first appearance of macroscopic burrows is evolving, and it is timely to reassess how closely their appearance coincides with the sedimentary changes they are proposed to explain. Furthermore, the record of meiofaunal ichnofossils – those created by organisms of 32–1000 µm in maximum dimension – requires consideration. Recent discoveries from the latest Ediacaran of Brazil demonstrate an active meiofauna in Ediacaran–Cambrian siliciclastic strata.

Modern meiofaunal burrows influence substrates in multiple ways, such as promoting microbial growth, encouraging organic matter decay, and hastening the turnover of pore waters. Such effects have the potential to significantly impact redox conditions and the cycling of elements within marine sediments. Meiofaunal burrows, and indeed cryptobioturbation (the total reworking of sediments with no distinct traces), is only rarely reported in the Phanerozoic, with the timing of origin of the creators of such features, and their impact on sediment properties, presently unknown. It is possible that the onset of meiofaunal bioturbation could pre-date macroscopic burrowing, and tracking the fossil record of meiofaunal activity therefore has the potential to provide critical insight into both the origin of the earliest burrowing animals, and their impact on marine benthic settings.

We here outline the current state of understanding regarding the timing of initiation of burrowing in marine sedimentary environments, and assess the evidence surrounding proposed correlations with geochemical and physical changes to sediments. We will also highlight ongoing work to track meiofaunal activity back through the Neoproterozoic.

Notes

Unique Neoproterozoic carbon cycle sustained by coupled evaporite dissolution and pyrite burial

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The Neoproterozoic Era witnessed a succession of biological innovations that culminated in a wide range of animal body plans and behaviours during the Ediacaran-Cambrian radiations. Intriguingly, this interval is also marked by perturbations to the global carbon cycle, as evidenced by extreme fluctuations in both climate and carbon isotopes. The Neoproterozoic isotope record has defied parsimonious explanation because periods of sustained 12C-enrichment (low δ13C) seem to imply that substantially more oxygen was consumed by organic carbon oxidation than could possibly have been available given the timescales required. Here we propose a solution to this problem, in which carbon and oxygen cycles can maintain dynamic equilibrium through prolonged and extreme negative δ13C excursions when surplus oxidant is generated through bacterial reduction of sulfate that originates from evaporite weathering. Coupling of evaporite dissolution events with pyrite burial drives a positive feedback loop whereby oxidative remineralisation of dissolved organic matter (DOM) can sustain greenhouse forcing of chemical weathering, nutrient input and ocean margin euxinia. Non-steady state sulfate dynamics are likely to have contributed to climate change, episodic ocean oxygenation and opportunistic radiations of aerobic life forms during the Neoproterozoic Era

Notes

The distribution and paleoecology of Cambrian Burgess Shale-type faunas in South China

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The Cambrian Burgess Shale-type (BST) fossil lagerstätten have a global distribution from Laurasia to Gondwana. Exceptionally well-preserved soft-bodied fossils from these lagerstätten provide unique information for elucidating the origin and early evolution of metazoans during the ‘‘Cambrian explosion’’. Over the past three decades, several famous BST fossil lagerstätten have been uncovered from the Cambrian of South China, and attracted worldwide attention and public interests. Among them, the Chengjiang Lagerstätte from the Maotianshan Shale Member of the Yu’anshan Formation in eastern Yunnan is the earliest and one of the most significant Cambrian BST fossil lagerstätten in the world. It has thrown new light on the origin and early evolution of major metazoan clades, such as arthropods and deuterostomes including the chordates. Another typical BST fossil lagerstätte from eastern Yunnan is the Guanshan biota from the Wulongqing Formation and a new Chengjiang-type lagerstätte from the Hongjingshao Formation, from which a number of soft-bodied fossils rivaling those from the Chengjiang biota have been found recently. The strata hosting Cambrian BST lagerstätten occur throughout South China, show variation in taxonomic diversity, faunal composition and fossil preservation. Taxonomic composition of these faunas indicates that arthropods mostly dominated the shallow water facies, whereas sponges dominated the slope basin facies. Cambrian BST lagerstätten in South China provide a good record of exceptionally preserved biotas through time. Comparison of these lagerstätten within their chronological framework may give us important clues on the nature of evolutionary and ecological diversifications during the Cambrian explosion.

Notes

Evidence for extremely high organic export to the early Cambrian seafloor

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The early Cambrian is commonly assumed to have high organic export to seafloor due to the rise of algae and filter-feeding animals. However, direct evidence for this assertion is lacking. In this study, we report abnormally high uranium isotopic composition ($\delta^{238}U > +0.2‰$) and what are, to our knowledge, the most positive $\delta^{238}U$ values (up to +0.82‰) from the early Cambrian black shales at Yuanjia section from the Yangtze Platform (South China). The heavy $\delta^{238}U$ data indicate unusual large isotopic fractionation during U reduction in organic floccule layers over the seafloor and thus provide direct evidence for extremely high organic export in the early Cambrian oceans. Our integrated Fe-Mo-U, major and trace nutrient element data suggest that this extremely high organic export might be attributed to abnormally high productivity driven by episodic upwelling in early Cambrian oceans although persistent bottom-water anoxia and greatly enhanced biological pump and high weathering fluxes all contributed it. Our study supports the hypothesis that greatly enhanced organic burial triggered great atmospheric and oceanic oxygenation and subsequent Cambrian life explosion.

Notes

Widespread Putrefaction After the Marinoan-Nantuo Snowball Earth

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The aftermath of the Neoproterozoic Nantuo glaciation was a period of unprecedented deposition of highly unusual carbonate and phosphate-rich sedimentary rocks. While the origin of ^{13}C-depleted carbonate in these rock formations is widely viewed as an enigmatic feature, possibly related to the oxidation of organic matter or of methane, there lacks a connection between sedimentology and the evidence for the Neoproterozoic Oxygenation Event, including these perturbations in the carbon cycle. Here we show that a number of sedimentological structures from the ca. 599 million years old Doushantuo Formation arise from the oxidation of carboxylic acids. Characteristic mineral assemblages of diagenetic origin include quartz, carbonate, apatite, pyrite, and variably crystalline organic matter in concretionary structures of various types. The composition and distinct radial and concentric geometry of these mineral patterns in microscopic botryoids and rosettes, millimetric granules, and macroscopic concretions, leads to the argument that these sedimentological structures likely formed from chemically-oscillating reactions, during putrefaction, and from decaying biomass. Post-snowball oxygenation and perturbations in the carbon biogeochemical cycle of the Doushantuo Formation can thus be related to widespread biomass oxidation. Hence, there is sedimentological evidence for the Neoproterozoic Oxygenation Event and this new theory elegantly explains the preservation of exceptional microfossils in Ediacaran apatite granules, including fossils of animal embryos and adults.

Notes

Interactions of Ediacaran organisms with their local environment

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The Ediacaran – Cambrian transition is one of the most dramatic periods in the history of life on Earth, changing from a microbially populated world to one with an abundance of large animals. With this remarkable increase in body-size comes the ability to adapt and change their local environment. Therefore, resolving the interactions between animals and their environment is key to understanding the Ediacaran – Cambrian biosphere evolution. Determining the nature of the interactions between Ediacaran organisms and their environment can be undertaken in the Avalonian and White Sea Ediacaran assemblages because entire communities are preserved in-situ, so that the position of the fossil on the bedding plane reflects the organism's life-history. Therefore, statistical analyses of fossil specimens on their bedding planes using spatial point process analyses (SPPA) can be used to reconstruct how these Ediacaran organisms interacted with each other and their local environment. Previous work on Avalonian assemblages in Newfoundland, Canada and Charnwood Forest, UK (580 – 560 Ma) has found only very limited environmental interactions and habitat associations. Here we compare the environmental associations and interactions of the Avalonian with a younger community from the Winter Coast, White Sea, Russia (~555 Ma). This community is notably different in species composition from the Avalonian because it contains mobile organisms such as *Kimberella* and *Yorgia* as well as putative trace fossils such as *Radulichus* (thought to be produced by grazing activity of *Kimberella*) and horizontal traces which are not found during the Avalonian. We found that the community as a whole isn't aggregated over any spatial scales, so non-random patterns are likely to be biological/ecological not a taphonomic bias. *Kimberella* is aggregated and the trace fossils are segregated in contrast to rest of the community. The trace fossil spatial distribution is best-modelled by a heterogeneous Poisson process, which indicates an underlying habitat heterogeneity on which the trace-makers were utilizing, demonstrating that the trace-makers had a strong environmental correlation. Bivariate spatial analyses found that *Kimberella* segregates from the trace fossils in a pattern consistent with *Kimberella* actively avoiding trace fossil areas, thus demonstrating an environmental preference. Taken together our results show that in a relatively short period of time of ~5 Mya, Ediacaran organisms have gone from only weakly interacting with their local environment to organisms which have significant preferences for different types of substrates. Furthermore, this is the oldest example of an animal demonstrating the ability to choose to actively avoid unfavourable patchy areas due to other organism's use of local environment.

Notes

Dynamics of a "disaster": extinction and recovery following the Permian-Triassic mass extinction in marine benthic ecosystems

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The Permian-Triassic Mass Extinction saw the greatest culling of metazoan life, and lead to fundamental restructuring of marine ecosystems in perpetuity. Synergistic kill mechanisms stemming from greenhouse gas-induced climate change associated with the emplacement of the Siberian Traps Large Igneous Province are implicated as extinction drivers. At the onset, thermal stress, ocean anoxia, and acidification are thought to have led to selective extinction, geographic range restriction, and body size reduction in a number of marine benthic taxa, while allowing others to flourish in depauperate ecosystems in the aftermath of this event. Delayed taxonomic and ecological recovery following the extinction crisis is thought to have been exacerbated by continuing environmental instability for millions of years after, and is the longest documented recovery interval associated with any of the 'Big 5' mass extinctions. However, the dynamics of various facets of marine benthic ecology during this interval remains a topic of ongoing study, and so too is discerning the relative importance of specific environmental conditions on the extinction and suppressed recovery. This is complicated by the apparent temporal decoupling of some aspects of ecological and taxonomic recovery in different groups and environmental settings. Ongoing work points to thermal stress as one of the most important environmental suppressors of marine benthic community health both during the initial extinction event as well as during the recovery interval, as evidenced from temporal correlation of geochemical proxies for ocean temperatures and various metrics of ecological complexity. This apparent correlation in the timing of extinction and recovery with excursions in the d18Oapatite record is observable at several temporal scales across the Permian and Triassic extinction interval. The ecological impact of the extinction crisis is apparent in the proliferation of 'disaster taxa' in the Early Triassic recovery interval, coupled with an increase in commonness and abundance of ecological generalists despite a decrease in overall taxonomic diversity. This trend towards generalization is most readily observable in bivalves, which subsequently also outpace and eventually replace brachiopods in post-Paleozoic marine ecosystems. Ongoing efforts to comprehensively characterize ecological restructuring following the Permian-Triassic mass extinction reveal ever more nuanced patterns of complex and dynamic recovery in marine benthic ecosystems.

