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Gerta Keller and Andrew Kerr – Programme Organisers

Norm McLeod – Local Organiser

WELCOME

Volcanism, Impacts and Mass Extinctions:

Causes and Effects

International Conference, March 27-29, 2013

The Natural History Museum, London

The main objective of this international, multi-disciplinary conference is to bring together researchers across the geological, geophysical, and biological disciplines to assess the state of research into the causes of mass extinction events and evaluate the respective roles of volcanism, bolide impacts, sea level fluctuations and associated climate and environmental changes in major episodes of species extinction.

Over the last 30 years considerable research efforts have been directed toward understanding the context and nature of environmental changes that occurred immediately prior to, at, and after the five major Phanerozoic mass extinctions. In particular, important new data and observations have been published that bear on the interpretation of these events from the fields of palaeontology, stratigraphy, sedimentology, geochronology, geochemistry, mineralogy, volcanology, geophysics (notably palaeomagnetism) and astrophysics. Consequently, a critical review of these data/observations — along with a thorough consideration of their implications with respect to identifying the causes of these eco-evolutionary events — is warranted.

In this context the end-Cretaceous extinction event is particularly noteworthy because it serves as the benchmark for understanding the types of re-search projects that need to be undertaken throughout the geologic column in order to achieve a genuinely comprehensive understanding of major extinction episodes. Improving our understanding of these events is important not only because of its intrinsic link to understanding the history of life, but also because of the link that is often drawn between ancient mass extinctions and the modern biodiversity crisis.

In addition to reviewing the physical and biotic evidence, this conference will assess the present status of disagreements between proponents of different mass extinction cause hypotheses by integrating, refining, and evaluating discrepancies in the evidence from different disciplines. The conference is intended to foster a new, collaborative, interdisciplinary, community-wide approach to resolving outstanding problems in this field. The data and concepts presented and discussed at this conference are sure to have broad implications that will extend throughout, and well beyond, the geosciences because they will summarize the baseline data necessary for understanding both ancient and modern species extinction events.

Technical Programme

The conference programme covers many aspects of the five major mass extinction events, impacts and large igneous provinces and their hypothesized causes based on a wide range of keynote lectures, invited overview presentations, and contributed presentations and posters. Presenters will be able to offer their interpretations and opinions regarding likely causal scenarios consistent with their data, but a clear separation between presentation of data and observations and interpretations is encouraged.

Each day presentations will be followed by focused discussions and debate both formal and informal. The conference will end with a debate between proponents of the various mass extinction causal models whose purpose will be to encourage the audience to think critically about the extent to which mass extinctions can be seen as arising from a set of generalized causes intrinsic to the Earth, are the products of unique conditions imposed from outside the Earth systems, or a combination of both.

The programme is organized into Sessions I to VII.

Day 1 - ***Session I: Reviews of records on mass extinctions, volcanism and impacts*** are presented by a series of invited lectures that set the stage for the meeting.

Session II: Meteorite impacts and comet showers consists of invited lectures on recent advances in astrophysics with major implications for climate change and mass extinctions.

Session III: Large Igneous Provinces focuses on the relationship between LIPS and mass extinctions and the effects on atmosphere and climate.

Session IV: Ordovician and Devonian mass extinctions are reviewed by invited experts.

Debate and Posters: At the end of the day a short discussion of the key events is followed by informal discussion in a relaxed atmosphere during the poster session.

Day 2 - ***Session V: Permian-Triassic mass extinctions and LIPS*** emphasises the Siberian Traps and their effects on climate, atmosphere and life.

Session VI: Triassic-Jurassic mass extinction and LIPS focuses on this increasingly important mass extinction and its relationship to the Central Atlantic Magmatic Province (CAMP).

Session VII: End-Cretaceous mass extinction, Volcanism & Impacts focuses on this well-known and much debated mass extinction and its relationship to multiple impacts, Deccan volcanism and climate change.

Debate and Posters: At the end of the day a short discussion of the key events is followed by informal discussion in a relaxed atmosphere during the poster session.

Day 3 – continues ***Session VII: End-Cretaceous mass extinction, volcanism & impacts*** with the major emphasis on Deccan volcanism and its global effects.

Session VIII: Concluding Discussion and Debate: The meeting ends with a debate between proponents of the various mass extinction causal models, the search for links between disciplines and encourage multidisciplinary collaborations to solve outstanding problems of mass extinctions.

Acknowledgements

In addition to the hosting and organizational support of the conference by The Natural History Museum and the Mineralogical Society of Great Britain and Ireland, financial donations to offset conference expenses have been gratefully received from the Solid Earth Composition and Evolution Working Group of the International Mineralogical Association, the Volcanic and Magmatic Studies Group (VMSG) of the UK, the Society for Sedimentary Geology (SEPM) USA, and Earth Sciences Institute, ISTE, GEOPOLIS, Lausanne University, Switzerland. The Department of Geosciences, Princeton University, USA, provided website and secretarial support.

Publication of the GSA Special Paper

An edited volume of review and original research articles based on the conference presentations will be published by the Geological Society of America as part of its Special Paper Series. GSA Special Papers have been accepted into Thomson Reuter's Book Citation Index. Citations will be counted on the book, chapter, and author levels and will become part of an author's H index score.

To ensure inclusion in this volume, completed articles should be received no later than two months after the conference (May 31, 2013). GSA expects to publish this volume by spring 2014. To meet this deadline we must submit the reviewed/revised and finalized manuscripts for printing to GSA no later than September 2013. This is doable if we all hold to the deadlines outlined below and reviewers can be held to a reasonable time table of 4-6 weeks max.

Our objective is a series of review and original research papers that deal with recent advances concerning all five mass extinction events, impacts and volcanism (large igneous provinces) and integrating, as far as possible, the fields of volcanology, geophysics, geochronology, geochemistry, sedimentology, mineralogy, paleontology and astrophysics. The objective is to further a comprehensive integrative and multi-disciplinary approach that can significantly advance our understanding of major events in Earth's History.

To achieve this objective, authors are encouraged to incorporate new information and emerging data from various fields that may lead to more comprehensive or alternative scenarios than would be possible based on data from single disciplines.

The deadline for submission of papers is set for May 31, 2013, which permits incorporation of information gleaned from our multi-disciplinary conference.

Deadline for submission of manuscripts	May 31, 2013
Reviews completed	July 1, 2013
Revisions completed	August 1, 2013
Submission of final manuscripts to GSA	September 1, 2013

As you prepare your papers, please follow the GSA guidelines summarized below with more details posted at http://www.geosociety.org/pubs/bookguid.htm

- Manuscripts must have line numbers and should be double spaced.
- Abstracts should be restricted to no more than 250 words.
- The original text files should be in Word (Mac files are O.K.).
- Tables should be compiled in Word or Excel.
- For figures the information is extensive and is detailed on the GSA Web site

(http://www.geosociety.org/pubs/bookguid4.htm). In brief: the following native formats work best, as long as the version of the application is noted and the file is labeled with the correct extension: Corel Draw = .cdr; Canvas = .cvs; Freehand = .fh; Illustrator = .ai; and Photoshop = .psd. If you create either .tif or .eps files, they must be between 300 (for photos) and 1200 (for line art) dpi resolution at full size. Label figure files with author name, figure number, and extension.

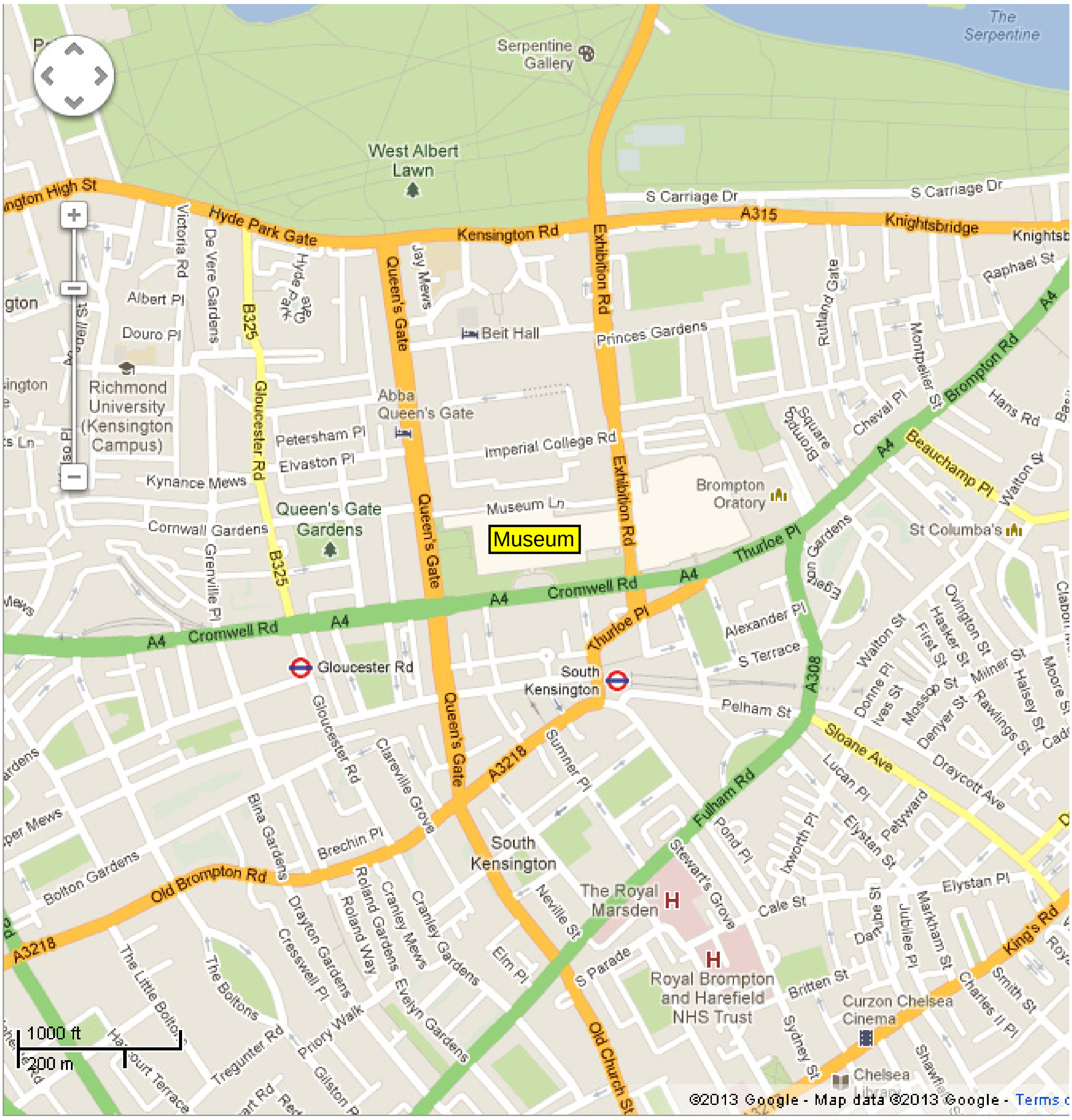
- GSA does print colour figures and has offered two free color figures per chapter in this Special Paper in honor of their 125th anniversary in 2013. If you wish to include more than two colour figures then the GSA will charge a modest $400 for the first additional page of colour in a chapter and $100 for each subsequent page of colour in the same chapter.

Please submit completed manuscripts via email as a single pdf file by 31 May 2013 to:

Either: Gerta Keller <gkeller@princeton.edu>

Or: Andrew Kerr <KerrA@cardiff.ac.uk>

Map of the area around the Natural History Museum



SCHEDULE OF ORAL PRESENTATIONS

WEDNESDAY MARCH 27th

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Vincent Courtillot, *Frédéric Fluteau*

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Tony Hallam

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Models for the recovery of life from mass extinction
Michael J. Benton

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Session II: Meteorite Impacts & Comet Showers

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Implications of the centaurs, Neptune-crossers and Edgeworth-Kuiper Belt for Terrestrial catastrophism: Dwarf planets, minor planets, giant comets and dust
Duncan Steel

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Invited Page 48
Revised flux of meteorite impacts on Earth; probabilities and consequences for the geological record?
Adrian P Jones

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The Boltysh Crater record of the K/Pg: Impact and the record of the K/Pg boundary

Simon Kelley*, Dave Jolley, Iain Gilmour, Robert Daly, Mabs Gilmour*

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Extraterrestrial driver for 536-537 AD climate catastrophe

Dallas Abbott

12:35-14:00 - **Lunch Break** – a wide variety of restaurants, snack bars and pubs are available in the area around the Museum.

Session III: Large Igneous Provinces (LIPS)

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The tropospheric chemistry of volcanic plumes

T.A. Mather

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Impact of large igneous provinces: a modelling approach

Frédéric Fluteau*, Mickael Mussard, Guillaume Le Hir, Yves Balkanski, Olivier Boucher, Vincent Courtillot*

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Assessing the atmospheric S burden of continental flood basalts through synchrotron light micro-XRF

Sara Callegaro*, Don R. Baker, Angelo De Min, Cecilia Viti, Hervé Bertrand, Fabrizio Nestola, Andrea Marzoli*

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Self-limiting chemistry, aerosol and climate effects of large-scale flood lava eruptions

Anja Schmidt*, Thorvaldur Thordarson, Marjorie Wilson, Kenneth S. Carslaw*

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The role of mantle volatiles in the formation of large igneous provinces and associated mass extinction events

Sally A Gibson

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Intrusive LIPs: Deep crustal magmatic processes and the dual-timescale problem for the emplacement of Large Igneous Provinces

Mark A. Richards

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Howard A. Armstrong, *David A.T. Harper*

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Michael Joachimski

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George R. McGhee Jr

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THURSDAY MARCH 28

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Linda T. Elkins-Tanton*, Benjamin Black, J.-F. Lamarque, Christine Shields, Jeffrey Kiehl*

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Paul B. Wignall*, David P.G. Bond*

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David P.G. Bond*, Paul B. Wignall, Yadong Sun,, Dierk Blomeier*

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Stephan V. Sobolev*, Alexander V. Sobolev*

Session VI: Triassic-Jurassic extinction & LIPS

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József Pálfy

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Andrew H. Caruthers*, Paul L. Smith, Darren R. Gröcke*

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Jacopo Dal Corso*, Andrea Marzoli, Fabio Tateo, Hugh C. Jenkyns, Hervé Bertrand, Nasrrddine Youbi*

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Grzegorz Pieńkowski*, Grzegorz Niedźwiedzki, Marta Waksmundzka*

12:20-14:00 - **Lunch Break** – a wide variety of restaurants, snack bars and pubs are available in the area around the Museum.

Session VII: End-Cretaceous mass extinction, Volcanism and Impacts

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Gerta Keller*, Thierry Adatte*

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T. Adatte*, G. Keller*

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Invited Page 22

What the dinosaur record says about extinction scenarios
J. David Archibald

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Latest Cretaceous continental vertebrates of Indo-Pakistan
Jeffrey A. Wilson*, Gregory P. Wilson, Dhananjay M. Mohabey*

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Gregory P. Wilson*, Casey J. Self*

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Geochemical proxies (major, trace and platinum group elements) across the KT boundary: What can they tell about the role of impacts and volcanism?
Brian Gertsch*, Gerta Keller, Thierry Adatte*

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FRIDAY MARCH 29th

Session VII: End-Cretaceous mass extinction, Volcanism and Impacts continued

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***Stephen Self**, Lori S. Glaze, Richard J. Brown*

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***Mike Widdowson**, Simon P. Kelley, Conall MacNiocall*

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***Eric Font**, Sébastien Fabre, Anne Nédélec, Thierry Adatte, Gerta Keller, Brooks Ellwood, Cristina Veiga-Pires, Jorge Ponte and José Mirão*

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***Christian Tegner**, Claus Heilmann-Clausen, Rune. B. Larsen, Adam J. R. Kent*

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Steve Miller

11:05-11:30 - **Coffee/tea break**

11:30-13:00 - Session VIII: Concluding discussion and debate

13:00 – Close of meeting

ALPHABETICAL LIST OF POSTERS BY FIRST AUTHOR

Abstracts in alphabetical order by first author

Extraterrestrial driver for 536-537 AD climate catastrophe

Dallas Abbott[1]
Dee Breger[1], Pierre Biscaye[1]and John Barron[2]

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[2]*US Geological Survey, Menlo Park, CA 94025*

In the time period from March 536 A.D. to June 537 A.D., tree rings and ancient writers document a dramatic climate downturn. This climate downturn produced widespread deaths from famine in Asia and Europe. During the growing season of 536 A.D., trees in Europe, North America and Central Asia formed frost rings. Frost rings are a result of below-freezing temperatures for several consecutive days during the growing season. In addition, four ancient writers record a faint sun lasting for 18 months in Mesopotamia, and for shorter periods further north in Europe and Asia. These durations point to an equatorial source for the fine atmospheric dust needed to drive the solar dimming. Volcanic aerosols and cometary dust have both been vigorously promoted as the primary cause of this solar dimming. We argue for a cometary source for this climate catastrophe based on ice core, geophysical and marine geological data. In contrast, we found 25 tropical to subtropical marine diatoms in the GISP2 ice core in two adjacent samples that span 536-537 A.D., based on the error of layer counting of ± 3 years. The GISP2 ice core was taken high on the Greenland ice cap, an area where most particulates originate from central Asian deserts. Similarly, most diatoms found in high altitude ice cores are terrestrial rather than marine in origin. One of the marine diatoms is benthic, implying a water depth of less than 100 meters. The particulates that accompany the marine diatoms include zircon, barite, and one terrestrial diatom. These point to a continental shelf, high productivity source for the ice core particulates. In addition, we found high Ni, no Cr dust and quench textured magnetite spherules that span the 536-537 A.D. interval. Some dust resembles cosmic dust in morphology and composition. Ion data show a modest sulfate anomaly, too small to be from a major, climate changing volcanic eruption. The few pieces of volcanic ash we found have a widely varying chemical composition inconsistent with a major, climate changing volcanic eruption. Thus, our ice core data to date point away from a volcanic eruption and towards a high-energy event that could move marine diatoms and other particulates from a low latitude shelf to the mountains of Greenland. Because we found accompanying high-Ni dust with no Cr, implying an extraterrestrial source, we infer an impact that hit a low latitude continental shelf. We identify a candidate impact ejecta layer in the Gulf of Carpentaria Australia, a shallow continental shelf with high biological productivity. The layer is dated to circa 536-537 A.D. but the errors are currently still large. The layer contains quench textured magnetite spherules, shocked ilmenite, silicate spherules and flow textured, nonvesicular glass. The layer is found in 4 marine cores whose locations form a rough square separated by over 130 kilometers on its 4 edges. The concentration of inferred impact ejecta in the layer increases towards two round gravity lows within the Gulf. Because the oscillation of water tends to fill submarine craters with low-density marine sediment as they form, circular gravity lows are the most robust expression of submarine impact craters. In addition, the back azimuths of V shaped chevron dunes located on nearby Carpentaria islands point towards these crater candidates. We have been able to visit one chevron dune complex. It is late Holocene in age and contains 10-20% carbonate, whereas wind blown sand typically lacks carbonate. One chevron contains 2-5 centimeter-sized pieces of beach rock and coral located kilometers inland and tens of meters above sea level. The largest rock fragments that can be moved by the wind are about 4 millimeters in diameter. We are actively examining candidates for impact ejecta taken from a lag deposit on the beach end of the chevron, the only part we have had permission to sample thus far. In addition, we are refining the dates for our ejecta layer in the four marine cores and continuing to search for more shocked minerals. Our continuing investigations are expected to determine whether the 536-537 A.D. climate downturn was driven by the Carpentaria event.

Chicxulub impact and the KT breccia from North America to Brazil: Stratigraphy, age, nature and origin

T.Adatte [1]
G. Keller [2]

[1] *Earth Sciences Institute, ISTE, GEOPOLIS, Lausanne University, Switzerland*
[2] *Geosciences, Princeton University, Princeton NJ, USA*

Of the five major mass extinctions in Earth's history, only the Cretaceous-Tertiary (K-T) mass extinction has been positively linked to an asteroid impact based primarily on the presence of a global iridium anomaly coincident with the near total mass extinction of planktic foraminifera, the discovery of the Chicxulub crater in northern Yucatan and impact glass spherules at the base of a sandstone complex below the K-T boundary in NE Mexico. Similar siliciclastic deposits with Chicxulub impact spherules have been documented from New Jersey, NW Atlantic, Alabama, Texas, northern to southern Mexico, Belize, Guatemala, Haiti and Cuba, whereas breccia deposits with impact melt rock or spherules are reported from southern Mexico, Belize, Brazil and the Chicxulub impact crater core Yaxcopoil-1. All of these impact ejecta-bearing deposits are generally assumed to have formed precisely at the time of the Chicuxlub impact, which is assumed to have caused the end-Cretaceous mass extinction (see poster by Mateo et al).

However, these assumptions are not supported by the stratigraphy, sedimentology, geochemistry and the fossil record. Problems include the presence of multiple impact spherule layers in latest Maastrichtian and early Danian sediments, where these layers are reworked from older deposits and redeposited into younger sediments [1-3]. Thus, multiple impact spherule layers are well known from the latest Maastrichtian zone CF1 (last 160 ky below the KTB) in Texas and NE Mexico, early Danian of Haiti, Belize and Guatemala and at the K-T boundary in some sections in the Caribbean and NW Atlantic. The strong belief that the Chicxulub impact caused the KT mass extinction has led some workers to define this impact as precisely KTB age, citing evidence of the thin spherule layer present in a few deep sea sections from the NW Atlantic. Apart from circular reasoning (one cannot determine the age of the Chicxulub by defining this impact as KTB age), NW Atlantic sites are known to be very incomplete due to current circulation and a major hiatus marks the K-T transition.

Based on time tested stratigraphic principles, in any vertically stacked sequence the lowermost sedimentary layers are the oldest. In the case of Chicxulub ejecta, the oldest impact spherule layer is found interbedded in undisturbed and horizontally bedded late Maastrichtian zone CF1 sediments in NE Mexico (El Penon) over 4 m below the sandstone complex and predating the KTB by about 150,000 years[3]. All stratigraphically younger impact spherule layers represent repeated episodes of reworking of the original layer during a sea-level regression and are part of siliciclastic deposition in submarine canyons via mass flows and turbidites (NE Mexico)[4], or incised valleys in shallow environments (e.g., Brazos, Texas, La Popa Basin NE Mexico)[5]. The widespread thick microspherule and spheroid deposits in southern Mexico, Belize Guatemala and Haiti are interbedded with breccia, microbreccias and conglomerates resulting from the erosion of shallow carbonate platform sediments[2].

These data indicate that the Chicxulub impact and KT mass extinction are two separate and unrelated events and that the biotic effects of this impact have been vastly overestimated. The cause for the KT mass extinction must be evaluated based on the totality of evidence and the convergence of multiple events, including the environmental effects of Deccan volcanism, impact(s), climate and sea level changes during the latest Maastrichtian.

1. Keller et al., 2003a, Earth Science Reviews 62, 327-3363. **2. Keller et al., 2003b**, J. Geol. Soc. London, 160, 783-795. **3. Keller et al., 2009,** J. Geol. Soc. London, 166, 393-411. **4. Schulte et al., 2003**, Int. J. Earth Sci. 92, 114-142. **5. Adatte et al., 2011,** SEPM Special Publication No. 100, 43-80.

Sharks across the K/T boundary at Stevns Klint, Denmark

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David J. Ward [3]

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The K/T-boundary is famous for its major extinction event, but details of the extent of the event and the resolution of the subsequent recovery suffer, in part, due to a lack of suitable exposures. The outcrop at Stevns Klint, south of Copenhagen, Denmark is one such locality. The marine boundary section at Stevns Klint is complete and the well defined. The Fiskeler (Fish clay) is separable into three different layers and has been investigated for its iridium signature and clay minerals ever since the impact theory was resurrected. However, despite its name, its vertebrate fauna has been largely ignored. The separability of the different layers of the boundary clay offers a unique opportunity to perform a highly detailed study of the elasmobranch faunal changes across the K/T-boundary, as the preservation and the isotopic signatures of the shark teeth suggest no reworking.

More than two tonnes of sediments were sampled layer by layer and processed. Residues were sorted for microvertebrates, principally sharks' teeth, separated into species, identified and imaged with an SEM.

Within the uppermost 60 cm of the Maastrichtian Chalk, a diverse fauna comprising 27 species of elasmobranchs was present. The fauna contained large Lamniformes, Hexanchiformes and Synechodontiformes, but also small Squaliformes and Carcharhiniformes. The fauna experienced a sudden drop in diversity prior to the boundary. Immediately after the Iridium layer, the impoverished shark fauna recovered to 22 species, the majority of which were present in the Maastrichtian chalk. The early Danian limestone, the Cerithium Limestone, has a diverse fauna of 18 species, again showing a close affinity with the Late Maastrichtian fauna. In the middle Danian bryozoan limestone (Faxe Fm.) the fauna has changed noticeably with an increase in diversity of Hexanchiformes and Synechodontiformes and the loss of some of the smaller species.

Nine species disappeared prior to the boundary at Stevns Klint of which six appear to have become extinct and three are present at a generic level later in the European Paleocene. Seventeen species survive the boundary event. With only a 33% disappearance at or before the boundary, these results differ radically from those from Morocco by Noubhani and Cappetta (1997) who reported a 96% drop in diversity! The reasons for this discrepancy are discussed.

The extinction event at the boundary appears to have severely affected shallow water rays, while Hybodont sharks, Sclerorhynchid rays (sawsharks) and one family of large lamniform shark, the Anacoracidae became globally extinct. The probable reasons include habitat loss and dietary specialisation

Noubhani, A. & Cappetta, H. 1997. Les Orectolobiformes, Carcharhiniformes et Myliobatiformes (Elasmobranchii, Neoselachii) des Bassins à phosphate du Maroc (Maastrichtien-Lutétien basal). Systématique, biostratigraphie, évolution et dynamique des faunes. Palaeo Ichthyologica, 8, 1-327

What the dinosaur record says about extinction scenarios

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In isolation, the dinosaur record offers a limited appraisal of extinction scenarios. Only when combined with records of other more frequently preserved fossils do we gain a better image of these extinctions and their likely causes. This said, a geographically limited but clear pattern for latest Cretaceous dinosaurs emerges. All continents preserve at least a limited record of latest Cretaceous dinosaurs, but despite continued fieldwork, only North America preserves a fossil record of vertebrates before, at, and after the K/Pg (Cretaceous/Paleogene) boundary. Despite repeated attempts to argue otherwise, a clear portrait emerges of decline in dinosaur taxonomic diversity in the waning 10 my (million years) of the Cretaceous in this region. The best record between 76 and 74 mya (million years ago) occurs in southern and western Canada and northern and western United States. The Late Campanian (Judithian) – aged sediments of Dinosaur Provincial Park in southern Alberta preserve both ornithischians and saurishcians, with the latter limited to theropods, the group including both birds and the mostly large to extremely large terrestrial, bipedal, mostly carnivorous nonavian dinosaurs. Late Cretaceous sauropods did not make it further north than southern Wyoming. Of the better-preserved material, ornithischians outnumber theropods by four to one. Of these ornithischians 50% are specimens of duckbilled hadrosaurs, 25% are horned ceratopsians, with the remaining 25% mostly armored ankylosaurs and boneheaded pachycephalosaurs. Taxonomically, the ornithischians in the park comprise: three genera of ankylosaurs, each with one species, three species of the pachycephalosaur, six species of ceratopsians belonging to four different genera, eight hadrosaurs in six genera, and on one hypsilophodontid. Although theropods make up less than 10% of fossils recovered, they are quite diverse, comprising 40% of the forty genera recognized in the park. In the latest Cretaceous, specifically, Late Maastrichtian (Lancian) a comparably well-sampled nonavian dinosaur fauna comes from the 69 and 66 mya Lance/Hell Creek formations in Wyoming, Montana, and the Dakotas. The Dinosaur Park and Lance formations represent similar intervals of time and similar depositional histories of coastal fluvial and floodplain deposits draining easterly into the Pierre or Western Interior Seaway, the large epicontinental sea divided North America into western Laramidia and eastern Appalachia continents for most of the 35 million years of the Late Cretaceous. Whereas Dinosaur Park preserves 38 species of nonavian dinosaurs, the taxonomically most diverse Lancian-aged nonavian dinosaur fauna from the type Lance Formation has only 18 species, a drop of about 53% species abundance in the last 10 my of the Cretaceous in North America. The Lance Formation includes only two species of ankylosaurs, one species of pachycephalosaur, four ceratopsians, two hadrosaur, two other ornithischians, and seven nonavian theropods. Even when all Judithian- and Lancian-aged nonavian dinosaur faunas in the region are included in a comparison, the loss of nonavian dinosaur species decreases only slightly to 52%. A common myth against comparing the Dinosaur Park and Lance formation nonavian dinosaur faunas concerns a lack of spatial equivalence; however, all Judithian-aged sediments in the region cover 48,000 sq km preserving some 48 taxa, whereas all Lancian-aged sediments in the region cover 57,000 sq km and yet yield at most 23 species. Detecting a decline nearer the K/Pg presents problems because of the nature of this dinosaur record. Read literally, the best nonavian dinosaur records show a decline of seven to five to three to two to zero species in the last four meters before the K/Pg boundary. This may be illusory as the exposure of this small part of stratigraphic section limits recovery of scarce dinosaur remains. As well, preservation is poor for any vertebrate fossils within the last three meters before the boundary. This renders such a literal reading of the fossil record suspect. Thus, given the nature and quality of these last few meters of section, we cannot be certain of a gradual or stepwise decline or of an abrupt extinction of the last nonavian dinosaurs, or even if a few survived the K/Pg boundary. With certainty we know that nonavian dinosaurs suffered over 50% decline in taxonomic diversity over the last 10 million years of their existence in at least North America as a result of some ecological changes, but what the rate of decline was for the very last of the nonavian dinosaur remains unresolved.

