International Geoscience Programme Project 653

The onset of the Great Ordovician Biodiversification Event

Third Annual Meeting

Trekking Across the GOBE

From the Cambrian through the Katian

Athens, Ohio 2018

Paleontological Society

Ohio University

IUGS UNESCO IGCP Project 653 The onset of the Great Ordovician Biodiversification Event

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Trekking Across the GOBE

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June 3-7, 2018

Program & Abstracts

Edited by

Alycia L. Stigall, Daniel I. Hembree & Rebecca L. Freeman

Athens, Ohio, USA 2018

Cover photo: Edenian through Maysvillian Strata (Kope through Bellevue Formations) at the US-68 "Big Maysville Roadcut" visited on the mid-conference field excursion.

Preface

Welcome to Ohio University and beautiful southeastern Ohio! Ohio University was established in 1804 and is the oldest university within the Northwest Territories of colonial America. Athens is known for its collegiate, environmentally friendly, and craft brew-loving culture. Our community values diversity, inclusion, and progressive ideals, which certainly characterizes our conference and participants as well.

The fossils and strata of North America have been key to building understanding of the critical coordinated Earth system and biotic changes of the Ordovician Period for nearly centuries. I am delighted to welcome this distinguished assemblage of over fifty scientists representing more than eight nations to Ohio University and the spectacular Ordovician strata of Ohio and Kentucky for an engaging week of vibrant discussions about the most recent discoveries and insights into the late Cambrian through Ordovician world.

The presentations this week span an array of topics and time intervals, but they are united by the underlying scientific questions which explore when and how changes in the oceans, climate, tectonics, and chemical cycles spurred the dramatic radiation of life observed during the Great Ordovician Biodiversification Event.

I wish to acknowledge all of the work of the organizing committee, and particularly our field trip organizers and the staff and students of the Ohio University Department of Geological Sciences, in developing this conference.

We look forward to sharing our university and our wonderful Ordovician strata and fossils with you during this week.

Alycia Stigall
On behalf of the organizing committee

Organizing Committee

Alycia Stigall, Ohio University (Chair)
Carlton Brett, University of Cincinnati (Field trip co-chair)
Seth Finnegan, University of California, Berkeley (Field trip co-chair)
Chris Aucoin, University of Cincinnati
Rebecca Freeman, University of Kentucky
Robert Gaines, Pomona College
Kyle Hartshorn, Dry Dredgers
Daniel Hembree, Ohio University
Timothy Paton, University of Tennessee, Knoxville
Sara Pruss, Smith College
Matthew Saltzman, Ohio State University
Allison Young, University of Cincinnati

IGCP 653 Co-leaders

Thomas Servias (Chair, France)
David A.T. Harper (UK)
Olga T. Olbut (Russia)
Christian M.Ø. Rasmussen (Denmark)
Alycia L. Stigall (USA)
Zhang Yuandong (China)

Venue

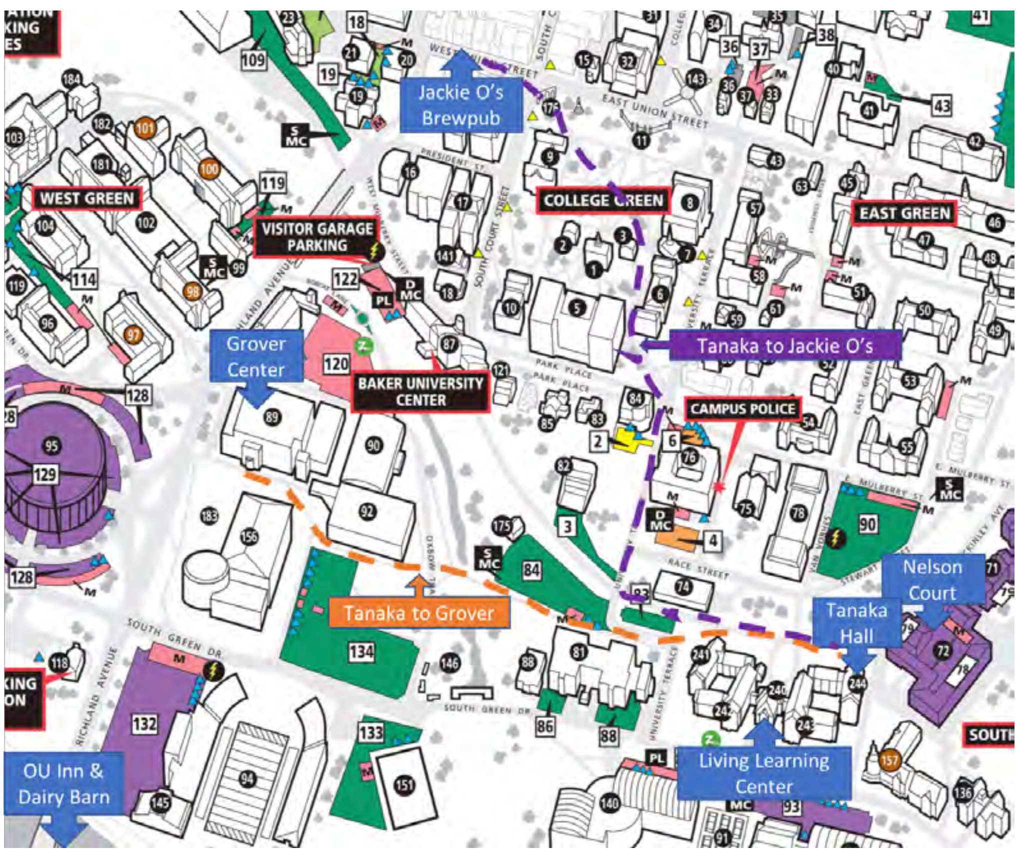
The sessions will take place on the campus of Ohio University. Complementary Wi-fi access is available throughout Ohio University's campus.