Notes

The Permian-Triassic sequence in North China: Implication to the Palaeozoic-Mesozoic transition on land

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The North China block evolved into a huge terrigenous inland basin in the late Paleozoic and the stratigraphic sequence of North China through the Paleozoic-Mesozoic transition can be clearly divided into two groups, i.e. Shihezi Group (Gr) and Shiqianfeng Gr. The Shihezi Gr is mainly composed of coal-measure strata containing typical Permian fossils while the Shiqianfeng Gr comprised of red beds short of fossils, indicating that a significant paleoclimate change happened between these groups in North China.

The Shiqianfeng Gr is subdivided into three formations, that is Sunjiagou Formation (Fm), Liujiagou Fm and Heshanggou Fm. Traditionally, the Permian-Triassic boundary is placed between the Sunjiagou Fm and Liujiagou Fm because some Paleozoic-type vertebrate and plant fossils occur in the Sunjiagou Fm and almost no fossils were found in the Liujiagou Fm except for very few plants and sporopollen making for a Triassic age. However, some intercalated marine flooding beds were found in the Sunjiagou Fm and Liujiagou Fm in the marginal areas of the terrestrial sedimentary basin and the marine fossils from the flooding beds suggest that the Permian-Triassic boundary should be correlated within the Sunjiagou Fm.

Our recent studies in North China indicate that the Permian-Triassic transition on land had experienced a similar process with the marine facies in South China.

1. The marine “Permian-Triassic Transitional Bed” (PTTB), corresponding to Beds 25-28 at the Meishan Section, can be correlated into the middle-upper part of the Sunjiagou Fm in North China via the littoral facies in the western Guizhou and eastern Yunnan;
2. The vertebrate and plant fossils from the lower-middle part of the Sunjiagou Fm denote the main mass extinction horizon, as well as the base of the PTTB in North China though no definite markers define the top of the PTTB in North China because no fossils have been found in the upper part of the Sunjiagou Fm but the anachronistic facies like wrinkle structures exist in the lower Liujiagou Fm;
3. The most significant climate change, rapid rising of temperature, occurred prior to the mass extinction and the extremely hot climate lasted through the Early Triassic though the aridity might be variable as indicated by the development of paleosols and ichnofossils in the Sunjiagou, Liujiagou and Heshanggou Formations;
4. The biotic recovery in the Triassic was very slow and the ecosystem had not rehabilitated until the early Middle Triassic in the upper Ermaying Fm overlying the Shiqianfeng Gr since the Liujiagou Fm is bare of fossils and the Heshanggou Fm contains more fossils, mostly plants in the lower part and a few vertebrates in the top part, but the

fossils are scattered and the strata are bright red beds, containing several layers of calcareous nodules. However, the Ermaying Fm shows a clearly transitional sedimentary sequence from drought to moisture and abundant plants and vertebrates occur in the upper part, even some thin coal beds intercalated.

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Notes

Textured Organic Surfaces in the Boreal Early Triassic: Microbial Life Thrived After the End Permian Extinction

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The marine Lower Triassic strata of the Sverdrup Basin, Arctic Canada, is dominated by a thick succession of hyperpycnite facies in mid-shelf settings that pass downdip into basinal mudrocks. Geochemical proxies for oxygenation (Mo/Al, Th/U and pyrite framboid analysis) suggest that dysoxic conditions prevailed in the Basin for much of the Early Triassic. This inhibited bioturbation and allowed the frequent development of textured organic surfaces (TOS) reminiscent of those from the Ediacaran Period, including wrinkle and pucker structures and bubble texture. The microbial mats responsible for these structures are envisaged to have thrived, in the absence of grazing, within the photic zone. The dysoxic history was punctuated by better-oxygenated phases, which coincide with the loss of TOS. Thus, Permo-Triassic boundary and Griesbachian mudrocks from the deepest-water settings have common benthos and a well-developed, tiered burrow profile dominated by Phycosiphon. TOS are also lacking from *Skolithos*-burrowed, shoreface sandstones that developed during basin-wide oxygenation in the late Dienerian. The presence of the intense burrowing in the earliest Triassic contradicts the notion that bioturbation was severely suppressed at this time due to extinction losses at the end of the Permian.

Notes

Ichnofossils from terrestrial P_3-T_2 succession at the Shichuanhe section in Shaanxi Province, North China

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Ichnological analysis has been attested valid for the palaeoenvironmental and palaeoecological interpretation in marine ecosystems during the Permian-Triassic Mass Extinction (PTME), but it's rarely used in understanding the evolution of continental ecosystems. Diverse trace fossils, including 17 ichnogenera and 5 loosely designated fossil types, were collected from a well-exposed Late Permian to Middle Triassic succession at Shichuanhe section in Shaanxi Province, North China. Moderate ichnodiversity in the marine-terrestrial mixed facies of Late Permian consists of *Helminthoidichnites*, *Lockeia*, *Palaeophycus*, *Protovirgularia*, *Taenidium*, Type A and Type B, Cruziana-type, Problematic 1 and Rhizoliths, declines significantly in several meters below the Permian-Triassic Transitional Beds marked by bivalves, conchostracans and lingulid brachiopods, accompanying by the decrease in bioturbation and burrow depth. No biogenetic structures are found in the Earlier Triassic until to the late Early Triassic. In the initial reoccurrence of biota, trace fossils are predominant by dense Skolithos in the lacustrine facies. This simple ichnocoensis is suggested to be constructed by opportunists, which pioneering recolonized the empty niches. Additionally, the deeply penetrated Skolithos (> 20 cm) probably indicate adaption for global warming. The PTME also mark the simplification of ichnocoenses, ichnoassemblages composed of domichnia and paschichnia coupled with cubichnia and fodinichnia in the latest Permian is replaced by dwelling traces in the Earlier Triassic. Whilst the overlying lacustrine sediments contains much diverse ichnofossils, including *Camborygma*, *Helminthoidichnites*, *Kouphichnium*, *Macanopsis*, *Palaeophycus*, *Planolites*, *Scoyenia*, *Skolithos* and *Taenidium*. High ichnodiversity, bioturbation and complicated vertical partitioning, together suggest for the reconstruction of rather stable ecosystems after the PTME. In addition, both mean diameter of all burrows or single ichnogenus show a reduction in the Latest Permian, which may also result from the high temperature, similar to the changes of soils fauna during the Paleocene-Eocene Thermal Maximum.

Notes

Pelagic deep-sea records of the end-Permian mass extinction event

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The largest mass extinction event in the Phanerozoic occurred at the Permian to Triassic transition. During this event, ~90 % of marine species were disappeared. As possible causes of this mass extinction, evidences of drastic environmental changes such as global warming, oceanic acidification, and oceanic anoxia have been reported mainly from the shallow water oceanic sedimentary rocks. However, it has been poorly known on response of pelagic ocean during such extreme conditions, because the pelagic Permian-Triassic boundary sections are rare.

We have reported environmental records in pelagic deep-sea facies of the palaeo-superocean Panthalassa during this mass extinction event. Our studied materials are the sedimentary rocks from the Japanese accretionary complexes. These sediments have been considered to be deposited at the low latitude pelagic region at least several thousands of km far from the main continents. The Upper Permian to Lower Triassic transition in the pelagic deep-sea is characterized by lithological changes starting from Upper Permian radiolarian-rich bedded chert through uppermost Permian siliceous claystone and Permian to earliest Triassic black claystone. Carbon isotope negative excursion which corresponds to global mass extinction horizon was recognized at the base of this black claystone. A decreasing trend in siliceous micro fossils dominated by radiolarian tests and diversity of radiolarian fossils (Sano et al., 2012) were detected at the boundary of the siliceous claystone and the overlying black claystone beds. Geochemical composition of redox-sensitive elements based on one of the best continuous Permian-Triassic boundary sections (Akkamori section; Takahashi et al., 2014) provided further information. Increases in vanadium [V], molybdenum [Mo], and uranium [U] occurred in the Upper Permian grey siliceous claystone beds. These trends indicate oxygen-poor depositional condition. The most severe sulphidic condition was estimated by the highest peaks of Mo and V in the uppermost siliceous claystone and overlying lowermost black claystone beds, in accordance with the end-Permian mass extinction event. Above the mass extinction horizon, these elements decrease significantly, despite high total organic carbon contents. A possible interpretation of this trend is drawdown of these elements in seawater after the massive element precipitation during the sulphidic water condition. A decrease in the Mo/U ratio despite enrichment of Mo and U also supports decrease in Mo from seawater. Furthermore, reactive iron [Fe] chemical species hosted in pyrite also decrease in pyrite-Fe across the boundary. This phenomenon would reflect a decrease in reactive Fe in the bottom water due to massive pyrite formation under prolonged sulfidic water.

Therefore, it was revealed that the redox changes in the pelagic Panthalassa at the end-Permian mass extinction have great impact on the seawater composition. Mo, V, and Fe act as bio-essential nutrients for primary producers and animals. The continuing reducing water column and lack of nutrient elements could have had a considerable effect on primary producer turnover and marine life.

Notes

Sulphur and mercury link the end-Permian terrestrial mass extinction to Siberian Traps volcanism

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The geologic record shows that 252 million years ago at the end of the Permian both marine and terrestrial ecosystems were severely disrupted, with the extinction of approx. 90% of marine species and 70% of terrestrial vertebrates. This most severe known extinction in Earth's history was likely triggered by the eruption of the coeval Siberian Traps, and several kill mechanisms have been proposed to explain such biological catastrophe. The release of volcanic gases from the Siberian Traps (CO_2, SO_2, halogens and metals) could have caused a cascade of environmental changes ultimately resulting in the biological crisis: Volcanic injection of large quantities of CO_2 into the atmosphere–ocean system can trigger global warming, ocean acidification, and anoxia, while SO_2 can cause short-term cooling and acid rains; Volcanic gases can also trigger stratospheric ozone depletion, with consequent increase of UV-B radiation on land, and ecosystems' poisoning with toxic metals like Hg, Zn and Cd. However, the vast majority of the published studies on the end-Permian mass extinction (EPME) have been focused on the marine realm, due to the less established chronostratigraphic framework and lower fossil preservation for the terrestrial successions. Therefore, the patterns and mechanisms of the EPME on land, and its temporal and causal relationships with the eruption of the Siberian Traps, are poorly understood. Here we present TOC, mercury, organic carbon-isotope, and preliminary sulphur-isotope data from Chinahe section (eastern Yunnan, South China) and Dalongkou section in the Junggar Basin (Xinjiang, Northwest China). At Chinahe, the latest Permian – early Triassic is represented by the Xuanwei and Kayitou Fms., a succession of sandstone, siltstone and mudstone deposited in a terrestrial (lowermost part) to shallow marine environment (upper part). At Dalongkou, the Guodikeng Fm. encompasses the Permian–Triassic boundary; it consists of a succession of grey to red mudstones deposited in a lacustrine environment and its age is well constrained by sporomorph and ostracod biostratigraphy. Negative carbon-isotope excursions (CIE) are recorded in both successions, and are synchronous with the crisis of terrestrial fauna and flora. Hg concentrations and Hg/TOC show peaks are correlated with the negative CIE and the biological turnover, showing a pattern that is similar to the marine records. Total S concentrations vary through the sections and preliminary □34S data from Dalongkou are consistent with an addition of volcanic sulphur. Altogether, the new geochemical data support a direct temporal link between the terrestrial EPME and the massive eruptions of the Siberian Traps, shedding new light on the kill mechanisms in continental ecosystems.

