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Journal of Micropalaeontology
An open-access journal of The Micropalaeontological Society

Editor-in-chief
Sev Kender

Editors
Laia Alegret | Thomas Cronin | Taniel Danelian | Kirsty Edgar | Luke Mander | Emanuela Mattioli | Francesca Sangiorgi

Aims and scope
The Journal of Micropalaeontology (JM) is an established international journal covering all aspects of microfossils and their application to both applied studies and basic research. In particular we welcome submissions relating to microfossils and their application to palaeoceanography, palaeoclimatology, palaeobiology, evolution, taxonomy, environmental change and molecular phylogeny. Owned by The Micropalaeontological Society, the scope of the journal is broad, demonstrating the application of microfossils to solving broad geoscience issues.

The journal subject areas are defined by the following index terms:
→ benthic foraminifera;
→ planktic foraminifera;
→ ostracods;
→ siliceous;
→ nannofossils;
→ palynology;
→ palaeoceanography and palaeoenvironment;
→ stratigraphy;
→ palaeobiology and evolution;
→ molecular phylogeny;
→ environmental change.

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PROGRAM

MONDAY 19th JUNE

9.30 – 1pm: Registration open: Biosciences Undercroft (Ground Floor Lobby)

IODP INDO-PACIFIC WORKSHOP

10.30 – 11.40am NG08 Lecture Theatre Geography Building
Keynotes: Pallavi Anand, Andy Henderson, Alex Farnsworth

11:40 – 12:00noon Coffee Break Biosciences Undercroft

12:00 – 1:00pm NG08 Lecture Theatre Geography Building
Keynotes: Dick Kroon, Ian Hall, Jeroen Groenveld

1:00 – 2:00pm Lunch Biosciences Undercroft

2:00 – 3.30pm Breakout Groups:
1. Monsoon Systems; (NG08 Geography Building)
2. Throughflow & S. African Climates; (311 Geography Building)
3. Ecosystems & Evolution (Paleolab Aston Webb A block)

3.30 – 4:00pm: Coffee

4.00 – 5.30pm: Group Feedback, Collaborations and Funding

DIGITAL CHRONOSTRATIGRAPHY WORKSHOP

(participants welcome to attend Indo-Pacific keynotes in the morning)

1:00 – 2:00pm Lunch Biosciences Undercroft

2:00 – 3.30pm Session 1: Overviews

3.30 – 4:00pm: Coffee

4.00 – 5.30 pm: Session 2: Discussion & future collaborations

5.30 - 7.30 pm ICEBREAKER RECEPTION LAPWORTH MUSEUM

5:00 – 7:30 pm: Registration desk open: Lapworth Museum of Geology
TUESDAY 20th JUNE

8.00 – 9.00am: Registration open: Biosciences Undercroft

SESSION 1: Bioscience Lecture Theatre 301; Chair Kate Darling

9.00 – 9.10am: Welcome, Tom Dunkley Jones

9.10 – 9.30 am: Robin Fentimen Recent benthic foraminiferal assemblages from a specific Cold-water coral environment: the Moira Mounds

9.30 – 9.50am: Malcolm Hart Foraminifera of the Fal Estuary (Cornwall), Including taxa associated with maerl (coralline algae) beds

9.50 – 10.10am: Magali Schweizer Biodiversity of Foraminifera (Rhizaria) in intertidal sites of the French Atlantic coast: comparison between individual specimen sampling and environmental DNA with Next Generation Sequencing

10.10 – 10.30am: Anna Weinmann Dwelling in a hot spot: Diversity of benthic foraminifera in tropical tide pools of eastern Africa

10.30 – 11:00am: Coffee Break

SESSION 2: Bioscience Lecture Theatre 301; Chair Kirsty Edgar

11.00 – 11.20am: Patrick Grunert Porosity and test ultrastructure of costate and non-costate Bulimina species

11.20 – 11.40am: Brent Wilson An eddy in a wake or a plume: What controls bathyal foraminiferal distributions around Tobago, southeastern Caribbean Sea

11.40 – 12:00noon: Isabel Fenton Consistency and accuracy in identifying Recent macroperforate planktonic foraminifera

12.00 – 12.30pm: Elevator Pitches – Poster Abstracts 1 to 15

12.30 – 1.30pm: Lunch (Bioscience Undercroft)

SESSION 3: Bioscience Lecture Theatre 301; Chair Martin Langer

1.30 – 2.00pm: Willem Renema (Keynote) Changes in LBF assemblages in an Indonesian reef over the past 30 years

2.00 – 2.20pm: Raphael Morard Tracing shifts of oceanic fronts using the cryptic diversity of the planktonic foraminifera Globorotalia inflata
2.20 – 2.40pm: Jaroslaw Tyszka *Energy flow in Foraminifera: from empirical to theoretical models*

2.40 – 3.10pm: Elevator Pitches – Poster Abstracts 16 to 30

**POSTER SESSION 1**

3.10 – 6:00pm: Bioscience Undercroft: We recommend that Presenters 1 to 15 are available by their posters from 3.40 – 5pm

7.30pm: **CONFERENCE DINNER** Celebrity Indian Restaurant

**WEDNESDAY 21st JUNE**

**SESSION 3: Bioscience Lecture Theatre 301; Chair Martin Langer**

9.00 – 9.20am: Kirsty Edgar *Evolutionary history biases inferences of ecology and environment from δ¹³C but not δ¹⁸O values*

9.20 – 9.40am: Lyndsey Fox *The sudden demise of Clavatorella bermudezi*

9.40 – 10.00am: Soma Baranwal *Insights of the Australian-Indonesian monsoon from the Mid-Pliocene, North West Australian shelf*

10.00 – 10.20am: Mariem Saavedra-Pellitero *Coccolithophore variability during Marine Isotope Stage 11 in the Pacific sector of the Southern Ocean and its potential impact on the carbon cycle*

10.20 – 10.50am: Coffee Break

10.50 – 11.20am: Paul Pearson (Keynote) *Depth habitat evolution of planktonic foraminifera: possible links to food supply, oxygenation and the biological pump*

11.20 – 11.40am: Cherry Newsam *Global calcareous nannoplankton extinction and population turnover across the Eocene-Oligocene transition*

11.40 – 12noon: Maria Grigoratou *A modelling approach of environmental control of non-spinose planktonic foraminifera shell size*

12.00 – 12.20pm: Tom Dunkley Jones *Single-lith records of Cenozoic coccolith chemistry*

12.30 – 1.30pm: Lunch (Bioscience Undercroft)
1.30 – 2pm: Heather Stoll (Keynote) *The role of coccolithophorid and foraminiferal adaptation and ecology in the quest for pCO₂ reconstructions*

2.00 – 2.20pm: Trine Edvardsen *Foraminiferal evidence for Late Maastrichtian warming event recorded in the Kjølby Gaard Marl, Denmark*

2.20 – 2.40pm: James Barnet *Climate change and carbon-cycling during the latest Cretaceous–Early Paleogene; a new 13.5 million year-long, orbital-resolution, stable isotope record from the South Atlantic*

2.40 – 3.00pm: Laia Alegret *Resilience of benthic foraminifera across Paleogene warming events*

**POSTER SESSION 2**

3.00 – 6:00pm: Bioscience Undercroft: We recommend that Presenters 16 to 29 are available by their posters from 3.40 – 5pm

**THURSDAY 22nd JUNE**

**FIELD TRIP:**

*Leave 8.30am from outside the Lapworth Museum*

*Return by 6pm to the Lapworth Museum*

Silurian of Shropshire and the Shropshire Hills Area of Outstanding Natural Beauty. Details at the end of this booklet.
POSTERS

1  Zainab Al Rawahi  Calcareous Nannofossils Biostratigraphy and Palaeoceanographic Significance from the Upper Cretaceous of Oman

2  Ulrike Baranowski  Early and middle Eocene sea surface temperatures and water column gradients of the Rockall Trough

3  Anieke Brombacher  Evolutionary response of the planktic foraminifer *Orbulinoides beckmanni* to climatic change during the Middle Eocene Climatic Optimum (MECO)

4  Alix Cage  Identifying *Cassidulina* and *Islandiella*: from correct species identification to accurate (palaeo)environmental reconstructions

5  Hannah Cheales  Tempo and mode of phenotypic evolution of Neogene planktonic foraminifera

6  Arianna Del Gaudio  Taxonomy of Miocene to Recent *reticulofenestrid* coccolithophores from the Southwest Indian Ocean

7  Witty D’Souzia  Changes in the water column OMZ during glacial-interglacial periods in the eastern Arabian Sea

8  Charlotte Fielder  Is the extinction of the planktic foraminifera *Acarinina bullbrooki* a reliable datum?

9  Lyndsey Fox  Former BP Micropalaeontology Collection PalaeoGIS project: Palaeoenvironmental evolution of the Central North Sea Basin using benthic foraminiferal biofacies

10  Jan Golen  Application of ApoTome.2 to actin-staining experiments on living foraminifera

11  Jeroen Groeneveld  Impact of the Indonesian Throughflow on northwestern Australian biochronology during the Pliocene

12  Patrick Grunert  Mg/Ca temperature calibration for costate *Bulimina* species: a paleothermometer for hypoxic environments

13  Pepe Guitian  Circular polarized light method for absolute calibration of coccolith thickness

14  Jonathan Hall  The Neogene evolution of the NE Atlantic Basin

15  Stephanie Hayman  Interdisciplinary approach to understand the development of the South Asian Monsoon and its concurrent oceanographic influences
16 **Ivan Hernandez** Developing micropaleontological proxy indicators of growth rates

17 **Heather Johnstone** Reconstructing North Atlantic Deep Water temperature using Mg/Ca of benthic foraminifera

18 **Amy Jones** Coccolithophore diversity and paleoecology across the Eocene-Oligocene Boundary of the Nanggulan Formation, Java, Indonesia

19 **Michal Kucera** Caught in the act: Anatomy of an ongoing benthic-planktonic transition in a marine protist

20 **Yvonne Milker** The use of foraminiferal-based transfer functions for the reconstruction of relative sea-level history

21 **Raphael Morard** Nomenclature for the Nameless: a Proposal for an Integrative Molecular Taxonomy of Cryptic Diversity Exemplified by Planktonic Foraminifera

22 **Wilf Pearson** Lost in time? Constraining the evolution of Chalk Sea sharks using nannofossil biostratigraphy

23 **Cecile Porchier** Variability in the Atlantic subpolar gyre: variability in a global climate model and a simplified conceptual model

24 **Julien Richirt** Morphological traits of selected phylotypes identified as *Ammonia tepida* (Cushman, 1926) along the European coast

25 **Lucia Rivero-Cuesta** Reassessment of foraminifera and nannofossils across the Bartonian in the Alum Bay section

26 **Mariem Saavedra-Pellitero** Paleoceanographic dynamics of the Japan Sea over the last 450,000 years – a coccolithophore perspective

27 **Wabyu Santoso** Cooling Phase Detection at Pliocene Sediment in North East Java Basin, Indonesia

28 **David Saunders** Plasticity in a changing world

29 **Daniela Schmidt** Testing the rate and amplitude of environmental change that marine plankton can adapt to

30 **Manuel Weinkauf** Shell calcification in planktonic Foraminifera: Ontogeny, environment, and geochemistry
Resilience of benthic foraminifera across Paleogene warming events

Laia Alegret¹, Gabriela Arreguín-Rodríguez², and Ellen Thomas³

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The general early-mid Paleogene warming trend was punctuated by short-lived, extreme warming events (hyperthermals), of which the Paleocene-Eocene Thermal Maximum (PETM, 55.8 Ma) was the most extreme. Hyperthermals were associated with global, negative carbon isotope excursions, carbonate dissolution, increased continental weathering, and biotic perturbations. Here we characterize benthic foraminiferal assemblages and their differential response to Paleocene and Eocene hyperthermals in globally distributed bathyal-abyssal sites. Benthic foraminifera suffered severe extinction during the PETM. Their turnover across other hyperthermals resembles that across the PETM in decreased diversity, but without extinctions. The cause of the extinction is debated, but analysis of widely distributed drill sites suggests that trophic conditions (strength of bentho-pelagic coupling, supply of refractory organic matter, processes controlling food availability on seamounts, and increased food demands triggered by higher metabolic rates at higher temperatures) and carbonate undersaturation, may have been synergistic.