For delegates staying on campus in university accommodations, you will stay in Tanaka Hall (#244 on map). Registration for campus housing will be from 2:00 to 6:00 pm in the main entrance of the Living Learning Center (#240). Campus parking passes will allow parking in the purple colored lots adjacent to Tanaka Hall. For those who purchased meal plans, breakfast and lunch will be served in Nelson Court (#72). Breakfast hours are 7:15-9:30 am and lunch is served from 11:00 am to 1:00 pm. For delegates without meal plans, meals can be purchased a la carte at Nelson Court (breakfast, lunch, and dinner) or at Baker University Center's 82 West (lunch only). There are a variety of additional dining options on Court Street and West Union Street uptown.

The Opening Reception will be held at a local brewery, Jackie O's Brewpub, 24 West Union Street from 7:00 to 9:00 pm on June 3rd. The suggested walking path is indicated in purple on the map.

Technical sessions will be held in W115 Grover Center (#89 on map). Posters will be displayed throughout the conference in W113 Grover Center. The suggested path is indicated in orange on the map.

The Conference Dinner will be at the Dairy Barn Arts Center, 8000 Dairy Lane at 6:30 pm on June 7th.



Schedule

June 3rd

2:00 - 6:00 pm	Registration – Living Learning Center
7:00 - 9:00 pm	Opening Reception and Pizza Buffet – Jackie O's Brewpub

June 4th

9:00 am - 5:00 pm	Technical Sessions – 115 and 113 Grover Center
5:00 pm	Subcommission on Ordovician Stratigraphy Meeting – 115 Grover Center

June 5th

9:00 am - 5:10 pm	Technical Sessions – 115 Grover Center

June 6th

8:00 am - 6:00 pm	Conference field trip – Board vans at Living Learning Center. Lunch provided.

June 7th

9:00 am - 4:00 pm	Technical Sessions – 115 Grover Center
4:30 – 5:30 pm	Optional tour of Ohio Museum Complex on the Ridges.
6:30 – 9:00 pm	Conference Dinner at the Dairy Barn. Shuttle vans will leave from Living Learning Center at 6:20 and 6:25

Special Issue for Conference Publications

A thematic issue in "*Palaeogeography, Palaeoclimatology, Palaeoecology*" will be published for papers presented at the conference. If you intend to contribute a manuscript to the special issue, you must submit an abstract for your intended paper no later than June 30th, 2018. Full manuscripts will be due by November 15th, 2018.

Conference Program

Monday June 4th 2018

9:00 Introductory Remarks

Introduction to the GOBE and paleoclimate

9:20 **Christian M.Ø. Rasmussen *(Keynote)***
Onset and duration of the Great Ordovician Biodiversification Event

9:50 **Cole T. Edwards,** Clive M. Jones, David A. Fike
Oxygen isotope ($\delta^{18}O$) trends measured from Early–Middle Ordovician conodont apatite using Secondary Ion Mass Spectrometry (SIMS): implications for ocean paleothermometry studies

10:10 **Christopher T. Conwell,** Matthew R. Saltzman, Cole T. Edwards
Continental weathering and the Ordovician greenhouse-icehouse transition: an assessment using paired strontium and neodymium isotope stratigraphy

10:30 Coffee Break

Paleoecology of the GOBE

11:00 **LI Qi-jian,** LI Y., Carlton E. Brett, Colin D. Sumrall, Timothy Paton, YU Shen Y., MAO Ying Y.
Pelmatozoan meadow attached to Early Ordovician stromatolites: hardground community at the dawn of the golden age for epizoans

11:20 **Petr Kraft,** Jana Bruthansová, Radek Mikuláš, Ondřej Zicha, Michal Mergl
Shells as a tiering boundary and a substrate for colonization in the initial stages of the Prague Basin, Czech Republic (Tremadocian to early Darriwilian)

11:40 **Richard Hofmann,** Jan P. Kehl
Diversity patterns and palaeoecology of the Pogonip Group (western US)

12:00 Lunch

Diversity patterns of the GOBE

1:30 **Jonathan M. Adrain**
Cyclical trilobite mass extinction and the GOBE: the Cambrian-Ordovician "shoulder" of the global diversity curve explained

1:50 **Bradley Deline,** Kathryn E. Hanson, Rachel Lester, Nicholas S. Smith
Contrasting and parsing echinoderm disparity during the Cambrian Explosion and Great Ordovician Biodiversification Event

2:10 **David F. Wright,** Selina R. Cole, William I. Ausich
Bayesian modeling of a comprehensive genus-level informal supertree reveals the diversification and evolutionary dynamics of Ordovician crinoids

2:30 **MA Junye,** Paul D. Taylor, Caroline J. Buttler, ZHANG Min
New bryozoans from Hubei Province (Central China) suggesting the onset of diversification of bryozoan in Early Ordovician

2:50 **Steven J. Hageman,** Andrej Ernst
Occupation of Bryozoa growth-mode ecospace during the GOBE

3:10 Coffee Break

3:40 ***Lightning talks by poster presenters***

Christopher D. Aucoin, **Carlton E. Brett,** Benjamin F. Dattilo
Carbon isotope chemostratigraphy of the Upper Ordovician (Katian, Richmondian) Waynesville and Liberty Formations and the timing of the Richmondian Invasion

Christopher D. Aucoin, Benjamin F. Dattilo, André Desrochers, **Carlton E. Brett**, William Gilhooly, Jeff Hannon
Relict aragonite during a calcite sea: unique preservation of gastropods from the Upper Ordovician of the Cincinnati Arch and Nashville Dome, USA

Teresa D. Avila, Matthew Saltzman
Effects of diagenesis on $^{87}Sr/^{86}Sr$ in Ordovician conodonts

Alyssa M. Bancroft, Patrick I. McLaughlin, Poul Emsbo
GOBE-interval chemostratigraphy in the southern Illinois Basin

Andrea M. Bryan, **Daniel Goldman,** Guillermo L. Albanesi, Gladys Ortega, Fernanda Serra
Computer-assisted graphic correlation of Ordovician conodonts and graptolites from the Argentine Precordillera and western Newfoundland using Constrained Optimization (CONOP9)

Olle Hints, Liina Antonovitš, Jaak Nõlvak, **LIANG Yan**
Assessing the quality of Baltoscandian chitinozoan biozones using quantitative stratigraphy

LIU Xinchun, HOU Mingcai, CHANG Xiaolin, **HUANG Keke**

Upper Ordovician oceanic red beds in northwest Tarim Basin and middle Yangtze region

JING Xiuchun, Svend Stouge, YANG Zhihua
Katian carbon-isotope chemostratigraphy in the Neixiang area of central China

Jack W. Kallmeyer, Kyle R. Hartshorn, Carlton E. Brett
The "Solenopora" of the Cincinnati Arch: algae or sponges?