Notes

Intrinsic engineer driving ecosystem recovery after the end-Permian mass extinction: Sponge pump and arms race in Triassic oceans

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The main driver – extrinsic or intrinsic factors- of biotic macroevolution has long been debated. Similarly, whether physical environmental improvement or biotic interactions, such as competition and predation drove ecosystem's recovery from major mass extinction has long remained unsolved. Here, we report two biotic interaction cases from South China that likely facilitated biotic recovery after the end-Permian mass extinction. The first finding is an association of the Burgess shale-type sponge *Crumillospongia* (Rigby) and Triassic-type brachiopod *Meishanorhychia* from the deep-water oxygen-deficient setting immediately after the Permian-Triassic extinction. This Cambrian-type sponge is characterized by the pronounced pores on side walls and a distinct mouth on the top, which suggest the same water circulation system as sponge pump observed in modern oceans. The modern demosponges are often found in association with cyanobacteria or other microbes, and the sponge-microbe complex act as the primary producers in marine ecosystem, and usually produce 3-5 times oxygen and dissolved organic matters (DOM) than that they can consume. The earliest Triassic sponges therefore are interpreted as an ecosystem engineer driving biotic recovery following the end-Permian crisis. Another case is the finding that worm's bulldozing behaviour and predatory interactions between arthropods and worms and between arthropods, which are observed from a diverse assemblage of superficial arthropod trackways and burrows from the Lower Triassic Daye Formation of Dangwu, Guizhou Province, China. The traces were produced by various arthropods, worms, and others. These include evidence of predation interactions between horseshoe crabs and other small arthropods, and arthropods feeding on polychaetes and other worms. The majority of mobile arthropods, infaunal suspension feeders (crustaceans), and deposit feeders (polychaetes or worm-like organisms) in Dangwu ichnofaunas may also manifest the bulldozing hypothesis proposed by Thayer. In his scenario, sediment bulldozers are the most efficient bioturbators, with their ability to displace sediment, manipulate sediment in burrowing and crawling, and manipulate sediment externally in feeding. Thus the polychaetes or worm-like organisms in Dangwu ichnofaunas bulldozed the oxygen-depleted sediments to make the substrate more habitable, and attracted an increasing number of trace-making organisms to inhabit. These worm-like organisms were eventually eaten by the returning arthropods, such as horseshoe crabs. Accordingly, the post-extinction sponge pump, worm-like organism's bulldozing and arms race between arthropods may become important ecological engineer driving biotic recovery in the Early Triassic.

Notes

Tetrapod body size was an important selective factor during the Permo-Triassic mass extinction

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The Permo-Triassic mass extinction devastated global ecosystems and was pivotal in reshaping tetrapod diversity. The concept of extinction selectivity has a long history and remains enigmatic. Why do some lineages perish during extinction events? Does luck determine which species survive or are some lineages more resilient? Could this be linked to aspects of morphology and ecology? In modern systems, some biological traits, such as body size, have been linked with selective extinction. In the fossil record the picture is unclear, with no consistent trends across clades, traits and time. Recent studies incorporating evolutionary modelling in a phylogenetic comparative framework have found no evidence for selectivity in bony fish body size during the Permo-Triassic mass extinction and archosauromorph morphology and ecology during the Late Triassic extinctions. Here we test if body size was associated with extinction in all tetrapods during the Permo-Triassic mass extinction event. As a test for extinction selectivity in fossil vertebrates, the study is unprecedented in scope. We utilise a novel supertree of tetrapods comprising 2142 species and a body size proxy for 990 species. We use phylogenetic modelling approaches to examine if body size was statistically correlated with extinction risk and test the effects of using multiple extinction intervals. Our results clearly show that larger body size is significantly correlated with tetrapod extinctions in the Changhsingian, and this result is robust to phylogenetic and dating uncertainty. If the extinction interval is extended to incorporate the Changhsingian–Induan interval there is no significant correlation between size and extinction, and the same is true if the preceding Wuchiapingian bin is tested. These results suggest that large-bodied tetrapods were less resilient to the extreme perturbations during the Permo-Triassic mass extinction event, and compliments work in modern systems that have shown large-bodied taxa may be less resilient to global change. Future work will examine trends within tetrapod subclades and incorporate additional aspects of morphology and ecology.

Notes

Developments in Fourier Transform Infrared spectroscopy imaging for the determination of modern and end Permian UV-B fluxes from palynomorph wall chemistry.

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Fourier Transform Infrared spectroscopy (FTIR) is established as a robust technique for the chemical interrogation of a range of materials. A novel application of FTIR is the determination of chemical functionality of the biopolymer, sporopollenin (Fraser *et al.*, 2011). Sporopollenin comprises the majority of the outer exine of palynomorphs (spores and pollen). Using FTIR to track abundance of aromatic components within sporopollenin is demonstrated to be reliable proxy for UV-B flux at the Earth's surface (Lomax *et al.*, 2008). Recent technological developments with FTIR imaging have enabled a substantially higher throughput of samples. In line with these FTIR imaging technological developments, a commensurate increase in data volume generated has occurred. To capitalise on this we have developed a software package, *sporoSpec*, to utilise the instrument's strengths whilst handling the gigabytes of data it produces, and have optimised this package for palynomorph chemistry. This affords the opportunity to analyse sporopollenin chemistry of individual palynomorphs in large numbers, opening the geological archive for intensive study.

UV-B fluxes are believed to be responsible for the observed malformation of sporomorphs at the end Permian (Visscher *et al.*, 2004; Foster and Afonin, 2005); the resultant damaged gametophytes led to forest sterility and decline, which may have played a role in the terrestrial mass extinction event at this time. Benca *et al.* (2018) exposed living *Pinus mugo* trees to UV regimes equivalent to those modelled for the end Permian extinction event (Beerling *et al.*, 2007). They found that the higher UV doses produced the same malformations in the pollen from living trees as observed in fossils from the end Permian. Here we present sporopollenin analysis from these experiments, and report the chemistry changes observed in response to these experimental UV-B fluxes. These data will aid calibration of UV-B reconstructions spanning the end Permian mass ecological crisis.

Notes

Permian-Triassic palynoflora turnover and implication for the palaeoclimatic reconstructions at Dalongkou section, northern Xinjiang

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The end-Permian extinction event was the severest biotic crisis during the Phanerozoic, which is associated with the turbulent environment during the crisis and its aftermath. But the former works were mainly focused on marine strata and now, more and more studies draw attention to the terrestrial organisms and strata. Dalongkou Anticline sections (northern Xinjiang, China) are important and concerned for the studies about the terrestrial biotic and environmental changes across the Permian-Triassic Boundary. Among the researches on different kinds of fossils at Dalongkou sections, palaeopalynology is one of the most indispensable contents. Many abundant, diverse and well preserved sporomorphs are recorded and illustrated from the upper part (including bed 22-28) of Guodikeng Formation at north limb of the Dalongkou Anticline sections, assigned to 36 genera. According to the changes of palynological abundance and main forms in succession, eight assemblages have been recognized in ascending order: Alisporites- Lunatisporites-Protohaploxypinus Assemblage; Platysaccus-Alisporites-Lunatisporites Assemblage; Lueckisporites virkkiae-Alisporites-Platysaccus Assemblage; Falcisporis-Alisporites- Lunatisporites Assemblage; Platysaccus-Alisporites Assemblage; Lundbladispora-Calamospora- Limatulasporites Assemblage; Alisporites-Platysaccus-Lundbladispora Assemblage and Lundbladispora-Limatulasporites Assemblage. The first five assemblages are dominated by gymnospermous pollen grains (commonly Alisporites, Platysaccus, Lueckisporites virkkiae and Lunatisporites), which can be attributed to coniferopsida. In addition, some pteridospermous (e.g. Peltaspermales) pollen grains (commonly Protohaploxypinus) and some non-cavate spores (commonly Punctatisporites, Leiotriletes and Cyclogranisporites) of pteridophytes (lycopsids and ferns) but also bryophytes have been also seen in these five assemblages. We can conclude that the age of these five assemblages should be the latest Permian and it may be dominated by conifers palynoflora during this period in this area. However, the palynological abundance of Lundbladispora increased explosively and became rapidly the main form at the upper part of bed 24. Moreover, Lundbladispora can be attributed to Lycopsida (Pleuromeiaceae). While nearly all taeniate bisaccate were disappeared (just Lunatisporites occured) and just some non-taeniate pollen grains (Alisporites and Platysaccus) held on. Curiously, it appeared once boom of Alisporites in the bed 28. Thus, the last three assemblages should be assigned to the earliest Triassic in age and the lycopsid palynoflora was in the lead but also once small boom of conifers flora happened during the earliest Triassic in this area.

The sudden catastrophic event affects terrestrial floras at the P–T boundary. Many taeniate bisaccate pollen forms were decreasing drastically, which may indicate that the latest Permian conifers-dominated hydrophilous but drought-tolerant palynoflora on better drained sandy soils of lowland (e.g. levees) or moist upland was gradually destructed. In the earliest Triassic, lycopsid cavate spore Lundbladispora increased rapidly and take over the predominant form, which may indicate that vegetation changed over to lycopsid spore-dominated hydrophilous but might xerophytic palynoflora and might be also once small boom of xerophytic conifers-dominated palynoflora in lowland near water in the earliest Triassic. The earliest Triassic lycopsid palynoflora with many xerophytic characteristics may adapt to the seasonal drought climate. Moreover, abnormal sporomorphs (abnormal pollen and spore tetrad) were yielded here. And the abnormal sporomorphs was thought to be tightly related to the increased UV-B intensity.