End-Ordovician mass extinction

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The end-Ordovician mass extinction is recognised as one of the "Big Five" reflecting a global and rapid rise in extinctions concomitant with a rise in originations. Estimates indicate that in the marine realm 20% of families and about 40% of genera went extinct at this time. This mass extinction established the Palaeozoic plateau in biodiversity that continued until the end of the Palaeozoic Era. Though of high taxic impact, the extinction removed few entire clades and caused minimal disruption to marine ecosystems, mainly at the community and clade level. Changing environmental conditions provided a range of cryptic refugia for a large number of Lazarus taxa. The mass extinction comprised two extinction phases; both have been linked to intense glaciation at the South Pole. The first phase of extinction occurred at, or just below, the *Normalograptus extraordinarius* graptolite Zone (base of the Hirnantian Stage). This particularly affected benthic organisms in shallow- and deep water environments greater than organisms at mid-water depths, the zooplankton, particularly graptolites, and nektonic groups. Coincidence of the S-isotope and major positive carbon isotope excursions indicates elevated rates of organic carbon and pyrite burial commenced during the early Hirnantian, a likely oceanic response to eutrophication during glaciation and suggestive of dramatic changes in the depth of the chemocline. Glacially-induced cooling also resulted in a concomitant equator-ward shift and contraction in the temperate zone and falling sea level. The second extinction pulse, occurred in the *N. persculptus* graptolite Zone (middle Hirnantian Stage), was less selective, removing faunas across a range of water depths and survivors from the first extinction, for example conodonts. Redox indicators suggest that euxinic and in some places ferruginous waters encroached onto the continental shelves at this time. Taken together, significant reduction in prospective niche space, a result of complex, dramatic and climatically-induced, oceanographic conditions was the primary causative mechanism for the end-Ordovician mass extinction.

Ginkgophytes at the Permian-Triassic boundary: How diverse were they?

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The ginkgophytes are a group of gymnosperms believed to have originated during the late Paleozoic. Nevertheless, Paleozoic fossils of these plants are rare and often difficult to interpret. Only a single Paleozoic foliage genus (i.e. *Sphenobaiera*) has been reported from localities worldwide. As a result, it is widely believed today that the major diversification within the ginkgophytes reflected in the Mesozoic fossil record did not commence before the Middle to Late Triassic. However, newly discovered fossils from the upper Permian of Bletterbach in northern Italy, together with a revision of the ginkgophytes from the famous German Kupferschiefer flora, shed new light on the diversity of these plants at the end of the Paleozoic. At least three distinct ginkgophyte foliage morphotypes occurred in Europe during the late Permian, including *Sphenobaiera, Baiera* and *Trichopitys*. In addition to the characteristic Permian *Baiera/Sphenobaiera digitata*, two other leaf taxa have recently been discovered in the Bletterbach flora, and still two others were recently identified in the Kupferschiefer flora. The new discoveries suggest that a first diversification (radiation?) within the ginkgophytes may have occurred before the end-Permian mass extinction, and not, as previously believed, first during the Middle or even Late Triassic.

Models for the recovery of life from mass extinction

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Palaeontological studies of the recovery of life from mass extinctions have focused on diversity and abundance data in well-dated sections. Such studies have shown the importance of 'disaster taxa', r-selected, fast-breeding, and adaptable forms that may radiate rapidly and occupy ecospace, but that are in turn replaced by different and often unrelated taxa that form the basis of the eventually stable replacing evosystems. In many cases, in ecological terms, the ecosystems seem to rebuild from the bottom up, primary producers becoming re-established first, then herbivores and low-level carnviores, and finally the top-level carnivores at the top of the food chain.

Many debates over the past 20 years have focused on somewhat semantic issues, such as the definition of 'recovery', and hence whether it can be claimed that life recovered 'early' after the end-Permian mass extinction, within 1-2 Myr, or 'late', within 8-15 Myr. Theoretical models, such as that of Solé et al. (2010), have been framed in terms of a uniform physical environment, and may be hard to assess in reality, when environments are not ideal, and indeed may continue to deteriorate at the time of recovery, for example through the Early Triassic (Chen and Benton 2012).

These studies do not address larger questions from evolutionary biologists who are interested in the nature of diversifications. Key questions concern how successful clades initially radiate, whether by an 'early burst' model, or in a more gradual way (Harmon et al. 2010). Further, are the clades that expand apparently opportunistically in the aftermath of a mass extinction any diferent from those that expand at other times, presumably for different reasons? Further, do major new clades speciate steadily as the new taxa occupy morphospace, or are diversity and disparity (= morphological variance) decoupled (Erwin 2007)? The widest questions of all concern the contribution of post-extinction recovery episodes to the overall evolution of life: how important, for example, were the recoveries from the end-Permian and end-Cretaceous mass extinctions in framing the key taxa today?

New phylogenetic methods allow exploration of some of these themes. A cladogram is required in order to provide a secure phylogenetic basis. **Disparity** can be assessed from continuous (e.g. landmark) characters, discrete characters (e.g. cladistic data), or from functional characters, and morphospace occupation then compared through time planes as a clade radiates after a mass extinction. The distribution and **rates of trait changes** can be assessed by comparative phylogenetic methods, which can highlight times of unusually fast or unusually slow evolution. Finally, the best-fitting **models of evolution** can be determined from the dated cladogram, and compared among major groups. These methods provide new insights into the role of recovery from mass extinction in the wider context of the history of life.

Chen, Z.Q. and Benton, M.J. 2012. The timing and pattern of biotic recovery following the end-Permian mass extinction. *Nature Geoscience* 5, 375-383.

Erwin, D.H. 2007. Disparity: morphological pattern and developmental context. *Palaeontology* 50, 57–73.

Harmon, L.J., J.B. Losos, J. Davies, R.G. Gillespie, J.L. Gittleman, W.B. Jennings, K. Kozak, M.A. McPeek, F. Moreno-Roark, T.J. Near, A. Purvis, R.E. Ricklefs, D. Schluter, J.A. Schulte II, O. Seehausen, B. Sidlauskas, O. Torres-Carvajal, J.T. Weir, and A.Ø. Mooers. 2010. Early bursts of body size and shape evolution are rare in comparative data. *Evolution* 64, 2385-2396.

Solé, R.V., Saldaña, J., Montoya, J.M., and Erwin, D.H. 2010. Simple model of recovery dynamics after mass extinction, *Journal of Theoretical Biology* 267, 193-200.

Latitudinal bias to extinction risk? Middle and end-Permian extinctions were severe and rapid in the Boreal Realm

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The middle to end-Permian (260-250 Myr BP) witnessed two mass extinctions that changed the course of life on Earth. The first, a Capitanian extinction, lay for many years undiscovered in the shadow of the greatest crisis in Earth's history, at the close of the Permian. The earlier of these events (occurring in the penultimate Stage of the Permian) wiped out >50% of marine invertebrate species and was discovered in the record of fusulinacean foraminifers in South China, where it is seen to precisely coincide with the onset of Emeishan large igneous province volcanism. This Capitanian extinction may be temporally associated with terrestrial losses amongst plants and megafauna suggesting an event of global scale with a suitably large trigger in the form of volcanic and thermogenic emissions from Emeishan. The results of two seasons' fieldwork in Spitsbergen, at Isfjorden (Festningen) and Van Keulenfjord have revealed the Capitanian extinction event for the first time from a northern mid- to high-latitude (Boreal Realm) setting, confirming its global extent.

Our carbon isotope record allows precise correlation of Spitsbergen with sections in China, the site of Emeishan LIP volcanism, because a prominent negative excursion is associated with the Capitanian extinction level in both regions. This temporal link indicates that Emeishan volcanism was a killer of global extent, capable of affecting remote regions thousands of miles from its epicentre in South China. Its effects were profound even in Spitsbergen, where brachiopod losses were as severe, if not more so, than in equatorial regions. To achieve such damage, Emeishan must have injected volatile gases and perhaps ash far into the upper atmosphere.

Although of less significance globally, the earlier, Capitanian extinction amongst brachiopods was just as severe in Spitsbergen as the latest Permian event. The Capitanian event was one from which the brachiopods never really recovered, instead giving way to a Late Permian radiation of (mostly pectinid) bivalves. These faunas have a prominent Mesozoic character, suggesting that the transition from Palaeozoic fauna occurred in the aftermath of the Capitanian crisis, rather than during the Triassic as generally assumed. In effect, the Capitanian mass extinction amongst brachiopods was a precursor to the Permian-Triassic crisis that marked their final loss as dominant members of the marine benthos.

The end-Permian extinction occurs at or just below the Permian-Triassic boundary in most regions, but in Spitsbergen the loss of shelly benthos occurs 10m below the lithologically and chemostratigraphically defined PTB, still within bioturbated strata. This raises the prospect that the likely cause, Siberian Traps volcanism, affected the less hospitable environments of the higher latitudes earlier than the tropics. Furthermore, anoxia might not be the only factor to be implicated in that crisis. That higher-latitude, cooler water environments suffered first during environmental disturbances has profound implications for the near future of our planet: concerns about the polar regions today appear to be well-founded in the geological record, where there exists a latitudinal bias to extinction risk.

Assessing the atmospheric S burden of continental flood basalts through synchrotron light micro-XRF

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Severe forcing of Large Igneous Provinces (LIPs) on the environment through massive outpours of volcanic gases such as SO_2 and CO_2 (Self et al., 2008) is suggested by their synchrony with major Phanerozoic mass extinctions, but gas contents of the basalts and gas emission rates are poorly constrained. Here we deal with three LIPs that are synchronous with, and may have triggered, major biotic crises, namely Siberian Traps (end-Permian, c. 250 Ma), CAMP (Central Atlantic magmatic province; end-Triassic, c. 201 Ma) and Deccan Traps (end-Cretaceous, c. 66 Ma) and two LIPs whose emplacement only had a minor impact on the biosphere, i.e. Early Jurassic Karoo-Ferrar (c. 181 Ma) and Early Cretaceous Paranà-Etendeka (PE, c. 134 Ma). Classically, the gas load of a continental flood basalt (CFB) is estimated through analyses of melt-inclusions from early crystallized olivines in degassed flows (Self et al., 2008), but these investigations may be hindered by the paucity of fresh olivine phenocrysts, as for CAMP or PE. Hence, here we illustrate an alternative approach in which the pyroxene/melt sulfur partition coefficient (K_D) was appraised on experimentally crystallized clinopyroxenes (augites) from sulphide-saturated basalts (at 525 MPa and 1200° or 1175°C in a piston-cylinder apparatus). S (and Cl) contents were then measured by in-situ micro-XRF (Diamond synchrotron, UK) in augite phenocrysts from rocks chemically representative of the above mentioned LIPs. The magmatic S burden was thus calculated through the experimentally determined K_D, starting from the analyzed S in clinopyroxenes. Transmission electron microscopy (TEM) analyses discarded any presence of sulphide or fluid inclusions in (CAMP) clinopyroxenes, thus justifying the use of the K_D approach, which hinges on the concept of S being distributed at equilibrium between the magma and the crystal lattice. Data are presently available only for CAMP, PE and Deccan, but will shortly be completed with those from the remaining provinces. So far, S contents for Deccan basalts (0.04-0.14 wt.%) are consistent with those obtained by Self et al. (2008) on melt inclusions. No paramount differences are highlighted between CFB provinces, but, surprisingly, PE high-Ti and CAMP low-Ti samples show the highest and lowest S values, respectively. Rationales for the decoupling between volcanic gas burden and severity of biotic crisis may either be due to PE magmas being emplaced during weaker magmatic pulses at lower eruption rates or S not being the primary cause of environmental perturbations (in favor of CO_2 or other gases). Another hypothesis though hinges on the oxidation state of magmas influencing S solubility (Moretti and Baker, 2008). In this sense, strongly oxidized PE high-Ti basaltic magmas would have retained more S, with consequent reduced gas emissions and minor environmental impact.

Moretti R. and Baker D.R., 2008. Chemical Geology 256, 286–298.
Self S., Blake S., Sharma K., Widdowson M., Sephton S., 2008. Science 319, 1654-1657.

Global carbon cycling: Major implications of some new insights on global zeolite occurrence

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Recently published mineralogical and geochemical data supported by extensive evidence embedded in the research literature, suggests that many bedded zeolite occurrences represent altered volcanic glasses from alkaline-carbonatitic extrusive sequences, in a "zeolitic masquerade" (Campbell et al. 2012). The hypothesis and conceptual model is based on rationale taken from widely reported current understandings of precursor-glass reaction mechanisms and conditions (high pH, lower temperature fluids, alkaline and peralkaline glass compositions), and from recent major advances in the nature and extent of alkaline-carbonatitic extrusives (Bailey and Kearns, 2012). The implications of the globally-applicable masquerade hypothesis for past rapid carbon flux, climate modelling and mass extinction studies are therefore major. It follows that the zeolitic record, and elucidation of subsequent reactive progression in deeper geological successions, shall potentially provide new lines of evidence for estimating Earth-atmosphere carbon transfer. We present trace element signatures of zeolites as an initial test of the hypothesis, but further testing is needed, ideally from multiple disciplines.

In line with the criteria of Woolley and Kjarsgaard (2008) for carbonatite occurrences and the insights of Ernst and Bell (2010) on large igneous provinces and carbonatites, intracontinental rift settings form a focus of attention. Rifts are commonly associated with the economically significant bedded, saline lake type zeolite deposits, with classic examples in the East African Rift and the western USA. Progression of zeolite mineral reactions is detailed in Langella et al. (2001), demonstrating authigenic generation of feldspars where silica activity is increased. In a wider geological context, established diagenetic and metamorphic reactions (forward and reverse) involving zeolite-group minerals at different temperatures (see throughout Bish and Ming, 2001) are readily applied in the context of the hypothesis where silica undersaturated end-members/precursors (alkaline brines and alkaline volcanic glasses) are considered. It is suggested that, as reactions progress towards silica enriched assemblages, so does the progressive masking of their possible alkaline-carbonatitic origins.

In the spirit of exploratory interdisciplinarity of this meeting, it is further considered that major rapid influxes of nutrients (e.g. C, K, Ca) into surface environments from carbonatite-associated alkaline fluids, could potentially disrupt the nutrient balance of an ecosystem (eutrophication), increasing biotic stress. Thus, the presence of zeolites in bedded sequences has the potential to be compared stratigraphically with other mineralogical and geochemical indicators shown to be associated with mass mortalities. One such example is in the Eocene Green River Formation (Hellawell et al. 2009), where algal bloom biomarkers have been linked with recurrent fish mass mortalities. Zeolites are very well documented from this formation, providing scope for detailed further investigation into effects on nutrient dynamics. In conclusion, further studies of the behaviour of carbonatite-derived rocks and fluids in surface geochemical environments, and critically, their preservation in the geological record, shall offer potential new lines of evidence towards understanding controls on climate and biotic stressors that relate to extinction events.

Bailey, D. K. and Kearns, S. (2012) New forms of abundant carbonatite-silicate volcanism: recognition criteria and further target locations. *Mineralogical Magazine,* **76,** 271–284. •**Bish D, Ming D (eds) (2001)** *Rev. Mineral. Geochem*. **45**. •**Campbell, L. S., Dyer, A., Williams, C. and Lythgoe, P. R. (2012)** The masquerade of alkaline-carbonatitic tuffs by zeolites: A new global pathfinder hypothesis. *Mineralium Deposita*, **47**, 371–382. •**Hellawell, J., Pancost R., Evershed, R., Gill, F. and Nicholas, C. (2009)** Dead in the water: An investigation into Eocene fish mass mortality events.*J. Vert Palaeontol*. **29 (3)**, 113A. •**Ernst R. E. and Bell K. (2010)** Large igneous provinces (LIPs) and carbonatites. *Miner Petrol* **98,** 55–76. •**Langella, A., Cappelletti, P. and De Gennaro, M. (2001)** Zeolites in closed hydrologic systems. *Rev. Mineral Geochem.* **45,** 235-260. •**Woolley A.R., Kjarsgaard, B. A. (2008)** Carbonatite Occurrences of the World: Map and database. *Geol Surv Can, Open File* 5796.

The Pliensbachian–Toarcian (Early Jurassic) extinction, a global multi-phased event

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In this study Pliensbachian–Toarcian ammonite and foraminiferal species diversity data from western North America are compiled and compared with pre-existing data to investigate the geographic extent of the multi-phased Pliensbachian–Toarcian second order mass extinction. Previous ammonite diversity data from Europe and parts of the Arctic suggest that this extinction occurred over six separate intervals with the main-phase of decline beginning at the Pliensbachian–Toarcian boundary and extending into the Early Toarcian to a level that is correlative with the Tenuicostatum / Serpentinum Zone boundary (Dera et al., 2010). To date, only the main-phase of extinction has been demonstrated as being global in extent and affecting multiple taxonomic groups. This multi-phased extinction has been attributed to regional and global controlling mechanisms that are associated with the Volcanic Greenhouse Scenario which links the eruption of the Karoo–Ferrar large igneous province (LIP) to global warming and mass extinction.

Results show six intervals of species level decline that correlate with those recognized in Europe: 1) middle of the Early Pliensbachian (middle Whiteavesi–middle Freboldi Zones), 2) middle of the Late Pliensbachian (late Kunae–early Carlottense Zone), 3) Pliensbachian / Toarcian boundary into the Early Toarcian (late Carlottense–middle Kanense Zones), 4) Middle Toarcian (late Planulata–early Crassicosta Zones), 5) late Middle–early Late Toarcian (middle Crassicosta–Hillebrandti Zones) and 6) Late Toarcian (early Yakounensis Zone). As compared with the previously established data from Europe and parts of the Arctic, data from western North America show a similar main-phase of extinction. This main-phase of extinction shows a gradual decline in species diversity that begins at the Pliensbachian–Toarcian boundary and reaches its lowest levels in the middle part of the Early Toarcian Kanense Zone. This diversity minimum within the middle Kanense Zone also correlates with a large negative excursion in carbon-isotope values, thought to be related to the global release of methane from the hydrate reservoir (Hesselbo et al., 2000; Caruthers et al., 2011).

Recognition of this multi-phased event in three separate ocean basins (paleo Pacific, paleo Arctic, and Tethys Oceans), in at least two taxonomic groups, greatly expands the known geographic extent of this multi-phased event and argues for a controlling mechanism that is global in its reach. In relation to the Volcanic Greenhouse Scenario, our study shows that four of the six pulses of extinction occur within the main-phase of Karoo magmatism (using previously established ages of magmatism established by Jourdan et al., 2008). The decline in the Early Pliensbachian, previously thought to be separate from this event, occurs within error range of the onset of Karoo magmatism and the decline in the Late Toarcian coincides with the later stages of magmatism. These observations extend the known duration of this multi-phased extinction event to the Early Pliensbachian and support the Volcanic Greenhouse Scenario, specifically the eruption of the Karoo–Ferrar LIP, as a preeminent factor driving the multi-phased extinction of the Pliensbachian–Toarcian.

Hesselbo, S.P., et al. 2000. Nature, 406, 392–395.
Caruthers, A.H. et al. 2011. *Earth Planet Sci Let* 307, 19-26.
Dera, G. et al. 2010. J Geol Soc, London, 167, 21–33.
Jourdan, F., et al. 2008. Geochem, Geophys, Geosys, 9, 1–20. Q06009, doi:10.1029/2008GC001994.

Extremely fast LIP eruption rates as constrained from the Bushveld and Skaergaard intrusions

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Radiometric dating has too large uncertainties to precisely constrain the duration of volcanic events adequately in view of their increasingly perceived abruptness. The recording of single eruptive events – SEE – involving several temporarily related flows (defining a single palaeomagnetic directional group of time interval less than 100 years), has been proposed, but repose intervals between such SEE cannot be constrained.

The emplacement and especially cooling and crystallization period for intrusions can be calculated far more precisely and provide an alternative estimate for modeling irruptive periods. We refer to two very different examples here, namely the Bushveld Complex and Skaergaard Intrusion.

Vertical sections through the Bushveld Complex (2056 Ma) show evidence of reversals in mineral fractionation, indicating periodic recharge of magma. The extent of fractionation (changing An in plagioclase and mg# in mafic minerals) can be quantitatively related to temperature decrease that, given assumptions about thickness of the magma chamber, can be related to time. An iterative heat flow model was developed that allows modeling the cooling in large intrusions into which there can be multiple additions (and extractions) of magma (Cawthorn and Walraven, 1998). Using this calculation procedure it was shown that 1 million km^3 of basic magma must have been emplaced in less than 65,000 years. If the time had been longer, greater degrees of fractionation would have been preserved in the mineral compositions.

The Skaergaard Intrusion (55 Ma) was emplaced as a single event with a volume of 280 km^3, but offers a different constraint on eruption rates. The intrusion occurred underneath a thickening volcanic pile (Larsen and Tegner, 2006). Three different methods, including fluid inclusion studies, and Plagioclase-Hornblende geothermobarometry collectively revealed that the pressure under the roof of the intrusion increased from 0.7 to 2.3 Kb in the course of the solidification of the intrusion. This pressure increase was attributed to rapid thickening of the volcanic overburden during cooling and crystallization. Previous estimates of cooling of the Skaergaard (Norton and Taylor, 1979) used a thermal model for a rectangular body of infinite length, i.e., heat loss was through top and bottom and two sides. The shape of the intrusion is very approximately cubic to ovoid (Nielsen, 2004), hence heat loss is through all six 'sides', leading to more rapid cooling. We suggest that a better approximation for heat loss would be to treat the body as a sphere for which heat loss equations exist. These calculations suggest that the intrusion solidified (from 1200^{o}C to 680^{o}C) in 60,000 years. The exact location of the studied samples with respect to the advancing cooling front becomes critical in terms of estimating the relative timing when P and T was recorded by minerals and fluid inclusions. Our calculations suggest that the time period from the first samples nearest to the edge recorded the lowest P to the last samples nearest to the centre is in the order to 20,000 years. The increase in pressure deduced for these two extremes is equivalent to the emplacement of 5.8 ± 2.7 km of volcanic overburden. Hence, we conclude that the volcanic pile increased by this thickness (a very large proportion of the entire volcanic succession) in that time period.

In summary it is suggested that two intrusions, very different in age, and using very different modeling techniques, indicate irruption rates of magma of extreme intensity over very short periods of time. The potential for atmospheric and climatic impact given such intensity is obvious. If a plume model is invoked for their generation, ascent and melting rates must also be extremely rapid.

Cawthorn, R.G. and Walraven, F. (1998). J Petrol, 39, 1669-1687. **Larsen, R.B. and Tegner, C. (2006)**. Lithos, 92, 181-197. **Nielsen, T.F.D. (2004)**. J Petrol, 45, 507-530. **Norton, D. and Taylor, H.P., Jr., (1979)**. J Petrol, 20, 421-486

Flood basalt volcanism is the main cause of mass extinctions: evidence and modelling

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In 1980, The Cretaceous-Tertiary (KT) mass extinction was convincingly connected to impact of an asteroid by Alvarez and colleagues. Six years later, our group and others suggested that it could be connected to massive flood basalts, namely the Deccan traps in India. The time scales of the two types of events appeared to be hugely different, less than a second vs. a million years. As more data accumulated, the time coincidence between the Deccan, the Chicxulub impact in Mexico and the KT extinction at ~65Myr ago generally improved. It was shown in India by Bhandari et al. and confirmed by us that Iridium (connected to the impact) could be found in sediments sandwiched between Deccan trap volcanic layers. Hence confirming both impact and volcanism, but implying that impact could not have caused volcanism, that had started before and ended after the impact. Further work over the next two decades by many groups, including ours, has shown that almost every mass extinction since the Devonian (and including the Frasnian-Famennian extinction likely connected to the Viluy traps in Siberia, as supported by some of our recent work) can be associated with a flood basalt (and oceanic anoxia events with underwater plateau basalts), whereas there was no convincing case of an asteroid/extinction connexion other than KT (whereas there were cases of large impacts with no related extinction). We made the successful prediction that the double mass extinction of the Guadalupian-Tatarian and Permo-Triassic implied two flood basalts some 8 Myr apart. Whereas the PT one was soon shown to be the Siberian traps, the second one was found only after the prediction had been made, in the Emeishan traps. Therefore, large igneous provinces seem to be the mechanism that generally causes mass extinctions.

There has been further recent work on the detailed timing of volcanic sequences showing that flood basalts may differ in latitude, strength, chemistry, intruded crust, but that the main parameter controlling the features and intensity of mass extinctions could be the exact time sequence and volumes of extruded lava and gases injected by these flows into the atmosphere (actually stratosphere). We have been able to determine the sequence of volcanic pulses in the Deccan traps (Anne-Lise Chenet's thesis and papers) and subsequently in the Karoo traps (Maud Moulin's thesis and papers). In the Deccan case, there appear to have been three main periods of volcanism spanning some 2.5 Myr, but with each sequence having lasted on the order of 100 kyr or less, and consisting of pulses that could have exceeded 10,000 km^3 in volume extruded in less than a century, possibly only a decade (using geomagnetic and paleomagnetic secular variation as a relative dating tool). Observations from paleontology (Keller's group) and physical volcanology (Self's group) have been blended with our own work to produce this picture. So volcanism appears as a fractal time sequence (somewhat like Cantor dust), with several embedded time scales from a million years down to a decade. In the end, it appears that some individual major pulses could have had durations and consequences rather similar to the impact. An impact alone is not likely to cause a mass extinction, but in the KT case an impact occurred after volcanism had started and added a major blow to the sequence of events. We are currently finishing the same kind of study for the Karoo traps and the Pliensbachian-Toarcian extinctions. We are also pursuing climate modelling to quantitatively analyse the consequences of massive CO_2 and SO_2 injection into the environment. Some of this recent work will be discussed.

Direct link between end-Triassic CAMP volcanism, C-cycle perturbation and mass extinction

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The eruption of continental flood basalts of the Central Atlantic Magmatic Province (CAMP) is one of the most famous examples of a continental Large Igneous Province (LIP) coeval with mass extinction and abrupt negative C-isotope excursion (CIE) at the Triassic–Jurassic (Tr–J) boundary. However, the temporal relationships between volcanism and CIE still remain circumstantial due to the difficulty in correlating a continental event (volcanism) with one recorded in marine sediments (CIE). Sediments underlying CAMP basalts in two stratigraphic sections in Morocco are characterized by high contents of MgO (10–32 wt.%) and of mafic clay minerals (11–84%). This geochemical signature must be linked to deposition of mafic clay minerals derived from early-erupted CAMP basalts. The measured C-isotope compositions of bulk organic matter show marked negative CIEs (up to -6‰) in association with the highest MgO peaks. This geochemical anomaly can be readily correlated with the initial negative CIE shortly preceding the Tr–J boundary. Our data show that the end-Triassic CIE and associated mass extinction occurred when CAMP had already been active and correlate with peaks of volcanic activity. This finding supports the hypothesis that the cause of the mass extinction was CAMP volcanism.

Stevns Klint – a World Heritage candidate

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Stevns Klint is a 15 km long and up to 40 m high costal cliff one hour drive south of the Danish capital of Copenhagen. The scenic locality shows a well exposed Cretaceous−Tertiary/Palaeogene boundary section with the exceptional boundary clay layer being easily recognisable immediately beneath a pronounced topographic overhang, which separates the underlying soft Maastrichtian chalk from the overlying, harder Danian limestone.

The key to the integrity of Stevns Klint lies in the completeness of the boundary section, the good preservation of rich fossil assemblages, and in the quality of the outstanding exposure of high permanency and great lateral extent.

Stevns Klint is a classical study site documented by more than 200 scientific papers. The locality has played a significant role in investigations of mass extinctions, their causes, effects and subsequent recovery, and the effect of extraterrestrial impact on life on Earth. It was among the original study localities that first led scientists to the hypothesis of an asteroid impact as a cause for mass extinction and thus of for understanding of key evolutionary problems.