Timothy R. Paton, Allison L. Young, Carlton E. Brett
Sequence stratigraphy, chemostratigraphy, and correlation of the Upper Ordovician Nashville Group, Tennessee and Lexington Limestone, Kentucky

William Wojcieszak
Quantifying and comparing fossil type and abundance at the nationally renowned fossil site of Caesar Creek State Park, Warren County, OH

Allison L. Young, Carlton E. Brett, Patrick I. McLaughlin, Timothy R. Paton, Peter Holterhoff
Revised stratigraphy of the Late Ordovician Early Katian Lexington and Point Pleasant Formation on the margin of the Point Pleasant Basin, northern Kentucky and Ohio

4:00-5:00 **Poster session**

5:00 **Meeting of the Subcommission on Ordovician Stratigraphy** (all are invited)

Tuesday June 5th 2018

Biostratigraphy

9:00 **Daniel Goldman,** Peter M. Sadler, Stephen A. Leslie
The Geologic Time Scale 2020: integrating the stratigraphic range data from conodonts and other carbonate facies fossils

9:20 **SHAN Longlong,** YAN Kui, Thomas Servais, LI Jun
An acritarch assemblage from the Fenghsiang Formation of Gudongkou section, Yichang, South China

9:40 **YAN Kui,** LI Jun, SHAN Longlong
A Tremadocian acritarch assemblage at Xiangshuidong, southwestern Hubei Province: biodiversification and palaeogeographical implications

10:00 **WANG Wenhui**, LI Ming
Middle Ordovician (Darriwilian) chitinozoans from the Qaidam Basin, China

10:20 Coffee Break

10:50 **LIANG Yan,** Jaak Nõlvak, Daniel Goldman, Olle Hints.
Morphological variation of chitinozoans: A case study from the Upper Ordovician Viola Springs Formation, Arbuckle Mountains, Oklahoma, USA

11:10 **Ian G. Percival** and ZHEN Yong Yi
Ordovician conodont biostratigraphy of deep water cherts from New South Wales, Australia and regional correlations

11:30 **ZHANG Yuanyuan**, LI Yue, Axel Munnecke
A hypothesis for facies differentiation of Late Ordovician carbonate rocks in the Central Tarim Uplift (NW China)

11:50 Lunch Break

Cincinnatian stratigraphy and paleontology

1:30 Cincinnatian workshop

2:10 **Carrie L. Tyler *(Keynote)*,** Hannah L. Kempf, Ian O. Castro, Ashley A. Dineen, and Peter D. Roopnarine
Ecosystem dynamics and the consequences of invasive species

2:40 **Rebecca L. Freeman,** Benjamin F. Dattilo
Über shell beds: an integrated stratinomic model for the genesis and concentration of small shelly-style phosphatic microsteinkerns

3:00 **Benjamin F. Dattilo,** Rebecca L. Freeman, Amanda Straw, Carleton E. Brett, Christopher Aucoin, Mason Frauhiger, Amanda Hartstein, Lincoln Shoemaker
Testing the "über shell-bed" model for the origin of phosphatic microsteinkerns in the Ordovician (Katian) of Cincinnati

3:20 Coffee Break

3:50 **Alycia L. Stigall**
Ephemeral invasions, epiboles, and biotic immigration events: contrasting ecosystem impacts of biotic invasions in the Type Cincinatian Series (Late Ordovician, Katian)

4:10 **Carlton E. Brett,** Christopher D. Aucoin, Benjamin F. Dattilo, Kyle R. Hartshorn, Patrick I. McLaughlin, Cameron E. Schwalbach
Revised sequence stratigraphy and chronostratigraphy of the upper Katian Stage (Cincinnatian) strata in the Cincinnati Arch reference area

4:30 **Carlton E. Brett,** Patrick I. McLaughlin, Benjamin F. Dattilo, Christopher D. Aucoin, Kyle R. Hartshorn, Timothy R. Paton, Allison L. Young
Sequence stratigraphy of mixed siliciclastic-carbonate successions in the Katian Stage of the Cincinnati Arch region (Ohio, Indiana, Kentucky, and Tennessee)

Wednesday June 6th 2018

Mid-Conference Field trip to Maysville, Kentucky

Meet at parking lot across from the Living Learning Center at 8:00 am
Return at approximately 6:00 pm

Thursday June 7th 2018

Paleoecology and biogeography

9:20 ZHANG Yuandong, Lucy A. Muir, Joseph Botting, MA Xuan, SONG Yanyan **(presented by WANG Wenhui)**
A review of Konservat-Lagerstätten in upper Cambrian and Ordovician shales in South China: biodiversity, facies and taphonomy

9:40 **FANG, Xiang,** ZHANG Yunbai, ZHANG, Yuandong
Dynamic evolution of the Middle and Late Ordovician cephalopod faunas and provincialism in the northeastern peri-Gondwana region

10:00 **Selina R. Cole *(Keynote),*** David F. Wright, William I. Ausich
Phylogenetic community paleoecology of crinoid echinoderms from the Upper Ordovician (Katian) Brechin Lagerstätte

10:30 Coffee Break

11:00 **Timothy R. Paton,** Carlton E. Brett, George Kampouris
Paleoecology and ecosystem evolution of an Upper Ordovician echinoderm Lagerstätte from southern Ontario, Canada