Notes

Resilience and Stability in the Phanerozoic: The Role of Complex Evolutionary Time

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Rates of molecular, physiologic, developmental and phenotypic change vary widely even within a single lineage, and similarly high variability of change in is recorded in ecosystems and for the physical environment. In most cases this high variability generates higher rates of change on short timescales than over longer intervals. But some differences in the tempo of evolution reflect complex evolutionary time, with evolution operating on multiple timescales. Evolution has modified the effective timescales of evolution by constructing slow variables, which coarse-grain environmental inputs to reduce uncertainty and risk and increase predictability. Some slow variables are external, ecological factors, such as niche construction, microbial biofilms, and the scaffolding of ecological communities while others are internal, including physiological homeostasis, modularity, developmental canalization and hierarchical structuring of developmental gene regulatory networks. The generation of slow variables can modulate rates of evolution and allow greater long-term stability than might otherwise be the case. Since slow variables tend to increase the robustness of organisms to environmental perturbations, it is hardly surprising that at a gross level they appear to have accumulated through time. An increase in slow variables in development, ecology and environmental dynamics may have influenced apparent increases in resilience and stability through the Phanerozoic. Understanding whether the development of external and internal slow variables is a passive or driven trend, and how they have influenced the course of evolution remains a challenge for future work

Notes

The uplift history of southern Tibet and related climate change

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The Himalaya-Tibet edifice (HTE) exerts strong influence on the Asian monsoon and global climate by acting as a high altitudinal heat source and by deflecting air flow (Boos & Kuang, 2010). The altitudeand surface characteristics of the HTE have changed over time but in various aspects still remain poorly understood (Wang, 2008), limiting our ability to distinguish the contribution of the HTE to climate change and the related orography to sub-surface crustal dynamics. Here we present the first uplifting history diagram (elevation vs time) of the HTE from the initial collision of India with Asia (~65 Ma; Ding et al., 2005) to the present day via combined proxies of atmoshpherical enthalpy derived from plant physiognomy and the δ18O value of meteoric water. The results from plant and oxygen isotope palaeoaltimeters indicate the main part of the protoTibetan highland consisted of at least two large central mountain ranges, one is the central watershed range in the Qiangtang Terrane and the other is the Gangdese Mountain in the southern Lhasa Terrane (Ding et al., 2014). These two ranges attained their current elevation at 60 million years ago, whereas the Himalaya to the south were still low at that time, close to or even below sea level. At the beginning of Miocene (~23-22 Ma) the protoHimalaya had risen to ~ 2.3 km from ~ 1 km in the late Paleocene and by the mid Miocene (15 Ma) was over 5 km, exceeding its present altitude (Ding et al., 2017). Direct comparison with convergence rate of India demonstrates that our time/elevation model is applicable widely across the southern HTE and suggests a post middle Miocene southward shift in the locus of compression to build the high Himalaya. Our data also show that the rise of the southern HTE was accompanied by progressive drying on the plateau and strengthening of the Indian monsoon system.

Notes

Exploring 'Shangri-La' – The Elevation and Climate of a Tibetan Paleogene Hidden Valley

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Understanding the landscape evolution of the Himalaya-Tibet edifice is essential for understanding the origins and resilience of the monsoons and biodiversity in southern Asia. The last 30 years have seen radical changes in conceptual models describing the evolution of the Tibetan landscape. Two popular end members have been a late Miocene rapid uplift treating Tibet and the Himalaya as more or less a single entity, to a progressive rise in a general SW-NE direction. Both these models assume that uplift has been driven largely, if not completely, by continued northward movement of the Indian plate. More recently a different model has emerged encompassing significant varied topographic relief before and during the early phases of the India-Asia collision. This is because India was not the first plate collision affecting southern Asia in the region we now call Tibet, and not the first to build mountains. The Qiangtang Terrane impacted Asia from the south in the Jurassic and that was followed by the Lhasa Terrane under-thrusting the Qiangtang Terrane in the early Cretaceous. These two blocks now form the core of the Tibetan Plateau, joined at the Bangong-Nujiang suture.

Recent isotopic palaeoaltimetry points to a northern Paleogene Qiangtang mountain system (~ 5 km) and an elevated (>4.5 km) Gangdese mountain chain along the southern margin of the Lhasa Terrane by the Eocene. Along the Bangong-Nujiang suture isotopic estimates suggest very high (>4.5 km) elevations leading to claims of a high and dry Tibetan plateau in the Eocene. However, fossil finds and biomarkers in 4 km thick sedimentary successions within the suture zone contradict this. Using climate model-mediated terrestrial lapse rates and enthalpy estimates derived from plant fossils we evidence an Eocene through Oligocene deep valley system between the Gangdese and Qiangtang highs with a valley floor elevation only ~2 km above sea level. The fossils include large (~ 1 m long) palm fronds that cannot have been transported far from their growth site prior to burial. Moreover, because palms are inherently cold-sensitive they provide a secure upper elevation limit of 2.3 km for their growth site. A large diversity of woody dicot leaves, fishes, insects and mammals show that this valley at times hosted a 'Shangri-La'-like warm humid tropical-subtropical ecosystem with high biodiversity that experienced monsoon-like seasonal variations in rainfall. Around 23.7 Ma regional uplift and drying began, coincidental with a resistive slowing of the Indian plate and a rapid rise of the Himalaya, and only in the late Miocene did continued N-S compression from India and sediment accumulation raise the valley floor to form the plateau landform of today's Tibet. It is around this time that molecular phylogenetics suggests a major diversification of biodiversity in the region.

Notes

Can novel techniques using climate models aid in determining the palaeoaltimetric history of the Himalayas and Tibet Plateau?

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The Himalaya -Tibetan Plateau (HTP) is the largest and highest plateau in the world with an average elevation exceeding 4.5km. The HTP plays a fundamental role in modern climate both regionally and globally through teleconnections by perturbing atmospheric circulation and energetics. The HTP is known as the 'Third Pole' due to it storing more snow and ice then anywhere on Earth outside of the polar regions, making it an important source of fresh water that sustains around half the world's human population, as well as the Asian biodiversity hotspots. Understanding the topographic evolution, in particular the height of the Himalaya and the Tibetan Plateau is crucial for understanding the development of monsoon systems, biodiversity and the wider climate through the Cenozoic (the last ~66 million years). Several methods have been proposed to reconstruct the height of the QTP through the use of proxy-records such as fossilised plants, shells and mammalian teeth as well as carbonate minerals formed in lakes and soils. Thermodynamic approaches using moist enthalpy and thermal lapse rates utilise climate signals derived from fossil plants to produce a thermal profile at two isochronous locations, i) a priori at sea level and ii) an unknown height at elevation to be reconstructed. These approaches derive a height based on the relationship between temperature and altitude (lapse rates) and the conserved quantities of sensible and latent heat of moist air (enthalpy) which also varies with height. These approaches assume the same relationships between plants and atmospheric properties existed in fossilised plants as we observe in modern plants. A third method, stable isotopes, identifies the isotopic signature of precipitation as an airmass transgresses a topographic feature, isotopically fractionates (Raleigh distillation) and becomes increasing isotopically depleted in heavy isotopes thus providing a relationship with height. All three methods incorporate inherent uncertainties and assumptions within their methodologies with elevation estimates sometimes widely varying by as much as +/-4km at the same site in space and time. Here we show with the aid of novel paleoclimate modelling techniques how these uncertainties in each approach can be constrained allowing for an improved estimate of paleo-elevation and offer case studies showing how combined approaches of the various methodologies should be used to estimate the topographic height, extent and interpretation of paleogeography paving the way for more accurate and robust reconstructions.

Notes

The evolution of plant diversity in the Qinghai-Tibetan Plateau: Evidence from fossil records

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Fossils are pivotal to understand histories of plant diversity and biogeography under dramatic paleoenvironmental changes in the Qinghai-Tibetan Plateau (QTP); however, fossil floras there have been far from sufficiently investigated. During recent years, we did plenty of field work and found several well-preserved fossil floras ranging from the Paleocene to the Pliocene in high altitudes of the plateau. For the late Paleocene Liuxiang flora in southern Tibet, evergreen elements including Lauraceae and Moraceae are the most abundant; the late Paleocene-middle Eocene Baingoin flora in north Tibet shows relatively high plant diversity, and is quite similar to Eocene Green River flora from western interior USA in floristic components. The late Eocene Kajun flora in eastern Tibet is dominated by *Cyclobalanopsis* and *Betula*, representing evergreen-deciduous broadleaf forest. For the late Oligocene Dayu flora in northern Tibet, grasses firstly occurred together with Arecaceae and *Koelreuteria*; whereas the Pliocene Zhada flora in western Tibet is represented by small-sized leaves. The occurrence of some extinct taxa in these paleofloras, e.g., *Hemitrapa*, *Limbophyllum*, and *Cedrelospermum*, as well as many taxa being still widely distributed in the QTP, e.g., *Betula*, *Cyclobalanopsis*, *Koelreuteria*, and *Rosa*, suggests that there were frequently floristic exchanges between the QTP and other parts of the North Hemisphere. Besides, the vegetation types gradually changed from the evergreen broadleaf forest to evergreen-deciduous broadleaf forest, then to open vegetation, and finally to alpine shrub and meadow. Most notably, plenty of palm fossils were discovered from the late Paleocene of southern Tibet and the late Oligocene of central Tibet, which are solid evidence for much warmer climate and lower elevations in the geologist past than these at the present day. Generally, evidence based on our current plant fossils clearly indicates that, the evolutionary history of the biodiversity closely associated with dramatic paleoenvironmental changes in the QTP, which were mainly induced by the tectonic activities of the QTP and the Himalayas. In future, more fossil floras are urgently needed to better understand the evolution of biodiversity and the history of paleoenvironmental changes in this large region.

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Notes

Cenozoic floras of Yunnan, and their response to environmental change

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Yunnan, SW China, is one of the world's biodiversity hotspots. Even though Yunnan accounts for only 4% of the Chinese territory, it is home to more than 19,333 species of higher plants, grouped into 3084 genera and 440 families. 96.7 % of genera and 86.2% families of Chinese higher plants can be respectively found in Yunnan. Among them, 113 species, 25 genera and 9 families are gymnosperm, representing 37% of species, 73.5% of genera and 90% of families in China; and 15951 species, 2367 genera and 244 families are angiosperm, representing 48% of species, 84.5% of genera and 98.0% of families in the country. Furthermore, more than half of these plant species are endemic to Yunnan.

Yunnan not only house a high diversity of modern plants, but also archives rich fossil floras for the past. Totally, 386 fossil species of ferns, gymnosperms and angiosperms belonging to 170 genera within 66 families have been reported from the Cenozoic, chiefly the Neogene, of Yunnan. Angiosperms display the highest richness represented by 353 species grouped into 155 genera within 60 families, with Fagaceae, Fabaceae, Lauraceae and Juglandaceae being the most diversified. Floristic analyses indicate that in the late Miocene, Yunnan had three floristic regions: a northern subtropical floristic region in the northeast, a subtropical floristic region in the east, and a tropical floristic region in the southwest. In the late Pliocene, Yunnan saw two kinds of floristic regions: a subalpine floristic region in the northwest, and two subtropical floristic regions separately in the southwest and the eastern center. Recent fossil findings indicate that the floristic modernization of Yunnan started as early as early 33 Ma years ago, much deeper than the Miocene initiation as previously interpreted. These fossil flora contain several taxa which widely occurred in the Northern Hemisphere, North America and Europa, such as *Sequoia, Metesequoia, Cryptomeria, Dipteronia, Berryophyllum*, *Cedrelospermum*, *Palaeocarya* and *Podocarpium*, etc. It seems that there was strong floristic link among East Asia, North America and Europa in the Tertiary. Among them, some are extinct worldwide, such as *Berryophyllum*, *Cedrelospermum*, *Palaeocarya* and *Podocarpium*, but some are still survived in China, such as *Metesequoia, Cryptomeria* and *Dipteronia* known as Tertiary relics. We present fossil histories of plants in Yunnan in order to understand the evolution of plant diversity and distribution, and its response to environment changes.

Notes

Linking Tibetan Uplift to Vegetation and Biodiversity change in the Cenozoic?