World Heritage

Stevns Klint is proposed to be inscribed on UNESCO's World Heritage List under the criteria (viii) of Paragraph 77 of the Operational Guidelines for the Implementation of the World Heritage Convention (2008), stating that the nominated properties shall *"be outstanding examples representing major stages of earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiogeographic features"*.

An example of the major changes influenced by an asteroid impact is presently not found on the World Heritage List nor is a complete Cretaceous−Tertiary/Palaeogene boundary section. Stevns Klint is proposed to be inscribed as it is an outstanding example representing a major stage in Earth's history and the record of life: The mass extinction at the Cretaceous−Tertiary boundary.

Damholt, T. & Surlyk, F., 2012. Nomination of Stevns Klint for inclusion in the World Heritage List. Østsjællands Museum, Denmark 160 pp.

Surlyk, F., Damholt, T., Bjerager, M., 2006. Stevns Klint, Denmark: Uppermost Maastrichtian chalk, Cretaceous–Tertiary boundary, and lower Danian bryozoan mound complex. Bulletin of the Geological Society of Denmark 54, 1–48.

Miocene vegetation in the Columbia River Basalt Province, Washington State, USA

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The Columbia River Basalt Province (CRBP) provides excellent records of the effect of different types of volcanism on palaeo-vegetation dynamics. The CRBP is a Miocene-age continental Large Igneous Province (LIP) within the Columbia Basin in South Washington, North Oregon and West Idaho, USA. The province comprises a number of extensive basaltic lava flows, intercalated with sedimentary interbeds of fluvial, lacustrine and associated palaeosol environments. Based on sedimentary facies analysis the intra-basaltic drainage system development can be divided into an early, middle and late stage.

The early stage of CRBP evolution is characterised by high volcanic effusion rates and effusion volumes. Palynological data record vegetation, which is dominated by *Taxodium*, *Alnus*, *Castanae*, *Tilia*, *Pterocarya*, *Carya*, *Platycarya*, *Ulmus*, fresh water greenalgae (*Schizosporis*), fungi, ferns and fern allies (*Filicopsida* and *Sphagnaceae*).

The middle stage CRBP evolution marks the onset of waning LIP volcanism. The vegetation is characterised by mainly *Nyssa*, *Taxodium*, various mosses, ferns and fern allies, as well as increased fungal colonisations establishing in predominantly shallow lakes, swamps and wetland environments.

Late stage CRBP evolution is characterised by low eruption rates, and an increase in felsic ash delivery from the Cascade Range and the Yellowstone Hotspot. The vegetation is dominated by *Alnus*, *Nyssa*, *Ilex*, ferns (*Osmunda*), mosses (*Sphagnaceae*, *Lycopodium*), fresh-water green algae and fungal colonisations. Despite low effusion rates and effusion volumes associated with large fluvial and lacustrine environments (up to 45 m thick interbeds) establishing on the lava field. The vegetation record is relatively poor. The less-evolved flora diversity is inferred to relate to the up to 2 m thick ash fall out deposits, which covered wide areas of the lava field leading to a lack of nutrients supply, soil acidification and a vegetation regression.

The Siberian Flood Basalts: Connecting the mantle, the continental crust, and the atmosphere

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Around 252 million years ago the Siberian flood basalts intruded into and erupted onto the Siberian craton. The flood basalt event is among several possible causes for the end-Permian extinction, the largest extinction in Earth history. Our team hypothesizes that the magmas caused the injection of sufficient volatiles into the atmosphere to produce global climate change. These volatiles were in part sweated out of the crustal rocks by the chambered magmas, and in part assimilated from the crust by the magmas and released upon eruption.

The magmas intruded a 12-km-deep evaporate basin containing hydrocarbon reservoirs. The complex interactions of heat and rock with silicate, hydrous, and hydrocarbon fluids produced rich ore bodies, a variety of magmatic rocks including carbonatites, and significant volumes of carbon, sulfur, chlorine, and fluorine-bearing volatiles. We will present an overview of our results to date, including field and laboratory data on volatile release from intrusive aureoles, interactions between magmas and coal, melt inclusion measurements of magmatic volatile loads, and early climate model results.

Because of its volume and the specific crustal region it passed through, the magmatic event produced significant chemical and heat transfer between Earth's interior and its surface. Though other continental flood basalts are similarly sized, the Siberian event interacted with particularly toxic crustal rocks and is a likely candidate for triggering the end-Permian global climate change and mass extinction.

Gypsum- and carbonate-rich sediments from the basin that chambered the flood basalts. This cliff is on the Kotuy River, just south of the Taimyr Peninsula. Photo: Ben Black.

Magnetite dissolution by acid rains due to volcanogenic atmospheric halogen input: an "experimental" approach

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The origin of the Cretaceous-Palaeogene crisis is still disputed, notably because the duration of the two causal phenomena - Deccan volcanism and Chixculub impact - can hardly be separated in the sedimentary record. Below the Iridium-rich layer of the Bidart (France) section, there is a low magnetic susceptibility interval hypothesized to result from Deccan Phase-2[1]. This interval shows a drastic diminution of detrital magnetite content regarded as a consequence of enhanced magnetite dissolution on the continent. This hypothesis is supported by the recent recognition of basaltic trap volcanism as a major contributor to the halogen budget of the atmosphere[2].

We constructed a geochemical weathering model with the code PHREEQC[3], in order to constrain the time required to reach nearly complete magnetite dissolution inland. Results show that such a process is possible in ca 33,000 yrs when considering acid rain (pH=4.3) waters resulting from the Deccan volcanism and a runoff typical of intertropical conditions. This time interval matches duration of the Deccan phase-2[4]. Finally, we propose a sedimentary model linked to environmental changes induced by Deccan volcanism.

References

1. Font, E., Nedelec, A., Ellwood, B. B., Mirao, J. & Silva, P. F. A new sedimentary benchmark for the Deccan Traps volcanism? *Geophysical Research Letters* **38**, doi:10.1029/2011gl049824 (2011).

2. Self, S., Blake, S., Sharma, K., Widdowson, M. & Sephton, S. Sulfur and chlorine in Late Cretaceous Deccan magmas and eruptive gas release. *Science* **319**, 1654-1657 (2008).

3. Appelo, C. A. J., and D. L. Parkhurst, 1999, User's guide to PHREEQC version 2 - A computer program for speciation, batch-reaction, one -dimensional transport, and inverse calculations. Water-Ressources Investigations Rep. 99-4259, U.S. Geological Survey, Denver, Colorado.

4. Chenet, A. L., Quidelleur, X., Fluteau, F., Courtillot, V. & Bajpai, S. K-40-Ar-40 dating of the Main Deccan large igneous province: Further evidence of KTB age and short duration. *Earth Planet Sc Lett* **263**, 1-15, doi:DOI 10.1016/j.epsl.2007.07.011 (2007).

Impact of large igneous provinces: a modelling approach

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The temporal synchronism between mass extinctions and the emplacement of large igneous provinces suggests a causal connection between the two. However, the mechanisms linking volcanism and mass extinctions are not well understood. We know from the studies of recent and historical volcanic eruptions that the sulfur dioxide injected in the atmosphere, and subsequently converted into sulfate aerosols modifies the Earth's radiative budget and favors global cooling of the Earth's surface during the year(s) following the eruption. In case of trap volcanism, the impact on climate and environment is more complex. It depends on both the tempo (and dynamics) of eruptions and the nature and amount of volatiles released. Among the volatiles released during the emplacement of traps, we focus on the impact of SO_2 and CO_2 more specifically.

Recent studies on the Deccan traps (Chenet et al., 2008, 2009), the Karoo traps (Moulin et al., 2011) and the Siberian traps (Pavlov et al., 2011) provided high-resolution constraints on the tempo of emplacement through the analysis of the secular geomagnetic variations recorded by lava flows (used as a relative chronometer; the absence of secular geomagnetic variations recorded in successive lava flows suggests an outpouring in less than ~100 yrs).

In the case of the Deccan traps, Chenet et al. (2008, 2009) proposed using this procedure that the 3500-m-thick lava pile of the Main Province was erupted in some 30 volcanic pulses (successive volcanic eruptions having not recorded secular geomagnetic variation) and some 41 individual lava flow units. The total time of volcanic activity may have not exceeded 10 kyr over a 400 kyr-long period of trap emplacement. With some assumptions about the geometry of lava flow units and volcanic pulses, Chenet et al. (2008, 2009) estimated that a volcanic pulse may have released 0.1 Gt/yr to 1 Gt/yr of SO_2 and 0.1 to 2 Gt/yr of CO_2, such releases lasting about a century.

Numerical modelling is a powerful tool to investigate the impact of gases released during the emplacement of traps. Previous studies have never tested the consequences of such large amounts of sulfur dioxide within the atmosphere. We have adapted the INCA module (Interaction of chemistry and aerosol, developed within the LSCE in collaboration with IPSL) to include volcanism. The INCA module is coupled to the LMDz General Circulation Model (developed by the LMD-IPSL). Preliminary results of the impact on climate will be presented. Various parameters (rate of SO_2 released within the atmosphere, duration of a volcanic pulse, etc) will be discussed. Such a numerical model allows to simulate the consequences on climate at a global scale over a short timescale. To investigate the impact of trap volcanism on environment over a 1-Myr timescale, we have used a biogeochemical cycle box model (COMBINE, Goddéris and Joachimski, 2004). Various scenarios for trap emplacement (amount of CO_2 and SO_2 released within the atmosphere, duration of quiescence period) will be discussed (see also the poster by Le Hir et al.).

Chenet A-L. et al. 2007. ^{40}K/^{40}Ar dating of the Main Deccan Large Igneous Province: Further Evidence of KTB Age and short duration. EPSL 263: 1-15. **Chenet, A.-L., et al. 2008.** Determination of rapid Deccan eruptions across the Cretaceous-Tertiary boundary using paleomagnetic secular variation: Results from a 1200-m-thick section in the Mahabaleshwar. J Geophys Res, 113, DOI: 10.1029/2006JB004635. **Chenet A.-L., et al. 2009.** Determination of rapid Deccan eruptions across the Cretaceous-Tertiary boundary using paleomagnetic secular variation: 2. Constraints from analysis of eight new sections and synthesis for a 3500-m-thick composite section: J Geophysl Res, 114, B06103, doi:10,1029/2008JB00564. **Godderis, Y. and Joachimski, M.**M., 2004. Global change in the Late Devonian: modelling the Frasnian-Famennian short-term carbon isotope excursions. Palaeogeo Palaeoclim Palaeoecol, 202(3-4): 309-329. **Moulin, M., et** al. 2011. An attempt to constrain the age, duration, and eruptive history of the Karoo flood basalt: Naude's Nek section (South Africa), J Geophys Res 116, B07403, doi:10.1029/2011JB008210. **Pavlov, V.E. et a**l. 2011. Secular Geomagnetic Variations and Volcanic Pulses in the Permian-Triassic Traps of the Norilsk and Maimecha-Kotui Provinces. Izvestiya, Phys Solid Earth, 47 (5) 402–417.

The chlorine perfume of the Deccan Traps

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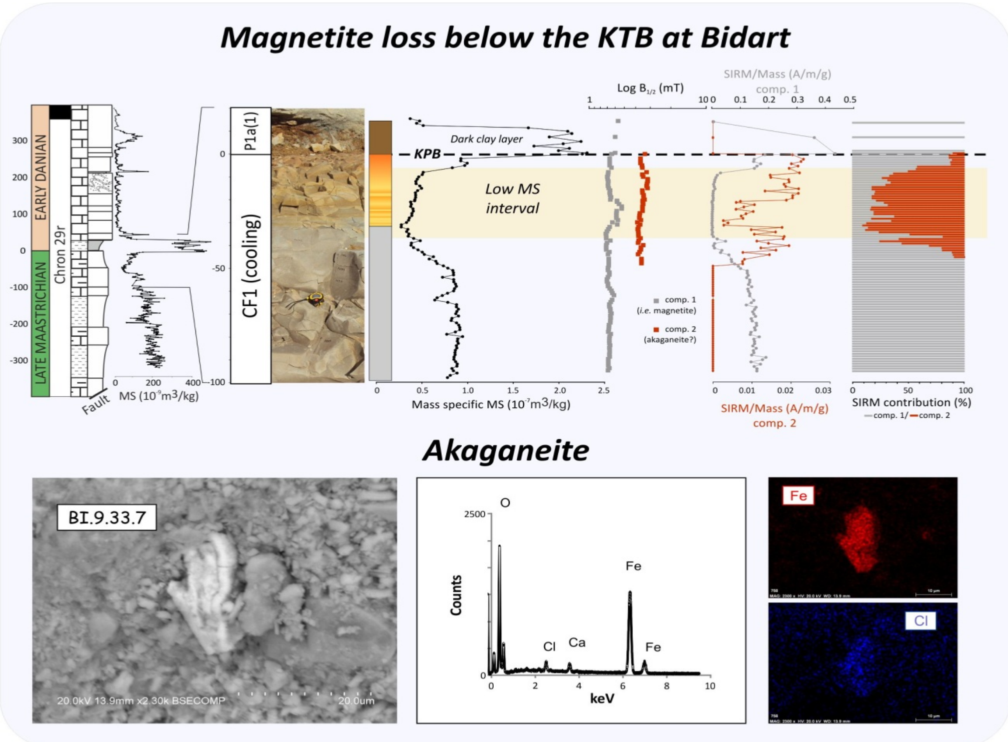
The origin of the Cretaceous-Palaeogene crisis is still a matter of debate. A major limitation resides in the paucity of direct Deccan volcanism markers and in the geologically short interval where both impact and volcanism occurred, making it hard to evaluate their contributions to the mass extinction. We investigated the low magnetic susceptibility interval just below the Iridium-rich layer of the Bidart (France) section, which was recently hypothesized to be the result of palaeoenvironmental perturbations linked to paroxysmal Deccan phase-2. Results show a drastic decrease of detrital magnetite and presence of fine specular akaganeite, a hypothesized reaction product between FeCl2 from the volcanic plume with water and oxygen in the high atmosphere. A weathering model of the consequences of acidic rains on a continental regolith reveals nearly complete magnetite dissolution after about 33,000 years, which is consistent with our magnetic data and the duration of the Deccan phase-2. This discovery represents an unprecedented piece of evidence of the nature and importance of the Deccan related environmental changes.



Geochemical proxies (major, trace and platinum group elements) across the KT boundary: What can they tell about the role of impacts and volcanism?

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Elemental geochemistry (major, trace and platinum group elements) offers a wide array of powerful proxies to gain crucial information about the causes (extraterrestrial impact and volcanism) and the environmental changes (redox, paleoclimate and weathering) during the Cretaceous-Tertiary (KT) boundary mass extinction.

Most geochemical studies have concentrated on identifying the composition of the KT red layer based on major, trace and platinum group elements (PGEs) measured in several world-wide KT sites. Results show that the KT red layer in marine sequences records generally peak concentrations in major elements (P, Fe), trace elements (As, Ba, Co, Cr, Cu, Ni, Sb, Sc, Th, U, V, Zn), and platinum group (Ir, Rh, Ru, Pd, Pt) elements. To explain the particular geochemical composition of the KT boundary red layer, several processes have been put forward: (1) Extraterrestrial impact, (2) Volcanic activity, and (3) Redox processes and sedimentation rate. An extraterrestrial impact might explain the enrichments in PGEs and some major (Fe) and trace (Ni) elements, other processes must be taken into account to better understand the composition of the KT red layer and its origin. However, redox sensitive proxies (U, V) and very high values in some trace elements (As, Cr, Co, Cu, and Ni) suggest that dysoxic environmental conditions occurred during the deposition of the red clay layer. Low/high sedimentation rates associated with the depositional environment and sea-level changes are known to respectively concentrate or dilute the concentration of major, trace and platinum-group elements. Volcanic proxies (Na/K, K/(Fe+Mg), Ca/Na, Mg/Na) show generally no causal link at the KT boundary, though single element concentrations cannot rule out volcanism as direct (e.g. triggered by a sudden eruption) or indirect (e.g., intense basalt weathering) source.

More recently, studies have focused on the application of elemental geochemistry to unravel the environmental consequences of Deccan volcanism. First results in Meghalaya, India, show that weathering proxies (CIA, CIW, PIA) are indicative of strong continental weathering associated with pulsed Deccan eruptions and abundant rainfalls (acid rains) that resulted in mesotrophic waters. These data reveal that detrimental marine conditions prevailed surrounding the Deccan volcanic province during the main phase of volcanism in the terminal Maastrichtian just prior to the KT boundary.

Latest advances in elemental geochemistry reveal the complex geochemical composition of the KT red layer, and the still little known geochemical signal of Deccan volcanism in marine environments. Future research need to focus on the systematic application of elemental geochemistry on intervals spanning the latest Maastrichtian to the early Danian to better constrain the environmental consequences of Deccan volcanism and to determine precisely the origin of the KT red layer. Ultimately, these results will offer critical information to gain a better understanding of the KT mass extinction.

The role of mantle volatiles in the formation of large igneous provinces & associated mass extinction events

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Large Igneous Provinces (LIPs) are widely believed to be related to impingement of lower-mantle derived, thermo-chemical mantle plumes on the base of the Earth's rigid plates, which results in melt generation in both the upwelling plume and overlying lithosphere. The immense volumes of flood-basalt magma (up to several million km^3) erupted over short time periods (**<1 Ma**[1]) in LIPs, intermittently throughout most of Earth's evolution, make them exceptional events. They have been linked to dramatic changes in environment and climate: at least seven have been associated with mass extinctions. Mantle volatiles, such as H_2O and CO_2, play an important role in the genesis of LIPs. They are especially prevalent in small-fraction melts emplaced both pre- and post-eruption of the main continental flood basalt (CFB)[2] pulse. Almost all continental Phanerozoic LIPs (*e.g.,* Deccan, Karro-Antarctic, North Atlantic, Paraná-Etendeka and Siberian) exhibit a close spatial and temporal relationship between these volatile-rich and volatile-poor magmas, reflecting their common association with sub-lithospheric plume impact. Despite their shared cause, generation of mantle melts with widely different volatile contents involves contrasting, but controversial, dynamic processes.

Continental flood-basalts from most LIPs are now known to contain a significant melt contribution from the convecting mantle. In the case of the Siberian and Paraná -Etendeka CFBs, geochemical and petrological data indicate the style of mantle melting is almost identical and involves adiabatic decompression melting at mantle potential temperatures of 1500-1600 °C. Initially, this entails melting of pyroxenite (at depths <150 km) beneath thick lithosphere to form small volumes of ferropicrites[3,4], followed by melting of anhydrous peridotite at shallower depths (<120 km) to generate picrites[5]. The latter fractionate in the crust and erupt forming the main CFB pulse. Recent studies of olivines and their melt inclusions from Siberian ferropicrites[6,7] suggest a large melt contribution (50%-100%) is derived from carbonate-bearing recycled oceanic crust, *i.e.,* pyroxenite, in the upwelling plume. Sobolev *et al.*[7] suggest incipient melting of pyroxenite caused rapid release of CO_2 and HCl during **early stage** interaction of the plume with the lithosphere (*i.e.,* immediately before the main CFB event) which was responsible for mass extinctions at the Permo-Triassic boundary. Despite similarities in mantle melting processes no such mass extinctions are associated with the Paraná-Etendeka LIP.

Unlike CFB eruptions, emplacement of volatile-rich, strongly-alkaline igneous rocks occurs through-out the duration of LIP formation. *Early-phase*, strongly-alkaline igneous rocks are generated **up to ~10 Ma** prior to the main plume melting event whereas *Late-phase* emplacement of similar volatile-rich melts postdates this event by **~5 Ma** [2,8,9]. Early-phase volatile-rich strongly-alkaline igneous rocks are less abundant than their late-phase equivalents; to some extent this may be due to them stalling in the crust as a result of greater density differences prior to the injection of huge volumes of mafic CFB-related melts. Thermal models will be presented to show that: (i) early-phase volatile-rich lithospheric mantle melts are instantaneous and small volume because the temperature increase associated with plume impingement affects a limited depth interval at the base of the lithosphere; (ii) conductive heating is a relatively slow process but the timescales are consistent with late-phase formation of volatile-rich, strongly-alkaline igneous rocks and end of LIP volcanism, ~15 Ma after plume impact.

In summary, there is currently no direct evidence from LIPs that supports conceptual models invoking large volumes of volatile-rich mantle melts reaching the Earth's surface immediately prior to, or during, the main outpouring of CFBs. If the volatile budget of mantle-derived magmas does contribute to mass extinctions then this must involve pre-concentration during crustal processing, prior to rapid and immense eruptions of CFBs. It is not obvious why this should vary significantly between LIPs.

[1]**Courtillot & Renne (2003)** *C. R. Geosciences.* 335, 113-14; [2]**Gibson *et al.* (2006)** *Earth Planet Science Letts.* 251, 1-17; [3]**Gibson, S.A. (2002)** *Earth Planet Sci. Letts. 174, 355-374;* [4]**Tuff *et al.* (2005)** *J. Petrology* 46, 2023-2058; [5]**Herzberg & Zhang (1996)** *J. Geophys. Res.* 101, 8271-8295; [6]**Sobolev *et al.* (2009)** *Petrology* 17, 253-286; [7]**Sobolev *et al.* (2011)** *Nature* 477, 312-316; [8]**Basu *et al.* (1993)** *Science* 261, 902-06; [9]**Comin-Chiaramonti *et al.*, (2007)** *GSA Special Paper* 430, 603-633.

The Boltysh Crater record of post K/Pg event recovery and climate change

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The Boltysh impact crater formed in the Ukrainian shield on the margin of the Tethys ocean a few thousand years before the K-Pg boundary and was rapidly filled by a fresh water lake. Sediments filling the lake vary from early lacustrine turbidites and silts to some 300 m of fine silts, organic carbon rich muds, oil shales, and laminated shales that record Early Danian terrestrial climate signals at very high temporal resolution.

High resolution palynological studies of the core reveal an expanded record of post K/Pg vegetation destruction and subsequent floral recolonisation. A post-destruction barren zone is succeeded by a fern spore spike recording the initial recovery vegetation. The Boltysh fern spore spike is divisible into two phases. Phase 1 is characterised by low abundances of fern spores of the Polypodicaeae and Pteridaceae, while the overlying Phase 2 has high fern spore abundances and contains common palm pollen. Comparison of the Boltysh Phase 2 fern spore spike to other palynological records shows strong similarities with the immediately post K/Pg record of the Western Interior, North America. The absence of the barren zone and Phase 1 fern spike in the Western Interior sections may be significant since it would indicate earliest Danian non-deposition. Variation in the composition of the Boltysh palynofloras has defined four moisture availability cycles between the K/Pg and the Early Danian Hyperthermal event. Time constraints consequent on these events indicate that early post K/Pg vegetation community recovery followed a common seral successional pathway at rates seen in Large Igneous Provinces, although enhanced by high moisture availability.

Combined carbon isotope and palynological data show that the fine grained organic carbon-rich lacustrine sediments preserve a uniquely complete and detailed negative carbon isotope excursion (CIE) in an expanded section of several hundred meters. The position of the CIE in the early Danian, around 250 ka above the K-Pg boundary, leads us to correlate it with the Dan-C2 hyperthermal event previously only documented in marine sections. The more complete Boltysh CIE record indicates a $\delta^{13}C$ anomaly of around -4‰ including the doublet apparent in some marine carbonate sections, but also a more extended recovery period, strikingly similar pattern to the highest fidelity CIE records available for the Toarcian and Paleocene/Eocene hyperthermal events. Changes in floral communities through the CIE recorded at Boltysh reflect changing biomes caused by rapidly warming climate, followed by recovery indicating that the Dan-C2 event had a similar duration to the PETM event. The close temporal correlation of the Dan-C2 event with major eruptions of the Deccan continental flood basalt province, and initiation of rifting between India and the Seychelles bank, may indicate that the Deccan province was the most likely cause of the Dan-C2 global warming and the carbon-isotope excursion, although variations in orbital parameters may have paced the climate changes. If this is the case, then the Boltysh crater sedimentary record may provide a unique opportunity to distinguish the relative roles the Chicxulub impact and Deccan volcanism played in the K/Pg mass extinction event.

Prolonged intraplate volcanism in Eastern Australia: new finds, causes and effects.

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Eastern Australia has had a prolonged, though complex intraplate volcanic history over the last 100 million years. This has largely been confined to the eastern coastal passive margin, though at times, has extended several hundred kilometres inland. The volcanism began following the collapse and fragmentation of the East Gondwana margin and the onset of Tasman and Coral sea rifting and spreading. The volcanism has developed central volcanoes, lava fields, scoria cones, smaller maar volcanoes and maar complexes, tuff rings, plugs, long lava flows, dykes and sills. Geochemically, the volcanics range from ultrabasic (leucitites, melilitites, nephelinites) to acidic (rhyolites), though basaltic rocks and evolved types are the most voluminous. There are also distinctive groupings of age progressive central volcanoes along eastern Australia, and a small but distinctive leucitite line.

Our understanding of this volcanism has expanded, with discoveries of new provinces (Rouchel, Upper Hunter Valley of NSW), new occurrences (Era Beach south of Sydney) and new and more precise geochronological and geochemical constraints (Belmore Province of northern NSW, dykes along the coastal regions of NSW, post-10 Ma basalts of Victoria). However, more studies remain to be done, particularly isotope geochemistry for many of the provinces, and geochronology of the youngest sequences. Many previous interpretations concerning the evolution of the volcanism is largely based upon K-Ar and Ar-Ar dating of the preserved volcanic sequences. However, a more complete volcanic history is found when U-Pb zircon fission track ages and U-Pb zircon SHRIMP ages are included in the overall picture. This is because zircons are highly resistate, surviving weathering and remaining in the landscape, thus providing evidence of former volcanic events. Such studies show that volcanism within individual provinces, such as at Barrington, NSW can be episodic in nature, changing from alkaline to tholeiitic in nature over a few million years, with volcanic activity lasting for over 60 million years. There is also evidence to suggest that the volcanism is not extinct, just dormant, and further eruptions may occur.

Although volcanism has prevailed in eastern Australia for the past 100 million years, much of it has been episodic in nature due to tectonic activity along the eastern margin of the Australian Plate. This includes processes such as subduction, rapid roll-back and progressive detachment of the Loyalty slab. Most basaltic activity along the eastern Australian margin is due to asthenospheric melt injections into the Tasman rift zone mantle. The effects and outcomes of this prolonged volcanism are both widespread and diverse. They include, though are not limited to, the development of major geomorphological landscape features, preservation of palaeoalluvial gold deposits as ‘deep leads’, providing a source of building materials for major cities and towns and aquifers for drinking water, transportation of xenocrysts (including sapphires, rubies and diamonds) and xenoliths from various depths to the surface, creation of geological sites of interest for teaching and tourism, basaltic soils for agriculture, and development of unique rain forest habitats.

The current status of sea-level change as a causal factor in mass extinctions

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Newell (1967) was the first to identify Raup and Sepkoski's "big five" marine mass extinctions. He related them to eustatic regressions causing loss of habitat area on the continental shelf. However, in many cases, for these and lesser mass extinctions, the most significant factor promoting extinction was not regression, but spreads of anoxic bottom waters associated with the subsequent transgression (Hallam 1989).A striking case in point is the largest of all mass extinctions, at the end of the Permian. Until the beginning of the 1990s there had been a widespread consensus that this correlated with a major regression, but subsequent intensive research in a variety of fields has established that the global spread of anoxic waters associated with the early Triassic sea – level rise was the significant factor (Hallam and Wignall 1997, Wignall and Twitchett 1996).

Since the start of the 1980s the main focus has been on bolide impacts versus the volcanism associated with Large Igneous Provinces, but the role of sea-level should not be ignored. In an important paper by Purdy (2008), who analysed the Sepkoski compendium of marine genera, taxon diversity was found to generally parallel both sea-level change and Sr isotope stratigraphy, if the "Pull of the Recent" is eliminated, which implies that the Sr isotopes reflect continental runoff. In Hallam's most recent summary chart of the potential causes of mass extinctions (Hallam 2004,fig 9.1)an important regression is still noted for the end- Ordovician, which is generally related to a glacioeustatic fall, and for the end-Cretaceous, which has received little attention in recent years. Two other relevant regressions are noted, end-Guadeloupian and end-Triassic. The former was linked by Raup and Sepkoski to the end –Permian event, but is now seen as a distinctive event. The best evidence comes from China. Detailed studies have recently established that the major eustatic regressive event, now dated as mid-Capitanian, did not coincide with the mass extinction, but exhibits a clear temporal link with Emeishan volcanism (Bond et al.2012).