11:20 **Mark E. Peter**
Aberrations in the infrabasal circlet of the cladid crinoid genus Cupulocrinus (Echinodermata) and implications for the origin of flexible crinoids

11:40 Lunch Break

Chemostratigraphy and chronostratigraphy

1:30 **Patrick I. McLaughlin,** Alyssa M. Bancroft, Poul Emsbo, Thijs R.A. Vandenbroucke, Carlton E. Brett, Allison Young, Matthias Sinnesael, Julie De Weirdt, Tim De Backer, Mark Williams, Brian J. Witzke, Matthew Rine
US midcontinent Upper Ordovician integrated chronostratigraphy project: introduction and advances

1:50 **Matthias Sinnesael,** Alain Mauviel, André Desrochers, Patrick McLaughlin, Julie De Weirdt, Philippe Claeys, Thijs R.A. Vandenbroucke
Upper Katian cyclostratigraphy of the Vauréal Formation, Anticosti Island (Gulf of St. Lawrence, Canada)

2:10 **MA Xueying**, FAN Ru, LU Yuanzheng, DENG Shenghui
Cyclostratigraphy of the Katian Pagoda Formation, South China

2:30 **GONG Fang-yi,** WU Rong-chang, LUAN Xiao-cong
Upper Ordovician carbon isotope chemostratigraphy in Shitai, Anhui Province, East China

2:50 Geneviève Riopel, Colin Matassa, **André Desrochers,** Patrick I. McLaughlin, Alyssa M. Bancroft
Significance of the lower Katian $d^{13}C_{carb}$ *Guttenberg Excursion (GICE) in the Ottawa Embayment, Eastern Canada*

3:10 **Y. Datu Adiatma,** Matthew R. Saltzman, Seth A. Young, Nevin P. Kozik, Sean M. Newby, Cole T. Edwards, Stephen A. Leslie
Carbon isotope stratigraphy of the Middle to Upper Ordovician in the Central Appalachian Basin at Arc Hollow, Germany Valley, WV

3:30 **Closing Ceremony**

3:45 Refreshments

4:30 Optional Tour of Ohio University Museum Complex

6:30 **Conference Banquet at the Dairy Barn Arts Center**
Shuttle vans will leave the Living Learning Center at 6:20 and 6:30

Participants

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Conference Abstracts

Carbon isotope stratigraphy of the Middle to Upper Ordovician in the Central Appalachian Basin at Arc Hollow, Germany Valley, WV

Adiatma, Y. Datu[1*], Saltzman, Matthew R.[1], Young, Seth A.[2], Kozik, Nevin P.[2], Newby, Sean M.[2], Edwards, Cole T.[3] and Leslie, Stephen A.[4]

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A new stable carbon isotope ($\delta^{13}C$) curve from Germany Valley (West Virginia, USA) is presented in this study, which covers a Middle to Upper Ordovician sequence in the Appalachian Basin. We aim to determine whether changes in the $\delta^{13}C$ curve is driven by the global carbon cycle or may be a local perturbation and response to sea level fluctuations (i.e., aquafacies) related to local tectonics, as this period represents an episode of active tectonism in the Appalachian Basin. Therefore, this study aims to document the carbon isotope curve from the Germany Valley section and determine the global significance of the observed trends by intra-basinal and inter-basinal correlation to nearby sections in the Appalachian Basin and Baltoscandia region, respectively.

The Germany Valley section (consisting of Arc Hollow and Dolly Ridge segments) is dominated by shallow water peritidal (supratidal to deep subtidal) carbonate. The units observed, from oldest to youngest, are the New Market, Lincolnshire, Big Valley, McGlone, McGraw, Nealmont, and Dolly Ridge formations.

Several carbon isotope excursions are observed in the Arc Hollow and the Dolly Ridge sections. The excursions at Arc Hollow are correlated to the declining limb of MDICE (Mid Darriwilian Isotope Carbon Excursion), the Kukruse low, and the UDIS (Upper Darriwilian Isotope Shift). The GICE (Guttenberg Isotope Carbon Excursion) was previously described at Dolly Ridge by Young et al. (2005). The general trend observed in this section is similar to the global stable carbon isotope signal in this period. However, there is a decreasing interval from 0 ‰ to -2 ‰ that is not present in other correlative sections (Clear Spring, USA and sections from Baltoscandia). This decreasing trend at the middle part of The Big Valley Formation to the base of the McGraw Formation may be a local signal due to platform restriction. This notion is supported by lithofacies data which indicate a shallow peritidal, evaporative depositional environment.

References:

Young, S.A., Saltzman, M.R., & Bergström, S.M. (2005) Upper Ordovician (Mohawkian) carbon isotope (δ13C) stratigraphy in eastern and central North America: Regional expression of a perturbation of the global carbon cycle: *Palaeogeography, Palaeoclimatology, Palaeoecology*, **222**, p. 53–76, doi: 10.1016/j.palaeo.2005.03.008.

Cyclical trilobite mass extinction and the GOBE: the Cambrian-Ordovician "shoulder" of the global diversity curve explained

Adrain, Jonathan M.[1*]

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Higher-taxon (family and genus level) diversity curves for the early Paleozoic have two well-known features reflecting large scale diversification: striking increases in summed diversity in the early and middle Cambrian, and again in the middle and late Ordovician. These phenomena - the Cambrian Explosion and the Great Ordovician Biodiversification Event - are separated by a "shoulder" in the diversity curves, showing a decline from a mid-Cambrian peak and a late Cambrian-early Ordovician interval of reduced diversity preceding the GOBE. Reasons for this period of reduced diversity have received scant historical attention, and much of the work investigating the onset of the GOBE has focused on potential Ordovician trigger mechanisms.

Trilobites are the most common fossil group during the period of initial diversification and the period of reduced diversity. In order to explore diversity dynamics during these intervals I created a relational database of all trilobite taxa to species level, compiled with ongoing systematic revision from the primary literature. Currently there are over 26,000 species-level entries, of which just under 22,000 are considered valid formally named species. I tabulated species diversity using 37 approximately stage level sampling bins for the Phanerozoic, and on individual paleocontinents during the interval of interest, to zone level according to regional schemes.