Analysis of benthic foraminiferal turnover across hyperthermals of different magnitude allowed us to investigate: 1) the idea that “a warmer world is a hungrier world” (McInerney and Wing, 2011); 2) the existence of a critical temperature threshold above which assemblages were more severely affected; 3) potential changes in resilience of benthic assemblages, as their ability to survive disturbance and recover may have changed. Benthic foraminifera were less affected by Paleocene than by Eocene hyperthermals, possibly due to a higher resilience of the highly diverse Late Cretaceous-Paleocene assemblages, which had been stable for millions of years, whereas early Eocene biota were recovering from the major PETM extinction.
Calcareous Nannofossils Biostratigraphy and Palaeoceanographic Significance from the Upper Cretaceous of Oman

Zainab Al Rawahi¹, Tom Dunkley Jones¹, Richard Hallett²

¹ School of Geography, Earth and Environmental Sciences, University of Birmingham, UK, ² Petroleum Development Oman, Muscat, Sultanate of Oman

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The Late Cretaceous Fiqa Formation in North Oman yielded rich and diverse calcareous nannoplankton assemblages that enable the recognition of seven nannofossils biozones of Burnett (1998) UC scheme for the Tethyan realm, spanning the Early Coniacian to Late Campanian (UC9 to UC15). Current biostratigraphic correlation included core samples, side wall core samples and ditch cuttings from five hydrocarbon exploration wells across North to South Oman in order to constrain the age of the formation and understand the basinal history of the Aruma foreland basin and its sequence stratigraphy. Integration of nannofossils and microfossils data from one well suggested fluctuation of climate, sea-level and nutrient supply. The planktonic:benthic ratio of foraminifera and the overall microfossils assemblages indicate an open marine condition with intervals of shallowing sea-level that resulted in development of submarine fan system in which the Lower Fiqa was deposited. The nannofossils assemblages indicate a change from more oligotrophic, warm ocean water to more eutrophic, shallower and colder ocean water. This might be coincided with the overall cooling trend and the general shallowing of the Aruma basin toward the Maastrichtian. The biostratigraphic nannofossils analysis will be extended to more wells across Oman and followed by analysis of the evolutionary trends of some Upper Cretaceous taxa, isotope analysis, and foraminifera analysis.
Early and middle Eocene sea surface temperatures and water column gradients of the Rockall Trough

Ulrike Baranowski¹, Tom Dunkley Jones¹, Kirsty Edgar¹, Ian Boomer¹, Steve Jones¹, James Bendle¹ and Heiko Moossen²

¹ School of Geography, Earth and Environmental Sciences, University of Birmingham, UK, ² Max Planck Institute for Biogeochemistry, Jena, Germany

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The Eocene (~56-33 Ma) period included conditions of peak climatic warmth for the Cenozoic. To date, the available proxy data for the early Eocene, including the Early Eocene Climatic Optimum (EECO) indicate that the equator-to-pole temperature gradient was substantially smaller during this Eocene greenhouse period compared to the modern latitudinal temperature gradient. If the proxy data are correct, this reduced latitudinal gradient is still not adequately reproduced by climate models. There are, however, large geographic gaps in the availability of reliable sea surface temperature (SST) proxy data for conditions of early Eocene peak warmth, most notably in the mid and high latitudes of the North Atlantic Ocean.

Here, we seek to fill this gap by generating new sea surface temperature (SST) estimates from sediment core 16/28 Sb-01 from the Rockall Trough, to the West of Ireland. This sediment core yields exceptionally well-preserved marine and terrestrial microfossils and organic biomarkers, suitable for multi-proxy palaeoclimate and palaeoenvironmental reconstructions. Here we present initial SST datasets for the early and middle Eocene, including stable isotope analyses from planktonic foraminifera and GDGTs.
Insights of the Australian-Indonesian monsoon from the Mid-Pliocene, North West Australian shelf

Soma Baranwal¹, Jochen Knies¹,² and Giuliana Panieri¹

¹Centre for Arctic Gas Hydrate, Environment and Climate, University of Tromsø, Norway, ²Department of Geological Survey of Norway (NGU), Norway

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Global-scale impact of monsoon variability is unprecedented as it accounts for more than 70 per cent of Earth’s habitation, sustaining some of the highest and most vulnerable biodiversity. The modern climate of the Australian tropics is dominated by the Australian-Indonesian monsoon (AIM).

International Ocean Discovery Program (IODP) Site U1463 archive, with a relatively high sedimentation rate (5-7 cm/ka), was recovered from the Northern Carnarvon Basin from 145 m water depth, near the location of the austral summer Inter Tropical Convergence Zone (ITCZ) immediately downstream of the Indonesian Throughflow (ITF). Earlier studies from ODP Site 763 lacks a higher temporal resolution and also likely to be influenced by the northward flowing West Australian current which may affect interpretation of the strength of the Leeuwin current and consequently AIM dynamics.

Here we present a 2-3 kyr resolution record of AIM variability based on oxygen (ranging ~ 0.85 to 1.21 VPDB ‰) and carbon (ranging ~ -0.72 to -1.35 VPDB ‰) isotopic composition of benthic foraminifera Cibicides wuellerstorfi during the mid-Pliocene Warm Period from Site U1463. Marine Isotope Stage (MIS) M2 (also known as the ~3.3 Ma event) has been globally recognized as a cooling event in an otherwise warm background climate of the Pliocene (e.g. Dolan et al., 2015). The high-resolution stable isotopic compositional record can enhance our understanding of the impact of reduced equator-to-pole heat transfer in response to a reduced ITF and probably linked to dynamic topography.

References:
Dolan et al., 2015. Modelling the enigmatic Late Pliocene Glacial Event Global and Planetary Change, 128, 47-60.
Climate change and carbon-cycling during the latest Cretaceous–Early Paleogene; a new 13.5 million year-long, orbital-resolution, stable isotope record from the South Atlantic

James Barnet¹, Kate Littler¹, Dick Kroon², Melanie Leng³, Thomas Westerhold⁴, Ursula Röhl⁴ & James Zachos⁵

¹University of Exeter, UK, ²University of Edinburgh, UK, ³NERC Isotope Geosciences Laboratory, British Geological Survey, UK ⁴MARUM, University of Bremen, Germany, ⁵University of California-Santa Cruz, USA

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The “greenhouse” world of the latest Cretaceous–Early Paleogene (~70–34 Ma) was characterised by multi-million year variability in climate and the carbon-cycle, with a periodic cyclicity corresponding predominantly to orbital eccentricity and precession. Periodic “hyperthermal” events, occurring largely in-step with these orbital cycles, may be the closest analogues for anthropogenic climate change. This project utilises CaCO₃-rich marine sediments recovered from ODP Site 1262 on Walvis Ridge, South Atlantic, of late Maastrichtian–mid Paleocene age (~67–60 Ma). We have derived high-resolution (2.5–4 kyr) carbon and oxygen isotope data from the epifaunal benthic foraminifera species Nuttallides truempyi. Combining the new older record with the Late Paleocene–Early Eocene record generated from the same site by Littler et al. (2014), yields a single-site reference curve detailing 13.5 million years of orbital cyclicity in paleoclimate and carbon cycle from the latest Cretaceous to near the peak warmth of the Early Paleogene greenhouse. Spectral and cross spectral analysis of this new combined dataset allows us to elucidate the principle forcing mechanisms governing pacing of the background climate and carbon-cycle, along with phasing relationships. The benthic isotope responses of comparatively understudied potential Early Paleocene “hyperthermal” events including the Dan-C2 Event (e.g. Quillévéré et al., 2008), Latest Danian Event (e.g. Bornemann et al., 2009; Deprez et al., 2016) and Danian/Selandian Transition Event (e.g. Arenillas et al., 2008) are also identified within this new record, confirming the global nature of the Latest Danian Event but questioning the Dan-C2 event as a global “hyperthermal”.
Evolutionary response of the planktic foraminifer *Orbulinoides beckmanni* to climatic change during the Middle Eocene Climatic Optimum (MECO)

Anieke Brombacher¹*, Kirsty Edgar², Paul Wilson¹, Thomas Ezard¹,³

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Evolution is most likely driven not by any single environmental variable, but by the whole climate system. Analogously, selection on one organismal trait often generates a response in others. Thus, to quantify biotic responses to abiotic drivers it is crucial to study the effects of multivariate climate change on multiple morphological traits. Planktonic foraminifera are particularly well suited to this because their fossil record is extraordinarily complete, well-dated and yields a diverse suite of environmental parameters from geochemical analysis.

Here, we present the first study of a species’ evolutionary response to climate change through its entire duration from origination to extinction, using the Eocene planktonic foraminifera *Orbulinoides beckmanni*. This species’ short range (40.5 Ma to 40.0 Ma) defines planktonic foraminiferal Zone E12 and includes the Middle Eocene Climatic Optimum (MECO). We measured test size, test shape, final chamber size and shape, and the number and size of sutural and areal apertures for *O. beckmanni* and its immediate ancestor *Globigerinatheka euganea*. Cluster analysis of all measured traits is used to determine the exact timing of the origination of *O. beckmanni* (and morphological criteria for defining this key species), and so the base of Zone E12.

To quantify evolutionary response of ancestor and descendant species to multivariate environmental change before, during and after the MECO, all traits are compared to existing regional environmental reconstructions. The results will provide new insights in a species’ response to multivariate climate change from origination to extinction, and in particular to transient climate change during the MECO as compared to ‘background’ Eocene environmental variability.
Identifying *Cassidulina* and *Islandiella*: from correct species identification to accurate (palaeo)environmental reconstructions

Alix G. Cage¹ and Anna J. Piénkowski², ³

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Proper identification of species is vital for accurate and robust representations of ecological responses to environmental conditions. However, some genera of foraminifera are difficult to taxonomically separate and this problem is often exacerbated by poor access to well-illustrated and high quality taxonomic resources (with clear SEM, light microscope or line illustrations and taxonomic descriptions), and changes in synonyms over time. This can lead to confusion and the ‘lumping’ of specimens (especially when specimens are not ‘pristine’) resulting in issues with accuracy of environmental information, especially when species can have very different environmental/habitat preferences.

Two such genera of ‘problematic’ benthic foraminifera found in Arctic and North Atlantic environments are *Cassidulina* and *Islandiella*, in particular, the species *Cassidulina neoteretis*, *Cassidulina teretis*, *Cassidulina laevigata*, *Islandiella norcrossi* and *Islandiella helenae*. These hyaline species look similar in morphology with a biconvex lenticular test, displaying an undulating margin, clearly visible chambers (often similar in number) meeting in the umbilical area, and a narrow apertural slit on the margin of the final chamber. However, these species have very different environmental preferences, for example, *C. neoteretis* is found primarily in cold water masses, whereas *C. laevigata* is common in temperate water.

Here we present an illustrated comparative study of these four morphologically similar species and highlight the key ways to identify their genus to species level.
Tempo and mode of phenotypic evolution of Neogene planktonic foraminifera

Hannah Cheales¹, Isabel Fenton² & Andy Purvis²

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Planktonic foraminifera possess one of the most temporally-resolved geological histories of any clade. Determining how a clade has evolved, and the speed at which this occurred, is of key interest to both palaeontologists and biologists in understanding a lineages’ life history. Analysis of morphometrics and population dynamics can give insight into which evolutionary model best describes a lineages’ evolutionary history. The occurrence of these models (Brownian Motion, stasis and directional evolution) within the geological record has been under scrutiny, and the prevalence of directional evolution is highly contested. However, few datasets provide sufficient quantities of data to determine which of these models are most common. Here I show that of the eleven lineages of planktonic forams sampled, none show directional evolution. I found that the evolutionary model is somewhat correlated with the lineages depth habitat and that species found in more discrete oceanographic zones are more likely to undergo evolutionary change. Furthermore, it was found that the lineages which live within the surface layer, *Trilobatus* and *G.ruber*, appear to be in direct competition with each other and show some level of competition with deeper dwelling symbiont bearing forms. I anticipate that the results of this study, in addition to studies of a similar nature, will further corroborate the importance of planktonic forams for understanding evolutionary history as a whole.
Here we present an initial assessment of the evolution of the reticulofenestrid coccoliths over the past ~10 million years. New detailed imaging aims to improve the taxonomy of the group over this interval and to define the major transitions in dominant species. Major shifts in species compositions are compared to long-term environmental forcing. This new analysis is conducted on a 535m thick sequence of clay-rich sediments from the NW Australian continental margin (IODP Expedition 363, Site U1482) that host well-preserved calcareous nannofossils. The location of Site U1482 is within the prominent hydrographic front separating tropical and subtropical water masses, therefore is ideally positioned to record the changes in both tropical and sub-tropical reticulofenestrid species through time.
Changes in the water column Oxygen Minimum Zone during glacial-interglacial periods in the eastern Arabian Sea

Alexandrina Witty D'Souza 1, Syed W.A. Naqvi 2, Kirsty Edgar 1 and Tom Dunkley Jones 1

1 School of Geography Earth and Environmental Sciences, University of Birmingham, UK, 2 Kuwait Institute of Scientific Research, Kuwait City, Kuwait.