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Numerous climate modelling studies have shown that uplift of the Qiantang-Tibetan Plateau can have a profound impact on climate in the region and globally. Uplift changes the structure and strength of the Asian monsoon. However, fewer studies have examined the resulting impact on vegetation and biodiversity. We present a unique series of modelling studies for the Cenozoic, including sensitivity studies to isolate the impact of various changes. The climate response is then used to force vegetation models (BIOME4 and the Sheffield Dynamic Vegetation Model) and biodiversity models (JeDI). The simulated vegetation and biodiversity change are consistent with existing published reconstructions and show that the evolution of Tibet plays a vital role in the distribution of vegetation and biodiversity in the region.

Notes

Biosphere resilience from Precambrian to present day

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The Gaia hypothesis posited that life plays a key role in self-regulating negative feedback mechanisms that give the biosphere resilience to perturbations. Resilience implies that a system returns to a pre-existing stable state and resilience can be quantified as the rate at which the system recovers to that state. Sometimes in the past the biosphere lost resilience altogether and did not return to its previous stable configuration but rather underwent an abrupt transition (or 'revolution') to a new configuration (or 'attractor' in the language of dynamical systems). Candidates for such transitions include the 'complexity revolution' across the Proterozoic-Phanerozoic boundary, and the Permian-Triassic boundary event. I will introduce methods for quantifying the changing resilience of the biosphere, including detecting the loss of resilience that occurs at a 'tipping point', and will show some applications of the methods to data from deep time. Quantifying changes in biosphere resilience is challenging in terms of the data required. However, known perturbations of the Earth system give us an opportunity to measure recovery rates. Furthermore, as we gather longer, higher-resolution records, changing resilience can be more continuously monitored – as I will show using the Paleocene-Eocene as an example.

Notes

The end Ordovician extinction: ecosystem resilience decoupled from taxonomic loss

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The end Ordovician was the first of the five major mass extinctions that affected metazoan life on Earth. Paradoxically although the extinction was substantial in taxonomic terms, disruption to the ecosystem was relatively minimal, confined mainly to changes at the community levels, across marine habitats. Recent advances in the correlation of strata through the event, using both the ranges of biological taxa and stable isotope curves, revision of key genera and species and their palaeobiogeography have emphasised that the extinctions are clustered around two main phases; both are associated with the waxing and waning of a major ice sheet that extended across the southern continents. The causes and consequences of the event related to, for example, global cooling, regression (species-area effect on marine platforms) and euxinia (habitat destruction in basins) have been well rehearsed. Moreover, potential victims can be predicted based on modelling responses of key groups to environmental and geographic changes prior to the extinctions. Revised correlations have confirmed that the near-cosmopolitan, low-diversity *Hirnantia* brachiopod fauna reached its acme during the interregnum between the first and second phases as cool water spread from high latitudes into the subtropics; following the second there was a greater differentiation across the global benthos with the development of the carbonate Edgewood Province at low latitudes whereas elsewhere many regions were dominated by black shale deposition. Other groups, however, such as the graptolites faced near extinction. Growing evidence for a series of ice ages, during the Ordovician, developed with increasing intensity may have aided the resilience of ecosystem structures, and sustained a characteristic 'Ordovician evolutionary fauna' that continued some way into the Silurian.

Notes

Improved past ocean anoxia reconstruction from combining the uranium and molybdenum isotope redox proxies

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Changes in the ocean oxygenation state are implicated in many of the major Earth system transitions. The sedimentary abundances and isotopic compositions of redox sensitive trace metals play a prominent role in attempts to reconstruct the history of surface and ocean oxygenation. Of all the redox sensitive metals that have been used, molybdenum (Mo) and uranium (U) have been among the most prominent. Both are soluble under oxidizing conditions and exhibit conservative behaviour in the modern open ocean, with residence times that are significantly longer than ocean mixing time, making them potential proxies for global ocean-scale processes. Furthermore, the U and Mo isotope redox proxies show distinct, but systematic isotope fractionations when incorporated into different marine anoxic and oxic sinks. These Mo and U isotope systematics have been utilised to reconstruct the ocean seafloor anoxia over time using geological records of marine sediments.

Marine organic-rich sediments offer an archive that incorporate both authigenic (seawater-derived) U and Mo. The authigenic Mo and U, however, may be incorporated into organic-rich sediments with a range of isotope fractionations, dependent on the exact localised redox deposition conditions and the hydrological setting. Thus, localised deposition effects need to be disentangled from that of a global ocean signature in such sediments, for the robust reconstruction of global ocean redox conditions. Our work on modern and near-modern organic-rich sediments shows that using the U and Mo isotope redox-proxies, in combination, enables a better quantification of the localised redox conditions and hydrological effects on the isotope systematics (Andersen et al. 2018; Bura-Nakic et al. 2018). This provides a framework for improving the interpretation of Mo and U isotope systematics in organic-rich sediments over geological time-scales and therefore more reliable reconstructions of past ocean redox structure.

Notes

Dynamic marine redox conditions during the end-Ordovician mass extinction event

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The end-Ordovician mass extinction (EOME) was the first of five Phanerozoic great mass extinction events. Traditionally, climate cooling and glacioeustatic sea level dropping (habitat loss) associated with the Hirnantian glaciation is regarded as the main kill mechanisms for the end-Ordovician Mass Extinction (EOME), especially the first pulse of it (Johnson, 1974). Recent studies proposed that the spread of anoxia is the main kill mechanism for not only the second (Melchin et al., 2013; Bartlett et al., 2018) but also the first pulse of EOME (Zhang et al., 2009; Hammarlund et al., 2012; Zou et al., 2018). However, the causal relationships between anoxia and EOME are difficult to establish, especially when the spatial and temporal relationships between them are still controversial.

Here, we utilize uranium (U) isotope compositions in Upper Ordovician to Early Silurian successions from Guizhou Province on the Yangtze Platform, South China to document patterns of global-ocean redox variations. Importantly, comparison with existing data from Anticosti Island, Canada (Bartlett et al., 2018) shows that U isotope trends can be utilized as a novel chemostratigraphic tool. There are three major negative excursions (NE2, NE3 and NE4) and one major positive excursions (PE3) in δ238U of similar magnitudes at both South China and Canadian carbonate sections. Besides, a small secular negative δ238U excursion (NE1, ca. −0.2‰) is exhibited through the upper Katian black shales of Heshui Section; and two positive δ238U excursions (PE1, PE2) with variable magnitudes developed after each of the EOME pulses.

All δ238U negative excursions except NE3 are coupled with decreased δ18O and/or increased sea level. The rapid warming and release of fresh meltwater right after glacial intervals leads to stratification and anoxia.

The most pronounced δ238U NE3 in South China and Canada has nearly identical value (ca. −0.8‰). It is coincident with the most significant δ18O positive excursion and a major unconformity, suggesting shift toward more-reducing conditions during Hirnantian glacial maximum (HGM). The deep ocean redox condition could be decoupled from the surface ocean during glaciation, as indicated by enhanced burial of redox-sensitive trace metals during the last glacial maximum (LGM) (Jaccard et al., 2009). Moreover, the HGM deep ocean seafloor could have had larger suboxic area and more chance to develop sulfidic conditions because of lower atmospheric PO2.

Glacial–interglacial cycles during the Early Palaeozoic Icehouse may have promoted the dynamic redox conditions in the deep ocean. Meanwhile, during the Paleozoic Oxygenation Event, the atmosphere, as the source of oxygen in the ocean, still has lower-than-modern PO2. Therefore, the deep ocean can be deoxygenated during not only greenhouse climate, but also icehouse climate. Although the biological impact may have been different.

Notes

Life, culture, and modes of stability

Tyler Volk[1]

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This talk offers perspectives on how to conceptualize the stability of the biosphere. The basis involves modes of stability from my book “Quarks to Culture” (Columbia U. Press, 2017) and from my work on biosphere-Gaia theory and its applications.

“Quarks to Culture” presents a case for 12 fundamental levels of entities and relations that were formed by what I call “combogenesis,” a rhythm (not a law of nature) in which smaller, independent entities on a prior level were combined and integrated into new, larger entities with new relations on each higher level. The levels are: 1) Fundamental particles; 2) Nucleons; 3) Atomic nuclei; 4) Atoms; 5) Molecules; 6) Prokaryotic cells; 7) Eukaryotic cells; 8) Multicellular organisms; 9) Animal social groups; 10) Cultural metagroups; 11) Agrovillages; and 12) Geopolitical states. The biosphere started with level 6 (the base level of biological evolution), and levels 7 through 10 took place within the context of biological evolutionary dynamics within the overarching biosphere (with level 10 beginning cultural evolutionary dynamics, a new overarching dynamics for subsequent levels of stability).

This proposed grand sequence involves a progression from thermodynamic stability to the start of life with Darwinian dynamics of biological evolution, and then to our most recent large-scale dynamics of cultural evolution. Stability of various patterns in the “evolutionary realms” of life and culture come about from particular evolutionary dynamics that engage and shape entities directly, by subprocesses of propagation, variation, and selection (PVS). Thus, I prefer to not use the term “evolution” to apply to the entirety of the biosphere itself. So what can we say about the stability of the biosphere, and can it increase over time?

For such questions about the biosphere, we might make use of analyses of large-scale, biosphere properties both derived from organisms and affecting (downward influence) organisms subject to PVS. Such properties could include pool sizes, buffers, complementary metabolisms, effects from the evolution of nested complexity with changes in relations of living things (levels 6 to 9, above), cycling ratios, biochemical guilds, and byproduct effects from evolutionary innovations that alter the kinds and quantities of nutrient uptake and waste export.

Notes

Community structure and ecosystem collapse across major extinction events

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In order to fully understand ecosystem collapse across mass extinction events, it is essential to consider extinction dynamics within a trophic community framework. As palaeobiologists, we often make the assumption that all taxa that went extinct at times of mass extinction did so in response to severe abiotic stress. However, ecological theory suggests that many victims of past extinction events did not become extinct as a direct effect of abiotic stress, but probably did so in response to cascading secondary effects brought about by the loss of prey resources and changing competition dynamics.

Here, we review a case study of using trophic network models to assess the impact of extinction cascades in response to the early Toarcian extinction event. Species and guild-level food webs were reconstructed for pre- and post-extinction ecosystems. Trophic extinction cascades were simulated across the extinction event in order to assess ecosystem robustness to informed and random primary extinction events. Model outputs were then compared to empirical post-extinction food webs to determine the likely abiotic driver of ecosystem collapse. Results show benthic organisms with high metabolic demands were selected against which fits well with an anoxia primary kill mechanism.

We will then outline plans for assessing ecosystem robustness to extinction cascades throughout the Late Permian mass extinction and recovery interval and to test long-held ideas about extinction kill mechanisms in both the marine and terrestrial realms.

Notes

Did Devonian climatic variation driven by the rise of terrestrial vascular plants？

Chen Bo[1]

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The colonization of terrestrial landscapes by rooted vascular plants is considered as a key factor in driving climate changes in the Devonian. New comprehensive Devonian conodont apatite oxygen isotope record from various low latitude areas indicate a dynamic Devonian climate variation, with first climatic cooling appearing at the early Devonian (the Pragian-Emsian) transition, followed by a climatic warming during the middle to late Devonian (the Givetian-Frasnian) transition and a further cooling at the Famennian.