Trilobites show much the same pattern as summed marine life: there are two periods of sustained diversification separated by the late Cambrian and early Ordovician. Trilobite data show an unequivocal pattern during the "shoulder," however - they record unreversed net diversity drops from bin to bin. The boundaries between bins are mass extinction events comprising a sequence, spaced 3–5 ma apart, of five significant crises. Three of these have long been recognized but have been considered exclusively Laurentian phenomena. A fourth has a sparse literature history but little significant study, and a fifth was documented for the first time in the course of this study.

There is abundant emerging evidence that these mass extinctions were global events. The same pattern of nearly constant diversity decline can be retrieved using time-standardized data from virtually all continents. A similar family-group level pattern of sudden and near-complete turnover at the events (historically termed "biomeres" in the North American literature) can be documented on all tropical continents. Data are sparse from temperate regions, but what is available seems consistent. In terms of proportional extinction, the events rank among the most severe of the Phanerozoic. Following the fifth and final extinction in the late Tremadocian, trilobites began a sustained diversification that has been shown to be similar in all respects to that of Sepkoski's Paleozoic Fauna.

Hence, while other factors may certainly have been important, the GOBE likely reflects the cessation of a series of closely spaced global mass extinctions. Diversification was sustained until the onset of the events, each extinction bounded interval records sustained diversification (albeit from a lowered starting point with each successive event), and sustained diversification resumed unabated until the end of the Ordovician following the last of the events.

Carbon isotope chemostratigraphy of the Upper Ordovician (Katian, Richmondian) Waynesville and Liberty Formations and the timing of the Richmondian Invasion

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The Upper Ordovician (Katian, Richmondian) Waynesville Formation of the Cincinnati Arch is known for being the peak of the Richmondian Invasion, a biological event that saw nearly 100 taxa migrate into the region from elsewhere. One of the questions that has revolved around this event was whether or not migrations and invasions can be seen in other contemporaneous strata around the globe. To assist with answering these questions, we collected carbon isotope samples from Core #3245 near Cedarville, Ohio, stored at the Ohio Geological Survey Core Library. The core was selected for its completeness, unambiguous definition of member and submember boundaries, existence of parallel gamma ray logging, and for its proximity to Waynesville, OH. A total of, 75 samples were selected for carbon isotope analyses at 2 ft (~60 cm) intervals between 301ft and 450 ft. Several key epiboles and flooding surfaces were identifiable in the core, permitting detailed correlation with the outcrop belt as described in Aucoin and Brett., (2016), The sampling interval encompassed the upper Arnheim Formation, the Waynesville Formation, Liberty Formation and lower part of the Whitewater Formation.

The resulting data show that the Waynesville positive isotopic excursion comprises four primary positive peaks, two closely spaced 1.5 per mil shifts in the Bon Well Hill submember of the Fort Ancient Member one 1.5 per mil shift in the Mid-Clarksville submember of the Clarksville and a slightly lower 1.0 per mil peak in the middle Blanchester Member. The strongest, Fort Ancient, peaks appear to correspond with those previously documented in the Fisherville submember of the Rowland Member of Drakes Formation in central Kentucky, corroborating sequence-based correlation of that interval with the Bon Well Hill beds; this unit also lies a few meters above Holland and Patzkowsky's (1996) C1 sequence boundary. Moreover, strongest phase of the Richmondian invasions coincides approximately with the third or Clarksville peak. Using this newly refined isotopic curve, we can now test for synchronicity of events regionally, which will assist in future correlation of the Waynesville Formation and associated fauna to other paleobasins and improve understanding of regional and global bioevents associated with Late Ordovician climatic oscillations.

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Relict aragonite during a calcite sea: unique preservation of gastropods from the Upper Ordovician of the Cincinnati Arch and Nashville Dome, USA

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The Upper Ordovician was a time of 'calcite seas' which promoted preservation of calcite over that of aragonite. For this reason, the majority of molluscan fauna display poor preservation, showing moldic preservation or replacement/void filling by blocky calcite, or matrix. Mollusk shells preserved in this way generally show no evidence of the original shell structure.

However, in the case of the Marble Hill Gastropod beds of the Waynesville Formation (Richmondian) of the Cincinnati Arch, and the newly discovered Cato Road gastropod bed of the Leipers Formation (Maysvillian) of the Nashville Dome, the gastropods exhibit unusual preservation. Although the gastropods have been replaced by calcite, "ghost" of the original shell laminations are clearly visible in hand sample and in thin section. The Marble Hill and Cato gastropod beds are not time equivalent, yet they are strikingly similar in lithologic and diagenetic features. this suggests that they formed under similar, "reproduceable" conditions.

We examined samples from these two occurrences through petrography, cathodoluminescence (CL), scanning electron (SEM) microscopy, and energy dispersive spectrometry (SEM-EDS).

To allow for the preservation of relict aragonite structures, the local conditions would have had to be such that mimics aragonite seas, allowing for neomorphism to occur at the micro-scale. There are a number of possible mechanisms that could promote aragonite preservation over calcite, including: 1) elevated Mg:Ca ratios 2) enhanced CO_2 levels as the result of the decay of large masses of organisms 3) increases in temperature, and 4) higher sea levels.

In order to promote the preservation of relict aragonite, we hypothesise that local conditions mimicked aragonite seas through elevated Mg:Ca ratios, resulting from Mg loss from echinoderm material, elevated CO_2 levels resulting from the decay of large quantities of organisms (echinoderms, molluscan, primary producers, etc), and increasing sea levels during the ongoing transgressions.

These gastropods occur as shoal bars, are phosphatic, and appear to be strongly reworked time-rich deposits that grade laterally into greenish shales with more isolated well-preserved snails.