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To infer the oxygenation state of the mesopelagic and bathypelagic realms in the eastern Arabian Sea over the last 300 kyrs, records of δ\(^{13}\)C of benthic foraminifera Cibicidioides wuellerstorfi (δ\(^{13}\)C\(_{\text{C.wuell}}\)), d\(^{15}\)N, C\(_{\text{org}}\) and redox sensitive elements (Fe, Mn, V, Co, Mo, Cr) have been generated from two new sediment cores (water depth ~2500 m within the oxygen minimum zone (150 – 1200 m). The high and low values of δ\(^{13}\)C\(_{\text{C.wuell}}\) exhibited during interglacial and glacial stages, respectively suggest that bottom waters were relatively well oxygenated during the interglacial and comparatively less oxygenated during the glacial maxima in good agreement with downcore profiles of redox-sensitive elements. The d\(^{15}\)N and C\(_{\text{org}}\) data indicate that relatively high oxygen levels during the interglacials were associated with higher biological productivity and intensified denitrification. The observed relaxation of denitrification during glacial times is not merely because of a decrease in productivity, but also because of significant changes in the mid-depth circulation. The overall co-variation of sedimentary δ\(^{15}\)N, δ\(^{13}\)C\(_{\text{C.wuell}}\) and redox elements suggests that there has been see-saw variability in oxygen concentrations of deep waters and at mesopelagic depths.
Single-lith records of Cenozoic coccolith chemistry

Tom Dunkley Jones¹, Katy Prentice² Jeremy Young³, Paul Bown³, Jackie Lees³

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Our understanding of the Cenozoic history of the Earth’s oceans and climate is largely derived from the fossil remains of single-celled marine organisms. In the deep-oceans these biomineralized remains are a dominant component of sea-floor sediments and provide the basis for high-resolution palaeoceanographic records spanning millions of years. Typically these are based on the geochemistry (stable isotopic and/or trace metal composition) of planktic and benthic foraminifera. Here, I present complementary approaches using the fossil remains of the dominant group of Cenozoic marine calcifying phytoplankton, the coccolithophore algae. These approaches focus on: 1) the use of exceptionally well-preserved, Lagerstätte-quality, fossil coccolith assemblages; and 2) the application of novel techniques to derive single-coccolith - and hence species-specific - trace element records from fossil assemblages. Both of these approaches can be used to better understand the coupling of Earth’s climate and biosphere during major climate transitions, such as the onset of Antarctic glaciation at the Eocene/Oligocene boundary.
Evolutionary history biases inferences of ecology and environment from $\delta^{13}$C but not $\delta^{18}$O values

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Closely related taxa are, on average, more similar in terms of their physiology, morphology and ecology than distantly related ones. How this biological similarity affects geochemical signals, and their interpretations, has yet to be tested in an explicitly evolutionary framework. Here, we compile and analyze planktonic foraminiferal size-specific stable carbon and oxygen isotope values ($\delta^{13}$C and $\delta^{18}$O) spanning the last 107 million years. After controlling for dominant drivers of size-$\delta^{13}$C and $\delta^{18}$O trends, such as geological preservation, presence of algal photosymbionts and global environmental trends, we identify that shared evolutionary history has shaped the evolution of species-specific “vital effects” in $\delta^{13}$C, but not in $\delta^{18}$O. Our results lay the groundwork for a phylogenetic approach for bias-free inference from long-term $\delta^{13}$C records – a key measure of holistic organismal biology and of the global carbon cycle.
Foraminiferal evidence for Late Maastrichtian warming event recorded in the Kjølby Gaard Marl, Denmark

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The mid- to late Cretaceous period of Northwest Europe records a warm, greenhouse climate, though with a distinct cooling of the high latitudes in the latest Maastrichtian. Within this latest Maastrichtian cooling a brief warming event is recorded with polar migrations of planktic foraminifera. A high-resolution study of foraminifera recorded in a drill core from the Danish subsurface chalk was undertaken for the present study. The core reveals a 25 cm thick layer of marl, located roughly 79 m below terrain and 11 m below the Cretaceous-Palaeogene boundary, interpreted to represent an equivalent of the Kjølby Gaard Marl of Troelsen (1955). This marl has also been reported from other quarries in northern Denmark and several water wells in eastern Denmark. At the type locality of Kjølby Gaard in north-western Denmark, the marl layer contains a particularly rich foraminiferal assemblage, including the double-keeled Contusotruncana contusa not otherwise found in the ordinary white chalk of Denmark. C. contusa is regarded as a ‘southern’ species and is, therefore, interpreted by Troelsen as a proxy for an incursion of warm water into the north-western part of the Baltic area. The foraminiferal data from the present study of the core reveal subtle differences in the foraminiferal assemblages throughout the section, along with the presence of several keeled taxa not otherwise found in the Danish chalk and perhaps indicative as a proxy for a latest Maastrichtian warming event.
Recent benthic foraminiferal assemblages from a specific Cold-water coral environment: the Moira Mounds

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Cold-water coral mounds are well documented features along the North-east Atlantic continental margin and have been extensively studied these last 20 years. These bioconstructions occur at depths ranging from 600 to 1200 metres and can reach giant sizes of up to 200 metres high. On the other hand, small numerous mounds have also been described off-shore Ireland as is the case for the Moira Mounds. These small carbonate build ups, mostly formed by living corals colonizing hard substrates, form a network of small patchy mounds. These build ups provide an ecological niche for a wide variety of organisms, amongst then benthic foraminifera.

The study of stained (living) and unstained (dead) benthic foraminiferal assemblages along with the investigation of their distribution in depth has provided us with insights concerning their distribution and their potential role as bioindicators. Previous studies have shown that the distribution of benthic foraminifera in cold-water coral environments follows specific trends and that distinct facies changes can be concurrent with shifts in the benthic foraminiferal assemblage. We show here that assemblages in the Moira Mounds show a different distribution than in all other documented settings of the kind. We highlight here the differences that distinguish these small abundant mounds to their larger analogues.

Much of the work that is done on planktonic foraminifera relies on the assumption of accurate taxonomic identifications. However that assumption is rarely tested. Planktonic foraminifera provide an interesting group for this type of study, as they have a range of distinctiveness with some taxa that are immediately identifiable and some near cryptic taxa that have only been identified morphologically after molecular analysis. In this study we randomly selected 100 specimens of planktonic foraminifera from a coretop site in the Pacific. We then asked a group of scientists at different stages in their career – including some with only a few days’ experience – to identify them to species level, and provide a level of confidence in their identification. They were provided with a standard taxonomy and access to reference material. With these data we identify correlates of inconsistency in identification across foram workers. We hypothesise there are two main sets of factors which are likely to affect consistency: individual-level characteristics (e.g. career stage, main study group, training) and specimen-level characteristics (e.g. size, number of closely related species). We can test how consistent different workers are in their taxonomic identifications, and which factors are most important in determining accuracy. The conditions of the exercise were designed to maximum comparability and ease of analysis rather than necessarily maximising identification accuracy. In particular everyone was working on a standard scope with only 35x magnification, and each specimen was studied in isolation. Consequently these data provide a lower limit for an estimate of consistency.
Is the extinction of the planktic foraminifera *Acarinina bullbrooki* a reliable datum?

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Key to robust age models is the reliability of biostratigraphic datums, e.g., whether or not they are isochronous, and calibration to the geomagnetic polarity timescale to obtain an absolute age. One interval across which it has proven difficult to obtain high quality sections is planktic foraminiferal Zone E12 in the middle Eocene, defined by the total range of *Orbulinoides beckmanni* (~40.0-40.5 Ma; Wade et al., 2011). Recognition of this zone is key because [1] the global warming event the Middle Eocene Climatic Optimum (MECO) occurs within it, and [2] it breaks up an otherwise very long biozone between the HO of *Guembelitrioides nuttalli* at 42.3 Ma and the HO of *Morozovelloides crassatus* at 38.0 Ma. A high dissolution susceptibility and a distribution limited to tropical waters means that *O. beckmanni* is often absent in low-mid latitude sections, and therefore, Zone E12 can prove difficult to define. The robust and cosmopolitan species *Acarinina bullbrooki* may be an alternative marker for the base of Zone E12 at these latitudes, as it is thought to have become extinct at ~40.5 Ma, coincident with the LO of *O. beckmanni* (Wade et al., 2011). However, this datum has yet to be comprehensively tested, in part due to its complex taxonomy. This project will generate relative abundance records of *A. bullbrooki* at ODP Site 1051 in the (sub)tropical N. Atlantic, where high quality magnetostratigraphic and isotopic stratigraphies are available, to determine if its extinction is a reliable substitute datum for the base of Zone E12.

Reference:
Former BP Micropalaeontology Collection Palaeo-GIS project: Palaeoenvironmental evolution of the Central North Sea Basin using benthic foraminiferal biofacies

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Foraminiferal assemblages from continental margins are sensitive to changes in sea level because of the complex biological, chemical, and physical oceanographic variables. Therefore, data on foraminiferal distribution and abundance provide useful proxies for palaeoenvironment. Here we present a synthesis of the palaeoenvironmental interpretations made using a number of Cenozoic well run and outcrop sequences from sites across the southern North Sea. We present the results of quantitative analyses of Paleogene and Cretaceous foraminiferal assemblages from eight well-sites located in the Tail End and East Central Grabens. We document stratigraphic variations in foraminiferal assemblages and elaborate on the palaeoenvironmental significance and utility of using planktic:benthic ratios, diversity indices, and similarity coefficients for interpreting changes in relative sea level using samples from the BP Micropalaeontology collection.
The sudden demise of *Clavatorella bermudezi*

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The middle Miocene is marked by the transition from an extended phase of global warmth (Miocene Climate Optimum) into a colder mode with the establishment of a permanent and stable East Antarctic Ice sheet. The response of planktonic foraminiferal assemblages at the tropics during this interval of major climate change is relatively unstudied due to the scarcity of continuous, well-dated Miocene sedimentary archives. Using the extremely well preserved planktonic foraminifera recovered from Integrated Ocean Drilling Program Site U1338 (equatorial Pacific Ocean) we present a study of the palaeobiology of Miocene tropical foraminifera and their response to times of climatic stress with particular focus on the unusual clavate taxa; *Clavatorella bermudezi*, whose extinction is closely linked with the palaeoclimate.
Application of ApoTome.2 to actin-staining experiments on living foraminifera

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Actin is one of main proteins forming cytoskeleton in eukaryotic cells. Cytoskeleton is a dynamic network extending through protoplasm that have a lot of functions. It shapes the cell, being involved in its morphogenesis. In foraminifera actin is largely responsible for dynamics of reticulopodia involved in behaviour, movement, sensing, and feeding. Most likely it plays a crucial role in morphogenesis of foraminiferal tests. Because actin is involved in so many processes, it should be an object of detailed investigation. Documentation of F-actin meshwork behaviour during the chamber formation is one of the main challenges in research on physiology of foraminifera. To achieve this goal we need high resolution records of actin meshwork.

ApoTome.2 is a device attached to the fluorescent microscope that improves the resolution of images obtained. It helps remove scattered light using principle of structured illumination. Main part of ApoTome.2 is a special grid placed in the beampath that gives the light a specific pattern. Different position of the grid produces slightly different patterns of illumination and enables to differentiate between light coming from the focus plane (signal) and scattered light (noise). We started testing device on foraminifera. So far we successfully recorded images of F-actin in reticulopodia with SiR-actin probe using Axio Observer Z.1 with ApoTome.2. We are going to test F-actin meshwork and other components of cytoskeleton during the chamber formation. We further plan to confront ApoTome results with confocal records. The research presented in the paper received support from the Polish National Science Center – project UMO-2015/19/B/ST10/01944.
A modelling approach of environmental control of non-spinose planktonic foraminifera shell size

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Planktonic foraminifera are marine holoplanktonic heterotrophic protists with calcite shell. They are the main proxy carrier for paleoclimate reconstruction, since their growth, distribution, size and the elemental composition of their shells are strongly related to environmental conditions. They grow by adding chambers. Their final size indicates environmental conditions optimal for growth. As the entire life cycle of planktonic foraminifera cannot be cultured, it is challenging to assess and predict their response to a changing climate, especially the impact of multiple drivers on physiology, distribution, and carbonate production. Here we take a novel approach for studying planktonic foraminifera ecology based on traits and trade-offs. We are combining observations and novel ecosystem modelling to investigate drivers of their diversity, their impact on ecology and ultimately response to climate change in modern and future climates. We developed the first, as far as we know, mechanistic model for planktonic foraminifera modern species. We studied different life stages (prolocular and adults) in varied environments to better understand costs and benefits of calcification. We considered energy loss and protection as the main cost and benefit of calcification respectively. The results showed that the energetic loss of calcification varies from 10 to 30\% of their metabolic energy. It decreases with size and from oligotrophic to eutrophic ecosystem. Also, the model showed that protection from predation is not the only reason why planktonic foraminifera calcify. Protection from a combination of biotic (e.g virus, bacterial infection) and abiotic (e.g. ultraviolet radiation) could be the reason for this.
Impact of the Indonesian Throughflow on northwestern Australian biochronology during the Pliocene

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International Ocean Discovery Program (IODP) Expedition 356 drilled a transect across 10° latitude of seven sites (Sites U1459-U1464) off Western Australia with the RV JOIDES Resolution. One of the main objectives was documenting the evolution of the Indonesian Throughflow (ITF) since the early Pliocene, a critical component of global thermohaline circulation and a driver of the southward-flowing Leeuwin Current. Subsidence of the shelf during the late Miocene created an upper-bathyal setting, so that open-marine conditions prevailed during the Pliocene. Site U1463 is located directly in the outflow of the ITF, which allowed the accumulation of a unique sequence of sediments constituting a high-resolution record of ITF changes since the early Pliocene.