The early Devonian cooling coincided with the earliest occurrence of vascular plant roots−soil interaction and significant promotion in spore and mega plants fossil diversity, plant biomass, vegetation cover area as well as terrestrial organic carbon burial. It is thus argued that the early Devonian cooling may be a direct climatic consequence resulted by accelerating silicate weathering rates associated with the first well-established vascular plants root-soil interaction. Whereas the warming over the middle to late Devonian transition is suggested to may relate to the decelerated silicate weathering rate due to the soil shielding effect and lower temperatures produced by the pervious weathering, with metamorphic CO_2 degas from the Acadian orogeny potentially also being an important contributor. The Famennian cooling is coincident with the advent of seed plants, which able to colonize various drier and harsher habitats, as a consequence, the Famennian vegetation’s distribution dramatically expanded, which is accompanied by development of deeper and more morphological complicated root system in order to obtain more water and nutrients. The expanding habitats and deeper and more complicated root system would have boosted the terrestrial silicates weathering again, ultimately lead to global climate transition from the early Paleozoic green house to the Late Paleozoic Ice house.

Notes

Stepwise oxygenation of the Paleozoic atmosphere

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Geochemical proxies have been instrumental in determining the broad evolutionary history of oxygen on Earth, but much of our insight into the temporal variability of atmospheric oxygen levels over the Phanerozoic comes from biogeochemical modelling. However, there are fundamental disagreements amongst the different models, and between models and geochemical proxies, particularly during the early Paleozoic.
Here, we revisit the GEOCARBSULF model [1], which calculates atmospheric oxygen by estimating the burial and weathering rates of organic carbon and reduced sulphur, from the sedimentary records of $\delta^{34}S$ and $\delta^{13}C$. The model estimates near present day levels of oxygen in the Paleozoic but is restrained from predicting much lower levels by its simplified treatment of a complex geochemical process: sulphur isotope fractionation, which is used to calculate pyrite burial. We update the model by replacing the sulphur cycle equations with ones which eliminate the requirement for sulphur isotope fractionation values to calculate pyrite burial [2], thus lifting this constraint on its calculation of atmospheric oxygen levels.
Our new model produces a new history of atmospheric oxygen levels over the Phanerozoic. Crucially, our results are compatible with both geochemical indices and previous biosphere-driven modelling and support the hypothesis that the evolution of land plants caused a stepwise change in Earth's oxygen levels.

Notes

Transitioning into Cretaceous Oceanic Anoxic Event 2: CO_2 induced climate forcings on the wildfire record.

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Oceanic anoxic events are periods in Earth history that represent significant disruption to the 'background functioning' of the Earth system, exhibiting major environmental changes, global perturbations of the carbon cycle and loss of oxygen in bottom waters.

Cretaceous Oceanic Anoxic Event 2 (OAE2), presents a period of significant and rapid changes in the carbon-cycle. Likely induced by the release of large quantities of volcanic CO_2 from contemporaneous volcanism, the release of this CO_2 is hypothesized to have been capable of triggering marine anoxia through a series of biogeochemical feedbacks. Published high-resolution stomatal index reconstructions of atmospheric CO_2 concentrations across the initiation of the event, suggest that there were also distinct, 'rapid' pulses of CO_2 drawdown that took just 10-100 kyrs to drawdown. These fluctuations in CO_2 are hypothesized to have led to significant Earth system changes, driving fluctuations in regional-to-global scale temperatures and changes in the hydrological cycle.

Palaeo-fire proxy records, such as charcoal abundance, suggest that wildfire was a common occurrence throughout the Cretaceous period, likely fuelled by the estimated high atmospheric O_2 concentrations at this time. However, over geological timescales, the likelihood and behaviour of fire is also controlled by other factors such as climate. This implies that CO_2-driven climate changes may also be observable in the fossil charcoal record. We test this hypothesis, and present a high resolution study of fire history through the use of fossil charcoal abundances across the onset of OAE2 at the Cenomanian-Turonian boundary, and compare our records to the estimated CO_2 fluctuations published from the same study sites based on other proxies.

Our study illustrates that CO_2-climate driven changes to inferred wildfire activity can be detected despite the estimated high atmospheric O_2 concentrations for this time period. Our results provide further insight into the relationship between rapid changes in the carbon cycle, climate and wildfire activity, occurring during the lead up to and transition period into the early stages of OAE2.

Notes

Drivers and driven: how to test environmental impacts on life

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Palaeontologists and geologists have long been criticized for having access only to patterns, not processes. In exploring global change and the responses of life, we have often relied on simple correlations and linear model fitting, but these can only test for correlation but not causation. For example, if body size correlates negatively or positively with atmospheric oxygen, we infer a causal relationship, or if peaks and troughs in a time series of temperature match peaks and troughs in a time series of species richness, we assume temperature drives diversity. But it could be the other way round, or both time series may be responding to a third signal ('common cause hypothesis' of Shanan Peters), or they may both represent wiggles caused by some collecting or instrumental bias (this is likely true of correlated time series of species richness and number of fossiliferous localities or formations). Stochastic differential equations can be used to postulate whether two time series might interact or not (Liow et al. 2015, *Ecol. Lett.*), but there might be problems if carrying capacities change through time (Marshall & Quental 2016, *Phil. Trans. B*). Converting the fossil data to dated phylogenetic trees can change all this by taking account of the fact species are not independent, but connected, and by posing more realisatic models. In tree form, the analyst can estimate rates of change and whether one rate might, or might not, impinge on another. For example, most likely evolutionary models can be applied to cases of proposed competition or trend to test whether these can be discriminated statistically from random; frequently, the 'trend' is not supported. Further, density-dependent birth-death models implemented in a Bayesian framework can test for clade interactions and so determine whether the rise of one clade could have driven another clade out by competitive interaction (Silvestro et al. 2017, *Evol. Ecol. Res.*). There is also now a test for positive phenotypic selection, implemented in BayesTraits (Baker et al. 2016, *Biol. J. Linn. Soc.*) which can test whether clades evolved fast or slow and whether a particular trait, or trait complex (e.g. feeding adaptations) drove evolution or not. Finally, extinction selectivity can be tested within a phylogenetic framework to account for shared evolutionary history when exploring the link between extinction, morphology and ecology (Puttick et al. 2017, *Palaeontology*).

Notes

Earth System Resilience: A Contest between Destabilising Factors and Stabilising Feedbacks

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Earth's biosphere remained habitable over something like 3 billion years despite various upheavals at transition points between more stable periods. It might be concluded, therefore, that the biosphere is extremely resilient. However, because of observer selection, even if 3 By of habitability is extremely improbable for an Earth-like planet then we would have to find ourselves on one of the fortunate few that stayed habitable. From this perspective, Earth might have been lucky rather than resilient. How then can we make sense of Earth's apparent resilience?

I will present results from a simulation of the climates of thousands of randomly different planets that were each run multiple times with the same feedbacks but different perturbations. Outcomes were found to depend on the natures of both the destabilising factors and the stabilising feedbacks. Successful planets were seen to be restricted to those possessing stabilising mechanisms but their success in individual runs was also contingent on the magnitudes and timings of perturbations. Results from the same simulation will also be presented that examine climate resilience over the next 1 million years of those planets that, like Earth, have already remained habitable for 3 billion years.

If we accept that good fortune played a role in Earth staying habitable, then how can we improve our understanding of the degree of contingency that was involved? I will propose that we should consider, for past events and periods, not only "what happened?" and "why?" but also "what if?". For instance, what would have happened to Cenozoic climate if calcium concentration had halved during it and magnesium concentration doubled, rather than the other way round? Or, would Earth have become inimical for life if the K/Pg asteroid had been twice as large or had impacted an icehouse rather than a greenhouse Earth?

Notes

A carbon cycle perspective on Earth system transitions and resilience

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Earth's long-term carbon cycle plays a pivotal role in determining the chemical composition of the surface environment. It regulates the atmospheric concentrations of the biologically-critical gases CO_2 and O_2, as well as leaving a trail of cryptic clues to its past endeavours via the $\delta^{13}C$ isotope record. A number of abiotic factors may be responsible for Earth's climate and geochemical transitions, but biological evolution has also undoubtedly altered the operation of the long-term carbon cycle, and it is possible that changes in biosphere resilience may be distinguishable from the carbon isotope record or other carbon cycle phenomena. In celebration of the society's 'year of carbon' join me for a broad-scale assessment of the long term carbon cycle and the $\delta^{13}C$ isotope record, including attempts to answer the following fundamental questions: 1. Does atmospheric CO_2 control Earth's surface temperature? 2. Are changes in CO2 concentration biologically or abiotically driven? 3. What controls the $\delta^{13}C$ isotope record? 4. Can a signal of biosphere resilience be derived from the behaviour of the long-term carbon cycle?

Notes

The Transition from the Holocene to the Anthropocene: Do humans make the biosphere more resilient or less resilient?

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Of all the transitions of geological time, the proposed shift in epochs from the Holocene to the Anthropocene is certainly the most relevant to modern global change. Current models of climate change do not consider humans as having a significant effect on climate until the industrial evolution (circa 1750), which is a proposed start of the Anthropocene. If humans had little or no influence on the pre-industrial land and atmosphere, then ecosystem conservation through restricting human activities might improve resilience of the biosphere. If, however, humans significantly influenced continental land cover and the global climate much earlier, then restricting human activities may not have the desired impact on the biosphere.
Here I suggest that the Anthropocene, as a global climate phenomenon, has origins of more than 10,000 years BP. This proposal is based on evidence that human land use change is a first order effect on climate, via its role in altering surface albedo, aerosols, air chemistry, vegetation composition, soil morphology, carbon storage, and surface hydrology. Human use of fire as a tool for landscape management dates from about 1 million years BP. Evidence of intensive regional-scale land management prior to 10,000 years BP is evident in all the forested continents. Indigenous agriculture, especially in western North America, the Amazon, and Australia, appears to be much more widespread than previously thought.

Findings from coastal California indicate that, for more than ten millennia, indigenous people have altered and shaped the regional ecosystems and atmosphere using fire, shell middens, and agricultural terraces, creating anthropogenic landscapes that juxtapose, over a distance of just a few meters, ancient oak and redwood groves with youthful grasslands and chaparral. These wellmanaged communities served as oft-repeated mosaics of grassland, shrubland, woodland, and forest that promoted an extension of ecotones, where biotic diversity could thrive. Coastal prairie ecosystems, one of the most endangered in California, are disappearing at a sharp rate due to fire suppression and other conservation measures. Studies have shown that these ecosystems are climatic anomalies in that the frequency of naturally-started (mainly lightning) fires is far lower than is required to create these prairie ecosystems. The preponderance of evidence suggests that indigenous fire management over several millennia was fundamental in shaping this landscape.