Effects of diagenesis on $^{87}Sr/^{86}Sr$ in Ordovician conodonts

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Strontium isotope ($^{87}Sr/^{86}Sr$) stratigraphy is a useful method for tracking changes in the Earth's marine system over geologic history. Due to strontium's relatively long residence time in the ocean (~10^6 yrs), researchers have long worked off the assumption that the ocean's $^{87}Sr/^{86}Sr$ value is essentially homogenous and that changes in the marine $^{87}Sr/^{86}Sr$ value reflect global changes in the Earth's system. Therefore, $^{87}Sr/^{86}Sr$ is used as a relative dating technique across sites and as a proxy for global silicate weathering patterns.

One source of $^{87}Sr/^{86}Sr$ data is conodonts, a tooth-like bioapatite microfossil. Conodonts' abundance in Paleozoic carbonates makes them valuable for those seeking a complete record of Paleozoic $^{87}Sr/^{86}Sr$ values. Conodont $^{87}Sr/^{86}Sr$ data for a single rock sample is collected from an amalgam of microfossils that have been extracted. However, a better understanding of the heterogeneity of a rock sample's conodont $^{87}Sr/^{86}Sr$ values is still needed; a study by Saltzman et. al., (2014) included replication of 24 samples, which produced an average difference of 4×10^{-5}. If conodont elements are heterogeneous enough, this could lead to low reproducibility, i.e. how well one can replicate a single rock sample's data. This, in turn, could lead to high dispersion, i.e. how much an $^{87}Sr/^{86}Sr$ data set of multiple rock samples is spread out. Ideally, one wants a data set with low dispersion, as it produces a relatively tight, cohesive $^{87}Sr/^{86}Sr$ curve. In this case, the trend of the global marine $^{87}Sr/^{86}Sr$ signal is clear and it serves as an effective tool for dating samples. Low reproducibility and high dispersion derive from several sources; this study seeks to isolate dispersion that rises from diagenesis, or geologic alteration. This is accomplished by analysing the $^{87}Sr/^{86}Sr$ of a single carbonate's conodont elements multiple times, in multiple "slices". In this case, the sources of dispersion that come from having multiple field sites are eliminated. Sources of dispersion that come from machine analysis, such as a mass spectrometer's internal and external analytical uncertainty, can be accounted for and are small due to a new Triton TIMS at Ohio State (i.e., $< 1.5 \times 10^{-5}$). Any remaining difference between slices of the same carbonate can be attributed to geologic alteration.

In short, this study seeks to characterize the $^{87}Sr/^{86}Sr$ heterogeneity of a carbonate's conodont elements and to determine how much of that heterogeneity is due to diagenesis. This is useful for understanding sample reproducibility and, in turn, the dispersion of a data set of multiple samples.

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GOBE-interval chemostratigraphy in the southern Illinois Basin

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Study of two deep subsurface cores from the southern Illinois Basin represents the first high-resolution look at Darriwilian and Sandbian chemostratigraphy in the Midcontinent. Previously established conodont biostratigraphy provides the chronostratigraphic foundation for these sections. While the new chemostratigraphic trends generally agree with those documented elsewhere, some tantalizing new features have been discovered.

Revised sequence stratigraphy and chronostratigraphy of the upper Katian Stage (Cincinnatian) strata in the Cincinnati Arch reference area

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The Upper Ordovician Cincinnatian Series is among the best preserved, most fossiliferous, and best studied upper Katian successions in the world. Holland and Patzkowsky recognized six 3rd order depositional sequences (C1 to C6), now frequently used as regional time slices. Recent research, however, indicates a need for critical revisions and additions, including the recognition of additional 3rd and 4th order sequences. We propose amendments based upon high-resolution correlations using a combination of regional disconformities, cycle stacking patterns, bioevents, marker beds, and chemostratigraphy. In addition, distinctive depositional patterns aid in the recognition of systems tracts, with shell-rich limestone packages representing transgressive systems tracts (TSTs) overlain by more shale prone highstand systems tracts (HSTs), themselves overlain by silty falling stage systems tract (FSST) deposits that are commonly removed beneath substantial unconformities (sequence boundaries). At present, we recognize eight 3rd order sequences, described below. C1 through C3 are similar to earlier interpretations. C1: the provincial Edenian Stage, with the upper Point Pleasant Formation as a TST and the Kope Formation and equivalent parts of the Clays Ferry Formation as a compound HST containing at least five 4th order sequences; FSST siltstones are recorded by the upper Kope and correlative Garrard Siltstone. C2: the lower Maysvillian Stage, consists of the Fairview Formation (=Calloway Creek Limestone) with three 4th order sequences and analogous FSST siltstones at the top, represented downramp by the Miamitown Shale. C3: the upper Maysvillian, includes most of the Grant Lake Formation, starting with the shelly Bellevue Member (=Tate Member of the Ashlock Formation) as TST followed by the Corryville Member as a HST with two 4th order cycles and local minor representation of FSST siltstones. The sequences of the Richmondian Stage are significantly revised, with adjustments to the base of C4 and the overly generalized middle-upper Richmondian “C5” succession split into three renumbered 3rd order sequences (C5-C7). C4 (revised): uppermost Maysvillian and lower Richmondian, with the Mount Auburn Member of the Grant Lake (=Terrill Member of the Ashlock) and Sunset Member of the Arnheim Formation as TST, followed by Oregonia Member shales as HST and FSST. C5 (revised): the lower middle Richmondian, including the Fort Ancient and Clarksville Members of the Waynesville Formation (and equivalent lower-middle Rowland Member of the Drakes Formation). In upramp areas, the latter is truncated beneath a major regional unconformity at the base of C6 (revised), which comprises the Blanchester Member of the Waynesville (upper Rowland) and the entire Liberty Formation (=Bardstown Member of the Drakes). An unnamed bundle of sparsely fossiliferous silty limestones and dolomudstones in the upper Liberty/Bardstown forms a distinctive FSST. C7 (new): consists of the complex Whitewater Formation divided into three 4th order sequences separated by tongues of peritidal laminated dolosiltites (Saluda facies). In addition, we tentatively recognize the former “C6”, here renumbered C8 (new), as a 3rd order sequence with upper Whitewater (in part) limestones as basal TST and the more shale-rich Elkhorn Formation as HST-FSST. A younger (Hirnantian?) sequence may be present at some localities as the enigmatic Centerville Formation and/or basal Belfast Member of the Brassfield Formation (generally presumed to be Lower Silurian).