Typically, Pliocene bio-datums are either from the Atlantic or the Pacific and often have differences of up to several 100 kyr between them. We aim to improve the biostratigraphy in the eastern Indian Ocean by testing the following hypotheses: a) Biochronology off the northwest coast of Australia remained similar to the equatorial Pacific until 3.3 Ma; b) The Pliocene development of the biogeography of shallow- and deep-dwelling planktonic foraminifera was distinct due to restriction of the Indonesian Throughflow. To provide a reliable reference frame a benthic foraminiferal stable oxygen isotope record with orbital-scale resolution is constructed that will be tuned to the global benthic δ¹⁸O stack (LR04). This age model will then be used to calibrate the foraminiferal biostratigraphy in the eastern Indian Ocean.
Porosity and test ultrastructure of costate and non-costate *Bulimina* species

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SEM-based investigations of porosity and test wall ultrastructure of Recent costate and non-costate *Bulimina* species reveal significant differences in pore diameter, pore density and ultrastructural architecture between these two groups. Costate tests of *B. inflata* and *B. mexicana* display low pore density, a large pore diameter, and test walls built by a single type of columnar ultrastructural elements. In contrast, non-costate tests of *B. aculeata* and *B. marginata* are characterized by significantly higher pore density, smaller pore diameter, and an additional type of ultrastructural elements formed by oblique, tabular crystallite units which encase the pore channels.

We interpret the observed combination of traits in *B. aculeata* and *B. marginata* as a set of adaptations to poorly oxygenated, intermediate to deep infaunal microhabitats which they typically occupy today. The evolutionary trend towards increased pore density in this group seemingly involved a major modification of the biomineralisation process resulting in the lining of pore channels with a specific type of ultrastructural element to ensure stability of the densely perforated test. The significant alteration of biomineralisation may be reflected in the large genetic divergence between costate and non-costate species reported in molecular studies as well as different vital effects observed in geochemical studies.
Mg/Ca temperature calibration for costate Bulimina species: a paleothermometer for hypoxic environments

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Costate species of Bulimina are cosmopolitan, infaunal benthic foraminifers which are common in the fossil record since the Paleogene. In the present study, we evaluate the temperature dependency of Mg/Ca ratios in Bulimina inflata, B. mexicana and B. costata from an extensive set of core-top samples from the Atlantic, Pacific and Indian Oceans. The results show no significant offset in Mg/Ca values between costate morphospecies when present in the same sample. The apparent lack of significant inter-specific/inter-morphotype differences amongst the analysed costate buliminids allows for the combined use of their data-sets for our core-top calibration. Over a bottom-water temperature (BWT) range of 3–13°C, the Bulimina species show a sensitivity of ~0.12 mmol/mol/°C which is comparable to that of epifaunal Cibicidoides species and higher than that of the shallow infaunal Uvigerina spp., the most commonly used taxa in Mg/Ca-based palaeotemperature reconstruction. The reliability and accuracy of the new Mg/Ca-temperature calibration is corroborated in the fossil record by a case study in the Timor Sea which demonstrates the presence of southern-sourced waters at intermediate depths for the past 25 kyrs. Costate species of Bulimina might thus provide a valuable alternative for BWT reconstruction in mesotrophic to eutrophic settings where many of the commonly used (more oligotrophic) species are rare or absent, and be particularly useful in hypoxic settings such as permanent upwelling zones where costate buliminids often dominate foraminiferal assemblages.

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Circular polarized light method for absolute calibration of coccolith thickness

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The calcification degree of coccolithophores, major producers of calcite in the open ocean, is especially sensitive to changing CO₂ and ocean acidification. Hence, there is significant interest in quantifying past and present variations in this cellular calcification by quantifying the thickness of the coccoliths. Recent works have been employing polarized light microscopy for quantifying the thickness of these calcite plates, but the reproducibility and accuracy of such determinations has been limited by the absence of appropriate calibration materials in the coccolith thickness range (0-4 µm). Here, we present a new method based on circular polarized light and the fabrication of a calcite wedge over this thickness range and its independent thickness determination. We show how the calcite wedge provides more robust calibrations in the 0 to 1.55 µm range than previous approaches using rhabdoliths, and allows to examine specimens whose birefringence spans beyond the greyscale into the colour range, by developing equations that relate thickness to the interference colours. The calcite wedge approach can be applied to develop equations relevant to the particular light spectra and intensity of any polarized light microscope system and could significantly improve within and inter-laboratory data comparability.
The Neogene evolution of the NE Atlantic Basin

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Transient (1-10 million year) uplift and subsidence of the Greenland-Scotland Ridge during the late Neogene is believed to be associated with Icelandic thermal anomalies, and is considered responsible for changes in regional ocean circulation and climate during this period. Such interaction between North Atlantic Solid Earth processes, ocean circulation and late Neogene climatic events (e.g. the mid-Piacenzian Warm Period) is a contemporary and unproven concept and requires further investigation. δ¹³C in calcareous tests of benthic foraminifera is a useful nutrient water mass tracer, reflects the nutrient content of source regions, and can be used to quantify water mass mixing. A review of NE Atlantic geochemical data indicates pre-existing records are uncommon, low resolution and often discontinuous. My research involves extending and generating higher resolution isotopic and sedimentological (including sortable silt, biomarker analysis) data for the last 8 million years on four scientific boreholes located north and south of the Greenland-Scotland Ridge, to gain a greater understanding of the regional geochemical trends and possibly reveal evidence for the timing and magnitude of potential bathymetric-induced changes in ocean circulation, and speculated knock-on climatic effects.
Foraminifera of the Fal Estuary (Cornwall), Including taxa associated with maerl (coralline algae) beds

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Maerl is the collective name for a number of species of red seaweeds (Rhodophyta) that develop hard, calcareous skeletons (Corallinaceae). Maerl forms twig-like, branching forms and, as the living alga, requires sunlight to grow. They are found down to depths of 51 m in the NE Atlantic Ocean but are usually restricted to depths of <20 m. Maerl beds are particularly important near-shore habitats as they support a high benthic diversity of marine invertebrates. Areas of maerl are a ‘Priority Habitat’ within the UK Biodiversity Action Plan (see http://jncc.defra.gov.uk/page-6023 and links to UK BAP priority species and habitats). As a result of devolution, the country-level biodiversity strategies in the UK Post-2010 Biodiversity Framework include ‘Habitats of Principal Importance in England’ (Natural Environment and Rural Communities (NERC) Act, 2006) which includes maerl beds as being of national importance. Dead maerl accumulates very slowly over thousands of years and can also contain small patches of living maerl such as near the channel into Falmouth Docks. A high diversity of foraminifera in maerl beds has also been reported in a number of locations, but our work in the Fal Estuary indicates that the assemblage is largely transported, trapped in the branches of the maerl. The assemblage includes both open marine and estuarine species, as well as many species that are most probably associated with the nearby sea grass meadows.
Interdisciplinary approach to understand the development of the South Asian Monsoon and its concurrent oceanographic influences

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The International Ocean Discovery Program (IODP) Expedition 359 enables the development of the Maldives regional oceanographic setting and its influences on carbonate platform development to be constrained. Furthermore, wind driven deposits of paleoceanographic site U1467, from the Inner Sea, constitute a continuous record of the development of the South Asian Monsoon (SAM). Oceanographic properties can, therefore be reconstructed including changes in thermocline stratification and the establishment of the Oxygen Minimum Zone (OMZ). We propose coupling quantitative planktonic foraminifera assemblage data with multi-species isotope analyses to decipher changes in water mass properties and stratification from select time-intervals within the last 5 my. Currently, our research focusses on assemblage counts and multi-species isotope plots of Marine Isotope Stages (MIS) 11 – 12, sampled at a sub-millennial temporal scale from site U1467. Recognised analogues for our present interglacial are ample; however, each possess limitations in their application. Future analyses of MIS 1 and 5e high-resolution sample sets, in conjunction with MIS 11, will thus allow us to make the respective comparisons. With the additional inclusion of mid (2 my) and distal (3.5 my) sampling intervals a further comparison can be extended into the Mid-Pliocene. Presently our data is also supplemented by an astronomically tuned, oxygen isotope stratigraphic record, from site U1467, of a single planktonic foraminifera species Globigerinoides ruber (white) s.s. By combining foraminifera assemblage data with stable isotopes, we hope to gain an in-depth understanding as to how the SAM and its concurrent ocean currents have changed over the last 5 my.
Developing micropaleontological proxy indicators of growth rates

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Phytoplankton growth rate is an essential parameter required to estimate pCO2 from carbon isotopic fractionation in coccoliths (εp). However, this factor has not been adequately accounted for in many published phytoplankton pCO2 estimates. The current approach is based on determination of εp which is correlated with the PO4 concentrations in the photic zone. There is not direct proxy for PO4 concentration in surface waters in the past, and consequently, this parameter is usually assumed as constant. Changes in the water column structure over glacial-interglacial timescales involve also changes in the PO4 concentration. Thus, estimates of past [CO2aq] using εp and same constant PO4 as observed in the modern water column are likely biased. We propose the estimation of past growth rates based on several microfossils proxies and their modern relationship to changes in photic zone. The relative abundance of lower photic coccolithophorid Florisphaera profunda is proportional to water column stratification and nutricline depth. We hypothesize the %F. profunda will vary inversely with the growth rate/CO2 enhancement factor. We will evaluate a similar construction based on foraminiferal δ18O gradients and planktonic foraminifera assemblages ratios between the upper mixed layer (e.g. Globigerinoides sacculifer) to thermocline (e.g. Globorotalia menardii) taxa. These proxies reflect the upper photic zone temperature and salinity gradients, which control stratification of the water column, and hence related to past PO4 of the surface waters and phytoplankton growth rate.
Reconstructing North Atlantic Deep Water temperature using Mg/Ca of benthic foraminifera

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Reconstructions of temperature and salinity of the deep ocean are important to the understanding of major climate reorganizations. However, it has become apparent that parameters reconstructed from the test chemistry of benthic foraminifera are subject to bias, and are sensitive to the carbonate chemistry of the water. We measured Mg/Ca and Sr/Ca of C. wuellerstorfi from a sediment core (GeoB9508, 2,200 m water depth) which covers the last 50 ka, from off the coast of West Africa at 16°N. Temperatures obtained from Mg/Ca using a published calibration show a large cooling, > 3 °C, in the North Atlantic Deep Water during Heinrich Stadial 4, after which temperatures recover. δ¹⁸O sw decreases steadily from 30 ka to 5 ka. In order to verify these results we will compare with Uvigerina species, as this infaunal species is thought to be less sensitive to Δ[CO₃²⁻].
Here we present new coccolithophore assemblage data from the latest Eocene to early Oligocene of the Nanggulan Formation of south-central Java. Calcareous nannofossil diversity, evenness, range-through diversity and records of key ecological indicators are presented through the Eocene-Oligocene Transition (E/OT). During the E/OT global climates dramatically shifted from warm, high atmospheric carbon dioxide (pCO₂) conditions in the Eocene into a glaciated low pCO₂ Oligocene. Although climate and environmental perturbations are clear in the high latitude Southern Ocean, their connections to the low latitude oceans are less well constrained. Here we document a progressive loss in nannofossil diversity in the low latitude oceans through the late Eocene, which accelerates in the early stages of the E/OT.
Caught in the act: Anatomy of an ongoing benthic-planktonic transition in a marine protist