Similar findings are observed in Australia, where Aboriginal land management has been particularly well studied. Aboriginal Australians are known to have employed fire in managing their land for at least 40,000 years BP. Youthful grasslands grow alongside old-growth eucalyptus forests, creating mosaics that appear as well-planned as an English park. Shell middens and terraces are distributed much like those in California.

In addition to the effects on land cover, indigenous fire management undoubtedly affected the climate, especially through the effects on air chemistry and aerosol production. In modern landscapes still dominated by indigenous people, cultural burning is so common that the smell of smoke is ever present. While it is harder to quantify such effects in the past, we cannot assume that the pre-industrial atmosphere was pristine and unaffected by humans.

Notes

Big data Revolution in Geology

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During the past several centuries, a huge amount of information has been collected by geoscientists from the rocks in the form of pictures and scanned images, tables, notes, sketches, cross sections, video, samples and measurements. Those data are mostly scattered in documents or even in geoscientists' notebooks in not machine readable and searchable format. Many databases have been developed by scientists, geological surveys, governments, scientific organizations, and industry. Most of them are isolated "data islands" focusing on one specific area or subject without the ability to link to any other databases.

The authors designed an integrated modern database in the past 12 years, the Geobiodiversity Database (GBDB) (http://www.geobiodiversity.com). GBDB is a web-based open database with GIS functionality. It facilitates the integration of the data through a range of tools to understand spatial and temporal distribution of data. GBDB became the formal database of the International Commission on Stratigraphy (ICS) and International Palaeontological Association (IPA). It not only serves geoscientists across the globe but also grows fast by attracting big data owner such as the British Geological Survey (BGS) to share their data via this platform. It also established interoperable associations with other databases such as the Neptune Database, a relational database of microfossil occurrence records from the Deep-Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP). In recent years, GBDB has been expanded to cover a wide range of disciplines of geological science, such as palaeogeography and geochemistry. However, more efforts of the geology community are necessary to face the big data revolution in geology.

A new international program has been recently approved by the International Union of Geological Sciences (IUGS), the IUGS Recognized Big Science Program — "Deep-time Digital Earth (DDE)". The DDE program aims to establish linked earth big-data hubs that are interoperable with other databases including published data in the public domain and unpublished data in institutions and centres of expertise. Similar to OneGeology, which aims to provide a single map of world geology, DDE aims to provide harmonized data in a convenient form to science, public and industry, and thus facilitates open science in the big data world, and transdisciplinary research.

Notes

Is biosphere resilience an illusion?

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There is a potential observational bias that must be taken into account when we investigate Earth's history of biosphere resilience; biospheres which do not last long do not give rise to intelligent observers! Thus, all observers will see a history of resilience even if this is the exception rather than the rule. It is therefore possible that Earth's biosphere has survived the many challenges it has faced not because it is inherently robust but, rather, entirely by good fortune; good fortune that was a necessary precondition for our own existence.

This is an interesting idea but is there any support for it? In this presentation I will discuss evidence in the form of a time-scale coincidence. The time taken for intelligent life to appear is surprisingly similar to the timescales over which: (i) Earth's climate remains temperate; (ii) Earth's axis remains stable; (iii) Plate-tectonics and magnetism are retained. These 4 timescales are controlled by utterly different factors (biological evolution, solar evolution, Solar System architecture and secular-cooling of the Earth respectively). There is therefore no obvious reason why these very different processes should all have timescales of the same order of magnitude.

However, if the true "intelligence timescale" is extremely long (e.g. >>5 Gy) and the true "habitability lifetimes" are very short (e.g. <<5 Gy), the observational bias discussed above ensures that we will live on a planet where the appearance of intelligence was unusually fast and loss of habitability was unusually slow. This explains the coincidence but also implies that biosphere resilience is much less strong than it appears.

This paper will expand upon these arguments, present the data supporting the time-scales coincidence and conclude that this issue may have a very serious consequence—the robustness of the biosphere to human interference may be much less than we think.

Notes

Turnover in the early record of animal evolution

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Since the first known putative metazoans from the late Ediacaran (~571 Ma), early metazoan diversification reveals the progressive addition of biological novelty of form and process, and complexity within the Metazoa. The record can be recast as a series of successive, transitional radiations that extended from the late Ediacaran and continued through the early Palaeozoic. Each evolutionary fauna is long lived (> 10 million years) and appears to have remained incumbent until a turnover event. These coincide with geochemical evidence for a series of dynamic and global changes in redox conditions and nutrient supply, which, together with potential biotic feedbacks, may have enabled turnover events that also sustained phases of radiation. Highly heterogeneous and fluctuating redox conditions dominate the late Ediacaran to early Palaeozoic interval, where successive but temporary expansions of oxic seafloor and possibly changing availability of phosphorous and nitrogen, may have facilitated the transition from low oxygen Proterozoic oceans to more extensively oxygenated Phanerozoic oceans. This geochemical instability may have driven pulses of evolutionary innovation, but biotic feedbacks are poorly understood.

The oldest record of Ediacara-type macrofossils appears to be dominated by probable non-bilaterians metazoans, with bilaterian metazoans appearing by ~560 Ma. A reduction in diversity occurs at ~551 Ma and this is closely followed by the appearance of the first biomineralised taxa, but a well-documented expansion of seafloor anoxia postdates these events. Bilaterians, including predators, diversify after an episode of widespread anoxia at the Ediacaran–Cambrian boundary immediately succeeded by an inferred 'oceanic oxygenation event' at ~540 Ma. Inferred stem group poriferans, molluscs, and brachiopods were seemingly devastated by the early Cambrian Sinsk anoxic event (~513 Ma), in contrast to inferred crown group bilaterian phyla whose diversification continues through to the Great Ordovician Biodiversification Event.

Notes

Posters

Stepwise increases in Earth oxygenation are an inherent property of global biogeochemical cycling

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Progressive oxygenation of Earth's atmosphere and oceans was an essential requirement for the emergence and subsequent divergence of complex animal life. It is, however, increasingly apparent that oxygen levels on Earth rose across three major steps (the 'Great Oxidation Event', 'Neoproterozoic Oxygenation Event' and 'Paleozoic Oxygenation Event'), with only moderate variability between these events. Biological or tectonic revolutions have been proposed to explain each of these stepwise increases in oxygen, but the principal driver of each event remains unclear. Here, we employ an Earth system biogeochemical model to show that the oxygenation steps, including possible cyclic ocean oxygenation patterns in the Neoproterozoic Era, are a simple consequence of internal feedbacks within the long term biogeochemical cycles of carbon, oxygen, and the marine limiting nutrient phosphorus. Firstly a 'Great Oxidation' of the atmosphere occurs, driven by the transition from a reduced gases regulated anoxic atmosphere to an 'oxic' atmosphere regulated by oxidative weathering of organic carbon. Oxygenation of nearshore shelf environments, and then distal shelf environments follows via eventually overwhelming of oxygen consumption via equilibration with the oxygenated atmosphere. Finally, the deep ocean becomes resiliently oxygenated as the transition from anoxic to oxic C:P ratios occurs, restricting P recycling back to the water column and ultimately primary production and respiration. This sequence of events bears a clear resemblance to the oxygenation history of the Earth as recorded by multiple redox proxies. Our model suggests that there is no requirement for a specific 'stepwise' external forcing (i.e. the evolution of new modes of life or a major tectonic event) to explain the course of Earth surface oxygenation. We conclude that Earth's major oxygenation events are entirely consistent with gradual oxygenation of the planetary surface following the initial evolution of oxygenic photosynthesis.

Notes

Tetrapod spatial biodiversity patterns across the end-Permian mass extinction and recovery interval

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The modern-day latitudinal diversity gradient (LDG) is a general trend of increasing biodiversity from the poles to the equator. However, our understanding of the underlying processes is limited, and it remains unclear whether this pattern was present throughout the Phanerozoic. One approach to answering these questions is by examining spatial biodiversity patterns in the geological past, across different global climate regimes and continental configurations.

The Late Permian–Middle Triassic (~250Mya) represents an ideal time interval, characterised by large-scale volcanic episodes, extreme greenhouse temperatures, and mass extinctions and recoveries, while continental configuration was also markedly different from today (e.g. supercontinent Pangea). We examined tetrapod spatial biodiversity patterns across this time window by applying established quantitative techniques to a database of global tetrapod occurrences, to investigate the role of climate change and continental distribution in driving LDGs.

During the Late Permian and Early Triassic, peak tetrapod diversity moved from tropical to temperate latitudes, resulting in a bimodal richness distribution. However, a pattern akin to modern LDGs arose in the Middle Triassic, with highest tetrapod diversity in equatorial regions. These results are consistent with the hypothesis that extreme equatorial temperatures drove tetrapod extinction and migration in the wake of the end-Permian mass extinction.

Notes

Paleogeographic context of black shales deposition in South China during the Shuram anomaly, Ediacaran Period

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The Ediacaran Period (c.635 - c.540 Ma) witnessed major biogeochemical perturbations that were linked to profound global changes in ocean chemistry, marine environments and climate, which led into the emergence and diversification of modern animals, after about c. 550 Ma. This period of upheaval is undoubtedly reflected by the most negative carbon isotope excursion in Earth's history, the 'Shuram' anomaly of c. 570 - c. 550 Ma. However, its timing, causation and environmental implications remain poorly understood. Recent studies suggest the existence of a huge pool of dissolved organic carbon (DOC), which became progressively remineralised due to episodic oxygenation of the deep ocean. Some studies consider the Shuram anomaly as the result of the final oxygenation event, which removed the organic matter excess and increased the availability of free oxygen in the ocean, allowing the emergence of new ecological niches. This progressive oxygenation was accompanied by the accumulation and preservation of organic matter-rich deposits, suggesting that high productivity allowed organic matter production to surpass degradation/oxidation.

This study targets organic-rich shales that were potentially deposited during the worldwide Shuram anomaly on the Yangtze platform (South China) in order to tease apart the factors influencing their formation, i.e. primary productivity versus preservation, and to reconstruct the spatial and temporal evolution of paleoproductivity and redox conditions in different depositional environments. Up to seven different stratigraphic sections, from platform to deeper basinward environments, are used to characterize organic matter distribution at basin scale. Through this characterization, this project aims to achieve an improved understanding of the existing global chemostratigraphic framework and to assess the existence, evolution and importance of the ocean DOC reservoir, which holds some of the answers to how (and why) animal life first appeared on Earth.