The end-Triassic event cannot be firmly established stratigraphically as a eustatic, as opposed to very widespread epeirogenic uplift centred as the central Atlantic region, which makes it plausible to invoke a mantle plumes (Hallam and Wignall 1999). Uplift occurred largely because the crust was thickened by large quantities of new igneous rock generated by decompression melting. The initiation of basalt extinction marks the time of inception of subsequent collapse, correlated with the earliest Jurassic sea-level rise. Hallam (1997) attempted to estimate the rate and amount of sea-level rise in the early Toarcian and earliest Jurassic. The former is estimated to have been at a rate consistent with normal long-term tectonoeustatic change, but the latter was much faster with a sea level rise estimated to be $0.2ka^{-1}$. This is much too rapid for normal tectonoeustasy and there is absolutely no evidence supporting glacioeustasy at this time. The end-Triassic regression in the United Kingdom has several manifestations such as slumps which are consistent with seismic activity associated with rising magmas (Hallam and Wignall 2004). The latest detailed research in Austria indicates a sharp sea-level fall correlated with mass extinction (Mc Roberts et al.2012).This dramatic change is at least as plausible as the oceanic acidification model proposed by Hautmann (2004) to account for the spectacular reef disappearance at the end of the Triassic.

Bond, D.P.G., et al. 2010. The Middle Permian (Capitanian) mass extinction on land and in the oceans. Earth-Sci. Rev. 102, 100-116.

Hallam, A. 1989. The case for sea-level change as a dominant caused factor in mass extinction of marine invertebrates.Philos, Trans Roy Soc. Lond. B 325, 437-455.

Hallam, A. 1997. Estimate of the amount and rate of sea-level change across the Rhaetian-Hettangian and Pliensbachian-Toarcian boundaries (latest Triassic to early Jurassic). J. Geol. Soc of. Lond. 154, 773-779.

Hallam, Tony, 2004. Catastrophes and lesser calamities: the causes of mass extinctions, Oxford Univ. Press.

Hallam, A. and Wignall, P.B. 1997. Mass extinctions and their aftermath, Oxford Univ. Press.

Hallam, A. and Wignall, P.B.1999. Mass extinctions and sea – level changes. Earth-Sci, Rev. 48, 217-258.

Hallam, A. and Wignall, P.B. 2004, Discussion on sea-level changes and facies development across potential Triassic-Jurassic boundary horizons, SW Britain. J. Geol. Soc. Lond. 161, 1053-1056.

Hautmann, M. 2004. Effect of end-Triassic CO_2 maximum on carbonate sedimentation and marine mass extinction. Facies 30, 251-261.

Mc Roberts, C.A., et al 2012. Macrofaunal response to the end-Triassic mass extinction in the west- Tethyan Kossen Basin, Austria. Palaios 27, 607-616.

Newell, N.D. 1989. Revolutions in the history of life. Geol. Soc. Amer. Spec. pap. 89, 63-91.

Purdy, E.G.2008. Comparison of Taxonomic diversity, Strontium isotope and sea-level patterns. Int. J. Earth Sci. (Geol.Rundsch.) 97, 651-664.

Wignall, P.B. & Twitchett, R.J. 1996. Oceanic anoxia and end-Permian mass extinction. Science 272, 1155-1158.

Triggers of Permo-Triassic Boundary Mass Extinction: Siberian Traps or Paleo-Tethys ignimbrite flare-up?

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As an important scientific subject, the relationship between large scale volcanism and mass extinction received much attention. Early assessment of the synchroneity between the Siberian trap and Permo-Triassic Boundary (PTB) Mass Extinction has led to the proposition that the Siberian flood volcanism was responsible for this most severe biotic crisis in the Phanerozoic. However, questions surrounding this proposal arise as recent studies show that the Siberian trap may postdate the main extinction horizon. In this paper, we demonstrated, on the stratigraphic ground, a temporal coincidence between PTB volcanic ashes and main extinction horizon, thus enhancing the role of volcanism on PTB mass extinction. However, negative $\varepsilon_{Hf}(t)$ (−3.4 to −16) and high $\delta^{18}O$ (8.7 to 10.4‰) of zircons extracted from PTB ashes negate the possibility of the Siberian Traps as the case of mass extinction, because these ashes are most likely crustally derived. On the basis of spatial variation in number of ash layers and thickness of PTB ashes in South China, we propose that these PTB ashes may be related to Paleo-Tethys continental arc magmatism in Kunlun area. Ignimbrite flare-up related to rapid subduction during final assemblage of Pangea may have generated a volcanic winter scenario, which eventually triggered the collapse of eco-system and ultimately mass-extinction at the PTB.

Inflated pāhoehoe flows and the style of emplacement of part of the Lesotho Outlier, Karoo Continental Flood Basalt Province

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This study focuses on the Naudes Nek traverse of the Drakensberg Group in the Lesotho Outlier, Karoo Continental flood basalt province, South Africa. It is the first to comprehensively document the meso- and macro-scale morphologies of inflated pāhoehoe lobes and their internal features and draw conclusions from these observations. The Karoo continental flood basalt province (CFBP) is temporally associated with the end Pliensbachian mass extinction and the early Toarcian oceanic anoxic event and as such is important to understand the style of volcanism which occurred in order to lay the ground work for future studies into its environmental effects. In this study we logged 770 vertical m of basaltic lava that make up the Naudes Nek traverse. The majority of the lavas we encountered were small flow lobes (up to 10 m thick), toes and well developed tumuli giving a complex 3 dimensional architecture, typical of hummocky pāhoehoe found on modern volcanoes. Many of the tumuli were of dimensions similar to those described on Hawaii and Iceland, called sheet lobe tumuli. In these modern settings they typically occur at the leading edge of flow fields. From this we can suggest that some of our flow lobes formed the leading edge of a flow field. Within the lava pile 13 sheet lobes were also observed, the thickest being 70 m thick. These are typical sheet lobes that are characteristic of flood basalt volcanism.

This thick pile of lava dominated by hummocky pāhoehoe suggests that the main style of volcanism in this part of the Karoo CFBP was plains style volcanism, as described by Greeley (1982) interspersed with flood basalt volcanism. Although this mixture of the two styles of volcanism has not been widely documented in other CFBPs it has recently been observed in the Faroe Island Basalt Group (North Atlantic Igneous Province; Passey & Bell 2007). This combination of the two styles of volcanism could have large implications for eruption rates and volumes of lava produced by each eruptive event and as such the environmental effect of CFBPs as a whole. Plains style volcanism could be an under-represented part of all flood basalt provinces or an eruption style limited to small parts of some provinces. Further, detailed field observations are needed to understand the significance and extent of plains style volcanism in the Karoo CFBP and other flood basalt provinces worldwide.

Passey S.R. and, B.R. Bell, 2007. Morphologies and emplacement mechanisms of the lava flows of the Faroe Islands Basalt Group, Faroe Islands, NE Atlantic Ocean. Bulletin of Volcanology, 70(2), 139-156.

Characterising the mantle source region(s) of continental flood basalts: A melt inclusion investigation of high-Mg volcanic rocks from the Paraná-Etendeka Large Igneous Province

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Continental flood basalts (CFB) are high-volume magmatic outpourings extruded over very short timescales; the environmental consequence of such an event could be dramatic and has been linked to mass extinction events. These large-volume melts predominantly originate from the mantle and are associated with thermal anomalies, *i.e.,* mantle plumes. Chemical heterogeneity within mantle plumes has the potential to contribute significantly to both the chemistry and volume of CFBs; previous investigations based on olivine phenocryst composition have tried to quantify the proportion of a more fusible pyroxenite/eclogite lithology in the upwelling mantle, as opposed to less fusible peridotite [1].

This study examines high-temperature MORB-like picrites and rare ferropicrites in Etendeka, part of the Paraná-Etendeka Large Igneous Province (LIP). We focus on samples characterised by low $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$ whole rock ratios. These are high-MgO primary mantle melts associated with the impact of the proto-Tristan mantle plume, and the main ~ 133 Ma CFB pulse, so are ideally suited to study the nature of mantle source regions(s). The picritic melts are thought to reflect melting of peridotite [2] whereas ferropicrite may reflect a source pyroxenite component [3,4]. The ferropicritic melts have a trace-element signature distinct to those of MORB-like picrites, with characteristically high FeO_T (> ~13 wt %), low Al_2O_3 (< ~10 wt %) and fractionated heavy rare-earth element ratios ($[Gd/Yb]_n$ = 2-3.5).

Olivine-hosted melt inclusions preserve instantaneous melt compositions, and therefore are key to observing compositions of both mantle and crustal source regions. A SIMS investigation of experimentally-homogenised olivine-hosted melt inclusions, combined with EPMA mineral chemistry analysis, has been employed to make a preliminary assessment of the convecting mantle source characteristics and address lithospheric mantle and crustal contamination, which is often assumed to hinder the study of plume-derived melts in a continental setting. Initial findings suggest that both ferropicrite and picrite melt types have stalled in crustal reservoirs. Ferropicrite melts bear a signature of lower crustal interaction, whereas the picrites crystallised over a range of pressures in the upper crust [2]. Most melt inclusions indicate little lithospheric contamination, although a small subset is highly affected. Normally and reversed zoned clinopyroxene phenocrysts in ferropicrites indicate repetitive magmatic replenishment of lower crustal magma chambers during crystallisation.

Preliminary analyses of ferropicrite melt inclusions are consistent with their derivation from a fusible pyroxenite source, although their rare occurrence in the Paraná-Etendeka LIP suggests such a source is volumetrically minor in the starting head of the upwelling proto-Tristan plume and does not account for the overall large melt volume of Paraná-Etendeka flood-basalts.

[1] Sobolev *et al.* (2007) *Science*, 316, 412-417.
[2] Thompson *et al.* (2001) *J Petrology*, 42, 2049-2081..
[3] Gibson (2002) *EPSL*, 195, 59-74.
[4] Tuff *et al.* (2005) *J Petrology*, 46, 2023-2058.

Causes of the Late Devonian mass extinction: Extraterrestrial or Earth-bound?

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The Late Devonian (Frasnian-Famennian boundary) mass extinction was no instantaneous but prolonged event occurring over several million years with a series of extinction pulses in the late Frasnian (e.g. Schindler 1993). Coral-stromatoporoid reefs that were widespread during the Middle to early Late Devonian were among the most prominent victims. The impact of an extraterrestrial body was initially supposed by McLaren (1970) to have triggered mass mortality. Dating of the 65-75 km diameter Siljan Ring impact structure (Sweden; 377 ±2 Ma, Reimold et al. 2005; 378±4Ma, Jourdan et al. 2009) suggests that an impact may have occurred close to the Frasnian-Famennian boundary (376.1 ± 3.6 Ma). However, this relatively small and single impact cannot explain the series of extinction pulses in the latest Frasnian and multiple impacts have only been hypothesized.

Changes in the oceanographic and climatic system are relatively well documented for this critical time interval. Anoxic to euxinic conditions in the World's oceans are evidenced by widespread black shale facies developed in the latest Frasnian (Lower Kellwasser event) and at the Frasnian-Famennian boundary (Upper Kellwasser event). Oxygen-deficient conditions are substantiated by trace element geochemistry, pyrite framboid size populations and organic biomarkers indicating photic zone anoxia. Anoxic conditions were probably the result of higher primary productivity triggered by an intensified input of nutrients to the oceans. Enhanced weathering due to uplift during the Eovariscan orogeny and the evolution of land plants as well as eutrophication as consequence of release of e.g. phosphorus from volcanic ashes were suggested to have contributed to higher nutrient levels. Enhanced burial of organic carbon during the Kellwasser events is documented by positive carbon isotope excursions of inorganic and organic carbon (e.g. Joachimski et al. 2002) leading to a drawdown of atmospheric and oceanic CO_2 levels and culminating in significant climate cooling (Joachimski & Buggisch 2002). These short-term cooling episodes were superimposed on longer term climate warming starting in the late Givetian to early Frasnian with maximum and up to 8° C warmer temperatures reached in the latest Frasnian to early Famennian (Joachimski et al. 2009). The role of volcanism and its potential influence on Late Devonian climate are currently not well constrained. The Viluy traps in Eastern Siberia were suggested as being potentially coincident with the Late Devonian mass extinction. However, preliminary dating suggests an age of around 370 Ma (Courtillot et al. 2010) and thus a post-extinction age for Viluy magmatism. Current knowledge suggests that recurrent eutrophication, anoxic conditions in the World's oceans, perturbations in the global carbon cycle and climate changes occurred in the latest Frasnian that may have had a severe impact on faunal diversity in the latest Frasnian.

Courtillot, V., Kravchinsky, V.A., Quidelleur, X., Renne, P.R., Gladkochub, F., 2010. Preliminary dating oft he Viluy traps (Eastern Siberia): Eruption at the time of Late Devonian extinction events?- Earth and Planetary Science Letters, 300, 239-245.

Joachimski M.M., Buggisch, W., 2002. Conodont apatite $\delta^{18}O$ signatures indicate climatic cooling as a trigger of the Late Devonian (F-F) mass extinction. Geology 30, 711-714.

Joachimski, M.M., Breisig, S., Buggisch, W., Talent, J.A., Mawson, R., Gereke, M., Morrow, J.M., Day, J., Weddige, K., 2009. Devonian climate and reef evolution: insights from oxygen isotopes in apatite.- Earth and Planetary Science Letters, 284, 599-609.

Jourdan, F., Renne, P.R., and Reimold, W.U. 2009. An appraisal of the ages of terrestrial impact structures. Earth and Planetary Science Letters, 286, 1–13.

McLaren, D.J., 1970. Presidential address: time, life and boundaries. J. Paleontol. 48, 801–815.

Reimold, W.U., Kelley, S.P., Sherlock, S.C., Henkel, H., Koeberl, C., 2005. Laser argon dating of melt breccias from the Siljan impact structure, Sweden: implications for a possible relationship to Late Devonian extinction events. Meteoritics and Planetary Science, 40, 591–607.

Schindler, E., 1993. Event-stratigraphic markers within the Kellwasser Crisis near the Frasnian/Famennian boundary (Upper Devonian) in Germany. Palaeogeogr. Palaeoclimatol. Palaeoecol., 104, 115–125.

Revised flux of meteorite impacts on Earth; probabilities and consequences for the geological record?

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Impact flux curves are important for delimiting abundances of available bolides through time, irrespective of their mass extinction kill potential. Kill mechanisms have broadened from direct (cf Chicxulub, single or multiple) to indirect (cf. mantle plume enhancement), and coincidence-dating is a major challenge - which still obscures confirmation of timing. Could the surface expressions of hydrothermal activity within large impact craters constitute “impact volcanism”, did they persist for long periods of time (> 1 Ma), and were such unusual heat sources capable of generating secondary catastrophes?

A major paradigm shift of the impact flux record has been suggested for the early half of Earth, for which consequences may persist to today. The late heavy bombardment was previously thought to start and end abruptly at between ~4.1 and ~3.8 Ga respectively. However, new interpretations would completely revise the early impact flux and attribute the timescale of the late heavy bombardment (lhb) to a protracted event spanning >2 Ga. Impactor size and velocities back-calculated from a fit to well-dated impact condensate spherule beds, support a gradual decline in impact flux after the lhb (Johnson and Melosh, 2012[1]) over >2 Ga. Astrophysical modeling of a perturbed E-belt asteroid impactor-source undermines a plausible abrupt termination, and points out the potential significance the likely extended massive bombardment may have had for the evolution of life on Earth (Bottke et al 2012[2]). Some of those mechanistic consequences will be presented, and the competing signals attributable to, for example, volcanism and impacts, will be discussed. As an example, the new proposed models for the lhb might strengthen earlier suggestions of impact volcanism either directly, or by enhanced mantle plume activity expressed through large igneous provinces (LIPs)[3,4,5].

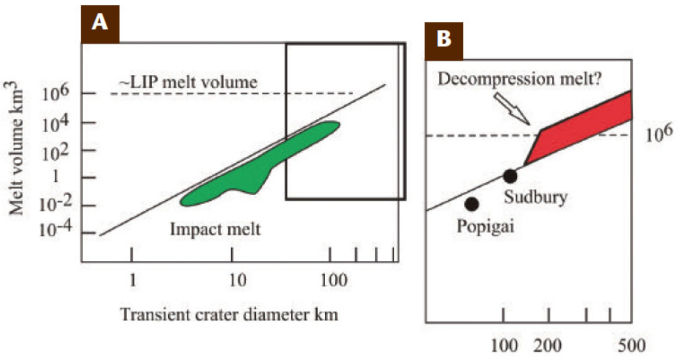

Fig. 1: Volume of impact melts generated by terrestrial impacts (A) and potential for LIP-scale (B) after Jones[5]

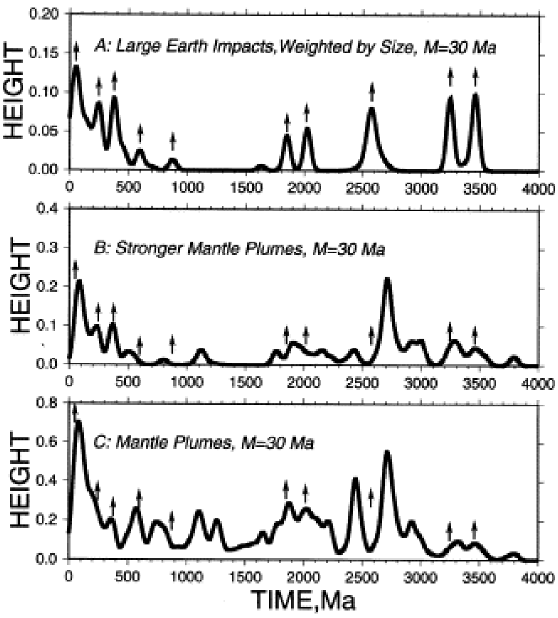

Fig 2. Large impacts and mantle plume events in the geological record after Abbott and Isley[3]

References **1. Johnson B. C. and Melosh H.J.(2012**) Impact spherules as as record of an ancient heavy bombardment of Earthj. *Nature* 486, 75-77. **2. Bottke, W.F. et al (2012)** An Archaean heavy bombardment from destabilized extension of the asteroid belt. *Nature* 485, 78-81. **3. Abbott, D. H. & Isley, A. E. (2002)** Extraterrestrial infuences on mantle plume volcanism. *Earth and Planetary Science Letters* 205, 53-62. **4. Jones, A. P., Price, G. D., Price, N. J., DeCarli, P. S. & Clegg, R. A**. (2002) Impact induced melting and the development of large igneous provinces. *Earth and Planetary Science Letters* 202, 551-561. 5. **Jones, A.P. (2005)** Meteorite impacts as triggers to large igneous province. *Elements,* **1**, 277-281.

Volcanism, impacts and mass extinctions across the KTB

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The nature and causes of mass extinctions in the geological past have remained topics of intense scientific debate for the past three decades. Central to this debate is the question of whether one, or several bolide impacts, the eruption of large igneous provinces (LIP) or a combination of the two were the primary mechanisms driving the environmental changes that are universally regarded as the proximate causes for four of the five major Phanerozoic extinction events. Recent years have seen a revolution in our understanding of interplanetary environments, LIP eruptions and their environmental effects such that the popular simple impact-kill scenario no longer seems an adequate explanation for the Cretaceous-Tertiary boundary (KTB) or any other mass extinction (see abstracts by Adatte and Keller; abstract and poster by Mateo et al.).

The KTB is the only mass extinction associated with both impact (Chixculub) and flood basalts (Deccan Traps) and therefore an excellent case study to evaluate the potential causes and effects. Deccan eruptions likely occurred as "pulses", with some gigantic megaflows 1500 km across India[1-3] and with estimated volumes >10,000 km^3 that may have erupted over very short time intervals[4,5]. The vast amount of carbon and sulphur dioxides injected into the atmosphere from just one Deccan megaflow is estimated to have been on the same order of magnitude as those estimated for the Chicxulub impact. In comparison, the Laki eruption in 1783 on Iceland ejected some 15 km^3 of lava in about a year leading to major climate perturbations[6], famine and death. A single Deccan megaflow was equivalent to 667 Laki eruptions.

Deccan Traps erupted in three main phases with 6% total Deccan volume in phase-1 (base C30n), 80% in phase-2 (C29r) and 14% in phase-3 (C29n)[3]. Phase-2 and phase-3 each produced four giant megaflows leading to the KTB mass extinction and the long delayed biotic recovery, respectively. Data from infra- and intertrappean sediments of these megaflows drilled in the Krishna-Godavari Basin by India’s Oil and Natural Gas Corporation reveal swift and devastating effects on marine plankton in India. A 50% drop in diversity of planktic foraminifera preceded the first megaflow, another 50% drop thereafter, leaving just 7 to 8 survivor species. No recovery occurred between the next three mega-flows and the mass extinction was complete with the last phase-2 megaflow at the KTB[2,3]. In Meghalaya, NE India ~800 km from the Deccan Traps phase-2 volcanism resulted in super stress conditions with planktic foraminiferal faunas dominated (>95%) by deformed disaster opportunist species *Guembelitria cretacea.*[7]

All three Deccan phases can be identified globally by decreased species diversity, selective extinctions (e.g., planktic foraminifera, inoceramids, ammonoids, rudists, dinosaurs), dwarfing, blooms of disaster opportunists and rapid climate changes. Effects of Deccan phase-1 were relatively short-term; phase-2 led to the KTB extinctions and phase-3 caused the long delayed marine recovery. Although debates regarding the proximate mechanisms of the KTB mass extinction are ongoing, they are likely linked to the enormous pulsed injections of gases into the atmosphere, generating alternating episodes of cooling and warming, acid rain leading to marine calcification crises, increased weathering and terrestrial runoff leading to large nutrient influx into oceans and causing oxygen-depleted conditions hostile to marine life. The Chicxulub impact would have exacerbated this already heavily stressed environment.

1. **Keller et al., 2008**, EPSL 268, 293-311. 2. **Keller et al., 2011**, J. Geol. Soc. India, 78, 399-428. 3. **Keller et al., 2012**, EPSL 341-344, 211-221. 4. **Chenet et al., 2007**, EPSL263, 1-15. 5. **Chenet et al., 2009**, J. Geophys. Res. 114, B06103. 6. **Chenet et al., 2005**, EPSL 236, 721-731. 7. **Gertsch et al., 2011, EPSL** 310, 272-285.

The Boltysh Crater record of the K/Pg: Impact and the record of the K/Pg boundary

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The end-Cretaceous mass extinction was viewed as a single, perhaps instantaneous event, and attributed by some researchers to a single asteroid impact at Chicxulub on the Yucatán Peninsula, Mexico. However, prior to the discovery of the Chicxulub crater multiple impacts were considered and two structures were identified as having similar ages to the KPg boundary, the 35 km diameter Manson Impact crater in Iowa, and the 65km diameter Kara crater in Russia. Later recent work demonstrated that both were in fact formed in the late Cretaceous period at 74.1±0.1 Ma (Izett et al 1993) and 70.3±2.2 Ma (Trieloff et al 1998) respectively. The hypothesis of a single giant impact was corroborated by the observation of a single global ejecta layer whose thickness decreased from the site of the Chicxulub crater, promoting the hypothesis of a single impactor caused by a random asteroid or comet impact.

The discovery of a second smaller crater with a similar age at Boltysh in the Ukraine dated at 65.61 ± 0.64 Ma (Kelley and Gurov 2002 ages recalculated to the constants recommended by Renne et al 2010) formed within analytical errors of the KPg boundary age of 66.1±0.05 Ma. While the age determination of the Boltysh age was not particularly precise, the samples were recovered from an old core, and not easily reproducible since the majority of the original core was lost. The age of this crater has raised the possibility that a shower of asteroids or comets impacted Earth close to the Cretaceous-Paleogene (K-Pg) boundary. Palynological and $\delta^{13}C$ evidence from crater-fill sediments in the Boltysh impact crater demonstrate that a post-impact flora, formed on the ejecta layer, was in turn devastated by the K-Pg event. The sequence of floral recovery from the K-Pg event is directly comparable with that in middle North America. We conclude that the Boltysh crater predated Chicxulub by 2–5 k.y., a time scale that constrains the likely origin of the bodies that formed the two known K-Pg craters. Such closely spaced events would be likely to yield a single global ejecta layer (although a double layer has been identified in Georgia, e.g. Smit 1999) and are more likely to be the result of asteroidal collisions, than a cometary shower.

The Chicxulub and Boltysh craters formed in a period of less than ten thousand years, and environmental changes associated with this global event appear to have lasted only a few tens of thousands of years. The timescale of meteorite impacts at the KPg boundary is thus much shorter than the emerging paradigm of the multi-phase KPg boundary events, which include flood basalt volcanism at Deccan, and last several hundred thousand years.

The Kellwasser Event –
A response to global plate reorganization?

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The Late Devonian Kellwasser Event is a classical example of a biological crisis that resulted in one of the five major mass extinctions. The biodervisity decline affected mainly the shallow marine environment of epicontinental seas at low latitudes, and the prolonged process (~1Myr) is contemporaneous with the widespread deposition of the anoxic facies in combination with multiple transgression-regression events. Although many workers have postulated a causal link between these phenomena, there is no consensus about the ultimate cause. Here we present a plate tectonic reconstruction explaining the major orogenic events in the Paleozoic with the existence of two spreading centers along Panthalassa. We propose that the Devonian formation of Proto-Pangea resulted in global plate reorganization and is responsible for the observed environmental change. For instance, the Devonian collision between Laurussia and Gondwana led to a contiguous shelf areal allowing for extensive faunal exchange. Due to the ongoing closure of seaways, in the late Devonian the global oceanic circulation pattern changed dramatically resulting in stagnant epicontinental seas. Furthermore, along the Circum-Pangean realm passive continental margins has been transformed to active plate boundaries. Such a process requires a change in the deep mantle circulation which is probably responsible for frequent sea level fluctuations. Additionally, along the newly evolved active plate boundaries a significant magmatic activity can be considered. Hence, the Late Devonian Kellwasser Event can be explained by a complex and prolonged interplay of endogenic and exogenic processes rather than by a temporary incident.

After the end-Permian mass extinction: the flora of the Early and Middle Triassic in Central Europe

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The dynamics of the biotic recovery of the land plants after the end-Permian mass extinction is still open to discussion also because plant fossils from the Lower Triassic are generally rare and poorly preserved. For most palaeobotanists the Permian-Triassic interval was a long period of turnover with hardly any evidence for the extinction of major groups at the boundary. Other palaeobotanists show a severely affected flora by the end of the Permian and an ecological wasteland during the Early Triassic giving origin also to the "goal gap". According to this concept the lycopsid *Pleuromeia* is the almost only taxon during the Early Triassic of Europe, reflecting both the extinction but also the environmental stress during this period. The study of several floras throughout Central Europe shows a slightly different picture during the aftermath of the mass extinction. The oldest Triassic flora comes from the Bernburg Formation (Early Buntsandstein, late Induan), is dominated by *Pleuromeia* and corresponds to the so called survival interval. The flora becomes more diversified during the late Olenekian (Solling Formation Middle Buntsandstein) with remains of *Pleuromeia*, various sphenophytes, ferns, conifers and putative cycadophytes. This would suggest that the so called recovery phase, characterized by an increased diversity and the resurgence of the conifers, took not place during the Bithynian (late Buntsandstein) but probably already during the Olenekian. The floral diversity increases during the early Bithynian ('Grès à *Voltzia*', upper Buntsandstein) with a dominance in herbaceous and arboreous conifers associated with sphenophytes, lycophytes, ferns and putative cycadophytes and gingkophytes. The recovery phase closes with a well-diversified flora during the late Anisian (Dont Formation). This flora is rich in conifers, ferns and cycadophytes, but also sphenophytes, lycophytes and seed ferns are well represented.

Modeling the environmental effects of sulphur dioxide released by Deccan traps

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One of the five largest mass extinctions of the Phanerozoic took place at the Cretaceous/Tertiary boundary (hereafter KTB). The outpouring of huge amount of basalt in India, the Deccan traps, synchronously with the KTB mass extinction, suggests a possible link between the two events. To decipher the environmental perturbations caused by the emplacement of the Deccan traps, we investigate the consequences of CO_2 and SO_2 released by volcanic eruptions and quantify the biological primary productivity evolution during the KTB. The environmental impacts of CO_2 and SO_2 emissions have been modeled using a global biogeochemical cycle box model (COMBINE, Goddéris and Joachimski 2004) coupled with a climate model, wherein scenarios of CO_2 and SO_2 emissions were constrained by data from Chenet et al. (2007, 2008, 2009). For short-live processes occurring into the atmosphere, the formation and evolution of sulphate aerosol is modeled by 3 equations: the SO_2 oxidation, the liquid aerosol formation and the gravitational sedimentation from the stratosphere (Miles et al, 2003, Pierazzo et al, 2003). To assess the climate forcing due to the related loading of aerosols, our model uses a relationship calculated using a General Circulation Model (GCM) (Robock et al. 2009, Fluteau pers. com). Long-lived processes are also included: over continents sulphate are supposed to react with carbonates and silicates, into the oceans sulphate act on the alkalinity budget and carbonate saturation state. Finally the oceanic primary productivity is computed as a function of all theses environmental changes (Behrenfeld and Falkowski 1997, Chen and Durbin, 1994). Preliminary tests show that a continuous release of CO_2 and SO_2 over 0.5kyrs (Deccan traps duration) fails in reproducing any of the environmental perturbations able to cause a significant drop of marine productivity. Contrastingly, intense degassing peaks lead to a breakdown of biological primary productivity.