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The transition from benthos to plankton requires multiple adaptations, yet so far it remains unclear how these are acquired in the course of the transition. To investigate this process, we analyzed the genetic diversity and distribution patterns of a group of foraminifera of the genus Bolivina with a tychopelagic mode of life (same species occurring both in benthos and plankton). We assembled a global sequence dataset for this group from single-cell DNA extractions and occurrences in metabarcodes from pelagic environmental samples. The pelagic sequences all cluster within a single monophyletic clade within Bolivina. This clade harbors three distinct genetic lineages, which are associated with incipient morphological differentiation. All lineages occur in the plankton and benthos, but only one lineage exhibits no limit to offshore dispersal and has been shown to grow in the plankton. These observations indicate that the emergence of buoyancy regulation within the clade preceded the evolution of pelagic feeding and that the evolution of both traits was not channeled into a full transition into the plankton. We infer that in foraminifera, colonization of the planktonic niche may occur by sequential cooptation of independently acquired traits, with holoplanktonic species being recruited from tychopelagic ancestors.
The use of foraminiferal-based transfer functions for the reconstruction of relative sea-level history

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In shelf and intertidal environments, benthic foraminiferal assemblages have been used in the past to successfully reconstruct Holocene relative sea-level changes. However, their applicability to reconstruct sea-levels in deeper habitats and over longer time-scales still needs to be investigated. Here, we present results from the application of a transfer function to reconstruct early to middle Pleistocene relative sea-level changes in a sediment section from Rhodes (Greece). Our results are compared to corresponding reconstructions from planktonic/epibenthic (P/B) foraminiferal ratios and to orbital parameters. Precession has a certain influence on the fossil assemblages of benthic Foraminifera, which is dominated by infaunal species, thus reflecting palaeo-productivity changes. Nevertheless, our long-term reconstructions correspond to those based on P/B-ratios. These long-term trends reflect tectonically-driven relative sea-level changes which are well known from Rhodes. We therefore suggest that transfer functions can be used to reconstruct large-scale, long-term relative sea-level changes.
Nomenclature for the Nameless: a Proposal for an Integrative Molecular Taxonomy of Cryptic Diversity Exemplified by Planktonic Foraminifera

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Investigations of biodiversity, biogeography and ecological processes rely on the identification of “species” as biologically significant, natural units of evolution. Morpho-taxonomy provides an adequate level of resolution if reproductive isolation matches morphological divergence. Morphologically defined species often disguise considerable genetic diversity. The diversity hidden by morphological species can be disentangled through genetic surveys. These units can be identified by unique DNA sequence motifs and allow studies of evolutionary and ecological processes at different levels of divergence. However, the nomenclature of genetically circumscribed units within morphological species is not regulated and lacks stability. This represents a major obstacle to efforts to synthesize and communicate data on genetic diversity for multiple stakeholders. To circumvent this problem, we have designed a stable and flexible nomenclature system for genetically circumscribed units. Our system is based on the definition of unique
DNA sequence motifs collocated within an individual, their typification (in analogy with holotypes), utilization of their hierarchical phylogenetic structure to define levels of divergence below that of the morphospecies, and a set of nomenclature rules assuring stability. The resulting molecular operational taxonomic units (MOTUs) remain outside the domain of current nomenclature codes, but are linked to formal morphospecies as regulated by the codes. We show how this system can be applied to classify genetically defined units using the SSU rDNA marker in planktonic foraminifera and we highlight its potential use for other groups of organisms where similarly high levels of connectivity between molecular and formal taxonomies can be achieved.
Tracing shifts of oceanic fronts using the cryptic diversity of the planktonic foraminifera *Globorotalia inflata*

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The use of planktonic foraminifera in paleoceanographic studies relies on the assumption that morphospecies represent biological species with ecological preferences that are stable through time and space. However, genetic surveys unveiled a considerable level of diversity in most morphospecies of planktonic foraminifera. This diversity is significant for paleoceanographic applications because cryptic species were shown to display distinct ecological preferences that could potentially help refine paleoceanographic proxies. Subtle morphological differences between cryptic species of planktonic foraminifera have been reported, but so far their applicability within paleoceanographic studies remains largely unexplored. Here we show how information on genetic diversity can be transferred to paleoceanography using *Globorotalia inflata* as a case study. The two cryptic species of *G. inflata* are separated by the Brazil-Malvinas Confluence (BMC), a major oceanographic feature in the South Atlantic. Based on this observation, we developed a morphological model of cryptic species detection in core top material. The application of the cryptic species detection model to Holocene samples implies latitudinal oscillations in the position of the confluence that are largely consistent with reconstructions obtained from stable isotope data. We show that the occurrence of cryptic species in *G. inflata*, can be detected in the fossil record and used to trace the migration of the BMC. Since a similar degree of morphological separation as in *G. inflata* has been reported from other species of planktonic foraminifera, the approach presented in this study can potentially yield a wealth of new paleoceanographical proxies.
Global calcareous nannoplankton extinction and population turnover across the Eocene-Oligocene transition

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The Eocene-Oligocene transition (EOT) was a critical event in the Cenozoic marking the transition from a greenhouse to icehouse world. It is associated with widespread climatic and oceanographic change, as well as elevated marine biotic disruption, with elevated rates of plankton extinction and turnover. Calcareous nannoplankton dominated the phytoplankton fossil record in the early Paleogene yet underwent severe diversity loss from the middle Eocene which intensified across the EOT. The cause of calcareous nannoplankton extinction and population turnover through this interval is still poorly understood.

Here we present a synthesis of EOT calcareous nannofossil data from a range of global sites that vary in latitude, ocean basin and oceanographic setting, in order to quantify the global response in calcareous nannoplankton, documenting the timing and magnitude of these widely observed assemblage shifts. Using high resolution semi quantitative data and simple abundance counts we identify significant and coeval population restructuring, including striking reorganisation of the dominant reticulofenestrid group, close to the Eocene-Oligocene boundary and prior to the early Oligocene climatic shift reflecting widespread perturbation to surface water environments. Range retractions, elevated rates of extinction and protracted declines in abundance in warmer water oligotrophic taxa are associated with a reduction of optimal habitat space for many coccolithophores, whilst increases and acmes occur in taxa that favoured cooler waters and elevated levels of nutrients or pulsed delivery of nutrients. Determining the precise timing of these events at widespread localities allows us to examine the relationship between calcareous nannoplankton evolution and the strongly shifting palaeoceanographic conditions through the EOT.
Planktonic foraminifera are adapted to various habitats in the ocean water column and they typically live and reproduce at different depths. This means that fossil assemblages potentially record much more information about palaeoenvironments than just 'surface' conditions. Indeed, in the modern tropical ocean, relatively few species are adapted exclusively to the surface turbulent mixed layer, which is generally nutrient depleted. Some species live in association with symbiotic algae and hence are restricted to the photic zone, either in the mixed layer or the upper part of the thermocline, controlled by the upward diffusion of nutrients. Other species live stratified through the thermocline, sometimes down to hundreds of metres, where they either predate other organisms or graze sinking detritus. A curious feature of the fossil record is that in times of globally warm climate, such as the mid Cretaceous and early Eocene, planktonic foraminiferal assemblages tend to be compressed into a narrow temperature range near the surface, whereas in colder climates, including today, the species appear more spread out. One possibility is that during warm climates, the supply of sinking food to deeper waters was restricted because of much faster bacterial respiration rates in the upper water column. Thus the base of the thermocline could have received less food and have had lower oxygenation levels, excluding foraminifera. Previous work on the Eocene suggests that the open ocean may have had much steeper carbon isotope gradients than the modern, which is consistent with this idea. There is also evidence that as climate cooled, so new groups evolved to occupy the deeper planktonic niches as they became available (for instance *Hantkenina*). We are currently testing this idea with new data and modeling from the Miocene to Recent. Our work underlines the fact that planktonic foraminiferal assemblages both record and respond to environmental gradients, and there is much still to learn about depth habitat evolution as well as environmental change.
Lost in time? Constraining the evolution of Chalk Sea sharks using nannofossil biostratigraphy

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The Late Cretaceous shows key intervals in the evolution of a major group of marine apex predators, the sharks. The Natural History Museum, London, currently houses a large collection of shark teeth from throughout this period, collected from the Chalk of the southern UK. A selection of these shark teeth have been sampled for associated chalk lithologies that host abundant calcareous nannofossils. Changes in the nannofossil content will be used to provide a temporal framework to constrain the age of these fossil teeth and hence the evolution of Chalk Sea sharks.

Globally important environmental changes such as the Cenomanian-Turonian boundary Ocean Anoxic Event (OAE2), and the effects that it had on sharks is poorly known. It is hoped that constraining the timing of recognised evolutionary changes within the shark lineage will improve our understanding of how these events influence marine predators, as well as enhancing the scientific importance of this national collection.
Variability in the Atlantic subpolar gyre: variability in a global climate model and a simplified conceptual model

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Because of the well-known link between the meridional heat transport and the meridional overturning circulation, the North Atlantic Ocean represents a key region for global climate. More specially, because of the deep water formation and the subpolar gyre circulation, the subpolar North Atlantic is known to have a strong impact on the global ocean circulation on interannual to decadal time-scale. Therefore, due to the concern of the consequences of climate changes, the understanding of the dynamics of this region is essential. The use of Global Climate Models is necessary in order to predict and study future and past changes in the subpolar Atlantic circulation. However, due to the complexity of these models, it can sometimes be difficult to fully understand the mechanisms working in this region. This motivates the use of simplified models of reduced physical complexity, especially if they reproduce results of the GCM.

In this study, we propose to analyse the subpolar North Atlantic variability in a state-of-the-art model in order to find the main mechanisms leading to modulations of the subpolar gyre intensity. This analysis is conducted for two simulations: one 1300 years long simulation with a prescribed CO₂ concentration and another one covering the pre-industrial millennium (850-1850 AD). A local chain of events is identified in these simulations, in which time-series of air-temperature and freshwater fluxes play a prominent role. The key mechanisms are subsequently tested in a simplified model. This model describes the western subpolar North Atlantic gyre circulation where buoyancy fluxes induce modulation of deep convection and a subsequent geostrophic adjustment of the gyre. This other analysis is conducted in order to see if the conceptual model can reproduce the same variability as the GCM one in this specific region of the globe.
Changes in LBF assemblages in an Indonesian reef over the past 30 years

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Time series recording baselines of reef conditions are rare, especially for reefs in the most biodiverse region, the Coral Triangle. Large benthic foraminifera (LBF) are an abundant and important component of the reef ecosystem, and are frequently used as indicators of environmental conditions. Here I evaluate new insights into the ecology of LBF, followed by a case study into changes in LBF assemblage composition over the past 40 years in an Indonesian reef system.

LBF are found in similar conditions as corals. They depend on photosymbionts for at least part of their energy, and are, as a consequence, restricted to the photic zone. Traditionally especially depth or depth related parameters have been used as a driver of change in LBF distribution. However, onshore-offshore transects show that tolerance to terrestrial influence is an equally important driver, resulting in distinct assemblages in brown and blue water reefs.

The Spermonde Archipeago (SW Sulawesi) is a carbonate shelf ecosystem with rows of patch reefs on equal distance to the shore, making it an ideal testing ground for quantifying the effect of terrestrial influence on community composition. Over the past 40 years changes in LBF assemblage were largest on the shallowest part of the reef, and smallest in the deeper parts, reflecting similar changes in benthic habitat. These observations provide further insights in the importance of sediments on reefs, and their influence on the benthic community.
Morphological traits of selected phylotypes identified as *Ammonia tepida* (Cushman, 1926) along the European coast

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*Ammonia* is one of the most abundant genera worldwide exhibiting a very high morphological variability, although commonly researchers use one to three morphospecies. Even if they are not often used, a plethora of species/subspecies descriptions of recent *Ammonia* exist and has led to “taxonomical chaos”. The tendency to consider the morphotypes as ecophenotypes belonging to a strongly reduced number of species has been challenged by molecular studies, showing that many supposed ecophenotypes were in reality well separated genetically and can/should be considered as different species.

This study aims to investigate morphological characteristics of phylotypes belonging to the genus *Ammonia*. We are particularly interested in three phylotypes widely encountered along the European coasts which are difficult to distinguish morphologically (T1, T2 and T6). For this purpose, about 360 *Ammonia* specimens were sampled and SEM (Scanning Electron Microscopy) imaged of the spiral, umbilical and lateral sides were obtained to perform morphometric measures. Pore features were investigated using 1000x magnified images of the penultimate chamber on the spiral side. In order to assign each specimen to a phylotype, a fragment of the 5' terminal region of the SSU rDNA (14F-N6) was sequenced and compared to previous data. Linking morphometric analyses and molecular identification will allow us to determine morphological traits useful to effectively distinguish these three phylotypes.