Precambrian organic matter research is highly challenging, impacted by strong limiting factors such as age, type of organic matter and, more importantly, preservation conditions and/or subsequent diagenetic/metamorphic alteration, which may hinder the recovery, to a greater or lesser extent, of original bio-signatures. Nitrogen and organic carbon are essential elements of all living organisms (organic matter, amino-acids, nucleic-acids), and their variable storage during the EdiacaranCambrian transition played a critical role in the biogeochemical cycling. Here we use coupled nitrogen and organic carbon geochemistry, both isotopes and total concentrations, as robust tracers of nutrient source, availability and cycling, marine paleoproductivity, ocean and atmospheric oxygen concentration variability and fluctuating

Notes

Gas exsolution bubbles in melt inclusions of CAMP basaltic rocks

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Melt inclusions (MIs) in basaltic rocks from Large Igneous Provinces (LIPs) provide important constraints on the evolution of their magmatic systems and of their volatile element budget. This in turn bears important implications for the understanding of the environmental effects of LIP magmatism during mass extinction events. One of the most severe mass extinctions in the Phanerozoic Eon, the end-Triassic mass extinction at ca. 201 Ma, is synchronous with emplacement of the Central Atlantic Magmatic Province (CAMP), one of Earth's largest LIPs. Here, MIs in basaltic rocks from all over the CAMP (America, Africa and Iberian Peninsula) have been studied. CAMP MIs are mainly hosted in clinopyroxene glomerocryst aggregates, and rarely in orthopyroxene, olivine and plagioclase. MIs have been characterized through micro-Raman Spectroscopy, EDS-SEM, and Electron Microprobe analyses. MIs, showing irregular shape, usually have maximum axis of ca. 20 μm and minimum axis of less than 10 μm. MIs in glomeroporphyric clinopyroxene ± plagioclase aggregates yield up to 25 C-/CO2-bearing gas exsolution bubbles per inclusion. Elemental C is present as amorphous or as disordered graphite. The glass composition of all these bubble-bearing MIs corresponds to that of an evolved CAMP basalt, suggesting that C was juvenile or inherited from assimilated crustal rocks at depths deeper than ca. 15 km. The abundant C-/CO2-bearing MIs would indicate that CAMP magmas had the potential to deliver significant amounts of CO2 into the ocean-atmosphere system.

Notes

Big Data' - Geoscience Opportunities: exploiting the stratigraphic archive

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For over a century geological data has been collected, compiled and interpreted to provide our current understanding of the Earth System, its evolution over the past 4 Ga. It also provides context for our current changing climate, environment and biodiversity, and is increasingly critical as the subsurface use increases for resource extraction (e.g., water, energy, and critical elements), storage (waste, energy) and infrastructure development. Recent efforts have by a number of groups have demonstrated the potential for using 'big data' approaches for interrogating the stratigraphic archive in order to develop our understanding of key intervals of Earth System development, using both structured and non-structured data systems. These systems are built upon either their own libraries of data or exploit open access datasets, however the current trend is the development of federated data archives that can be opened to a range of data collation and analyses systems. We will outline a number of 'big data' exemplars, discuss the direction of collaboration between data holders (e.g., national surveys, researchers, publishers, industry), and pose the question: what role will the UK research community play in the development and exploitation mof these systems?

Notes

Complex signals of weathering and redox in the late Pliensbachian–Toarcian of the Mochras borehole

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The late Pliensbachian–Toarcian transition is characterised by a significant perturbation in the carbon cycle, known as the early Toarcian negative carbon isotope excursion (TNCIE). Some other climatic/environmental stressors are associated with TNCIE including warming, increased weathering and a widespread anoxic event in the early Toarcian (T-OAE), ultimately leading to a major marine extinction at the top of the *Tenuicostatum* ammonite zone.

Here, we report high-resolution Fe speciation and trace metal data for marine mudstone from the Mochras borehole, Cardigan Bay Basin, Wales, UK, which archives a continuous and biostratigraphically complete late Pliensbachian to Toarcian succession, providing an important insight into the environmental changes of the early Jurassic.

Preliminary analyses of the Fe speciation data in terms of redox shows reactive iron enrichment ($Fe_{HR}/Fe_{Total}>0.38$) throughout the section with the exception of the lower Toarcian *Tenuicostatum* and *Falciferum* zones, which, at face value, suggests a persistent anoxic condition. However, these sediments are bioturbated and contain benthic bivalves and gastropods throughout, which indicates that, from a palaeoecological perspective, the system was oxygenated during these intervals. Either a locally elevated reactive iron baseline, or a dynamic oscillation between redox states may be the explanation for this apparent contradiction.

Enrichments of redox-sensitive elements (Mo, U, V) and high Fe/Al ratios, normally also indicative of anoxic settings, are only found in the late Pliensbachian, and are also surprisingly absent during the TNCIE interval. The trace element patterns, in particular, may also bear the additional imprint of basinal restriction.

An enhanced concentration of unreactive iron is observed during the TNCIE, likely resulting from a high transport flux of Fe-rich detrital sediment from the hinterland to the Cardigan Bay Basin. The inferred high sedimentation rate and elevated Fe supply in the early Toarcian are likely to have diluted any primary redox signal from Fe geochemistry and redox-sensitive elements, obscuring geochemical indicators of redox during the interval correlated to anoxic deposition in other basins. The high iron supply to the basin may also contribute to the extensive formation of siderite in the early Toarcian as evidenced by high carbonate-associated Fe contents, low TOC and pyrite concentrations. These new data possibly demonstrate an elevated local detrital supply to the Cardigan Bay Basin margin that may be linked to the enhanced terrestrial weathering and hydrological cycling at global scale during the warmest interval of the early Jurassic.

Notes

Geochemical constraints for the Latest Permian Extinction in East Greenland

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High-resolution geochemical data and sedimentological observations provide a record of changes in marine conditions on the southern margins of the Boreal Ocean during the latest Permian. Geochemical evidence suggests a general decrease in oxygen availability, probably due to a marine transgression and other factors including increasing temperatures, enhanced biological demand for oxygen due to fluxes of nutrients coupled to increasing water column stratification. Carbon isotope data (δ13Corg), with isotopically lighter values up section could reflect the incursion of deeper waters, although other factors modulating carbon isotope values cannot be fully discounted. Nitrogen isotope values (δ15Nbulk) are mostly close to modern values, implying nitrification and denitrification, although some values could indicate enhanced diazotrophy. Sulphur isotope values (δ34Spyr) are consistent with microbial sulphate reduction.

Prior to the establishment of monotonously laminated horizons, a series of benthic recolonization events, associated with the temporary re-establishment of oxygenated conditions, are identified at one site. Fluctuations in redox conditions and concomitant changes geochemistry and bioturbation abundance are attributed to fluctuations in fresh water and terrestrial nutrient delivery, processes which could have promoted variable stratification and biological demand for oxygen.

The mechanism behind these influxes of oxygen-rich waters remains unclear, but we detect a possible millennial-scale quasi-cyclicity to these events and speculate that environmental forcing might have influenced prevailing wind patterns promoting variations in runoff and nutrient delivery.

Notes

The subducted record of the Cryogenian-Ediacaran-Cambrian successions of South China

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Carbonate and phosphorite-bearing rocks that are part of the amphibolitic to blueschist facies Dabie-Sulu orogen, an exhumed Mesozoic-age HP-UHP subduction complex, have been considered to be either Paleo/Mesoproterozoic or Neoproterozoic in age. A combination of C-isotope chemostratigraphy supplemented by a handful of radiometric age constraints show that the latter age assignment is correct. Pebbly schist and phosphorous-rich marble units of the Jinping Formation (Haizhou Group) in the Sulu Orogen and a marble unit of the Daxinwu Formation (Susong Group) in the eastern Dabie Orogen are correlative to the Marinoan-equivalent Nantuo and Doushantuo glacial-cap carbonate couplet and overlying early Cambrian Dengying formations, respectively, of the Yangtze Block. These correlations establish that the HP-UHP metasedimentary rocks were part of the Neoproterozoic to Cambrian cover sequence of the continental margin of the Yangtze Block, South China. Thus, although metamorphosed, they have utility in providing additional underpinning knowledge to constrain palaeogeographic and tectonic reconstructions as well as models aimed at understanding the circumstances of Snowball Earth and the operation of the global phosphorus cycle.

Notes

Conodont natural assemblages in the earliest Triassic deep sea black claystone: An evidence of water column anoxia?

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We report the first discovery of Early Triassic *Neogondolella* natural assemblages: four natural assemblages of conodont elements from the lower Triassic pelagic black claystone of the North Kitakami Belt, Northeast Japan (Akkamori section; Takahashi et al., 2009). The fossils were from the black carbonaceous claystone corresponding to the end-Permian mass extinction event in the pelagic deep-sea Panthalassa. The horizon level has been dated to the earliest Triassic (Griesbachian) by the occurrence of *Hindeodus parvus*, an index species of conodont for the base of the Triassic, in the same and adjacent horizons. These fossil assemblages include a paired segminiplanate-formed P1 element, which is identified as the genus *Neogondolella*, and have fully or partially preserved the original components of conodont elements. The most complete assemblage among them includes 15 distinctive elements, namely S0 and pairs of M, S1, S2, S3, S4, P1, and P2. It is noteworthy that these fossil assemblages preserve probable imprints of their 'eyes,' which were replaced by aggregations of silicate, phosphate, and sulphide. The occurrence of several sets of fossils that retain the original positioning of the conodonts' elemental apparatuses, as well as the presence of soft tissue, may be attributed to the process by which the conodonts' bodies were transported to the deep seafloor, and by which the activity of agents of decomposition were inhibited in near-abiotic sediments under anoxic conditions in the pelagic deep sea during the earliest Triassic. As one of potential pathways of transportation process of conodont body into the deep seafloor without any significant disarrangement and decomposition is oxygen-poor possibly sulphidic water column which could protect conodont bodies against biotic decomposition from the shallow depths to the seafloor. Hence, fossil conodont natural assemblages of this study would be a reflection of the extreme environmental changes at the Permian–Triassic transition, which is characterised by the mass extinction event.

Notes

Calcium isotope constraints on carbonate sedimentation during the emergence of skeletonisation

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Hard body parts appeared relatively abruptly in a range of immobile, shallow marine benthos of diverse affinity ~550 Ma. While ecological factors were likely important, their development may have been facilitated by changes in seawater chemistry. We investigate changes in the marine carbonate factory during the emergence of skeletonisation, using new [Sr] and $\delta^{44}Ca_{CaCO3}$ data from the Nama Group, Namibia, from ~550 Ma to ~ 538 Ma. $\delta^{44}Ca_{CaCO3}$ progressively decreases from the base of the section upwards through the lower Nama Group from -1.25‰ to -1.60‰, an overall decrease of 0.35‰. One interpretation of this trend is a progressive change from fluid to sediment buffered diagenesis, potentially driven by increased burial rates. If this interpretation is correct, it enables a reassessment of the fidelity of existing geochemical data from the same sections, including $\delta^{34}S$ and $\delta^{238}U$. However, $\delta^{44}Ca$ shows no significant correlation with either [Sr] or $\delta^{13}C$ measured on the same samples, and trends in $\delta^{34}S$ and $\delta^{238}U$ in the same section are not synchronous. This is difficult to reconcile with a diagenetic interpretation, and the data may instead reflect changes in seawater $\delta^{44}Ca$. Lower $\delta^{44}Ca$ seems therefore more likely to result from an enhanced weathering flux consistent with the persistently high seawater $^{87}Sr/^{86}Sr$ values reported for around the same interval. Regardless of whether $\delta^{44}Ca$ records a diagenetic or a seawater signal, $\delta^{44}Ca$ data from the Nama Group are consistent with enhanced alkalinity and carbonate precipitation rates during the emergence of skeletonisation.

Notes

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Ground Floor Plan of the Geological Society, Burlington House, Piccadilly