Behrenfeld, M J. and Falkowski, P. G.,1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limol. Oceanogr. , 42(1), 1997, 1-20.

Chen C.Y, Durbin E.G., 1994 Effects of pH on the growth and carbon uptake of marine phytoplankton. Mar Ecol Prog Ser 109:83–94

Chenet A-L., Quidelleur X., Fluteau F., Courtillot V., 2007. $^{40}K/^{40}Ar$ dating of the Main Deccan Large Igneous Province: Further Evidence of KTB Age and short duration. EPSL 263: 1-15.

Chenet, A.-L., Fluteau, F., Courtillot, V., Gerard, M., and Subbarao, K.V., 2008. Determination of rapid Deccan eruptions across the Cretaceous-Tertiary boundary using paleomagnetic secular variation: Results from a 1200-m-thick section in the Mahabaleshwar. Journal of Geophysical Research, 113, DOI: 10.1029/2006JB004635.

Chenet, A.-L., Courtillot, V., Fluteau, F., Gerard, M., Quidelleur, X., Khadri, S.F.R., Subbarao, K.V., and Thordarson, T., 2009. Determination of rapid Deccan eruptions across the Cretaceous-Tertiary boundary using paleomagnetic secular variation: 2. Constraints from analysis of eight new sections and synthesis for a 3500-m-thick composite section:Journal of Geophysical Research, 114, B06103, doi:10,1029/2008JB00564

Godderis, Y. and Joachimski, M.M., 2004. Global change in the Late Devonian: modelling the Frasnian-Famennian short-term carbon isotope excursions. Palaeogeography Palaeoclimatology Palaeoecology, 202(3-4): 309-329.

Miles G. M.,Grainger R. G. and Highwoode J. 2003, Volcanic Aerosols the significance of volcanic eruption strength and frequency for climate *Q. J. R. Meteorol. Soc*, 128, pp. 1–999 doi: 10.1256/qj.

Pierazzo E, Hahmann AN, Sloan LC. 2003 Chicxulub and climate: radiative perturbations of impact-produced S-bearing gases. Astrobiology. Spring;3(1):99-118.

Robock, Alan, Caspar M. Ammann, Luke Oman, Drew Shindell, Samuel Levis, and Georgiy Stenchikov, 2009: Did the Toba volcanic eruption of ~74 ka B.P. produce widespread glaciation? *J. Geophys. Res.*, 114, D10107, doi:10.1029/2008JD011652

The geological record of extinctions

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The modern study of extinctions dates back to the 1960s when Otto Schindewolf (1962) in Germany, and Norman Newell (1963, 1967) in the United States began assembling data from biostratigraphic range charts to measure the variability of extinction intensity over geological time. These summaries showed that, contrary to the assumptions of Charles Darwin, Charles Lyell and others, research work of the first half of the 1900s did not result in a predicted filling in of the major discontinuities in the record of taxonomic diversification over time. Rather, certain geological intervals were characterized by many more extinctions than other intervals. Among the largest of these extinction events where the ones located towards the ends of the Cambrian, Ordovician, Devonian, Permian, Triassic, and Cretaceous periods. This group was identified by Newell (1967) as the set of 'mass extinctions'.

Schindewolf's and Newell's work was carried on by J. J. Sepkoski Jr. and David Raup who, in 1982 conducted a refined statistical analysis of a much larger family-level dataset. This analysis resulted in establishment of the 'Big Five' mass extinction events (end-Ordovician, late Devonian, end-Permian, end-Triassic, and end-Cretaceous) as well as the concept of background extinctions. The distinction between these two classes of extinction event was critical at the time because it was linked conceptually to differences in evolutionary regime (e.g., macroevolution vs. microevolution) a point that has often failed to be appreciated sufficiently in subsequent debates over the cause(s) of mass extinctions.

Another point that has failed to be understood was that both Sepkoski's family level, and later generic-level (Raup and Sepkoski 1986) datasets were parsed temporally at the level of the stratigraphic stage. This, along with the well-known, but often misinterpreted, Signor-Lipps effect (Signor and Lipps 1982) places a lower limit on the degree to which these data can be used to distinguish between alternative mass extinction causal hypotheses. Higher resolution data that are sufficient to document the fine-scale timing of mass extinction events is available for some groups (e.g., planktonic foraminifera across the K-Pg boundary). But such highly resolved data are not available for most groups across most mass extinction intervals. Moreover, even for the best datasets factors such as reworking, imprecise chronostratigraphic correlation, and sampling imprecision of last appearance horizons inevitably conspire to make the interpretation of such data less than straight-forward. Given these limitations — none of which are likely to disappear in the foreseeable future — ongoing empirical research must focus on two issues: (1) continued collection of high-resolution data for all organismal groups across all major extinction intervals with sampling programmes designed to report, and take full advantage of, the insights afforded by (a) stratigraphic confidence intervals *(e.g.*, Marshall and Ward 1996) and quantitative chronostratigraphy (*e.g.*, MacLeod and Keller 1991, Kemple, *et al.* 1996) and (2) forensic comparison of biotic turnover records both (a) across groups within a mass extinction (*e.g.*, MacLeod *et al.* 1997) and between mass extinction events (as recommended originally by Raup 1986). The goal of both sorts of investigations should be to detect commonalities in patterns of biotic turnover that might imply commonalities of cause and, ultimately, allow that/those cause(s) to be identified.

Kempell, W. G. et al. 1995, Extending graphic correlation to many dimensions: stratigraphic correlation as constrained optimization, *in* Mann, K. O. and Lane, H. R., eds., Graphic Correlation: Tulsa, Oklahoma, SEPM Society for Sedimentary Geology, Special Publication 53, p. 65–82.

Marshall, C. R., and Ward, P. D., 1996, Sudden and gradual molluscan extinctions in the latest Cretaceous of western European Tethys: Science, v. 274, no. 5291, p. 1360–1363.

Newell, N. D., 1963, Crises in the history of life: Scientific American, v. 208, no. 2, p. 76–92.

Newell, N. D., 1967, Revolutions in the history of life, *in* Albritton, C. C. et al. eds., Uniformity and Simplicity: A Symposium on the Principle of the Uniformity of Nature: Boulder, CO, Geological Society of America Special Paper 89, p. 63-91.

Raup, D. M., 1986, The nemesis affair: a story of the death of the dinosaurs and the ways of science, New York, W. W. Norton & Co., 220 p.

Raup, D. M. and Sepkoski, J. J., Jr., 1982, Mass extinctions in the marine fossil record: Science, v. 215, p. 1501–1503.

Raup, D. M. and Sepkoski, J. J., Jr., 1986, Periodic extinction of families and genera: Science, v. 231, no. 4770, p. 833–836.

Schindewolf, O., 1962, Neokatastophismus?: Deutsch Geologische Gesellschaft Zeitschrift Jahrgang, v. 114, p. 430-445.

Signor, P. W., III, and Lipps, J. H., 1982, Sampling bias, gradual extinction patterns and catastrophes in the fossil record, *in* Silver, L. T., and Schultz, P. H., eds., Geological implications of impacts of large asteroids and comets on the Earth: Boulder, Geological Society of America Special Paper 190, p. 291-296.

The Deccan Flood Basalts – Mascarene Islands volcanic series Petrology, geochemistry and geodynamics (PhD project)

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This project aims at bringing together petrological and geochemical data in order to build a time-lapsed, thermo-mechanical model of the Deccan Flood Basalts (DFB)-Réunion plume. This numerical model will bring new critical constraints on the deep-earth processes at play behind the emplacement of Large Igneous Provinces (LIP) as well as on their consequences at the surface of the Earth both in terms of eruption dynamics and degassing. It will also allow comparison with the Siberian LIP for which a thermo-mechanical model has already been published (Sobolev *et al.*, 2011) and where the geological setting was very different from that of the DFB (e.g. compression versus extension, respectively). The petrological approach follows three steps all based on high-precision electron-probe analysis of high-Mg olivine phenocrysts and included melts (Sobolev, 2007). 1- Calculation of the amount of reaction pyroxenite in the crystallizing melt and of the amount of recycled crustal material in the rising plume, 2- Reconstruction of the primary melts compositions (including volatile, Cl, S, F), 3- Source temperature and oxygen fugacity estimations. The geochemical approach consists in using incompatible trace elements to constraint the source depth and the amount of crustal assimilation in the rising magma. Isotopes will also be used as a way to double-check trace element-based observations.

So far, the petrological data indicate a significant involvement of reaction pyroxenite in the production of the DFB magmas (Western Ghats: ~ 70%) and slightly less (~ 50%) for the Réunion Island (Piton de la Fournaise). Melt inclusion data reveal volatile contents similar to typical OIBs (unlike most Siberian inclusions). Incompatible trace elements indicate there is much less crustal assimilation and much more garnet signature in the DFB than in the Siberian magmas. A reconstruction of the Western Ghats cross section (Chenet *et al.*, 2009) indicates a sharp trace element signature change within 200kyr around the K-Pg boundary (dropping Nb/La_n, temporary shift of Gd/Yb_n and Ce/Pb tending towards depleted mantle values). Clearly, the magmas erupted before (Kalsubai and Lonavala subgroups) and after (Wai subgroup) the K-Pg boundary are not the same. Therefore, the geodynamics must have changed rather rapidly and drastically around this time. On the other hand, the eruption rate seems to slow down during the emplacement of the Wai subgroup (many red boles reported on the field Chenet *et al.*, 2009, Chenet *et al.*, 2008). Finally, calculations of the erupted volumes through time for the Western Ghats based on Chenet *et al.* (2009) also indicate a sharp increase at the K-Pg boundary that correlates very well with the sharp trace element variations. Yet the final volume obtained corresponds to merely less than 25% of the alleged total DFB volume.

Chenet, A.-L., et al (2009). Determination of rapid Deccan eruptions across the Cretaceous-Tertiary boundary using paleomagnetic secular variation: 2. Constraints from analysis of eight new sections and synthesis for a 3500-m-thick composite section. *Journal of Geophysical Research* **114**.

Chenet, A.-L., et al. (2008). Determination of rapid Deccan eruptions across the Cretaceous-Tertiary boundary using paleomagnetic secular variation: Results frim a 1200-m-thick section in the Mahabaleshwar escarpment. *Journal of Geophysical Research* **113**.

Sobolev, A. V., et al. (2007). The Amount of Recycled Crust in Sources of Mantle-Derived Melts. *Science* **316**, 412-417.

Sobolev, S. V., et al. (2011). Linking mantle plumes, large igneous provinces and environmental catastrophes. *Nature* **477**, 312-316.

The carbon isotopic composition of CAMP basalts

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In the geologic record evidence for short-lived and thus devastating perturbations of the global C-cycle are provided by sudden negative carbon-isotope excursions (CIE's) in the ocean-atmosphere system. A well known example is the so-called initial CIE which occurs worldwide shortly before the Triassic-Jurassic boundary. According to most researchers, the marked size of this shift (up to -8‰) suggests that, besides volcanogenic CO_2 emissions from Central Atlantic magmatic province (CAMP) basalts, methane from destabilization of ocean floor clathrates ($\delta^{13}C$ -60‰) or from contact metamorphism of organic-rich sediments ($\delta^{13}C$ -35‰ to -50‰) may have had a dominant role. This interpretation is based upon the assumption that basaltic CO_2 has a $\delta^{13}C$ of approximately -5‰, comparable to that measured on present-day basaltic volcanoes. In order to test this latter hypothesis, we measured the bulk carbon isotopic composition of CAMP basalts and gabbros using sealed tube combustion. The preliminary bulk $\delta^{13}C$ of five CAMP basalts are in the range -26‰ to -29‰ while one basalt yields $\delta^{13}C$ of -14‰. However, this latter basaltic lava also has a high C content (1285 ppm), unlike the other basaltic lavas (C = 73-251 ppm) and intrusives (365-596 ppm). The anomalous basalt sample is quite altered suggesting that its more positive carbon-isotopic composition (-14‰) may be attributed to the presence of secondary calcite. The strongly negative composition of the other basalts and gabbros is more puzzling and may indicate contribution from soil-derived organic matter carbon ($\delta^{13}C$ = -22 to -25; Ekart et al., 1999), although it seems surprising that such a process would result in similar carbon isotopic compositions for apparently unaltered basic rocks coming from different geographic regions (e.g., central Brazil, Sierra Leone, Morocco, Portugal) and crustal depths. Whilst we presently can't constrain where the C is residing in the basalts, we note that the strongly negative $\delta^{13}C$ of CAMP basalts are consistent with some previously published $\delta^{13}C$ values for other LIP basalts (Hansen, 2007) and for mantle rocks (Deines, 2002) indicating that a primary origin of the low $\delta^{13}C$ signature can't be excluded.

Ekart, D.D, et al., 1999. *Am. J. Sc.* **299**, 805-827.
Deines, P., 2002, *Earth-Science Reviews* **58**, 247–278.
Hansen, H.J., 2006, *Lithos* **92**, 105–116.

Volcanism, impact, mass extinction and delayed recovery in the western North Atlantic and Caribbean

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The Chicxulub impact in the Yucatan Peninsula is commonly believed to have caused the Cretaceous-Tertiary boundary (KTB) mass extinction 65.5 million years ago. A thin impact spherule layer found in the western North Atlantic and Caribbean is frequently cited as proof of this hypothesis. We evaluated this claim in four of the best North Atlantic and Caribbean KTB sequences based on high-resolution planktonic foraminiferal biostratigraphy, stable isotopes, bulk-rock mineralogy and trace element analyses. Results reveal that a major KTB unconformity spans Maastrichtian biozones CF1-CF2 (~280 kyr) and most of Danian subzone P1a(1) in ODP Sites 1049A, 1049C and 1050C. Only in the Demerara Rise ODP Site 1259B is erosion relatively minor and restricted to the earliest Danian biozone P0 and most of subzone P1a(1) (~150 kyr). In all sites examined, Chicxulub impact spherules are reworked into the early Danian subzone P1a(1) about 150-200 kyr after the mass extinction (Keller et al., in press). A similar pattern of erosion and redeposition of impact spherules in Danian sediments has previously been documented from Cuba, Haiti, Belize, Guatemala, south and central Mexico (Keller et al., 2003a,b, 2004, 2009). The age of the Chicxulub impact cannot be determined from these reworked impact spherule layers, but can be evaluated based on the stratigraphically oldest spherule layer in NE Mexico and Texas, which indicates this impact predates the KTB by about 130-150 kyr based on the time scale of Gradstein et al. (2004).

The short hiatuses in the early Danian at the P1a(1)/P1a(2) and Pla(2)/P1b boundaries can be explained by climate and sea level fluctuations. The abrupt stable isotope shifts in biozone P1b mark the long delayed (~500 kyr) post-KTB biotic recovery, which is dominated by disaster opportunists and low-oxygen tolerant planktic foraminiferal species. During biozone P1b, isotopic and geochemical records suggest that increasingly high stress conditions may have been related to climate warming (Dan-C2 hyperthermal event), increased physical and chemical weathering under greenhouse conditions, eutrophication of surface waters due to increased nutrient influx (due to intense erosion of continents), and enhanced carbonate dissolution in the oceans. The likely cause for this increased P1b biotic stress is the last phase of Deccan volcanism that began near the C29r/C29n transition. Full biotic recovery, including the disappearance of disaster opportunists (*Guembelitria* spp.) and low oxygen tolerant taxa (*Chiloguembelina* spp.), and the appearance of larger morphotypes occurred only after the last phase of Deccan volcanism ended. These observations suggest that the delayed biotic recovery was likely caused by constant stress conditions due to persistent release of greenhouse gases into the atmosphere by Deccan volcanism during the early Danian (biozone P1a) and rapid, short-term perturbations to the system associated with major pulses of Deccan eruptions leading to the Dan-C2 warm event.

Gradstein, F., Ogg, J., and Smith, A., 2004, A Geologic Time Scale: Cambridge, U.K., Cambridge University Press, 598 pp.

Keller, G., Stinnesbeck, W., Adatte, T. and Stueben, D., 2003. Multiple Impacts across the Cretaceous-Tertiary boundary. Earth Science Reviews, 62, 327-363.

Keller, G., Stinnesbeck, W., Adatte, T., Holland, B., Stueben, D., Harting, M., C. de Leon and J. de la Cruz, 2003. Spherule deposits in Cretaceous-Tertiary boundary sediments in Belize and Guatemala. J. Geol. London, 160, 1-13.

Keller, G., Adatte, T., Stinnesbeck, W., Rebolledo-Vieyra, M., Urrutia Fucugauchi, J., Kramar, U. and Stueben, D., 2004. Chicxulub crater predates K-T boundary mass extinction. PNAS 101(11): 3721-3992.

Keller, G., Adatte, T., Berner, Z., Pardo, A., Lopez-Oliva, L., 2009. New Evidence concerning the Age and Biotoc Effects of the Chicxulub impact in Mexico. J. Geol. Society, London 166, 393-411. doi:10.1144/0016-76492008-116.

The tropospheric chemistry of volcanic plumes

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Over the past few decades our understanding of global volcanic degassing budgets, plume chemistry and the impacts of volcanic emissions on our atmosphere and environment has been revolutionized. Traditionally volcanic SO_2 budgets have been the best constrained but recent efforts have seen improvements in the quantification of the budgets of other environmentally important chemical species such as CO_2, the halogens (including Br and I) and trace metals (including measurements relevant to trace metal atmospheric lifetimes and bioavailability). Recent measurements of reactive trace gas species in volcanic plumes have offered intriguing hints at the chemistry occurring in the hot environment at volcanic vents and during electrical discharges in ash-rich volcanic plumes. These reactive trace species have important consequences for gas plume chemistry and impacts, for example, in terms of the global fixed nitrogen budget, volcanically induced ozone destruction and particle fluxes to the atmosphere. Volcanically initiated atmospheric chemistry was likely to have been particularly important before biological (and latterly anthropogenic) processes started to dominate many geochemical cycles, with important consequences in terms of the evolution of the nitrogen cycle and the role of particles in modulating the Earth's climate. This talk will explore what we can learn from studying present-day volcanic plumes, their atmospheric chemistry and their impacts that might scale up to large volcanic perturbations to the Earth system. It will also explore the implications of these studies in terms of identifying promising markers to locate these volcanic perturbations in the stratigraphic record.

The Late Devonian (Frasnian/Famennian) mass extinction: Harbinger of the Late Palaeozoic Ice Age?

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In this talk I shall discuss (1) the empirical biological data (Table 1) for late Frasnian and early Famennian global cooling, (2) the empirical oxygen-isotope evidence for late Frasnian global cooling, and (3) the empirical pattern of heavy-carbon anomalies in the Late Devonian stratigraphic record vis-à-vis the Cenozoic. These are the data that must be accounted for in any comprehensive hypotheses of the causal mechanisms, and their effects, for the Late Devonian mass extinction.

I shall then argue the hypothesis that the data for the Late Devonian match those seen in the onset of the Cenozoic glaciation, that the end-Frasnian and end-Famennian extinctions are causally equivalent to the Oligocene and Miocene glacial pulses, and that the Devonian extinctions are causally tied to the onset of the Late Palaeozoic Ice Age.

Table 1. Empirical biological observations in marine and terrestrial ecosystems that have been used to argue for global cooling in the late Frasnian and early Famennian.

A. MARINE ECOSYSTEMS:

1. Differential survival of high-latitude marine faunas:
    - Brachiopods (Copper 1977, 1986, 1998)
    - Microbial reef biota (Copper 2002)
2. Differential survival of deep-water marine faunas:
    - Glass sponges (McGhee 1996)
    - Rugose corals (Oliver and Pedder 1994)
    - Tornoceratid ammonoids (House 1988)
3. Migration of deep-water marine faunas into shallow waters:
    - Glass sponges (McGhee 1996)
    - Tornoceratid ammonoids (House 1988)
4. Blooms in cold-water plankton:
    - Prasinophytes (Streel et al. 2000b)
    - Radiolarians (Racki 1998, 1999; Copper 2002)
    - Chitinozoans (Paris et al. 1996, Streel et al. 2000b, Grahn and Paris 2011)
5. Differential survival of fresh-water versus marine species:
    - Acanthodian fishes (Dennison 1979)
    - Placoderm fishes (Dennison 1978, Long 1993)
6. Latitudinal contraction of geographic range in surviving equatorial marine faunas:
    - Foraminifera (Kalvoda 1990)
    - Stromatoporoid and coral reefs (Stearn 1987, Copper 2002)
    - Tentaculitoids (Wei et al. 2012)
    - Trilobites (Morzadec 1992)

B. TERRESTRIAL ECOSYSTEMS:

1. Differential survival of high-latitude terrestrial biota:
    - Land plants (Streel et al. 2000a)
2. Latitudinal contraction of geographic range in surviving equatorial terrestrial biota:
    - Land plants (Streel et al. 2000a)
    - Tetrapod vertebrates (McGhee 2013)

The public impact of impacts: how the media play in the mass extinction debates

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For a subject of such monumental importance, there are amazingly few communication studies of the debates around mass extinctions and impacts. Those that do exist have picked up on the fact that these debates involve scientists from several disciplines, scientists who are often unused to reading each other's journals (e.g. Elisabeth Clemens 1986). Under these circumstances, it is argued, more public or leading journals play a key role not only in getting ideas out into the public arena but in informing scientists across disciplinary boundaries of just what their colleagues elsewhere on the scientific spectrum are thinking. "Normal" communication processes, in which articles in peer-reviewed journals inform the scientific community and "simplified" versions may trickle out to the public via the mass media, become more complex, in a way noted by science communication scholar Bruce Lewenstein (1995). The motives of scientists in the mass extinction debates – particularly those who stress impact scenarios – in making their science public have also been questioned (see Felicity Mellor 2010).

"Mass media" presentations of the dinosaurs and their co-inhabitants have been around for some 200 years: the Crystal Palace Park versions of these creatures, created in 1854 by Benjamin Waterhouse Hawkins at the behest of Richard Owen, sent shivers down the spines of Victorian promenaders long before *Jurassic Park*. The question of what did for the dinosaurs and allowed mammals to take their leading place on Earth has a similarly lengthy history. So, one might have imagined that the dramatic impact answer to this question, due to Alvarez, Alvarez, Asaro and Michel (1980) would have settled the issue in the public mind once and for all. In fact, it seems to have attracted relatively little media attention. This paper will argue that it was the Great Crash of 1994, when Comet Shoemaker-Levy 9 collided with the giant planet Jupiter (see e.g. Spencer and Mitton 1995), that really put the impact scenario for the death of the dinosaurs in the public eye.

Luis W. Alvarez, Walter Alvarez, Frank Asaro and Helen V. Michel, 1980. "Extraterrestrial Cause for the Cretaceous-Tertiary Extinction", *Science* **208**, 1905-1108.

Elisabeth S. Clemens, 1986. "Of Asteroids and Dinosaurs: The Role of the Press in the Shaping of Scientific Debate", *Social Studies of Science* **16**, 421-456.

Bruce V. Lewenstein, 1995. "From Fax to Facts: Communication in the Cold Fusion", *Social Studies of Science* **25**, 403-436.

Felicity Mellor, 2010. "Negotiating uncertainty: asteroids, risk and the media", *Public Understanding of Science* **19**, 16-33.

John R. Spencer and Jacqueline Mitton (eds.), 1995. "The Great Comet Crash: the impact of Comet Shoemaker-Levy 9 on Jupiter" (Cambridge University Press).

The role of giant comets in the mass extinction of species

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The lunar cratering record indicates that there have probably been about a dozen Chicxulub-type impacts on Earth over the last billion years, but dynamical studies show that the main asteroid belt could only have yielded about one. A more promising source for large impactors is a dynamically unstable reservoir of comets orbiting between Jupiter and Saturn, itself fed from more distant reservoirs. Large comets leak from this region into short-period, Earth-crossing orbits on geologically interesting timescales. Every few tens of millions of years one expects a rare giant comet, say 100 – 200 km across, to cascade down from this reservoir into such an orbit, where it is at risk of disruption by solar or Jovian tides. With a mass equivalent to 10,000 – 20,000 Chixculub-sized impactors, the fragmentation of such a comet yields a highly enhanced impact hazard at all scales, with a prodigious dust influx into the stratosphere over the duration of its breakup, which could be anywhere from a few thousand to a few hundred thousand years. There is then an expectation of one or more terrestrial impact episodes from fragments in excess of 10 km diameter, accompanied by many smaller ones. Intermittent fireball storms of a few hours' duration, occurring at intervals while the comet is fragmenting, may destroy stratospheric ozone and reduce incident sunlight. These storms, as much as impacts, may be major contributors to biological trauma. Thus the disintegration of such comets has the potential to create mass extinctions by way of prolonged rather than instantaneous stress. Large impact craters are likewise expected to occur within bombardment episodes rather than in isolation, and this is seen in the high-precision impact cratering record of the past 250 Myr: nearly all impact craters >40 km in diameter are accompanied by lesser ones of similar age.

Trace fossils and related phenomena in the Brynglas Formation (Hirnantian) of Llangranog, West Wales.

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This poster describes a diverse assemblage of trace fossils which occur in rocks associated with the *anceps* and *persculptus* graptolite biozones in the Hirnantian rocks of West Wales. Other than the ichnofaunal record, the rocks are seemingly devoid of significant macrofaunal content. The lack of body fossils reflects the effects of the global end-Ordovician mass extinction, unique among the "Big 5" generally recognised Phanerozoic mass extinction events, in being intimately associated with a global cooling event, coeval high latitude glaciation, carbon isotope excursion and extensive shelf regression.

Trace fossils within supposed turbidite sediments (until recently ascribed to the "Yr Allt Formation" – see Davies et al, 2009) are diverse, and locally at least, abundant. However, rather than being a typical "nereitid" assemblage (preserved on the soles of turbidite event beds), the predominant mode of preservation is as epi-relief surface traces on bedding planes. Within the bedding sequences, occasional top surfaces show distinctive indications of algal? mats or other Microbially Influenced Sedimentary Structures. Intimately associated with the more abundantly populated bedding surfaces are extensively rippled surfaces suggesting a shallower (and potentially more oxic?) palaeo-environment than classical turbidite models of deposition would suggest.

A numeric estimate of ichnogeneric palaeo-diversity has been attempted and comparison is made with related results from other studies (McCann, 1990; Herringshaw and Davies, 2008; Challands et al, 2009; Davies et al , 2011a) in rocks from elsewhere within the associated sedimentary architecture of the Welsh Basin (Davies et al, 2011b).

Davies, J R, Waters, R A, Zalasiewicz, J A,Molyneux, S G, Vandenbroucke, T R A, Williams, M. (2011b). A revised sedimentary and biostratigraphical architecture for the Type Llandovery and Garth areas, Central Wales: a field guide. *British Geological Survey Open Report*, OR/10/037. 43pp.

Herringshaw, L G and Davies N S. (2008), Bioturbation levels during the end-Ordovician extinction event: a case study of shallow marine strata from the Welsh Basin. Aquatic Biology, Volume 2, 279-287.

Challands, T J, Armstrong, H A, Maloney, D P, Davies J R, Wilson, D, Owen A W. (2009). Organic-carbon deposition and coastal upwelling at mid-latitude during the Upper Ordovician (Late Katian): A case study from the Welsh Basin, UK. Palaeogeography, Palaeoclimatology, Palaeoecology, Volume 273, 395–410.

Davies, J R, Waters, R A,Williams, M,Wilson, D, Schofield, D I, Zalasiewicz, J A. (2009). Sedimentary and faunal events revealed by a revised correlation of post-glacial Hirnantian (late Ordovician) strata in the Welsh Basin, UK. Geological Journal, Volume 44, 322-340. Lethaia,Volume 23, 243-245.

McCann, T, (1990). Distribution of Ordovician-Silurian ichnofossil assemblages in Wales – implications for Phanerozoic ichnofaunas. Lethaia. Volume 23, Part 3, 243-255.

Davies J.R., Thomas A.T., Loydell D.K., Cherns L., Cramer B.D., Veevers S.J., Worton G.J., Marshall C., Molyneaux S.G, Ray D. (2011a) Siluria Revisited: a Field Guide, International Subcommission on Silurian Stratigraphy, Field Meeting.