The revision of the traditional nomenclature in the light of molecular data is urged to reach a taxonomic standardisation. We strongly believe that molecular identification combined with morphological analyses will help to disentangle these taxonomic issues.
Reassessment of foraminifera and nannofossils across the Bartonian in the Alum Bay section

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Benthic foraminifera and calcareous nannofossil assemblages have been studied across the Bartonian in the well-known Alum Bay section in the Hampshire Basin (Isle of Wight, UK), where twenty seven samples were collected across a 90 m-thick section. These results are part of a multidisciplinary study carried out by members of the International Subcommission on Paleogene Stratigraphy, which aims at describing in detail the base of the Bartonian stage for correlation with sections that have the potential to become the Global Stratotype Section and Point –GSSP- for the base of the Bartonian.

Our preliminary results are in line with previous studies on foraminifera (Murray and Wright, 1974) and calcareous nannofossils (Aubry, 1983, 1986). Small benthic foraminifera from the lower half of the studied interval indicate an inner shelf environment (0-100 m depth), with fine substrate and turbid water. The upper part is barren of foraminifera. Assemblages are strongly dominated by the genus *Cibicides*, which accounts for the low diversity recorded. Variations in benthic assemblages mainly consist of changes in relative abundance of the species *C. ungerianus* and *C. pygmeus*.

Calcareous nannofossils are common, and reworked specimens are present throughout the section. The upper part of the section is barren of calcareous nannofossils, except for one sample. The identification of bioevents suggest that the section spans from CNE14 to CNE15 Zone (Agnini et al. 2014). *Chiasmolithus solitus*, the marker species for the base of NP17 Zone (Martini, 1971) was not found, suggesting that the Middle Eocene Climatic Optimun (MECO) should be located above the studied interval.
Paleoceanographic dynamics of the Japan Sea over the last 450,000 years – a coccolithophore perspective

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The semi-enclosed Japan Sea, located in the northwest margin of the Pacific, is an ideal region to investigate the interaction between the ocean, climate, and sea level variability. Integrated Ocean Drilling Program (IODP) Expedition 346 (29 July-27 September 2013) from Valdez, Alaska to Busan, South Korea, drilled seven sites in the Japan Sea and two sites in the East China Sea.

Site U1427, located at 35°57.9’N, 134°26.1’E at 330 m water depth in the Yamato Basin, was selected for this study. Coccolithophore palaeoproductivity was reconstructed for the last 450 kyr using coccolithophore assemblages and coccolith absolute numbers. Samples were prepared following a combined technique of dilution and filtering. Following the counting routine, a minimum of 400 coccoliths per sample were recognized and classified using Scanning Electron Microscope. Coccolith preservation was in general poor to moderate and coccolith remained relatively low, except during interglacials, when Gephyrocapsa oceanica, Calcidiscus leptoporus, and Helicosphaera carteri peaked due to the influx of the Tsushima Warm Current into the Japan Sea.
Coccolithophore variability during Marine Isotope Stage 11 in the Pacific sector of the Southern Ocean and its potential impact on the carbon cycle

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Proxy-based reconstructions of past changes in the marine biological carbon pumps are limited, especially in the Southern Ocean. This work provides new insights into the productivity variations in the Pacific sector of the Southern Ocean. We provide new data from three sediment cores that show coccolithophore variability across Marine Isotope Stage 11. The cores were retrieved during R/V Polarstern cruise PS75 from the Subantarctic and Polar Front Zones.

Coccolithophore assemblages were dominated by the species Gephyrocapsa caribbeanica and small Gephyrocapsa. Total numbers of coccoliths, coccolith accumulation rates, coccolith fraction (CF; <20 µm-fraction) Sr/Ca data and temperature-corrected CF Sr/Ca records consistently showed an increase in coccolithophore productivity during Termination V, highest productivity throughout MIS 11, and a decrease during late MIS 11 in all the cores. We compared the temporal trends from the CaCO₃ productivity records and linked them to the regional paleoclimate variations during this period. We also calculated the coccolith calcification rate in the surface ocean and discussed potential contribution of coccolithophores to changes in the concentration of atmospheric CO₂.
Cooling Phase Detection at Pliocene Sediment in North East Java Basin, Indonesia

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The big event suspected as primary control for oceanographic setting in North East Java Basin is climate progressively cooled down during Late Cenozoic. Commonly, global cooling is detected by drop sea level which trigger major erosion and coarse sediment during the deposition. However, the cooling phase on Pliocene sediments in North East Java Basin did not leave the obvious erosion marks due to the domination of thick clay sediment called Lidah Formation. The monotonous thick claystone conduces the border of global cooling phase difficult to detect.

To detect the big climate cooling phase, qualitative and quantitative of foraminifera and nannoplankton analysis were performed for the samples that taken by systematically from Gunung Panti Section, Blora Area. Twenty samples were carried out along one kilometer section which covers the contact of Mundu Formation and Lidah Formation. The quantification of abundance population (Ab index) and diversification (Dv index) of foraminifera and nannoplankton were counted to detect the ecology and climate changes during the deposition of Lidah Formation.

The cooling phases are marked by the decrease of Ab index and Dv index of foraminifera and nannoplankton. The cooling phases triggered the lower temperature and emerged the ability of foraminifera and nannoplankton reproduction. Three cooling phases can be marked on Lidah Formation by the fluctuation of low Ab index and Dv index on N19, N20, and and N21. The major cooling phase occurred on N21 that detected by the lowest of Ab index and Dv index in Lidah Formation sediment.

Keywords: Cooling phase, Lidah Formation, abundance population, diversification.
Plasticity in a changing world

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Foraminifera are major carbonate producers in today’s ocean. However, with rapid inputs of anthropogenic CO₂ into the ocean, there is increasing concern over the long-term effects on marine ecosystems. The precise effects of ocean warming and acidification on biology are poorly understood making it difficult to determine the impact on marine carbonate production. Here we use a geological analogue (~56 Ma) of our current climate perturbation, the Palaeocene-Eocene Thermal Maximum (PETM), to assess impact of climate change on planktic and benthic foraminifers (Oridorsalis umbonatus and Nuttallides truempyi) before, during, and after this climate perturbation, at IODP Site-690B. We use X-ray tomographic microscopy to reconstruct the internal structure of foraminiferal tests. We are quantifying changes in test size, number of chambers, and size of the proloculus, and thereby development and reproduction, in benthic foraminifers, as well as community size changes in planktic foraminifers. Planktic foraminiferal community size was smaller during the PETM than before and after. If migration of warm water species to Site-690B would have driven the signal, we would expect to see an increase; therefore, we interpret this as a stress response to the environmental conditions leading to a reduction in size of individuals. The benthic foraminifers show species specific responses, with O. umbonatus showing little change in proloculus size whereas N. truempyi shows a distinct decrease during the PETM. Both species decrease in test size and numbers of chambers. These findings, especially those on planktic foraminifera, suggest that carbonate production could be negatively impacted by future climate change.
Testing the rate and amplitude of environmental change that marine plankton can adapt to

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Environmental change is predicted to impact species and ecosystems via a suite of physiological, behavioural and genetic changes, and hence their fitness to permit persistence. The ongoing truly remarkable rate of climate change is predicted to challenge organism’s adaptation to novel environments. Earth history has experienced a wide range of transient events, which differ in both the rate and amplitude of environmental change. Here we explore the geological record of marine calcifying plankton to quantify if there is a direct scaling between rate or amplitude of temperature changes and the body size of planktic foraminifers. We compare data generated from ‘icehouse’ conditions in the Pleistocene and Pliocene with that from ‘greenhouse’ times such as Middle Eocene Climatic Optimum, Eocene hyperthermals, the Cretaceous-Paleogene boundary and thus, also assess the associated response to gradual versus abrupt environmental change. Specifically, we quantify if there is a predictable and linear relationship between the environmental change, expressed as rate and degree of warming and biotic impact, and if there are differences in the relationship between icehouse and greenhouse worlds.

Size in planktic foraminifers responds predictably to the environment today with individuals reaching large size under optimal conditions and increases in overall community body size from the poles to the tropics. During glacial-interglacial cycles, there is a clear linear relationship between changes in ocean temperature and size. Therefore, the hypothesis is that individuals are able to track favourable conditions at low rates of environmental change but populations adapt by expanding their niche under rapid climate change.
Biodiversity of Foraminifera (Rhizaria) in intertidal sites of the French Atlantic coast: comparison between individual specimen sampling and environmental DNA with Next Generation Sequencing

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Traditionally, benthic foraminifera have been studied on the basis of morphological criteria. This strategy has led to much discussion about the range of variability that can be admitted in a single species, and largely different species concepts have been developed. Moreover, morphology-based taxonomy has been more or less restricted to fossilisable taxa with hard shells, whereas soft-shelled foraminifers have often been neglected. Since 20 years, DNA barcoding of single foraminifers has been developed. Foraminifers are usually collected alive one by one, their morphology is documented and they are individually extracted for DNA. This method allows linking the morphology-based taxonomy with DNA barcoding in one individual, but is very time consuming. Moreover, compared to traditional morphologically-based studies, it usually lacks a quantitative dimension.

Next Generation Sequencing (NGS) applied to environmental DNA (eDNA) has developed in the recent years and allows obtaining millions of sequences for a very low cost compared to methods with cloning and Sanger sequencing. However, to connect eDNA biodiversity with former knowledge based on morphological taxonomy, extended databases bridging DNA and morphological data are needed.

Here, we will compare single foraminifer DNA barcoding and eDNA NGS results for four sites situated on the French Atlantic coast: Bourgneuf Bay, Brillantes mudflat (Loire estuary), island of Bailleron and Bono river, both situated in the Gulf of Morbihan. Two of these sites, Brillantes and Bourgneuf, are also routinely studied with quantitative morphologically based methods for their foraminiferal biodiversity since several years, allowing further comparisons with morphology-based methods.
Atmospheric pCO$_2$ is hypothesized to be a key driver of evolution of coccolithophore and other phytoplankton over the Cenozoic. However, proxies for CO$_2$ themselves are strongly affected by coccolithophorid adaptive strategies such as modulation of cell size and active bicarbonate transport to photosynthesis. We review geochemical and morphological indicators of these adaptations, challenges and questions in applying them to understand pCO$_2$, and the role of micropaleontological indicators of upper water column structure in estimating phytoplankton growth rates for pCO$_2$ reconstructions. Models of cellular carbon uptake suggest that the carbon isotopic fractionation of coccoliths records the reallocation of intracellular bicarbonate from calcification to photosynthesis under CO$_2$ limitation. Debate remains regarding whether the absolute coccolith fractionation ($\varepsilon_{\text{coccolith}}$, determined relative to a planktonic foraminiferal indicator of $\delta^{13}$C DIC) or the relative fractionation among different sized coccoliths, is the more robust indicator of carbon reallocation. We use the model and initial data to compare where these two approaches are similar and when they may diverge. The degree of cellular calcification, or coccolith thickness, also potentially responds to intracellular carbon reallocation. Finally, we use cell models to suggest when coccolith Sr/Ca may elucidate growth rate variations and when other influences may dominate, and show some first calibrations between growth rate and other micropaleontological indicators.
Energy flow in Foraminifera: from empirical to theoretical models

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Foraminifers as organisms are open systems with a dissipative structure. We review crucial aspects of energy exchange between individual foraminifers and their microhabitats. Understanding the energy flow between the foraminiferal system and the environment is essential to unravel its complexity and adaptability to environmental changes. Energetic efficiency of individuals critically depends on their size and shape determined by development and controlled by dynamic changes in gene expression. Most foraminiferal cells are relatively large in comparison to other eukaryotic cells and often reach the size of smaller metazoans. In consequence, foraminifera face the same supply problem as multicellular organisms due to their low surface-to-volume ratio. The solution to this limitation was a major evolutionary innovation in metabolic design based on space-filling fractal networks, such as respiratory, circulatory systems in animals or vascular systems in plants. Foraminifera as unicellular organisms could not build multicellular veins, nevertheless, their cytoskeleton organization evolved into granuloreticulopodia. This special anastomosing fractal network highly enhances the surface/volume ratio and allows flexible regulation of ion exchange between the cell and its microenvironment. This gives us the unique opportunity to establish the group of foraminifera as model organisms for metabolic energy fluxes. We discuss metabolic adaptations of foraminifera associated with feeding, dispersal, and life history strategies. This empirical knowledge is used for the construction and development of mathematical and simulation models of organisms to test energetic, behavioural and evolutionary patterns. The research received support from the Polish National Science Centre (DEC-2013/09/B/ST10/01734).
Shell calcification in planktonic Foraminifera: Ontogeny, environment, and geochemistry

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Shell calcification intensity (the amount of calcite normalized for shell size) in planktonic Foraminifera is progressively established as palaeoenvironmental proxy, most notably for ambient carbonate systems. However, more research in this field is needed, as increasingly more inconsistencies across species emerge upon further investigation. Here, we use material from a two-year sediment trap series from the North Atlantic to study foraminiferal shell calcification and geochemistry across a wide size range and two seasonal cycles. The flux of species of the *Globigerinoides ruber/elongatus* plexus was found to be variable over the two years. Seasonal variations in shell calcification intensity occur unrelated to flux changes, but are consistent with environmental forcing, predominantly productivity. *Globigerinoides ruber* (pink), *G. ruber* (white), and *G. elongatus* show a constant and persistent offset in calcification intensity, and different size–weight relationships over a large size range (exponential in *G. ruber* (pink), scattered in *G. ruber* (white), and linear in *G. elongatus*). While the intensity of calcification appears not to influence shell geochemical compositions, it is paramount to further study individual species and their characteristics to establish shell calcification as an unambiguous environmental proxy.
Dwelling in a hot spot: Diversity of benthic foraminifera in tropical tide pools of eastern Africa

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Tide and rock pools in the tropics are extreme habitats and are ideal natural settings to test the resistance and resilience to rising temperatures. They face diurnal heating and increased evaporation due to the tidal cycles and can be critical environments for many organisms. While a lot of benthic foraminifera, including the group of symbiont-bearing, larger benthic foraminifera (LBF), can be sensitive to extreme temperatures, some taxa show higher tolerances towards heat exposure.