Sequence stratigraphy of mixed siliciclastic-carbonate successions in the Katian Stage of the Cincinnati Arch region (Ohio, Indiana, Kentucky, and Tennessee)

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The application of sequence stratigraphic approaches provided a major advance in understanding the regional relationships of the Upper Ordovician (Katian) rocks of the Cincinnati Arch. Holland and Patzkowsky (1996 and subsequent papers) recognized six 3rd order depositional sequences (C1 to C6), which have been widely used as regional time slices. However, extensive field study and sampling over the past two decades have shown that revisions and additions are necessary. In part, these updates reflect more detailed, higher resolution correlations derived from cycle, event, and chemostratigraphy. But more significantly they are based on new interpretations of sequence architecture, including reinterpretation of key surfaces and systems tracts. Aggradational to retrogradational patterns indicate that many of the thicker peritidal to shallow subtidal successions that sharply overlie offshore facies in proximal areas record lowstand to early transgressive systems tracks (TSTs). These intervals, formerly interpreted as late highstand-regressive facies, overlie regionally angular erosion surfaces and seem to have formed during early phases of slow base level rise matched by aggradation of pale greenish-gray argillaceous tidal flats, eventually retrograding into rhythmic lagoonal sediments with interbedded wackestones and organic-rich dark shales. These facies correlate downramp (to the north) with shoal deposits, comprising skeletal packstones or grainstones and/or coral-stromatoporoid biostromes. Farther downramp, these, in turn, correspond to thinner pack- and grainstones, that represent condensed sections formed offshore during sediment starvation. Conversely, highstands are recorded in downramp settings by relatively thick packages of shale and muddy packstone. These successions thin upramp, where they may be largely removed at sharp erosive surfaces (sequence boundaries), although maximum flooding zones are preserved in some instances. Inferred falling stage systems tract (FSST) successions are packages of sparsely fossiliferous shale with abundant and relatively thick hummocky bedded siltstones, commonly with soft sediment deformation. Based on these criteria, all 3rd order sequences can be redefined such that thicker TSTs are included at the bases of sequences and their sharp lower contacts are identified as modified unconformities, often with superimposed transgressive ravinement surfaces. This pattern appears to be fractal, as many meter-scale "parasequences" share the same stratigraphic motifs as the larger (4th and 3rd order) sequences, particularly transgressive facies preserved as condensed shell-rich limestones in offshore sections. These concepts have permitted us to establish a working methodology for consistent recognition of depositional patterns in the classic Upper Ordovician strata of the Cincinnati Arch and elsewhere.

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Computer-assisted graphic correlation of Ordovician conodonts and graptolites from the Argentine Precordillera and western Newfoundland using Constrained Optimization (CONOP9)

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The most fundamental tool for studying Earth System history is the geologic time scale. Modern studies on climate change, the evolution and diversity of life, biogeochemical cycles, geodynamical processes, and other aspects of the Earth System all rely on precise time-calibrated data. One of the main obstacles to constructing a widely applicable time scale is the problem of correlating across biofacies. Regional correlation of outcrops in different facies belts has always been difficult due to pronounced bio- and lithofacies differentiation. One solution to this correlation problem is to find zonal “tie-points” - levels at which index fossils from different biofacies fortuitously occur together. Integrated biostratigraphic frameworks based on more extensively interleaved taxon ranges facilitate more precise correlation across disparate lithofacies, and can aid in the construction of a higher resolution and more useful geologic time scale. The primary object of this research is to integrate conodont and graptolite biostratigraphies from the Ordovician rocks of Argentina and western Newfoundland in order to refine the Ordovician time scale. Ordovician graptolites and conodonts have been extensively documented in both the Argentine Precordillera and western Newfoundland providing a robust database for integrated biostratigraphy.

We used the computer program CONOP9 to construct a dual clade composite range chart and correlation model from 22 stratigraphic sections spanning the Floian to early Katian stages. We began with 11 sections from the Argentine Precordillera where conodont-yielding limestones of the San Juan Formation are disconformably overlain by dark siliciclastics bearing abundant graptolites. Initial CONOP solutions produced a range chart where conodont and graptolite faunas tended to succeed one another in blocks as opposed to being integrated. To solve this problem, we added 11 sections from the Middle Ordovician of western Newfoundland from which conodont and graptolite range data could be extracted. The resultant range chart exhibits much better integration, although some biofacies differentiation between North Atlantic and Laurentian Midcontinent conodont taxa is evident. This fully integrated range chart allows for a more precise correlation between carbonate and siliciclastic sections, and allows us to compare regional biodiversity patterns from different fossil groups within in a single biostratigraphic framework.

Phylogenetic community paleoecology of crinoid echinoderms from the Upper Ordovician (Katian) Brechin Lagerstätte

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The Great Ordovician Biodiversification Event (GOBE) resulted in rapid diversification of marine invertebrates and the development of complex communities during the Ordovician. As a result, characterizing the structure of Ordovician paleocommunities is critical for understanding the evolutionary trajectory of marine communities through the Paleozoic. Among crinoid lineages, peak species richness and morphologic disparity were reached during the Katian, but niche space occupation and the structure of Late Ordovician crinoid communities have proven difficult to assess because of the paucity of specimens preserving delicate skeletal structures reflecting niche differentiation (e.g., arms and stems). The Brechin Lagerstätte of southern Ontario (Bobcaygeon and Verulam formations; Upper Ordovician, Katian) preserves an exceptional echinoderm fauna with more than 30 crinoid species, many with unusually complete arms, stems and attachment structures preserved. As a result, this assemblage is ideal for evaluating niche space occupation and community assembly among Late Ordovician crinoids.