The impact of sediments on triggering of the Permo-Triassic mass extinction

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The mass extinction at the Permo-Triassic boundary has been unequivocally linked with the eruption of the Siberian Traps igneous province. The eruption likely caused a climatic perturbation, although there is uncertainty regarding its magnitude, as it is unlikely that the magma itself could contain enough volatiles to have as dramatic an environmental impact as observed. The missing component might be the degassing of the country rocks (oil shales and evaporites) during heating by sill intrusion [1]. It has been hypothesized that the fluxes of carbon gases derived during contact metamorphism of sedimentary rocks and intruded LIPs may be sufficient to cause climate change of the right order of magnitude [1]. Furthermore, gas-venting structures (filled with magmatic-sedimentary breccias) have been described in the Lower Tunguska region of the Siberian Traps, which might represent pathways through which the gas escaped to the surface [1]. While there has been much work done in quantifying the potential carbon yield from the devolatilisation of sediments, there has been no attempt to quantify the potential sulphur yield, despite this being perhaps the most important species for dramatic short-term climate change.

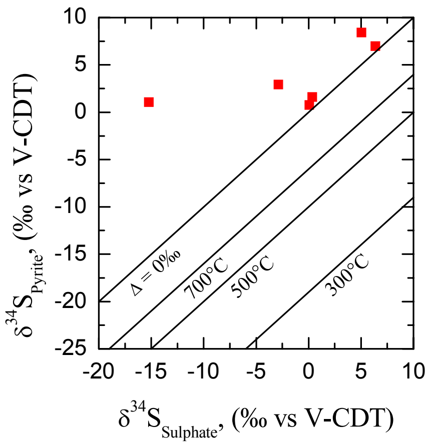

Figure 1. Plot of $\delta^{34}S_{Sulphate}$ vs. $\delta^{34}S_{Pyrite}$ for lavas of Siberian Traps.

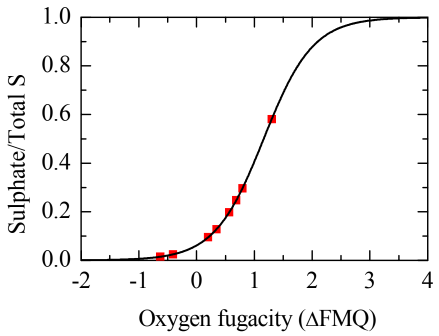

Figure 2. Oxygen fugacity in terms of fayalite-magnetite-quartz buffer.

We present bulk rock sulphur concentrations, monosulphide, bisulphide and sulphate concentrations and sulphur isotopic compositions, for both igneous (sill, lava flow, tephra) and sediments (shale, evaporates) for the Nepa and Norilsk regions of the Siberian Traps. Some samples are characterised by values $\delta^{34}S>2$‰ (the upper range of typical mantle values). The bisulphide-sulphate ratios indicate that the temperatures of sulphur-bearing phases formation were high (above 800°C) (Fig. 1). Our estimates of initial oxygen fugacity of Siberian Traps magmas are from 0.63 log units below the buffer of fayalite-magnetite-quartz to +1.3 this buffer values (i.e., from FMQ-0.63 to FMQ1.3) (Fig. 2), that is consistent with previous assumptions [2, 3].

First results allow us to conclude that low oxygen fugacity in conjunction with high temperature of lavas during the eruption provide the evidence that isotope fractionation through both crystallisation of different sulphur-bearing minerals and magma degassing was negligible. The interpretation of elevated $\delta^{34}S$ is complicated. The reason for this can be either contamination by crustal material ($\delta^{34}S$ of Cambrian evaporites is 22.6 to 34.5‰) or a source characteristic explained by oceanic crust contamination [3].

[1] Svensen, H., Planke, S., Polozov, A. G., Schmidbauer, N., Corfu, F., Podladchikov, Y. Y., Jamtveit, B., (2009) Earth and Planetary Science Letters 277, 490–500. [2] Li, C., Ripley E. M., Naldrett, A., Schmitt, A., Moore, C. (2009) Geology 37, 259-262. [3] Sobolev, S.V. et. al. (2011), Nature 477:312-316.

Volcanism of the Central Atlantic Magmatic Province as the trigger of environmental and biotic changes around the Triassic-Jurassic boundary

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In the last decade major advances have been made in our understanding of the end-Triassic mass extinction, related environmental changes, and the volcanism of the Central Atlantic Magmatic Province (CAMP). Much new data have been generated, significantly increasing the support for the causative role of the CAMP in the cascade of complex environmental and biotic events.

Previously, the end-Triassic extinction was often referred to as the least understood event of the five major Phanerozoic biotic crises. Such statements may no longer be justified, owing to detailed studies of individual sections and various fossil groups (e.g. radiolarians, corals, bivalves, ammonoids, terrestrial reptiles), and synoptic analyses on the diversity history across the Triassic-Jurassic boundary (TJB). A hallmark of the concomitant environmental changes is a series of perturbations in the global carbon cycle. After recognition of an initial and a main negative carbon isotope anomaly, a more complex picture is emerging with other anomalies, both negative and positive, prior to and following the TJB. The source of isotopically light carbon injections causing the negative anomalies remains debated, proposed scenarios evoke dissociation of marine methane hydrate or thermogenic methane released from contact of ascending magma with coal beds. Either process may be capable of amplifying an initial warming, resulting in runaway greenhouse conditions. Support comes from fossil plants through stomatal density studies and other paleobotanical work. Excess CO_2 entering the ocean causes rapid acidification, an effective killing mechanism for heavily calcified marine biota that appears responsible for the reef crisis.

The areal and temporal extent of CAMP volcanism is increasingly well established, mainly through a large dataset of $^{40}Ar/^{39}Ar$ ages. As CAMP is one of the largest Phanerozoic igneous provinces (LIPs), volcanic CO_2-driven warming is plausible as a key factor in the chain of TJB events. Greenhouse warming may have been punctuated by short-term cooling episodes due to H_2S emission and production of sulfate aerosols, a process more difficult to trace in the stratigraphic record. Indirect linkage of CAMP and the TJB events comes from dating studies, relying on a wealth of high-precision U-Pb single crystal zircon ages from marine sections. Direct evidence of synchroneity has been proposed in the form of distal fallout incorporated in a marine section. The position of the oldest CAMP flows with respect to the faunal and floral change remains debated.

Traces of a putative extraterrestrial impact at the TJB have long been sought to provide an alternative causal agent. The large Manicouagan crater has now been decisively shown to predate the TJB. The Rochechouart crater is too small to account for the observed crises. Unambiguous impact signatures are yet to be found in TJB sections. Reviewing the evidence available to date, in this paper I attempt to demonstrate that CAMP volcanism is a viable trigger for the environmental and biotic change around the TJB.

CAMP-related series of rapid climatic reversals caused the end-Triassic floral crisis – evidence from continental strata in Poland

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The Kamień Pomorski IG-1 borehole (Pomerania, NW Poland) yields a profile through the Triassic-Jurassic (T-J) transition in continental deposits (lacustrine-alluvial plain). An integrated study of the sedimentology, sequence stratigraphy, palynology, biostratigraphy, and geochemistry of these deposits has been carried out on the boundary interval which represents a time of major environmental change. Carbon isotope values obtained from palynomaceral separates, and thus reflecting isotopic changes in atmospheric CO_2, show significant fluctuations through the Rhaetian, most conspicuous negative $\delta^{13}C_{org}$ excursion is identified with the Rhaetian 'initial excursion' and shows two sub-peaks, pointing to short-term carbon cycle disturbances of lesser magnitude. Above the 'initial' negative excursion, there is a positive excursion followed again by more negative values, representing subordinate fluctuation within a positive excursion and identified with the T-J boundary. Seventy-two miospore taxa have been determined from the T-J transitional section studied. Two major palynological assemblages have been distinguished. Palynofloral turnover period commenced at the 'initial' $\delta^{13}C$ excursion, with the onset of CAMP (Central Atlantic Magmatic Province) volcanism and falls within a humid period (indicated also by clay minerals). This turnover is much more conspicuous than palynofloral changes observed in Greenland, Tethyan domain or NE Europe. However, comparison of T-J palynofloral assemblages from different European regions points to marked provincialism – for example, the assemblage from Asturias in Spain contains very few palynomorphs common with Poland, while the assemblages from North Sea Basin, Southern Germany or Austria are much more similar. Possibly, the extinction rate was also related to the original palaeolatitudinal position. Osmium isotope system is studied herein for the first time from T-J continental deposits and shows disturbances similar to those measured in marine deposits and is attributed to volcanic fallout. Carbon and osmium isotope correlation and coeval increase in polycyclic aromatic hydrocarbons (PAHs) content and darkening of miospores confirm that eruptions of the CAMP contributed to the perturbances in climate and crisis in terrestrial biosphere. A series of periodical atmospheric loading by CO_2, CH_4 or alternatively by SO_2, sulphate aerosols and toxic compounds is inferred to have caused a series of rapid climatic reversals, directly influencing the ecosystem and causing the crisis of Triassic flora. In addition, we would like to point out that release of toxic pollutants such as SO_2, sulphate aerosols and PAHs certainly led to defoliation, which increased forest flammability and resulting fire activity, similarly to the climate-driven shift from broad-leaved to narrow-leaved taxa at the T–J boundary. Obtained values of initial $^{187}Os/^{186}Os$ between 2,905 and 4,873 and very low iridium content (about 5 ppt) lend no support for a role for an extraterrestrial impact at the T-J boundary event. A new core from Central Poland (Kaszewy-1 borehole) yielded a Rhaetian-Hettangian profile which revealed 8 m thick disturbed level (seismite) at the top of Rhaetian. Preliminary results show that the most negative C-isotope values occur below, not above the seismite - contrary to the St.Audrie's profile, which would also speak against an impact-related seismite (for example linked to the Rochechouart impact crater in France) and would support tectonic origin of seismites occurring in western, southern and central Europe. The position of the initial negative carbon below the T-J boundary, position of sequence boundaries (emergence surfaces) and other isotope excursions allow reliable correlation with marine profiles, including St. Audrie's Bay (U.K), Csövár (Hungary) and GSSP profile at Kuhjoch (Austria).

Pieńkowski, G., Niedźwiedzki, G., Waksmundzka, M., 2012. Sedimentological, palynological and geochemical studies of the terrestrial Triassic-Jurassic boundary in northwestern Poland. *Geological Magazine,* **149**, 308-332

Late Maastrichtian, KTB and Early Danian global biotic and environmental stress linked to Deccan Volcanism

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Recent studies of infratrappean and intertrappean sediments from nine deep wells in the Krishna-Godavari Basin (drilled by ONGC, India's Oil and Natural Gas Corporation, and nearby outcrops in Rajahmundry (Andhra Pradesh) and Central India (Jilmili, Madhya Pradesh) indicate that the main phase (phase-2, 80%) of Deccan trap eruptions occurred over a relatively short time interval in magnetic polarity C29r and ended precisely with the Cretaceous-Tertiary boundary (KTB) mass extinction[1,2]. In these areas, catastrophic decimation of marine and terrestrial fauna and flora (e.g., planktic foraminifera, dinosaurs) began with the onset of gigantic lava eruptions, each with estimated volumes >10,000 km^3 and flows 1500 km across India and out into the Bay of Bengal[3]. The vast amount of carbon and sulphur dioxides injected into the atmosphere from just one of these gigantic eruptions would have been on the same order of magnitude as those estimated for the Chicxulub impact[4]. In more distant areas of NE India (e.g., Meghalaya) extreme stress conditions led to blooms (95%) of the disaster opportunist *Guembelitria cretacea* with stress deformed shells rarely seen elsewhere, whereas the KTB mass extinction is marked by one of the world's largest Ir anomaly[5] suggesting a major impact event unrelated to the well-known Chicxulub impact on Yucatan.

The last phase (phase-3, 14%) of Deccan eruptions, with at least four equally gigantic lava flows as in phase-2, began near the C29r/C29n boundary about 400 ky after the KTB mass extinction. High-stress environmental conditions persisted throughout the aftermath of the KTB mass extinction and continued through the last Deccan phase-3 eruptions. Throughout this long interval, the sole long-term Cretaceous survivor and disaster opportunist *Guembelitria cretacea* thrived and new short-lived, small (dwarfed) opportunistic species evolved. Correlative with the Deccan phase-3 eruptions climate warmed, which is now recognized as the global Dan-2 warm event, and blooms of the opportunist *G. cretacea* dominated. Only after Deccan volcanism ended did normal environmental conditions return along with higher diversity, normal-sized larger species and the disappearance of disaster opportunists.

We examined the environmental and biologic response of planktic foraminifera to Deccan volcanism phase-2 and phase-3 from India through the Tethys Ocean based on new and existing published records and using updated taxonomy to standardize species concepts. Biotic crises and ecosystem recovery in planktic foraminifera are assessed based on relative percent abundances of environmentally sensitive species, morphologic changes, dwarfing, disaster opportunist blooms, extinctions, delayed ecosystem recovery, stable isotopes ($\delta^{13}C$ and $\delta^{18}O$) and lithology. Biologic events are age-correlated with volcanic and/or impact events using high-resolution biostratigraphy, paleomagnetic stratigraphy and available radiometric dating methods.

Results show that high-stress environmental conditions correlative with the KTB and early Danian Deccan volcanic eruption phases are recognized globally by shifts in carbon and oxygen isotopes as well as in high-stress planktic foraminiferal assemblages and extinctions. Deccan phase-2 ended with the KTB mass extinction whereas Deccan phase-3 delayed biotic recovery in the aftermath of the mass extinction by over 500 ky. These results provide the critical information that can explain both the gradual extinction and faunal turnover patterns leading up to the KTB mass extinction and the long delayed recovery phase that has remained an enigma for so long. Neither of these important environmental and biological stress conditions can be explained by the Chicxulub impact hypothesis.

References: 1. **Keller et al., 2008**, EPSL 268, 293-311; 2. **Keller et al., 2009**, EPSL 282, 10-23; 3. **Keller et al., 2011.** EPSL 78, 399-428; 4. **Chenet et al., 2007**, EPSL 263, 1-15; 5. **Gertsch et al., 2011**, 310, 272-285.

Timing of critical events around the Cretaceous-Paleogene boundary

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Previous geochronologic data [1-3] suggest that the main extinctions at the Cretaceous-Paleogene boundary (KPB) and coincident impact signals occurred ~180 ka before the Chicxulub impact and coeval tektites. To test this apparent asynchrony, we have performed detailed $^{40}Ar/^{39}Ar$ and limited U/Pb dating of circum-KPB tephras in the western Williston Basin (Montana) and tektites from Beloc, Haiti. Results to date place the KPB at 66.043 ± 0.043 Ma (systematic uncertainties included), and indicate that the KPB was coincident with the Chicxulub impact to within 32 thousand years.

Our data applied to previous [4] carbon isotope data indicate that perturbation of the atmospheric carbon cycle at the boundary likely lasted less than 5 ka, exhibiting a recovery timescale 2-3 orders of magnitude shorter than that of the major ocean basins. Low diversity Puercan1 mammalian fauna [5] in the western Williston Basin persisted for as little as 20 thousand years after the impact. Additional work in progress is aimed at clarifying the rates and tempo of the post-KPB recovery and the nature of episodic sedimentary cycles, further refinement of the age of the Chicxulub impact, and improved calibration of the geomagnetic reversal time scale to enable comparison of terrestrial and marine KPB records with unprecedented resolution.

Although it is now clear that the KPB and the Chicxulub were synchronous to within analytical uncertainties (< 32 ka), the record of pre-KPB extinctions, climate fluctuations and sea-level changes are persuasive evidence that the impact was a tipping point for planetary state shift rather than the sole cause. We suggest that the Cretaceous hothouse-adapted ecosystem was particularly susceptible to climate fluctuations in the ca. 1 Ma prior to the KPB. The initial pulse of Deccan Traps eruptions remains a plausible culprit for inducing the initial stress on latest Cretaceous ecosystems. However, rigorous evaluation of this possibility awaits vastly improved geochronology to refine the timing and pace of the early history of Deccan magmatism.

References: [1] Swisher et al., 1992; [2] Swisher et al., 1993; [3] Dalrymple et al., 1993; [4] Arens and Jahren, 2000; [5] Clemens, 2002

Response of foraminiferal assemblages to the Toarcian Oceanic Anoxic Event: biotic crisis and recolonisation

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The Early Toarcian was characterised by an important environmental change marked by carbonate crisis coupled with enhanced organic matter accumulation, perturbation of the carbon cycle expressed by a negative excursion of $\delta^{13}C$, a climatic warming and a sea-level rise. This event is known as the Toarcian Oceanic Anoxic Event (T-OAE). Proposals concerning the genesis of the T-OAE include the massive enrichment of ^{12}C caused by a massive dissociation of methane hydrates in marine sediments (e.g., Hesselbo et al., 2007), or the production of thermogenic methane during the concomitant intrusive eruption of the Karoo-Ferrar province (e.g., McElwain et al., 2005). The T-OAE constituted a biotic crisis that produced a mass extinction with significant impact on several benthic groups, including bivalves, brachiopods, foraminifera, ostracods, and necto-planktonic faunas, such as ammonites (Wignall et al., 2005). Benthic foraminifera are good indicators of physical and chemical features of the sea-bottom. The present contribution revolves around the ecostratigraphic and palaeoecologic analysis of foraminiferal assemblages and their stratigraphic evolution as a response to ecosedimentary dynamics during the T-OAE in areas such as the Saharan Atlas (Algeria), Betic Cordillera (South Spain), and Anabar-Lena Basin (northern Siberia). The studied sections are composed by marls and limestones in Tethyan Province (Ratnek El Kahla section, Algeria and Fuente Vidriera section, Spain) and silty shales in Boreal Province (Kelymiar River section, Siberia). A negative excursion of $\delta^{13}C$ occurs while the total organic carbon (TOC) increases in the studied sections at the Polymorphum/Levisoni zone boundary (according to the ammonite Mediterranean biozonation) and Antiquum/Falciferum zone boundary (according to the ammonite Boreal biozonation). However, the TOC values are higher in northern Siberia (6 wt.%) resulting in a black shale, and the negative carbon isotopic excursion is more accentuated. This interval coincides with increasing values in the geochemical redox proxies (Reolid et al., 2012).

The foraminiferal assemblages in the Tethyan sections are dominated by calcitic and aragonitic forms (suborders Lagenina and Robertinina) whereas in northern Siberia dominate agglutinated forms (Suborder Textulariina). In the sections studied is observed a progressive decrease of the diversity from the top of the Pliensbachian, more accentuated in the Lower Toarcian related to the Polymorphum/Levisoni and Antiquum/Falciferum zone boundary and a decrease in the abundance (foram/g). In the case of Ratnek El Kahla section this results in a barren interval. This biotic crisis is related to suboxic conditions (probably anoxic in Ratnek El Kahla section). Survivals are usually opportunists being low-oxygen tolerant genera like *Eoguttulina* and *Lenticulina* in calcareous assemblages from Western Tethys, and *Trochammina* in agglutinated assemblages from Boreal Province. Other typical feature observed is a temporary size decrease within surviving species known as the Lilliput Effect (Morten and Twitchett, 2009).

The diminution in the TOC content and the recovery of $\delta^{13}C$ values in the upper part of the Levisoni and Falciferum zones indicates the end of the T-OAE. The recolonization of the bottom after the restricted oxygen conditions is led by the opportunists. Without tough competition *Lenticulina*, *Reinholdella* and *Eoguttulina* rapidly reproduced and augmented their population in Western Tethys sections. In the Anabar-Lena Basin from Boreal Province, *Trochammina* proliferates being the main colonizer. Abundance and diversity of foraminiferal assemblages increase toward the Middle Toarcian.

Hesselbo, S.P. et al. 2007. Earth Planet. Sci. Letters 253, 455–470. **McElwain, et al. 2005.** Nature 435, 479–482.
Morten, S.D. Twitchett, R.J., 2009. Palaeogeogr., Palaeoclimatol., Palaeoecol. 284, 29–38. **Reolid, M. et al. 2012**. GSA Bull. 124, 1646–1664. **Wignall, P.B. et al. 2005.** American Jour. Sci. 305, 1014–1032.

Intrusive LIPs: Deep crustal magmatic processes and the dual-timescale problem for the emplacement of Large Igneous Provinces

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Large Igneous Provinces (LIPs) are characterized by magmatic activity on two distinct timescales. While these provinces have total active lifetimes of order 10-30 Ma, most of the "main-stage" volume of basalt is erupted within ~1 Ma in many cases. In several cases, associated relatively-minor volume alkali basalt eruptions precede and/or postdate the main-stage flood basalt eruptions by at least several million years. These dual timescales are difficult to understand in terms of the geodynamic models for flood basalt generation that have been suggested so far (e.g., melting plume heads, lithospheric extension), and one general hypothesis is that the main-stage eruption timescale may be modulated by magma/lithosphere/crust interactions, whereas the much longer overall timescale associated with LIP emplacement may reflect the underlying mantle (plume) melting process.

Extensive fractionation of primary plume melts in the lowermost crust is suggested by seismic evidence for 5-15 km thick Moho-level ultramafic intrusive/cumulate layers underlying Phanerozoic LIPs worldwide. These deep crustal bodies are both observed and predicted to have volumes at least as large as the extrusive components of flood volcanism. The evidence for these layers is particularly clear for oceanic LIPs (plateaus), and also for many active hotspot tracks where high-quality seismic refraction imaging is available, with lowermost crustal velocities of Vp~7.4-8.0 km/s lying at or above the Moho. Ultramafic primary melts formed beneath mature oceanic lithosphere at pressures of order 2-3 GPa (60-90 km depth), and ponded at the Moho due to their relatively high density, can explain the observed ultramafic deep crustal bodies. In contrast, near-ridge plumes melting at ~15-30 km depth generate magmas of gabbroic composition. The velocity and density gradient is particularly strong in the pressure range 0.6-1.3 GPa due to the replacement of plagioclase by olivine as melts become more MgO-rich with increasing pressure of melting. This anomalous density gradient suggests a possible filtering effect whereby plume melts equilibrated at relatively shallow depths beneath very young and thin oceanic lithosphere may be expected to be of nearly gabbroic (mafic) composition (6-10% MgO), whereas ultramafic melts (12-20% MgO) formed beneath older, thicker oceanic lithosphere must pond and undergo extensive olivine and clinopyroxene fractionation before evolving residual magmas of basaltic composition sufficiently buoyant to be erupted at the surface.

A survey of well-studied hotspot provinces of varying lithospheric age at the time of emplacement shows that deep-crustal and upper mantle seismic refraction data are consistent with the above hypothesis. These results highlight the importance of large-volume intrusive processes in the evolution of hotspot magmas, with intrusive volumes being significantly larger than those of the erupted lavas in most cases. Pyrolite melting can account, to first order, for the total crustal column of magmatic products, whereas alternative models such as selective melting of pyroxenite blobs probably cannot.

The main-stage flood basalt timescale may be explained if thermally-activated creep of the lower crust due to deep magma chamber emplacement controls a transition from largely extrusive to largely intrusive magmatism during mantle plume impingement on the lithosphere. This hypothesis is explored by modelling the thermo-mechanical evolution of Moho-level magma chambers. Comparing the timescale for viscoelastic relaxation of intrusion-related stresses with the timescale for sill formation and magma differentiation suggests that fracture processes leading to diking from Moho levels may plausibly be shut off on a timescale of ~1 Ma. Continued melt influx therefore results in intrusive magmatism, which may be manifest as plateau growth in oceanic settings. In this scenario, maximum intrusion size may be limited by crustal thickness, resulting in smaller volume individual eruptions in oceanic versus continental LIPs. This particular hypothesis aside, the evidence for extensive lower-crustal fractionation in the formation of flood basalt lavas suggests the importance of achieving a better understanding mediating processes that may distinguish the shorter main-stage flood basalt eruption timescale from the longer timescale of mantle melting in the generation of LIPs.

Latest Ordovician and earliest Silurian brachiopods succeeding the *Hirnantia* fauna in Southeast China

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Shelly faunas dominated by brachiopods are well developed in the clastic facies of the basal Shiyang and Anji formations in western Zhejiang and northeastern Jiangxi provinces, Southeast China succeeding the cool-water *Hirnantia* fauna; elsewhere in the world, during this interval, brachiopod assemblages vary greatly, but are generally rare. The brachiopods, comprising the *Cathaysiorthis* fauna, of the *Normalograptus persculptus* to *Akidograptus ascensus* biozones, straddling the Ordovician and Silurian boundary, contain forty-one genera and forty-three species, indicating that this is the most diverse brachiopod fauna in the world immediately after the end Ordovician mass extinction. Comparison of the fauna with the preceding *Hirnantia* fauna in South China shows some major contrasts, but similarities in the dominance of orthides and strophomenides, the rarity of pentamerides and atrypides, and the lack of trimerellides. Virtually all the genera recorded are leftovers from the diverse latest Katian fauna and have long ranges and wide geographic distributions except for some endemics. New investigations demonstrate that a major faunal change in the brachiopod fauna occurred in the *Normalograptus persculptus* Biozone, rather than precisely at the Ordovician and Silurian interface. The end of the second episode of the end Ordovician extinction event of brachiopods may have extended from the middle *N. persculptus* Biozone, prior to start of the Silurian, coincident with *N. persculptus* Biozone-bearing beds generally overlying the *Hirnantia* fauna and a striking positive excursion of carbonate isotope, present in many places of the world. The end Ordovician extinction of brachiopods is substantially different from the end Permian extinctions characterized by sharp decline at all taxonomic levels with very high extinction rates, the absence of 'hold-overs', Lazarus and progenitor taxa, a zero rate of origination, prevalent miniaturization of shell size, and a much slower recovery rate during the Triassic. This sharp contrast was enhanced by the relative intensity of both extinctions with widely different causes, patterns and consequences and was enhanced by the relatively weak ecosystem disturbances through the Ordovician-Silurian transition rather than the ecosystem collapse during the early Triassic.

The end-Devonian Hangenberg event: causes and consequences of a major bottleneck in vertebrate evolution

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The end-Devonian Hangenberg mass extinction (359 Ma) was long considered a minor black shale bioevent, one among many in the "Late Devonian Biotic Crisis." However, recent work has linked the Hangenberg to the most severe extinction of vertebrates in the Paleozoic (Sallan and Coates 2010, Sallan et al. 2011; Friedman and Sallan 2012). This involved losses of 44% of higher-level clades (Fig. 1) and restructuring of both marine and freshwater ecosystems worldwide (Sallan and Coates 2010). Modern dominant groups (e.g., ray-finned fishes, sharks and tetrapods) experienced a severe bottleneck, with a handful of lineages radiating in a 10-20 My recovery interval associated with "Romer's Gap" (a lull in the tetrapod record; Sallan and Coates 2010; Sallan et al. 2011; Sallan and Friedman 2012). Vertebrate selectivity at the Hangenberg is difficult to parse, as taxa of every lineage, size and ecology were lost (Fig. 1). At higher levels, the Hangenberg event seems to have impacted pelagic and terrestrial faunas while sparing benthic invertebrates, the reverse of the more famous Frasnian-Famennian event that left vertebrates unscathed (Sallan and Coates 2010; Sallan et al. 2011; Friedman and Sallan 2012). The causes of the Hangenberg extinction need further examination; it might be a double event. Open marine fishes are lost at the start of black shale deposition associated with transgression, euxinia and volcanism. A subsequent regressive stage, linked to glaciation and either deposition of the Hangenberg sandstone or absence of the boundary, marks nearshore and freshwater losses. The Hangenberg extinction might coincide with an opening of the Siberian traps and/or the Woodleigh bolide impact in Australia, yet no attempt has been made to link these phenomena. Since similar drivers have also been implicated in other Devonian events, the "biotic crisis" interval illustrate how invertebrate and vertebrate extinction can be disjunct, and all attempts to determine causes must take such selectivity into account.