In our analysis of benthic foraminifera from the shallow waters of eastern Africa, we treat the local tide and rock pools as “natural laboratories” for diurnal temperature peaks. Here, we present field evidence for assemblages from these extreme habitats that show a remarkably high diversity with a total of 111 species. The foraminiferal communities were dominated by LBF such as Neorotalia calcar and Amphistegina spp., followed by a variety of miliolids and rotalids.

Our results show that a relatively wide range of local shallow-water foraminifera appear to be capable to withstand the exposure to diurnally occurring extreme temperatures. This could provide insights into the capacities of foraminiferal populations to acclimatize to higher temperatures. Ongoing ocean warming will likely lead to temperature increases in shallow-water environments and the foraminiferal assemblages from tropical tide and rock pools might be more resilient towards future conditions.
Oceanic islands induce wakes and stationary eddies. The situation leeward of Tobago is further complicated by the hypopycnal, nutrient-rich Orinoco Plume, which envelopes Tobago during the northern South American rainy season. We investigate the impact of the plume, wake and eddy on bathyal benthic foraminifera NW of Tobago. Three surface sediment samples were recovered from around each of five well-sites, Warap-A, Cassra-A and Cassra-CC being upper bathyal and Bene-1 and Sancoche-1 middle bathyal. The first four form a transect along the wake’s northern side extending into a stationary eddy. These were supplemented by four 80 cm piston cores. Benthic foraminifera reveal high nutrient flux *Cassidulina curvata* and *Uvigerina hispidocostata* biofacies at upper and middle bathyal depths respectively. *Martinottiella* spp. at Warap-A reflect dysoxic pore waters in the immediate lee of the island, where the percentage of the fauna as serial tests indicate lowest bottom water current strength. Species indicative of a perennial nutrient flux increase to the NW, indicating that the eddy induces a constant organic carbon flux to the seafloor. The short cores indicate that these environmental conditions have been in place throughout at least the later Holocene. The most northerly, upper bathyal core presented a stable community structure with low assemblage turnover, while upper bathyal and outer neritic cores had expansive structures and high turnover. These data suggest benthic foraminifera may be used to track the positions of the plume, wake and eddy since the Orinoco’s Miocene arrival in the Trinidad and Tobago area.
StrataBugs v2.1

(Workshop)

John Athersuch, Paul Britton and Rosa Townsend,

StrataData Ltd

StrataBugs software is widely used in the biostratigraphy community to record, manipulate and display biostratigraphic and related geological data. Key to the success of biostratigraphy is an understanding of how biostratigraphic events (tops, bases, acmes, etc.) relate to each other and to time. This poster display is a summary all aspects of biostratigraphy data management but a related presentation in the workshop will use StrataBugs to focus on how developing standard event schemes (composite standards) calibrated against a standard timescale using age/depth curves (graphic correlation) can lead to a better understanding of stratigraphy.
The potential for using mikrotax/nannotax to develop a database of biostratigraphic-event age-calibrations

(Workshop)

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A basic priorities for plankton statigraphy has always been to improve the age calibration of marker events, and also to investigate the reliability of different events, to identify new events and to document diachrony in known events. For the future there are increasing possibilities to achieve this as more holes are drilled with high quality recovery, and as cyclostratigraphy provides an ever more reliable framework. There is also increasing demand for higher precision in biostratigraphy, for example to correlate short cyclostratigraphic sequences into the global scheme.

One potential method to improve the calibrations would be to create an accessible database of existing calibrations - providing for each biostratigraphic event (e.g. the first or last occurrence of a taxon) a record of each calibration of it against magnetostratigraphy or cyclostratigraphy. This would include for each age-calibration the source-publication, geographic location, magnetochron or marine isotope stage against which it is calibrated, the position within the interval and the uncertainties associated with both the top and bottom of the interval and the position of the event. We believe that there is a clear potential to do this using the nannotax/mikrotax system since this already provides an online relational database framework including full documentation of the relevant taxonomy and a geological time framework.

In our presentation we will outline the data framework which would be needed to achieve this and promote discussion of how this might relate to other initiatives and possible user priorities.
FIELD TRIP: THE SILURIAN OF SHROPSHIRE HILLS

The varied geology of the Shropshire Hills results in diverse landscapes with hills, crags, scarps and valleys. The Long Mynd, Stiperstones, Wenlock Edge, Wrekin, Clun and Clee Hills all owe their distinct characters to the underlying geology. Geology also determines land use, settlement patterns and a long history of rock and mineral extraction. Regional structures are strongly orientated along a south-west to north-east axis, with many ridges being aligned in this direction. There is also evidence of Pleistocene glacial and periglacial processes, such as moraines, stone stripes and river capture. Two centuries ago the pioneers of geological science, notably Roderick Murchison and

Looking north across the town of Ludlow, including Ludlow Castle.

Charles Lapworth, worked extensively in the Shropshire Hills, with locally-derived stratigraphic divisions becoming world famous including the Caradoc, Wenlock, Ludlow, Onnian and Sheinwoodian. For more information please visit: www.shropshiregeology.org.uk
Satellite image of the region (left), note NE-SW trending structure.
Map of the region showing locations of the main stops.
Wenlock and Ludlow shelf facies. Bold numbers refer to benthic assemblages; 1 (shallowest) to 6 (deepest) (Cherns et al. 2006).
Bold numbers refer to benthic assemblages; 1 (shallowest) to 6 (deepest) (Cherns et al. 2006).
Pitch Coppice, Mortimer Forest Geology Trail, Ludlow (Stop 1)

Locality: Old quarry 35 m south of Wigmore Road (Mortimer Forest Stop 3), ~4 km SSW of Ludlow, Shropshire (SO 472 730). Two further small quarries (Mortimer Forest Stops 1 and 2), within the Much Wenlock Limestone Formation, occur immediately west of Pitch Coppice (SO 472 730 and SO 471 730). This is a designated Site of Special Scientific Interest and hammering is strictly forbidden. The description below is modified from that in Davies et al. (2011).

Pitch Coppice and the two stratigraphically lower quarries (Mortimer Forest Stops 1 and 2) contain the basal few meters of the Lower Elton Formation and upper 14 m of the Much Wenlock Limestone Formation. Sedimentation here occurred in an extension of the depositional setting represented by the off-reef tract recognised on Wenlock Edge, and the lithology comprises poorly fossiliferous, carbonate mudstones, wackestones and silty mudstones (Davies et al. 2011). At Pitch Coppice the Gorstian GSSP coincides with the rapid transition from the hard nodular limestones of the Much Wenlock Limestone Formation (Homerian) into the softer, predominantly argillaceous siltstones of the Lower Elton Formation (Gorstian). In terms of biostratigraphy the base Gorstian transition corresponds to the FAD *Saetograptus (Colonograptus) varians* and *Neodiversograptus nilssoni* (0.03m and 0.23m, respectively, above the base of Gorstian stage boundary).
These records support the notion that the base of the Lower Elton Formation lies at or close to the base of the *Neodiversograptus nilssoni* graptolite Biozone. However the graptolite specimens are fragmentary and no widely correlatable changes in microfaunas occur at the boundary (Melchin *et al.* 2012). Current research to further constrain the Wenlock-Ludlow Series boundary upon the Midland Platform has focused upon the correlation of parasequences and has allowed for an improved assessment of the utilisation of carbon isotope analysis (Blain *et al.* 2016) and absolute age constraint (427.9 ± 0.7 Ma; Cramer *et al.* 2012).

Location, sedimentary log, sequence stratigraphic interpretation and carbon isotope record of the succession exposed in Pitch Coppice (Mortimer Forest Stops 1 to 3). SM, silty mudstone; M, carbonate mudstone; W, wackestones; P, packstone; G, grainstone (Davies *et al.* 2011).
Sunny Hill Quarry, Mortimer Forest, Ludlow (Stop 2)

Locality: Disused quarries north of Sunnydingle Cottage, Mortimer Forest and exposures on the N side of the forestry track running SE (SO 4950 7255 - 4974 7244). This is a designated Site of Special Scientific Interest and hammering is strictly forbidden. The description below is modified from that in Davies et al. (2011).

The Sunny Hill Quarry section exposes 40-50 m of succession in fairly continuous outcrops that include the Upper Bringewood, Lower Leintwardine, Upper Leintwardine and Lower Whitcliffe formations. Sunny Hill Quarry is the GSSP for the base of the Ludfordian Stage (Melchin et al. 2012). The boundary is placed in the western part of the quarry within the top of the Upper Bringewood Formation (Aymestry Limestone) at the lower of two very thin shale bands (Davies et al. 2011). The upper shale band and higher thicker clay are bentonitic (SHQ3 and SHQ4 = ‘E’ and ‘G’). Zircons extracted from SHQ2 have been radiometrically dated at 407 ±14 Ma (Ross et al. 1982). Recent sampling of SHQ1, SHQ 2 and SHQ4 indicates that all three bentonites contain sufficient zircons for dating. Furthermore they contain a coarse grained heavy mineral fraction suggesting close proximity to the volcanic source region (Davies et al. 2011). Biostratigraphically the base Ludfordian transition corresponds to the FAD of the graptolite Saetograptus leintwardinensis (within bed D of the basal limestones of...
the Lower Leintwardine Formation). The conodonts *Ozarkodina confluens* and *Panderodus spp.* are recorded from limestones around the boundary, but are long ranging. A similar situation occurs with acritarch, brachiopod and coral floras and faunas. At present the GSSP is considered imprecise, but may be near base of *Saetograptus leintwardinensis* Graptolite Biozone.

Carbon isotope analysis stratigraphically above and below the GSSP and show a minor positive shift in isotope values begins some 50 cm below the top of the Upper Bringewood Formation. This may reflect the early Ludfordian Linde Event and act as an additional correlation tool (Davies *et al*. 2011). In terms of sequence stratigraphy the transition into the Lower Leintwardine Formation is conformable and is associated with a facies shift from carbonates to calcareous siliciclastics. However, limestone conglomerates indicate a widespread, short lived episode of non-deposition across inshore shelf areas at the base of the Lower Leintwardine Formation, while at the shelf margin a local, eroded hardground horizon marks the sharp, disconformable boundary between the Aymestry Limestone and overlying thin shaly siltstones of the Lower Leintwardine Formation (Cherns 1980, 1988). A limited transgression occurs across the shelf at the base of the Lower Leintwardine Formation, which represents a transgressive surface/sequence boundary. Above the Lower Whitcliffe Formation marks the onset of a shelf-wide facies transition into thicker bedded, calcareous and sandy siltstones with a common but low diversity brachiopod assemblage. The spread of calcareous siltstone facies into east central Wales indicates rapid progradation of shelf facies in response to relative sea level fall.
Location, stratigraphy and carbon isotope record for the lower part of Sunnyhill Quarry (Davies et al. 2011).
Richards’s Castle takes its name from the Norman Castle built by Richard Fitz Scrob (or Fitz Scrope), a Norman knight who was granted lands in Herefordshire, Worcestershire and Shropshire by the Saxon King Edward the Confessor before the Norman Conquest. He built Richard’s Castle before 1051 with a motte-and-bailey style construction, one of only three or four castles of this type built before the Norman conquest. In the 13th century the castle passed first to the Mortimer family, and then, in 1264, Hugh Mortimer was forced to surrender himself and Richard’s Castle to Simon de Montfort, 6th Earl of Leicester. By the 16th century it was in ruins. The original parish church was St Bartholomew’s Church situated close to and east of the castle. The church was founded by either Richard Fitz Scrobe or his son. The chancel was probably built in 1362. The north transept was probably consecrated in 1351 by Bishop John de Trillek. This was the Chantry Chapel of the local Knights Templar. The south aisle was built between 1310 and 1320. There is a detached bell tower (one of six in the county) that dates from the second half of the 13th century.

St Bartholomew’s is constructed in stone rubble with tile roofs. Its plan consists of a nave and chancel built in the 12th century, a south aisle and a north chapel built in the 14th century, and a south porch of the 15th century. On the north wall are two buttresses, and it contains two 12th-century round-headed windows. In the south wall of the aisle is a piscina, and against its west wall
is a 13th-century coffin lid inscribed with a foliated cross. In the nave and aisle are box pews from the 17th century. Elsewhere in the church are benches, and there is an 18th-century family pew in the chapel under a canopy. There are fragments of 14th-century glass in many of the windows. In the chancel are six hatchments on the walls, and 18th-century memorial slabs on the floor.

**Ludford Corner, Ludlow**

Locality: Junction of Whitcliffe Road (= ‘Ludford Lane’) and B4361 road towards Leominster (SO 512 742); outcrops continue for more than 100 m along Whitcliffe Road. This is a designated Site of Special Scientific Interest and hammering is strictly forbidden. The description below is modified from that in Davies et al. (2011).

Ludford Corner contains the transition between the Upper Whitcliffe and Downton Castle Sandstone formations, the boundary of which is marked by the Ludlow Bone Bed. The Upper Whitcliffe Formation locally (car park of the Charlton Arms Hotel) comprises interbedded calcareous siltstones and very fine-grained sandstones with beds up to 200 mm thick. Parallel lamination, hummocky cross stratification and cross stratification are present in the sandier beds, and amalgamated bedding and shelly lenses are also seen. The Ludlow Bone Bed sensu stricto here is the oldest of at least five thin vertebrate sands that lie within laminated siltstones, and these collectively comprise the Ludlow Bone Bed Member, which achieves a maximum thickness of 0.3 m. Above the Platyschisma Shale Member is 2 m thick, and comprises mudstones and siltstones with thin horizons of bone sand, and a biota including bivalves, gastropods, ostracodes, eurypterids and plant fragments (Bassett et al. 1982). The overlying and uppermost member of the Downton Castle Sandstone Formation is the Sandstone Member, comprising 15 m of yellow, micaceous well sorted sandstone. Here fossils are uncommon, but include brachiopods, molluscs, ostracodes and plant fragments. Extensive and well-preserved hummocky cross stratification occurs and is particularly well seen in the road section immediately south of Ludford Corner (Davies et al. 2011).

The sequence within which the Ludlow Bone Bed Member lies is clearly regressive overall: below lie calcareous siltstones and sandstones with a rather limited but fully marine fauna. Marine fossils occur in the Ludlow Bone Bed Member too, but fossils typical of the local Upper Ludlow virtually disappear, and the fauna of the overlying Platyschisma Shale Member is dominated by bivalves and gastropods. In addition the
passage upwards through the Sandstone Member and into the Ledbury Formation is considered conformable and marks the onset of Old Red Sandstone sedimentation. Most previous interpretations of the origin of the Ludlow Bed Member have relied implicitly on the regressive nature of this sequence, generally regarding the unit as representing very shallow subtidal or intertidal conditions. Characteristically however, marine bone-beds form during times of relative sea-level rise, resulting in sediment starvation and the formation of thin transgressive lags. Based on these considerations the Ludlow Bone Bed Member may represent a short-lived transgressive pulse within the generally regressive sequence (Davies et al. 2011).

Sedimentary log, percentage spore abundance and δ13Corg curves through the Upper Whitcliffe Formation and Lower Downton Castle Sandstone Formation exposed at Weir Quarry, near Ludlow (Loydell & Fryda, 2011).

The age of the Ludlow Bone Bed has long been debated, being a former candidate for the base of the Devonian, and in more recent times considered as representing the base of the Pridoli (Cocks et al. 1992). However recent δ13Corg data from the Ludlow area has identified a pronounced positive excursion commencing in the uppermost Upper Whitcliffe Formation (Loydell & Kryda, 2011). Should this represent the Lau carbon isotope excursion then a Ludfordian age
may be attributed to the Ludlow Bone Bed Member. Furthermore such a correlation would place the Bone Bed Member during a time of major environmental changes (Lau CIE and biotic events), which resulted in conodont, graptolite and pentamerid brachiopod extinctions, as well as enhanced microbial carbonate production and a decline in reef-builders (Calner, 2008). Based upon global comparisons the Lau CIE appears to correspond to two Ludfordian glaciations separated by an interval of deglaciation. This deglaciation may have resulted in a sea level rise of at least 30 m (Johnson, 2006) and may correspond to the Bone Bed Member.

Panoramic views of Shropshire geology from viewpoint situated upon Wenlock Edge

Locality: Outcrop adjacent to lay-by on NW side of B4371, about 5 km SW of Much Wenlock (SO 574 967), Wenlock Edge. The description below is modified from that in Davies et al. (2011).

In fair weather, this vantage point offers superb views of the surrounding parts of Shropshire and allows the close relationship between topography and the local geology to be appreciated clearly. The classic ridge-and-vale topography that develops over the Wenlock and Ludlow part of the sequence is especially notable. Immediately west of the viewpoint is the broad valley of Ape Dale, underlain by the Coalbrookdale Formation and predominantly shaly Llandovery formations. The three prominent hills in the distance to the SE are situated just east of Church Stretton, and are composed of the late Precambrian Uriconian Volcanic Group. The middle hill, with its conspicuous hill fort, is Caer Caradoc. To its left (south) is Ragleth Hill and The Lawley lies to the right (north). The prominent hill to the north of the viewpoint is the Wrekin: this is situated along the strike of the Church Stretton Fault, and is composed of Uriconian Volcanic Group also. Beyond Caer Caradoc and The Lawley, the skyline is marked by a flat-topped hill called the Longmynd, composed of late Precambrian
clastic sedimentary rocks that overlie the Uriconian Volcanic Group. An attenuated succession of Cambrian and Upper Ordovician sedimentary rocks occurs east of Caer Caradoc, and these rocks dip eastwards to underlie the Silurian in Ape Dale. The NE–SW-trending ridge of Hoar Edge, which flanks the eastern side of The Lawley, is formed of basal Upper Ordovician (Sandbian) sandstones and granulestones. On the eastern side of the viewpoint, the position of the road approximates to the contact between the Much Wenlock Limestone and Lower Elton formations. The low ground beyond is Hope Dale, underlain by the shaly Elton and Lower Bringewood formations. The prominent scarp in the middle distance is formed by the Aymestry Limestone facies in the mid-Ludlow. Hidden beyond this scarp is a further area of low ground – Corve Dale – underlain by upper Ludlow siltstones and Old Red Sandstone facies Pridoli sedimentary rocks. Further east, Old Red Sandstone, of Devonian age, forms a dissected plateau dominated by the hills of Brown Clee and Titterstone Clee, which are capped by Carboniferous sedimentary rocks with dolerite sills.
Lea Quarry South, Wenlock Edge

Locality: Lea Quarry South (SO 594 982), ~3 km SW of Much Wenlock, Shropshire. The description below is modified from that in Davies et al. (2011).

Lea South Quarry currently exposes the stratigraphic equivalent of Pitch Coppice. Lea Quarry South has exposed representative sections through the upper part of the Much Wenlock Limestone Formation in the reef tract (Scoffin, 1971; Bassett, 1989; Ray et al., 2010), and the
basal 16 m of the Lower Elton Formation. Gamma-ray logs and borehole records are also available and penetrate the full thickness of the Much Wenlock Limestone Formation (33 m) and underlying top few metres of the Farley Member (Coalbrookdale Formation). The Much Wenlock Limestone Formation, as exposed, is notable for conspicuous reefs associated with a series of bedded lithofacies belonging to the nodular limestone, interbedded limestone and silty mudstone, and crinoidal grainstone lithofacies described and interpreted by Ratcliffe & Thomas (1999). Recent carbon isotope analysis has identified that the Wenlock-Ludlow boundary broadly corresponds to the end of the Mulde carbon isotope excursion (Blain et al. 2016).

Carbon isotope and facies variability at the Wenlock–Ludlow boundary (Blain et al. 2016).
Ironbridge World Heritage Site

Located in a steep gorge of the River Severn, Ironbridge village takes its name from the famous 30-metre (100 ft) cast “Iron Bridge” that was built across the river in 1779. The oft-cited claim of being the "Birthplace of the Industrial Revolution" is based on Abraham Darby’s development of cheaper iron smelting techniques, using coke, in Coalbrookdale from 1709. These technical developments inspired further groundbreaking innovations including the practical application of the steam engine. These were used to pump water from mines, to recirculate water to the reservoirs and from 1776 to directly work the bellows of the blast furnaces. These engines were built at the Coalbrookdale works that became one of the principal suppliers of cylinders for engines built elsewhere in Britain. There was a virtuous circular link between the ironworks, coalmines and steam engine.

The use of the engines increased the productivity both of the mines and the ironworks, which in turn lowered the cost of iron and made engines cheaper. The development of iron rails and wheels for wagons, the construction of iron barges and the design and building of the Iron Bridge itself, constructed between 1777 and 1781, are all new technologies that were both developed and utilised within the Gorge. Darby’s iron smelting was but one small part of international industrial revolution, with Coalbrookdale soon eclipsed by the great centres of iron-smelting, but the Iron Bridge, being the first of its kind, remains an important symbol of the dawn of the industrial age.

As well as the extensive informal network of cart ways and footpaths within the Gorge, the rich natural resources of the area and their exploitation necessitated the creation of an infrastructure of strategic linkages to enable trade with both Britain and overseas. The River Severn was the earliest main artery of trade on which barges were in use by the early 15th century. By the early 17th century there was a community of barge and trowmen settled in the Gorge where, from riverside wharves, coal became the staple trade up to Shrewsbury and down to Bristol. Although horse tow paths began to be introduced at the end of the 18th century and the Coalbrookdale Company owned a small river fleet briefly c.1800, other industrialists never tried to integrate river transport into their operations. The competition from railways caused the river trade to decline sharply in the mid 19th century and it was virtually extinct by the mid 1880’s.

Before 1780, the Severn was not bridged between Buildwas to the west and Bridgnorth to the south, with coracles and ferries being used to
cross the stream. Abraham Darby’s grandson - Abraham Darby III - built the famous bridge to link the two banks of the River Severn. Originally designed by Thomas Farnolls Pritchard, construction began in 1779 and the bridge opened on New Year's Day 1781. Soon afterwards the ancient Madeley market was relocated to the new purpose-built square and Georgian Butter Cross, focusing development of the dispersed settlement of Madeley Wood into the village of Ironbridge. This became the commercial and administrative centre of the Coalbrookdale coalfield.

The Iron Bridge proprietors also built the Tontine Hotel to accommodate visitors to the new bridge and the industrial sites of the Severn Gorge. On the hillside above the river are situated the stone-built 16th-century hunting lodge at Lincoln Hill, many 17th- and 18th-century workers' cottages, as well as imposing Georgian houses built by ironmasters, mine owners and river barge companies. Many of the early Victorian villas are built from the coloured bricks and tiles of the locality.

The Ironbridge Gorge includes the deeply incised valley of the River Severn together with the two tributary valleys of Coalbrookdale and Washbrook. The Gorge is a glacial feature, which was deepened when the River Severn was diverted from its original course and cut through the southern end of the coalfield leaving its rich resource of minerals conveniently exposed. Productive Middle and Lower Coal Measures underline the area. Thinning beds of Upper Coal Measures siltstones and marl, with sandstones, occur at Coalport, in the Washbrook valley and around the western edge of a productive coalfield in a crescent from Woodside to Madeley Wood. The drift cover is mainly boulder clay but sands and gravels occur around Cuckoo Oak, Hills Lane and Blists Hill in the east and near Lodge and Strethill Farms in the west. There are alluvial deposits in the lower part of Coalbrookdale and westwards along the Severn. Lincoln Hill on the eastern side of Coalbrookdale is a spectacular outcrop of Silurian Limestone.

The steep slopes of the Severn Gorge and of Coalbrookdale are geologically unstable and prone to movement, with landslips occurring in areas of extensive fill; mining subsidence also affects the area. Local clay also allowed the manufacture of bricks and tiles that formed the core material from which the majority of post 17th century buildings within the Gorge were constructed. The range of different strata of clay allowed the diversification and specialisation of the clay industries, especially on the south bank of the river Severn in Broseley and Jackfield which became famous for roof tiles, white bricks, common
bricks and specials, as well as decorative tiles, pottery and clay tobacco pipes.

This photograph from the turn of the twentieth century was taken from the south side of the Severn looking over Nailers Row, now demolished, to the western end of Ironbridge and Lincoln Hill beyond. The impact of the years of limestone extraction on the hillside can be clearly seen.
References