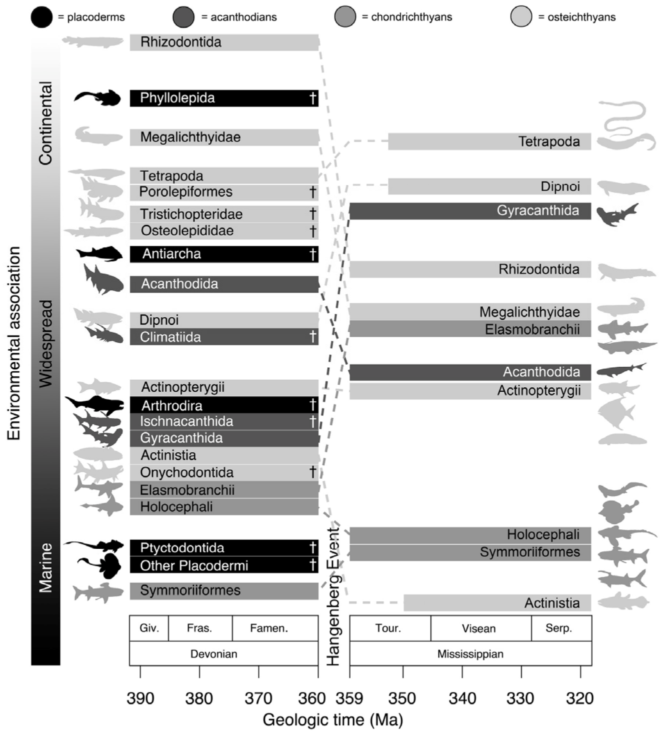

Figure 1. Jawed vertebrate ranges and inferred habitat change over the Devonian-Mississippian and Hangenberg event. Habitat based on correspondence analysis of well-sampled vertebrate sites. (from Friedman and Sallan 2012, data from Sallan and Coates 2010).

Friedman, M. and **L. C. Sallan** (2012) Five Hundred Million Years of Extinction and Recovery: a Phanerozoic Survey of Large-Scale Diversity Patterns in Fishes. *Palaeontology.* **55:** 707-742.

Sallan, L. C. and M. I. Coates (2010) End-Devonian Extinction and a Bottleneck in the Early Evolution of Modern Jawed Vertebrates. *Proceedings of the National Academy of Sciences* **107:** 10131-10135.

Sallan, L. C., Kammer, T. W., Ausich, W. I. and L. A. Cook (2011) Persistent Predator-Prey Dynamics Revealed by Mass Extinction. *Proceedings of the National Academy of Sciences* **108:** 8335-8338.

Sallan, L. C. and M. Friedman (2012) Heads or Tails: Staged Diversification in Vertebrate Evolutionary Radiations. *Proceedings of the Royal Society B* **279:** 2025-2032.

Deccan volcanic eruptions and its impact on flora close to the Cretaceous-Paleogene boundary: palynological evidence

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Palynological study of sediments associated with geographically separated Deccan Continental Flood Basalt (DCFB) sequences of Maastrichtian-Early Paleocene age was carried out for understanding the effect of volcanism on flora. The first observed floral change coincides with the onset of volcanic activity that changed pre-volcanic semiarid fluvio-lacustrine depositional environments of the low land valley to the deposition in the closed land-locked small lakes and ponds under sub-humid conditions. The floral change is marked by a replacement of gymnosperm-angiosperm dominant flora with newly emerging pteridophyte-angiosperm dominating flora. This new floral assemblage characterizes all the early Maastrichtian continental sediments, except in a few marine influenced intertrappean sediments where mangrove (*Nypa*) and Arecaceae pollen are also present.

Stratigraphically higher-up in the Deccan volcanic sequence a second floral change is observed wherein a sharp decline in recovery of palynomorphs is recorded. The sediments at this level are either barren or contain only some biodegraded organic matter. Volcanically induced mock aridity and intermittent wet spells are indicated during the deposition of the sediment at this level. The third floral change is observed at a still higher stratigraphic level where a characteristic and well preserved palynoassemblage of Paleocene age is observed, thereby indicating favorable conditions for the growth of vegetation due to diminishing volcanic activity.

Thus, this study indicates that the onset of volcanism triggered the first floral change in the Deccan province before the Cretaceous-Paleogene (K-Pg) boundary. Continued volcanic activity further affected the existing vegetation and only a few Maastrichtian taxa could survive through the entire volcanic episode. The data also indicate that volcanism induced changes were selective. Some taxa like *Araucariacites*, *Classopollis, Cycadopites*, *Gabonisporis, Aquilapollenites* spp., *Azolla cretacea* and the Normapolles group were affected severely by changing conditions. Palynological data from both terrestrial and marine sediments of India shows distinct disruption in pollen and spore recovery close to the K-Pg boundary. These observations suggest that the floral change in India is strongly linked to the Deccan volcanic eruptions and the cumulative effects of peak volcanic activity can be observed at the K-Pg boundary.

Self-limiting chemistry, aerosol and climate effects of large-scale flood lava eruptions

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We use a state-of-the-art global aerosol microphysics model (GLOMAP) coupled with a chemical transport model to simulate the atmospheric and climatic effects of large-scale flood lava eruptions. We use the 1783-1784 CE Laki eruption (Iceland) as our "standard eruption scenario". The Laki eruption injected around 120 million tons of sulphur dioxide (SO_2) into the upper troposphere/lower stratosphere over the course of eight months.

Using GLOMAP, our results compare well with volcanological and historical records (e.g., Thordarson and Self, 2003) and other modelling studies (Highwood and Stevenson, 2003; Stevenson et al., 2003; Chenet et al., 2005; Oman et al., 2006). We show that, following Laki, the chemical and microphysical processes controlling the formation of new aerosol particles and their removal are fundamentally different from a volcanically unperturbed atmosphere. Both the microphysical and chemical processes controlling the change in the particle concentrations and particle size distribution display a non-linear response to the season the eruption commences in. For example, a Laki eruption commencing in summer would yield around 170 million tons of volcanic sulphate (SO_4) aerosol whereas an equivalent wintertime eruption would yield around 20% less climate relevant SO_4 aerosol (Schmidt et al., 2010). We have also shown that a present-day Laki-type eruption could significantly degrade air quality in Europe and potentially cause more than 100,000 premature deaths (Schmidt et al., 2011) with implications for the environmental impacts of Laki-scale flood lava eruptions.

Subsequently, we scale the Laki standard scenario by factors of 10 and 100 in terms of the amount of SO_2 released and additionally conduct a set of model simulations in which several consecutive Laki eruptions or their scaled equivalents are simulated for up to ten years (i.e. Laki x100 scenario is representative of the 14.7 Ma ROZA member of the Columbia River Basalt Group). We also carry out sensitivity runs in which we change the location of the eruptions and introduce volcanically quiescent periods to quantify atmospheric recovery times. Our modelling results imply that the SO_4 aerosol lifetime is quasi equal across the eruption scenarios no matter how much volcanic SO_2 was injected. In sharp contrast, the SO_2 lifetime increases significantly (albeit non-linearly) the more volcanic SO_2 is injected into the atmosphere. We quantify both the chemical and the aerosol microphysical processes driving these self-limiting effects and show that the efficiency to form new particles (per unit of volcanic SO_2 emitted) drops the more volcanic SO_2 is injected. Therefore, the climatic effects of flood lava eruptions do not scale linearly with the amount of volcanic SO_2 injected into the atmosphere. We will discuss these aerosol-chemistry-climate feedback mechanisms and the magnitude of the climatic effects as well as the potential environmental consequences.

Highwood, E.J. & Stevenson, D.S. (2003). Atmospheric impact of the 1783-1784 Laki Eruption: Part II - Climatic effect of sulphate aerosol. *Atmos. Chem. Phys.*, 3, 1177–1189.

Stevenson, D.S.et al. (2003b). Atmospheric impact of the 1783-1784 Laki eruption: Part I Chemistry modelling. *Atmos. Chem. Phys.*, 3, 487–507.

Thordarson, T. & Self, S. (2003). Atmospheric and environmental effects of the 1783-1784 Laki eruption: A review and reassessment. *J. Geophys. Res*, 108(D1), 4011, 10.1029/2001JD002042.

Chenet, A.L. et al. (2005). Modelling massive sulphate aerosol pollution, following the large 1783 Laki basaltic eruption. *Earth Planet. Sci. Lett.*, 236, 721–731.

Oman, L. et al. (2006). Modeling the distribution of the volcanic aerosol cloud from the 1783-1784 Laki eruption. *J. Geophys. Res.*, 111, D12209, 10.1029/2005JD006899.

Schmidt, A. et al. (2010). The impact of the 1783–1784 AD Laki eruption on global aerosol formation processes and cloud condensation nuclei, *Atmos. Chem. Phys.*, 10, 6025-6041, doi:10.5194/acp-10-6025-2010.

Schmidt, A. et al. (2011). Excess mortality in Europe following a future Laki-style Icelandic eruption, Proceedings of the National Academy of Sciences, 108, 38, 15710-15715.

Severe climatic warming during the end-Permian

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The end-Permian mass extinction has been associated with rapid and severe global warming. Main stage volcanism of the Siberian traps occurs at or near the extinction interval and has been proposed as a likely greenhouse catalyst (Wignall and Twitchett, 1996). The worldwide occurrence of a negative $\delta^{13}C$ excursion is a second prominent feature often directly related to volcanism and associated CO_2 degassing (Erwin, 1993). The 4‰ negative carbon isotope shift requires carbon sources depleted in ^{13}C (CH_4 and CO_2), possibly from synergistic effects such as oxidation of sedimentary organic matter and destabilization of marine methane clathrates (Berner, 2002). However, proxy studies providing support for the hypothesis of extreme climate change are limited (Brand et al., 2012; Joachimski et al., 2012).

Oxygen isotope records are presented from two Iranian sections spanning the Permian-Triassic interval. Pre-extinction values are remarkably stable between 19 and 20‰ VSMOW. Calculated seawater temperatures range between 30-35°C assuming an ice-free ocean with a $\delta^{18}O_w$ of -1‰ VSMOW. In comparison, $\delta^{18}O$ values of late Permian pristine brachiopod calcite range from 2.3 to 3.5‰VPDB and give palaeotemperatures ranging from 27-35°C. A continuous $\delta^{18}O$ record across the Permian-Triassic boundary was reconstructed by analyzing the conodont taxa *Hindeodus* sp. A distinct 1 to 3‰ excursion (5-10°C increase) is observed, which plateaus in the early Griesbachian. These tropical seawater temperatures match inferred temperatures from CO_2 models (Kiehl and Shields, 2005; Rampino and Caldeira, 2005) and temperatures from clumped isotope palaeothermometry (Brand et al., 2012). However, they are higher then temperatures reported in an previous $\delta^{18}O$ study on conodonts from the P-T sections in China (Joachimski et al. 2012) but similarly peak temperatures seem to lag the extinction event as well as the decrease in $\delta^{13}C$. However, calculated temperatures would have been lethal for many organisms and could certainly have added to the slow recovery in the aftermath of the extinction (Romano et al., 2012; Sun et al., 2012).

Berner, R.A., 2002, Examination of hypotheses for the Permo-Triassic boundary extinction by carbon cycle modeling: Proceedings of the National Academy of Sciences of the United States of America, v. 99, p. 4172-4177.

Brand, U., Posenato, R., Came, R., Affek, H., Angiolini, L., Azmy, K., and Farabegoli, E., 2012, The end-Permian mass extinction: A rapid volcanic CO_2 and CH_4-climatic catastrophe: Chemical Geology, v. 322, p. 121-144.

Erwin, D.H., 1993, The Great Paleozoic Crisis. Life and Death in the Permian.: New York, Columbia University Press.

Joachimski, M.M., Lai, X., Shen, S., Jiang, H., Luo, G., Chen, B., Chen, J., and Sun, Y., 2012, Climate warming in the latest Permian and the Permian-Triassic mass extinction: Geology, v. 40, p. 195-198.

Kiehl, J.T., and Shields, C.A., 2005, Climate simulation of the latest Permian: Implications for mass extinction: Geology, v. 33, p. 757-760.

Rampino, M.R., and Caldeira, K., 2005, Major perturbation of ocean chemistry and a 'Strangelove Ocean' after the end-Permian mass extinction: Terra Nova, v. 17, p. 554-559.

Romano, C., Goudemand, N., Vennemann, T.W., Ware, D., Schneebeli-Hermann, E., Hochuli, P.A., Brühwiler, T., Brinkmann, W., and Bucher, H., 2012, Climatic and biotic upheavals following the end-Permian mass extinction: Nature Geoscience, v. 6, p. 57-60.

Sun, Y., Joachimski, M.M., Wignall, P.B., Yan, C., Chen, Y., Jiang, H., Wang, L., and Lai, X., 2012, Lethally hot temperatures during the early Triassic greenhouse: Science, v. 338, p. 366-370.

Wignall, P.B., and Twitchett, R.J., 1996, Oceanic anoxia and the end Permian mass extinction: Science, v. 272, p. 1155-1158.

A review of likely atmospheric emissions from lava-forming and explosive super-eruptions: understanding the potential environmental effects?

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Explosive super-eruptions (> 10^{15} kg of erupted silicic magma), such as Toba and Yellowstone-type events, have stirred much interest in the environmental effects caused by such prodigious magma-gas release events. While some atmospheric modeling has predicted severe global cooling for longer than a decade, recent models accounting for self-limiting aerosol effects suggest shorter and less severe effects on temperature and precipitation for less than a decade. There is some evidence that such eruptions may have several phases, spaced over a few months-years, but overall strong climatic effects and environmental impacts might have been quite brief and localized, except perhaps for vegetation changes. Questions still exist such as the magmatic sulfur (S) content, and S-gas release, from these huge eruptions, and whether these magmas provided the masses of S gases implied to be released to the atmosphere in the modeled cases.

The generation of a flood basalt province on Earth is, at a broad view, a series of basalt-magma super-eruptions usually occurring over a period of < 1 Myr, and including in some cases the largest volcanic eruptions Earth has experienced (1.5 - 3 x 10^{16} kg magma). There is much interest in the environmental effects of these massive magmatic events. A possible cause of widespread environmental impacts from flood basalt eruptions is emission of S, chlorine (Cl) and fluorine (F) from erupting magmas. Much new data on S, CL, and F contents of rare glass inclusions and matrix glasses preserved in quenched lava selvages from various provinces show that the erupted magmas release substantial masses of these gases. Likely magma emission rates and durations of flood basalt eruptions (years to decades to perhaps a century) imply annual SO_2 emission rates of several hundreds to thousands of teragrams. This is many times greater than the present day total of global natural and anthropogenic rates. Heights of injection into the atmosphere of these gases above fire-fountains may have ranged from 6 -15 km, controlled mainly by the amount of ash in the eruption columns, and thus also by vent dynamics and mass eruption rates. Understanding the eruptive style indicated by proximal vent deposits may help in future modeling of atmospheric behavior of eruption columns, and in refining our knowledge of how long these atmospheric plumes of gas and ash could have been maintained above fissure vents during an individual flood-basalt eruption.

Hiatuses between flood basalt eruptions were probably long enough for ocean and land surface systems to partly recover, although there is much interest in CO_2 released from associated intrusions into sediments and the cumulative effect of these on the carbon cycle. CO_2 release from individual magma batches may have causes only minor effects. Evidence to date provides only a first-order basis for interpretation and modeling of the impact of gas releases from past flood basalt activity. The fate of gases, rates of conversion to aerosols, and longevity and radiative impact of the aerosols are all vital areas for which we lack knowledge for ancient atmospheres or with very high, maintained gas release rates. The significance of flood basalt volcanism is that the erupted volumes, and hence the potential environmental pollution caused by the gases released, were immense on a scale compared to any other volcanic activity on Earth.

Rapid fluctuations in stable isotopes during the Triassic-Jurassic extinction

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The approximately 200 million year old Triassic-Jurassic extinction that cleared ecological space and gave rise to the dinosaurs has been attributed to many controversial but unresolved theories from meteorite impacts to volcanic events. Rapid environmental change is a mechanism for reducing species diversity. Carbon stable isotope data and molecular fossils of marine and terrestrial organisms at Queen Charlotte Islands, British Columbia can be interpreted as evidence for rapid climatic fluctuations at, and above, the Triassic-Jurassic boundary. Located close to a humidity-aridity transition the depositional site may have recorded repeated run off events which deposited land-derived material in the marine setting.

Understanding environmental impacts of Siberian Traps and Ontong Java Plateau: insight from geodynamic modeling

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Two largest continental and oceanic Large Igneous Provinces (LIPs) that are Siberian Traps (ST, 252 Ma) and Ontong-Java Plateau (OJP, 120 Ma) share common features that make their origin apparently controversial. Extreme magma production at large areas and high potential temperature of mantle sources of both LIPs support a classical model of melting of a large starting plume head. However, contrary to the prediction of the classical model there was no pre-magmatic uplift associated with ST, and OJP remained at about 1 km depth below the sea level despite ~~of~~ exceptionally thick (30 km) oceanic crust. Moreover, average seismic velocities of the OJP crust are lower than velocities expected for the high-Mg basalts derived from the hot mantle plume. Here we extend our previous study (Sobolev et al., 2011) with ~~a~~ data for OJP and a combined thermomechanical-geochemical model that explains controversial observations and compositions of basalts for both ST and OJP. The model implies that both LIPs originate from decompression melting of a similar low-buoyancy mantle plume head with potential temperature of 1600-1650°C that contained about 15-20wt% of the dense recycled oceanic crust. Differences in volumes of melts and their compositions in OJP and ST are explained by difference in the initial thickness of the lithosphere that was thicker than 130 km in the case of ST and thinner than 50 km for OJP. Our model also explains trace element~~s~~ and isotope~~s~~ data for OJP basalts equally well as the ancient primitive peridotite source model (Jackson et al, 2011).

Our model suggests that in both ST and OJP events similar enormous amount of CO2 (more than 170 Ttones) was released by plumes, mostly derived from a recycled crust component in the plume. However, according to our data and model, the Siberian plume also generated huge amounts of HCl (more than 18 Ttons), likely also derived from the recycled component. This quantity of toxic HCl must have been extremely damaging for the terrestrial species and was sufficient to trigger deadly instability of the stratospheric ozone layer (Beerling et al., 2007). .

We suggest that much of the more destructive effects of the gases released by ST on biota is explained by (1) stronger acidification effect of the released CO_2, SO_2 and HCl on the Permian Ocean that was much less resistant to the acidification than the Cretaceous Ocean (Payne et al. 2010), and by (2) large amount of halogens released to the atmosphere during ST event likely caused extreme depletion of the ozone layer followed by de-forestation, enhanced chemical weathering and associated increase in nutrients that in turn enhanced ocean anoxia.

Beerling, D. J. et al. (2007). The stability of the stratospheric ozone layer during the end-Permian eruption of the Siberian Traps. *Phil. Trans. Royal Soc.*365, 1843-1866

Jackson, M.G.& Carlson, R.W. (2011). An ancient recipe for flood-basalt genesis. *Nature*, 476, 316-19

Payne, J. L., Turchyn, A.V., Paytan A. et al.(2010). Calcium isotope constraints on the end-Permian mass extinction. *Proc. Natl. Acad. Sci. USA*, 107, 8543-8548

Sobolev, S.V., Sobolev, A.V., Kuzmin, D.V., et al. (2011). Linking mantle plumes, large igneous provinces and environmental catastrophes. *Nature*, 477, 312-316

Plant extinctions and floral change at the K/Pg: Three decades on

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Several factors confound the use of plant fossils in extinction studies but the most important are firstly that plants rarely are preserved whole and secondly that individual organs evolve at different rates (heterobathmy). Inevitably the extinction record of plant fossils is one of loss of organ morphology, not lineage loss expressed at the level of whole plant form. Moreover, unlike animals land plants have a variety of ways by which they can survive prolonged adverse conditions, the most effective of which is survival in the soil seed bank. With seed viabilities often measured in decades, if not centuries, it is not short-term (minutes to years) ecological disturbance, but persistent and pervasive adversity over centuries to millennia that is likely to lead to extinction. The resilience of plant life ensures a rapid recovery from short-term devastation, a characteristic noted across the K/Pg transition.

Evidence worldwide shows that Cretaceous terrestrial ecosystems were adapted to disturbance from wildfires and volcanism. Modern vegetation similarly disturbed displays a recovery seral succession virtually identical to that seen not only at the K/Pg boundary but throughout the Cretaceous and earlier. Recovery begins typically with an increase in abundance of pteridophytes followed by an increasing diversity of shrub and tree taxa. Such a signature is not by itself an indicator of global trauma as a causal mechanism for the loss of a genetic lineage, or any kind of boundary event. Although global wildfire has been proposed as a contributory factor in the demise of many taxa at the K/Pg evidence for enhanced fire frequency at the boundary is lacking and even in intact boundary deposits close to the Chicxulub impact site charcoal is notably absent. It seems there was no immediate global wildfire associated with the thermal signature of the impact.

Thirty years of investigation has confirmed patterns of vegetation change at the K/Pg that were evident within a decade of the impact scenario being proposed. Ecological disturbance was most marked at low and middle latitudes and absent at high latitudes. In the Arctic the most significant floral turnover occurred in the early Maastrichtian and not across the K/Pg interval. Longer-term climate change and associated plant migration appears to have been the primary cause of floral turnover. High latitude vegetation was overwhelmingly deciduous and adapted to freezing and extended periods of darkness. Thus any 'post-impact winter' mostly affected plants at lower latitudes that were frost sensitive and evergreen, a pattern seen most strongly in North America.

The Boltysh impact occurred just prior to that at Chicxulub and infilling of the crater records in detail vegetation changes at the K/Pg in the Ukraine. Ecological recovery appears almost identical to that seen in the Raton, Denver and Powder River basins, but palynological data from the more continuous lacustrine sedimentation of Boltysh suggests wet-dry climate cycles extended the period required for recovery. Such climatic instability was also a worldwide feature of Maastrichtian climate.

Floral change in India across the K/Pg is far less dramatic than in North America. Throughout the Deccan eruptions gradual floral change is evidenced, seemingly driven by an increasingly humid Danian climate. The K/Pg transition is marked by a reduction in diversity of triprojectate pollen with only a few species of *Aquilapollenites* surviving. However, even late stage intertrappeans contain evidence of diverse forests as well as terrestrial reptilian faunas so it is implausible that Deccan volcanism influenced ecosystem collapse locally, let alone globally.

Overall K/Pg terrestrial plant extinctions were few compared to those of animals and marine plankton, but ecological trauma was marked proximal to the Chicxulub impact site. In several locations floral change earlier in the Maastrichtian exceeded that at the K/Pg, and it is likely that Maastrichtian climatic instability, not short-term ecological disturbance, sensitised ecosystems to impact trauma. Climatic instability continued into the Danian and may have exacerbated post-event recovery. In the absence of such background fluctuations asteroid impacts alone probably cause, at most, only continental scale short-term ecological trauma and result in minimal long-term global vegetation change and few extinctions.

Implications of the centaurs, Neptune-crossers and Edgeworth-Kuiper Belt for terrestrial catastrophism: Dwarf planets, minor planets, giant comets and dust

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The outer solar system contains a cosmic zoo of large, cold, solid objects classified according to the various terms contained in the title of this paper. It is lamentable that the recent re-classification of some of the 'minor planets' (and one 'planet': Pluto) as 'dwarf planets' by the International Astronomical Union proceeded as it did, because the opportunity was missed to rectify the situation whereby many objects that appear stellar in telescopic images – i.e. literally 'asteroidal' and are therefore classified as 'planets' with some preceding qualifier – might have been better-defined by dint of their physical nature as being 'giant comets'. That is, many centaurs, Neptune-crossers and EKB objects are actually icy bodies that would certainly be counted as being comets should they have been discovered on paths bringing them sufficiently close to the Sun such that cometary emissions of gas and dust would soon have been observed. A particular example is the centaur (2060) Chiron = 95P/Chiron: classified as a minor planet on discovery in 1977, but later recognised to exhibit comet-like outgassing. Many such cross-over objects are now known to exist, confusing the IAU's illogical classification scheme.

This mixed-bag of distant objects contains bodies that must occasionally be forced to misbehave through collisions with each other and close encounters with the gas giant planets. In a small fraction of such contingent events the intact objects (or perhaps their decay products) will be thrown into orbits with small perihelia. Then chaos will reign in the inner solar system as they disintegrate due to thermal stresses and other factors yet to be fully comprehended.

Consider what might happen should a 100-km object (i.e. a giant comet) be diverted first into an orbit with perihelion $q < 1$ AU, and then a cis-jovian orbit similar to that of 2P/Encke. Such an orbit is dynamically-stable for a period of $>10^5$ years, over which time it would be expected (based on the disparate behaviour of observed comets) to undergo a hierarchical disintegration into a vast complex of smaller bodies (which we might classify as minor planets/Earth-crossing asteroids, comets, meteoroids, and dust). The currently-observed Earth-crossing interplanetary dust and meteoroid complex has a total mass equivalent to a comet only about 20 km in diameter, so that the influx of such small debris to Earth would be hugely enhanced, with substantial environmental effects. The 100-km giant comet, if sub-divided into neat 1-km fragments, could also result in catastrophic terrestrial impacts on a once-per-century timescale for more than a million years.

The above might be considered to be wildly speculative, but our expanding knowledge and understanding of the outer solar system should be leading us to an expectation that events such as this – long-lived severe perturbations of the inner solar system space environment with concomitant consequences for Earth – must have occurred many times over the course of our planet's history.

In this paper I will examine the likelihood of such events occurring, starting with an estimation of the probability of a Neptune-crosser or a centaur being diverted directly into an Earth-crossing orbit, and from there deducing how often episodes like those envisioned above might occur. The results have implications for the interpretation of the Earth's geological and biological history, and also for our understanding of the present and future hazards posed by asteroids, comets, meteoroids and dust to our contemporary civilization.

East Greenland flood basalt volcanism: duration, volatile flux and correlation to the Paleocene-Eocene thermal maximum

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Massive flood basalt volcanism in the NE Atlantic 56 million years ago can be related to the initial manifestation of the Iceland plume and ensuing continental rifting, and has been correlated with a short (c. 200,000 years) global warming period, the Paleocene-Eocene thermal maximum (PETM). A hypothesis is that magmatic sills emplaced into organic-rich sediments on the Norwegian margin triggered rapid release of greenhouse gases. However, the largest exposed volcanic succession in the region, the E Greenland flood basalts provide additional details.

The alkaline Ash-17 provides regional correlation of continental volcanism and perturbation of the oceanic environment. In E Greenland Ash-17 is interbedded with the uppermost part of the flood basalt succession. In the marine sections of Denmark Ash-17 postdates PETM, most likely by 3-400,000 years. While radiometric ages bracket the duration of the main flood basalt event to less than a million years, the subsidence history of the Skaergaard intrusion due to flood basalt emplacement indicates it took less than 300,000 years and likely much less (Cawthorn et al., this meeting). It is therefore possible that the main flood basalts in E Greenland postdates PETM. This is supported by a scarcity of ash layers within the PETM interval.

Continental flood basalt provinces represent some of the highest sustained volcanic outputs preserved within the geologic record. Recent studies have focused on estimating the atmospheric loading of volatile elements and have led to the suggestion that they may be associated with significant global climate changes and mass extinctions. Estimates suggest that c. 400,000 km^3 of basaltic lava erupted in E Greenland and the Faeroe islands. Based on measurements of melt inclusions and solubility models, approximately 3000 Gt of SO_2 and 220 Gt of HCl were released by these basalts. Calculated yearly fluxes (based on eruption over 300,000 years) approach 10 Mt/y SO_2 and 0.7 Mt/y HCl. Refinements of these estimates, based largely on further melt inclusion measurements, are proceeding.

Our estimates for volatile fluxes can also be considered as minima, as we have only considered the volume of the E Greenland and Faeroe lavas. If volcanism associated with continental breakup in the remainder of the North Atlantic occurred over a similarly short duration, then fluxes will be considerably higher. For example, if the 4 x 10^6 km^3 volume estimated for the southern portion of the Northeast Atlantic Igneous Province then our flux estimates would be an order of magnitude higher. These fluxes approach those associated with shorter duration historic basaltic eruptions, such as Laki (190 Gt SO_2 over ~9 months), which had markedly deleterious effects in Iceland and throughout northern Europe. The climatic effects of the release of S and Cl in these amounts, and for periods extending for several hundred thousand years, remain unclear, but are likely to be significant. One consequence of East Greenland and related flood basalt volcanism may have been initiation of global cooling to end the Palaeocene-Eocene thermal maximum.

Contributions from Deccan Volcanism to the K-Pg Mass Extinction

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Evidence for a large bolide impact at the end of the Cretaceous Period is largely accepted in the geological community, but its importance as a causal mechanism of the Cretaceous – Paleogene (K-Pg) mass extinction remains a subject of debate among paleontologists. The coincidence of the K-Pg extinction with the eruption of the Deccan Traps large igneous province has raised questions about the relative importance of the bolide impact *versus* volcanic eruption as a kill mechanism. Eruptions associated with large igneous provinces are the leading causes of major mass extinctions at the end of the Permian and Triassic Periods, while other large impact events identified in the geologic record have not produced similar biological crises. The relative importance of these individual causes, or of their synergistic effects, is still in question.

The highly expanded outcrop sections of the Lopez de Bertodano Formation on Seymour Island, Antarctica provide an ideal location for investigating the causes of the K-Pg mass extinction. In combination with the high sedimentation rate, a newly developed magnetostratigraphic record across the Maastrichtian-Danian interval allows for very high temporal resolution for an outcrop section. The local environment would likely have been subject to polar amplification of climatic shifts due to its high paleolatitude (~62°S), facilitating the detection of global climatic disturbances. The extremely (macro-) fossiliferous nature of the outcrop allows investigation of biological patterns to assess extinction timing, and additionally, the diagenetically unaltered carbonate molluscan fossils provide ideal geochemical reservoirs for reconstructing paleotemperature.

By combining extinction statistics on fossil occurrences from the Lopez de Bertodano Formation with isotopically derived paleotemperatures, and placing them in a new geochronologic context built on magnetostratigraphy, we demonstrate that two distinct extinction horizons are present in the very latest Cretaceous. The stratigraphically lowest extinction event occurs ~40 m, or ~200 ka before the Ir defined K-Pg boundary, and is synchronous with a 5°C warming. This earlier extinction is selective only against benthic organisms.

A second extinction event occurs simultaneous with the K-Pg boundary and is selective primarily against nektonic organisms, though some benthic organisms also disappear. The observed warming associated with the earliest extinction is contemporaneous with, and presumably caused by, the eruption of the main phase of the Deccan Traps, as correlated by magnetostratigraphy. The later extinction is caused by bolide impact, the biological effects of which may have been magnified by the environmental stresses precipitated by volcanism. The combination of isotopically derived paleotemperatures and a high precision magnetostratigraphy have provided a more nuanced view of the K-Pg extinction, uncovering a major role for flood volcanism in one of the five largest mass extinction events in earth's history. Our data reconciles concerns that other known bolide impacts do not cause major extinctions, and is consistent with the proposed importance of flood volcanism at other extinction horizons.

Post-impact plant macrofossils from the Boltysh Crater illustrate survival of a Cretaceous fern relict *Weichselia reticulata* into the Paleogene within a refugial geothermal ecosystem

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The Boltysh plant macrofossils represent an ancient, and now extinct, intermediate from temperate to tropical vegetation type that developed on the coastal plain of the ancient European Peri-Tethys Ocean following the K/Pg mass extinction. The **Boltysh crater**, 48.9°N 32.25°E, in Kirovograd province of the Ukraine, the south of the Russian Platform, formed around the same time as the *Chicxulub*, a city size asteroid, slammed into what is now the Yucatan Peninsula, and it is now believed that the mass K-Pg extinction was caused by multiple asteroid impacts coeval to 65 Ma (Jolley *et al* 2010). New promising data on finely preserved Boltysh plant macrofossils have been obtained by the Komarov Botanical Institute, Russia (Vikulin 2012). Core drill slabs of the oil shales-filled **Boltysh crater contain plant macrofossils of the Paleocene epoch,** 65, 5 to 55, 8 Ma. It is known that within disturbed post-impact K/Pg plant communities of the early Paleocene were many pioneer communities numerically dominated by ferns, often of a single species (Vajda *et al* 2001). During the Paleocene - Early Eocene, the Boltysh vegetation evolved in the estuarine and near sea-shore ecosystem of post-impact crater-lake with “heated bottom” under influence of geothermal activity (Gurov, 1996). As the thermal phase of the Boltysh lake had decreased, a succession of pioneer vegetation took place, which has recently been preliminarily confirmed palynologically by Jolley *et al* (2010), who had noticed an increased content of fern spores in the Paleocene core drilling samples. This "fern spike" can be attributed to a massive loss of terrestrial angiosperm-gymnosperm vegetation as a consequence of the mass disruption in the K/Pg impact zone and germination of spores enabling early colonization of ferns in the devastated lands (Vajda *et al* 2001). Similar ecological disruption and mass kill (Wolfe & Upchurch, 1986) associated with the so called "fern spikes" are not confined only to the K/Pg boundary, but also found in other stratigraphic levels, marked by volcanic activity (Krasilov, 2006). The Paleocene oil shales from the Boltysh crater are also enriched with macrofossils of ferns, especially a xerophytic Cretaceous relic *Weichselia reticulata* and shrubby angiosperms: *Salix, Myrica* and *Comptonia*. These early successional ecological groups dominated by ferns together with Salicaceous and Myricaceous angiosperms are considered to represent riparian and post-disturbance niches. Amongst Paleocene Boltysh ferns is *’Blechnum’ dentatum,* previously known only from West European Eocene (Schneider *et al* 2004). Boltysh ferns with *blechnoid* and *asplenioid* pinnae morphology (Vikulin 2012) are representatives of modern lineages and showing marked similarities with some Early Paleogene ferns from Western Europe: Messel, Geizeltal (Barthel 1976; Collinson 2001). Meanwhile, occurrence of *Weichselia reticulata* presumably illustrates survival of a Cretaceous relict into the Paleogene within the Boltysh refugial geothermal ecosystem (Vikulin 2012). A living ecological analogue of the extinct *Weichselia* might be *Pityrogramma calomelanos*, capable of survival under similar extreme environmental conditions, i.e. high acidity of the fallen volcanic ashes, high concentration of sulfur, carbonates, etc (Kornas 1978; Spicer 1985; Riba & Reyes 1990; Craw 2000). The local environment near Boltysh hydrothermal area might have created a unique combination of edaphic environmental factors enabling survival of relict Cretaceous ferns during the Paleocene by easing competition with the evolutionarily young species of flowering plants, whose adaptability to ecological extremes was still low compared with that of ferns. Subsequent disappearance of the Boltysh refugial ecosystem inhabited by the Cretaceous relict *Weichselia* fern, fossilized in oil shales of the geothermal Boltysh crater-lake, was due to the marine transgression of the middle-late Eocene (Vikulin 2012; Zosymovych & Ryabokon 2010).

Jolley DW *et al* (2010) Two large meteorite impacts at the Cretaceous-Paleogene boundary. Geology 38 (9): 835 – 838; **Schneider H *et al* (2004)** Ferns diversified in the shadow of angiosperms. Nature. 428 (6982):553–557; **Vikulin SV (2012)** Cretaceous Fern *Weichselia* in post-impact pioneer vegetation succession of Boltysh Impact Depression. Abstr. scientif. reports, presented to the International Paleobot. Conf. Moscow (1st Feb-3rd February 2012), Russ. Acad. Sc. Geol.Inst. (GIN RAS), dedicated 100 jubilee V.A. Vakhrameev (1912-1986). p.19.

Plant life in the Siberian Large Igneous Province

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Widespread tree mortality may have been a critical element of the end-Permian biosphere crisis. A wealth of palaeobotanical, palynological, and geochemical evidence suggests that terrestrial ecosystems suffered preferential loss of deep-rooted arboreal vegetation. In many parts of the world surviving shrubby and herbaceous plant species played a pioneering role in repopulating deforested and denuded terrain, while ecosystem recovery to pre-crisis levels of structure and function was not reached until the Middle Triassic.

It is increasingly argued that the formation of the Siberian Large Igneous Province has been responsible for triggering the end-Permian crisis. Volcanic eruptions are major ecological disturbances with profound consequences for plant life. Hence, vegetation that must have grown in the vicinity of the Siberian eruptive centres represents the most obvious biota to be analyzed for irreversible adverse effects of volcanic activity upon end-Permian terrestrial ecosystems.

By evaluating palaeobotanical and palynological inventories from volcano-sedimentary successions, we review the basic question of to what extent Siberian floral records could substantiate temporal and causal correspondence of igneous events in Siberia and biotic events worldwide. Notably assemblages of plant remains from lake deposits intercalated at different stratigraphic levels in the voluminous pyroclastic sequences and flood basalts on the Siberian Platform provide an informative source of information.

We believe that the following conclusions must be accounted for in any comprehensive scenario of end-Permian biosphere crisis and associated mass extinctions:

- The onset of Siberian volcanic activity in the Middle Permian coincides with the demise of peat-forming ecosystems characterized by the distinctive Carboniferous-Permian ‘cordaites flora’, representative of the Angaran floristic province in the northern middle-to-high palaeolatitudes of Pangaea (early start of ‘coal gap’ in Siberia).

- Following a province-wide hiatus, at least spanning the entire Wuchiapingian, a surprisingly diverse flora indicates an exclusively Changhsingian age for the flood basalts exposed on the Siberian Platform (the uppermost basaltic suites of the Maymecha-Kotuy region may have been emplaced during the Permian-Triassic transition, but fossil evidence is lacking).

- Latest Changhsingian floral assemblages have not been identified on the Siberian Platform and there is no floral evidence of irreversible volcanically induced ecosystem collapse. At the contrary, during the successive periods of relative quiescence in the volcanic activity, the Changhsingian vegetation demonstrates a remarkable resilience in the face of long-term adverse environmental conditions (post-crisis floral records with dominant lycopsids are probably known from volcano-sedimentary successions on Taymyr Peninsula).

The Cretaceous-Paleogene boundary section on Seymour Island, Antarctica

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The modern Antarctic marine fauna arose following the Cretaceous-Paleogene (K-Pg) mass extinction event and biotic recovery occurred throughout the Cenozoic Era. New detailed stratigraphic sequences linked with comprehensive fossil collections from Seymour Island, located on the Antarctic Peninsula (65°S), enable the study of biotic change through this key time period. This locality comprises one of the best exposed and most complete high latitude sedimentary sequences through the Cretaceous to the Eocene anywhere in the world. Lithologies comprise marine sandstones and siltstones deposited in a back-arc setting in the James Ross Basin.

Fossil assemblages on Seymour Island are well preserved and include marine invertebrates and vertebrates, as well as terrestrial plant material washed in from the nearby Antarctic Peninsula. Recent fieldwork concentrated on collecting fossils at regular intervals through the Maastrichtian to Paleocene López de Bertodano Formation, the Paleocene Sobral Formation and into the lowermost units of the La Meseta Formation, which is Eocene in age.

Assemblages from the Late Maastrichtian of Seymour Island include ammonites, bivalves, gastropods, decapod crustaceans, echinoids, annelids and marine reptiles. A distinct, low diversity recovery fauna characterises the basal Paleocene sequence immediately above the K-Pg boundary, which is dominated by the bivalve *Lahillia*. In the lower levels of the Sobral Formation a radiation of new molluscan taxa occurred. Predatory neogastropods are particularly prominent in this assemblage. At this horizon some taxa, for example gastropods belonging to the Buccinoidea, bear striking resemblances to certain modern Southern Ocean genera. Taxonomic diversity continues to increase throughout the Sobral Formation, with another burst of new species following the Paleocene-Eocene Thermal Maximum in the lower part of the Eocene La Meseta Formation.

Deccan SO_2 release across the KTB: integrating $^{40}Ar/^{39}Ar$ and palaeomagnetic chronologies with lava unit volatile contents

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Volcanic volatile release is commonly cited as a driver for environmental change and mass extinction events during the emplacement of continental flood basalts (CFBs)[1]. However, a more precise understanding of the role of CFBs in environmental deterioration has been hampered by a lack of constraints, including the timing and duration of the eruptions, and reliable estimates of volatile release. This lack of constraint has combined to produce significant uncertainties regarding both total and secular volatile flux. To date, there have been few quantitative determinations of volatile release from CFB basalt eruptions, yet such data remain crucial if these links are to be cogently argued.

We present an integrated $^{40}Ar/^{39}Ar$, palaeomagnetic and chemostratigraphic study based upon the classic Western Ghats Deccan Traps sections; these provide access to key parts of the Deccan stratigraphy, and a complete record of eruptions across the KTB. The established chemostratigrahy recognizes 11 Formations, placed within 3 chemically distinct subgroups which are, from oldest to youngest; the Kalsubai, Lonavala and Wai subgroups.

Magnetostratigraphic data from the Western Ghats provides a useful chronological framework[2]. Two magnetic polarities were identified in five of the sampled sections which, in line with previous studies, are assigned to chrons 29r and 29n; the reversal is occurs in the base of the Mahabaleshwar Fm, indicating that the KTB lies stratigraphy beneath, and within the upper Wai Subgroup.

$^{40}Ar/^{39}Ar$ analyses were performed on the stratigraphically lowest (earliest), and highest (final) Deccan lavas, with additional analyses of units above and below the 29r/n reversal level. These data provide determinations of Deccan timing and duration, and ages of key units bracketing the KTB. Earliest lavas yield a late Maastrictian ages (66.7 +/- 0.5 Ma), indicating the onset of volcanism c. 0.5 – 2 Ma before the KTB, and the last units an early Palaeocene age (63.7 +/- 0.3 Ma). Previous studies reveal Deccan eruptions reached an acme of eruption during chron 29r and into early 29n when the upper part of the volumetrically important Wai Subgroup was emplaced[3].

Determining volatile content and eruptive degassing of ancient lavas has proved challenging. Direct petrographic measurements on rare glass inclusions within crystals, and on glassy selvages from Deccan lava flows, reveal S concentrations ranging from c. 1400 ppm S in inclusions, down to a few hundred ppm in the degassed selvages. However, this method is impracticable for the bulk of Deccan samples; instead, a chemical ratio proxy is used to obtain original S content estimates for Deccan lava units. Magma S contents of between 1250-1750 ppm can be estimated for each of the major sub-groups. Finally, we combine our established eruptive chronology and associated volcanic stratigraphy to provide an integrated history of Deccan S release across the KTB.

[1]Wignall, P.B.,2001. Large igneous provinces and mass extinctions. *Earth Science Reviews*, **53**, 1-33.
[2]Jay, A.E., et al., 2009. New palaeomagnetic data from the Mahabaleshwar Plateau, Deccan Flood Basalt Province, India: implications for the volcanostratigraphic architecture of continental flood basalt provinces. *JGSL*, **166**, 13-24.
[3]Chenet, A.L., et al., 2008. Determination of rapid eruptions across the Cretaceous – Tertiary boundary using palaeomagnetic secular variation: Results from a 1200m thick section in the Mahabaleshwar escarpment. *JGR*, **113**, B4.
[4]Self, S., et al., 2008. Sulfur and Chlorine in Late Cretaceous Deccan Magmas and Eruptive Gas Release. *Science*, **319**, 1654-1657.

Death by fire: The volcanism/extinction link in the Middle and End Permian

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Our knowledge of the greatest of all crises at the end of the Permian has changed significantly in recent years with the recognition that the end-Permian crisis was preceded by an earlier event in the Middle Permian. Initially identified as an end-Guadalupian event, based on literature records, more detailed field studies have shown that extinction losses occurred significantly earlier within the mid Capitanian Stage and principally affected shallow-marine benthos from low latitude shelf seas (Bond *et al.* 2010). This redating allows the marine losses to be closely tied with a major terrestrial extinction in which the ruling tetrapods, the dinocephalians, were wiped out. The Capitanian crisis thus affected both marine and terrestrial realms and truly deserves the "mass extinction" epithet.

Both the Capitanian and end-Permian mass extinctions correlate with the eruptions of large igneous provinces; the Emeishan and Siberian traps respectively. More precisely they coincide with the onset (rather than the acme) of eruption of these vast lava provinces. However, the corresponding global environmental changes show clear differences. End-Permian oceans saw the rapid onset on anoxic conditions followed by the widespread development of organic-rich shale deposition, notably in oceanic settings and high latitude shelf seas whilst Capitanian oceans show no such redox change (Wignall et al. 2010). Ocean acidification has also been championed as a killer for the end-Permian oceans albeit based on indirect evidence, such as a supposed selectivity to extinctions, but this cause has yet to be clearly implicated for the Capitanian event. Indeed the proximate cause of the earlier event is far from clear. The well-known eustatic lowstand of the Middle Permian, probably one of the lowest points of sea level in the entire Phanerozoic, approximately coincides (Bond et al. 2010) but the most complete sections for this interval show losses prior to the sequence boundary. Further data is required for the Capitanian mass extinction, especially knowledge of the extinction selectivity in higher latitude seas, before the causal link between volcanism-extinction can be fully understood.

Bond, D.P.G., Hilton, J., Wignall, P.B., Ali, J.R., Stevens, L.G., Sun, Y-D., Lai, X-L. 2010. The Middle Permian (Capitanian) mass extinction on land and in the oceans. *Earth-Science Reviews* **102**, 100-116.

Wignall et al 2010. An 80 million year redox history from Permian to Jurassic pelagic sediments of the Mino-Tamba terrane, SW Japan, and the origin of four mass extinctions. *Global and Planetary Change* **71**, 109-123.

Mammals across the K/Pg boundary: Ecological selectivity and immigrant-fueled ecospace filling

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Mass extinctions have had a disproportionate effect on the course of evolution[1-3]. More than just massive losses to biodiversity, these geologically rapid events unseated successful incumbents, devastated otherwise stable ecosystems, and, in turn, generated open ecospace and new opportunities for survivors, some of which were minor ecosystem components that only later became dominant. Detailing the dynamics of mass extinctions and their ensuing biotic recoveries thus bears directly on evolutionary and ecological theory as both aim to explain the loss and origination of biodiversity and the fragility, collapse, and assembly of ecosystems.

The Cretaceous-Paleogene (K/Pg) mass extinction event is an excellent model for analyzing mass extinction and biotic recovery dynamics. On land, it marked the end of Mesozoic dinosaur-dominated faunas and the beginning of an early Paleocene biotic recovery, which later transitioned into an unrivaled adaptive radiation of a previously marginal group—eutherian mammals [4-6]. As the most recent of the 'big five' mass extinctions, the quantity and quality of the geological and paleontological data for the K/Pg interval are better than those available for more ancient mass extinctions[7]. Moreover, many of the affected organisms have living descendants or modern analogs with known ecologies.

Most previous studies of K/Pg extinction and recovery dynamics have focused on taxonomic diversity on coarse spatiotemporal scales, but here, we provide a detailed ecomorphological view from the perspective of mammalian paleocommunities in a single ecosystem. We measured orientation patch count (OPC) of three-dimensional surface models of mammalian tooth rows from latest Cretaceous (Lancian) and earliest Paleogene (Puercan) faunas of northeastern Montana. OPC is a proxy for 'dental complexity' and correlates to diet in a variety of modern mammal groups [8,9]. The restricted spatiotemporal framework of this study area and the focus on mammalian dental morphology provide an ecologically relevant scope to investigate community-level processes[10]. Specifically, we aim to document the ecomorphological pattern of the K/Pg extinction to test for selectivity and elucidate causal mechanisms, and to document the ecomorphological pattern of the earliest Paleocene survival fauna to better understand ecospace filling in relation to the recovery process and the subsequent adaptive radiation of placental mammals.

Our results reveal several key findings: (1) latest Cretaceous mammals, particularly metatherians and multituberculates, had a greater ecomorphological diversity than is generally appreciated, attaining dental complexities that reflect strict carnivory, plant-dominated omnivory, and herbivory; (2) the decline in OPC disparity across the K/Pg boundary shows a pattern of constructive extinction selectivity against dietary specialists, particularly taxa with plant-based diets, that suggests the kill mechanism was related to depressed primary productivity at least locally; (3) ecospace re-filling in the earliest Paleocene was fueled by immigrants, namely three multituberculate families and to a lesser extent archaic ungulates, of larger body size and herbivorous diets; and (4) although the taxonomic richness of eutherians increased immediately across the K/Pg boundary, their well-known post K/Pg ecomorphological expansion was delayed for at least 400,000 to 1 million years after the

1. Gould, S. J. 2002. Belknap Press Harvard University Press.
2. Erwin, D. H. 1998, Trends in Ecology & Evolution 13:344-349.
3. Jablonski, D. 2005, Paleobiology 31(suppl.):192-210.
4. Krug, A. Z., and D. Jablonski. 2012, Geology G33091.1.
4. Alroy, J. 1999, Systematic Biology 48:107-118.
5. Archibald, J. D. 2011, The Johns Hopkins University Press, Baltimore, Maryland.
5. Smith, F. A., et al., 2010, Science 330:1216-1219.
7. Jablonski, D., et a., 2003, Science 300:1133-1135.
8. Evans, A. R., et al., 2007, Nature 445:78-81.
9. Santana, S. E., S. Strait, and E. R. Dumont. 2011, Functional Ecology 25(4):839-847.
10. Bambach, R. K. 1977, Paleobiology 3:152-167. 11.

Latest Cretaceous continental vertebrates of Indo-Pakistan

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The Indian subcontinent had a dynamic geographic and geologic history that is key to understanding major paleobiogeographic and macroevolutionary events, including the Cretaceous-Paleogene (K-Pg) mass extinction event as well as the origin, evolution, and dispersal of major groups of continental tetrapods. Originally interlocked with other Gondwanan landmasses until ca. 150 Ma, Indo-Pakistan migrated northwards, apparently in isolation, across the equator to contact Asia ca. 50 Ma. Although the timing and nature of the trajectory of Indo-Pakistan are disputed, it transported both its living and fossil biota from southern Gondwana to Asia, an event may have profoundly affected the Asian and Indian biotas and has become a favored explanation for the origin and dispersal of major taxonomic groups (e.g., ranid frogs; Bossuyt & Milinkovitch 2001) among molecular systematists. Meanwhile, India's geologic history included outpouring of the Deccan Trap flood basalts, whose eruptive volume is estimated to have been among the largest in Earth history (ca. 1.3 x 106 km3) and implicated as a major causal mechanism for the K-Pg mass extinction (e.g., Keller et al. 2009).

The record of continental tetrapods leading up to the K-Pg event in Indo-Pakistan is known from uppermost Cretaceous sedimentary deposits exposed in both India and Pakistan. The most extensive of these are sediments associated with the Deccan Trap continental flood basalts in central and western India, which are either capped by them ('infratrappeans;' e.g., Huene & Matley 1933) or sandwiched between them ('intertrappeans;' e.g., Prasad & Sahni 1988). Deccan Trap-associated fossil localities are distributed across 7.0° of latitude and 11.5° of longitude, and they occur within geographically isolated outcrops that have limited stratigraphic thickness. Their broad but sparse geographic distribution and limited thickness mean that fossiliferous localities in India can be difficult to put in a stratigraphic framework, which has resulted in the misconceptions that (1) intertrappean beds are superposed over, and therefore younger than, infratrappean beds, and (2) both infratrappean and intertrappean deposits are everywhere of equivalent age. In fact, infratrappeans may be stratigraphic extensions of, and syn-depositional with, intertrappean rocks (Sahni et al. 1984), infratrappeans were deposited during both magnetochrons 29R and 30N, and sequences of intertrappeans are sandwiched between flows of different ages (Jay & Widdowson 2008). It is critical to revise the current stratigraphic framework of the continental tetrapod record using chemostratigraphy, paleomagnetics, and geochronology, which will have important implications for interpretation of paleobiogeography and K-Pg extinction/survivorship of the Indian biota.

Since the early 19th century, hundreds of fossil bones and teeth of continental tetrapods have been collected from Deccan Trap-associated localities, including amphibians, squamates, turtles, crocodylomorphs, saurischian dinosaurs, and mammals. Pterosaurs, ornithischian dinosaurs, and birds are conspicuously absent. Despite the taxonomic breadth represented and large number of bones collected, most specimens consist of only one or a few bones—few complete or nearly complete specimens are known. This has led to a coarse and profligate taxonomy in which many specimens can only be placed in broad taxonomic categories (e.g., "titanosaur sauropod" or "discoglossid frog"), while named fossil species are based on limited anatomical information and restricted overlap with previously named taxa. For example, among the 28 dinosaur species that have been named from India and Pakistan since 1877, only 4–7 are recognized as valid taxa today (Wilson et al. 2011). There are, however, several examples of exquisite preservation that result in well-defined species whose lower-level phylogenetic affinities and paleoecology can be resolved (e.g., *Sanajeh indicus*, Wilson et al. 2010). Since the 1980s, collecting efforts have shifted to focus on intertrappean microfossil sites (Prasad & Sahni 1988; Prasad 2012), which, like infratrappean sites, preserve a broad range of taxa represented by isolated specimens. Fortunately, many of these isolated fossil elements are anatomically complex and preserve species-level diagnostic features (e.g., mammal teeth).

Our study of the continental tetrapod record of Indo-Pakistan indicates that the vast majority have Gondwanan sister taxa (n = 21). This includes both reptiles and mammals, which occur in both infratrappean and intertrappean deposits from chrons 30N and 29R. In contrast, very few Laurasian sister taxa are known (n = 5), all of which are eutherian mammals occurring in intertrappean deposits. These results suggest that despite geophysical evidence suggesting Indo-Pakistan was geographically isolated from other landmasses, its biota retains strong connections to southern landmasses. There is no evidence for endemism, which agrees with previous conclusions arrived at by Sahni (1984) on the basis of a much coarser taxonomy of Cretaceous Indian continental tetrapods.

Greenhouse effect of large igneous provinces: SIMS oxygen isotopes of conodonts from the Meishan and Penglaitan sections in South China

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The possible link between mass extinctions and large igneous provinces (LIPs) has long been proposed based on their temporal coincidence. Various hypotheses have been put forward to suggest how global climate changed by large scale volcanism. To further explore the effect of LIPs on mass extinction, we carried out oxygen isotope analyses using SIMS techniques (SHRIMP and CAMCA 1280) on monogeneric conodonts from both of the Meishan Global Stratotype Section and Point (GSSP) of the Permian-Triassic (P-Tr) boundary and the Penglaitan GSSP section of the Guadalupian-Lopingian (G-L) boundary in south China. Both boundaries are marked by severe bio-crisis, which are temporally related to the Siberian Traps and the Emeishan basalts, respectively. During the Late Permian, both sections were located on the Yangtze Platform at 19-20°N in subtropical latitudes.

New SIMS data are essentially similar to those obtained by bulk analyses. High-resolution oxygen isotopes measured on phosphate-bound oxygen in conodont apatite from the Meishan section document the timing and magnitude of global warming across the P-Tr boundary. $\delta^{18}O$ values decrease by 2‰ immediately across the main extinction event boundary, translating into low-latitude surface water warming of 8 °C. Lethally hot temperature or warm climate conditions in the latest Permian (after the main extinction horizon) and Early Triassic is in temporal agreement with emplacement of the Siberian trap, suggesting a possible genetic relationship between them. $\delta^{18}O$ of conodonts of Penglaitan section decrease by 1‰ in the latest Capitanian before the G-L boundary, suggesting warming of ambient water temperature of about 4°C in the Capitanian (from *J. postserrata to J. granti Zone*), cooling of 6°C across the G-L boundary. Shift warming in the latest Capitanian is temporally coincident with the emplacement of the Emeishan LIP which terminated before the G-L boundary, suggesting a possible link between two events. Interestingly, the global warming (4-6 °C) is also apparent at the K-T boundary, across which the Deccan LIP was emplaced.

It can thus be suggested that the emplacement of some LIPs, especially those intruded sedimentary covers, may have caused greenhouse effect on Earth. Whether this global warming triggered bio-crisis requires further investigations. For instance, at the P-Tr boundary, the major temperature rise started immediately after the main extinction phase. The temporal relationship between climate warming and the main pulse of extinction suggests that global warming may not be main causes of the mass extinction. This global warming might have played a major role in the delayed recovery in the aftermath of the P-Tr crisis.

The extent of volcanism at Permian-Triassic boundary: New constraints from mineralogy, geochemistry and geochronology of Bed 26 at Meishan section, South China

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The Permian-Triassic Boundary (PTB) mass extinction was the most severe event throughout the Earth history[1]. There are several claystone layers at PTB section at Meishan (one of Global Stratotype Section and Point), namely Beds 25, 26 and 28. Bed 25 with 4 cm in thickness is well known by its volcanic genesis[2], whereas Bed 26 (6 cm thick) is generally known as sedimentary black shale [2] or mudstone[3]. This study presents newly acquired mineralogy, whole-rock geochemistry, in-situ U-Pb and Hf-O isotopic data on the Bed 26. Bed 26 consists of 32.6% quartz, 8% feldspar, 9% calcite and 48.1% clay minerals, which is significantly different from Bed 25 (3.2% quartz and 94% clay minerals). Discrimination diagrams based on immobile elements show that sources of Bed 26 are felsic rocks. Zircons from Bed 26 are all euhedral, showing prismatic to acicular crystal habits, with SIMS U-Pb ages clustering at 252.1 Ma. These ages are identical within the uncertainty to the age of Bed 25. Negative $\varepsilon_{Hf(t)}$ (-11.4 to -6.0) and high $\delta^{18}O$ values (8.2 to 9.1‰) of Bed 26 zircons, are also similar to those of Bed 25. The resemblance of Bed 26 with Bed 25 in terms of geochemistry and geochronology strongly suggests that Bed 26 is reworking deposits of Bed 25 volcanic ashes. Given the thick layer of Bed 26, the extent of PTB volcanism in South China could be much larger than previously thought. It is therefore necessary to reappraise the role of PTB volcanic ashes on the cause of the PTB mass extinction.

[1] Raup and Sepkoski, 1982, Science 215(4539), 1501–1503.

[2] Mundil et al., 2001, Earth and Planetary Science Letters 187(1-2), 131-145.

[3] Cao et al., 2002, Chinese Science Bulletin 47(13), 1125-1129.