We collected and analyzed morphological data from exceptionally preserved Brechin Lagerstätte specimens to (1) characterize functional morphology and niche occupation of crinoid taxa and (2) assess community structure and faunal gradients. In addition, we incorporated a recently developed phylogeny of Ordovician crinoids into our analyses to assess the structure of crinoid communities in terms of niche partitioning and clade composition (e.g., how functional diversity is partitioned among clades).

Continental weathering and the Ordovician greenhouse-icehouse transition: an assessment using paired strontium and neodymium isotope stratigraphy

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Modeling the control of global carbon fluxes on atmospheric carbon dioxide (CO_2) levels through time in accordance with oxygen isotope paleotemperature curves is one of the leading approaches used to understand the origin and timing of the Ordovician greenhouse-icehouse transition. Primary fluxes considered in carbon cycle models are the release of carbon dioxide by volcanic and metamorphic degassing, drawdown by chemical weathering of calcium silicate minerals, and to a lesser extent burial and oxidation of marine organic matter.

A modeling study by Young et al. (2009) utilized the seawater Sr isotope curve to drive enhanced non-radiogenic basaltic weathering and a mid-Ordovician drawdown of atmospheric CO_2, albeit with the assumption that volcanic degassing balanced this flux for most of the Late Ordovician to match the temperature curve of Trotter et al (2008). More recently, McKenzie et al. (2016) proposed that a lowering of the degassing flux was the principal cause of the Ordovician greenhouse-icehouse transition; in contrast, Swanson-Hysell and Macdonald (2017) presented a Laurentian paleogeographic reconstruction which supports the basaltic weathering hypothesis by placing the paleocontinent and Taconic arc in the humid tropics. Collectively, these studies raise questions about the importance of silicate weathering in driving Ordovician atmospheric CO_2 and climate.

Our current effort examines the possibility that the decrease in mid-Ordovician Sr isotope ratios was actually caused by a flux of non-radiogenic Sr from mid-ocean ridge hydrothermal alteration. We measured paired Sr ($^{87}Sr/^{86}Sr$) and Nd ($^{143}Nd/^{144}Nd$) isotopes in marine carbonates in the Appalachian region because there is no appreciable hydrothermal flux of Nd and therefore changes in Nd isotopes should signify changes in weathering sources. Our results show a fall in Nd of 10 epsilon units that is coeval with the mid-Ordovician $^{87}Sr/^{86}Sr$ drop of 0.0005, which is consistent with enhanced basaltic weathering in the Appalachian region that was large enough to affect the global Sr cycle. Ongoing and future studies will construct bulk rock and conodont Sr and Nd curves for other sections in the Appalachian Basin and beyond (e.g. Nevada, Oklahoma) to constrain the timing of shifts in these signals to clarify the role of hydrothermal Sr input.

Testing the "über shell-bed" model for the origin of phosphatic microsteinkerns in the Ordovician (Katian) of Cincinnati.

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The "über shell bed" model envisions both the genesis and concentration of phosphatic microsteinkerns ("small shelly fossils") as natural outcomes of the shell bed genesis through episodic sediment starvation. Thus, a single stratinomic process explains both shell-bed limestone maturity and the accumulation of phosphatic microsteinkerns. This model predicts that more mature shell bed limestones will tend to contain more phosphatic microsteinkerns, but that even the least reworked limestones may contain some phosphatic particles. Cincinnatian limestones contain microsteinkerns of mollusks, bryozoans, and other fossils. The concentration of these steinkerns varies among limestone units. This variation makes it possible to test the predictions of the hypothesis by petrographically. This study tests the hypothesis by comparing non-skeletal phosphate content to proxies for limestone maturity for individual depositional units. These proxies include: 1) Dunham categories (mudstone, wackestone, packstone, grainstone) based on the relative abundance of shells, mud, and spar. 2) taphonomic condition of bioclasts (breakage, abrasion, bioerosion, and discoloration), 3) and the relative abundance of different bioclast types (aragonitic mollusks, calcitic brachiopods, bryozoans, and echinoderms).

To test the hypothesis, we made dense stratigraphic collections of limestones from a 10-meter stratigraphic interval (from the upper Fairview and lower Grant Lake formations) at four localities covering an area approximately 50 km in diameter around Cincinnati, Ohio. Additional collections were made from sections across the outcrop region and throughout the classic Cincinnatian (upper Katian) strata. Limestones were cut to make vertical thin sections. For each of approximately 50 distinguishable depositional units in each locality, a 2 X 2 cm square was selected for study. Each square was assigned a Dunham classification (expanded to 6 categories using mud content of intergranular space) and a breakage rank (4 categories from pristine to comminuted). Phosphate was quantified both by visual estimation and by particle counting, with particle counts ranging from none detected to over 1000 per square. Preliminary analyses show a strong positive relationship between phosphate content and both Dunham maturity and fragmentation. Work in progress will quantify fragmentation and relative bioclast abundances using point-counts. The positive relationship between phosphate content and both textural and fragmentation proxies for maturity is consistent with the "über shell bed" model. This finding suggests that shell bed processes may make a significant contribution to the generation and accumulation of phosphatic particles.

Contrasting and parsing echinoderm disparity during the Cambrian Explosion and Great Ordovician Biodiversification Event

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The Cambrian Explosion and the Great Ordovician Biodiversification Event (GOBE) have been hypothesized to have contrasting patterns in regard to taxonomic and morphologic diversity. The Cambrian Explosion likely represents an interval of low taxonomic diversity, but high morphologic disparity with the appearance of novel body plans. Alternatively, the GOBE is proposed to have a large increase in diversity, but a decline in disparity that is the result of extinction as well as ecological and developmental constraints. However, these patterns have not been sufficiently examined at higher taxonomic levels (e.g. phylum) because of the time and effort required to quantify morphology.

A novel character suite was constructed to explore morphologic patterns across Early Palaeozoic echinoderms. This suite of 457 discrete characters was used to analyse a comprehensive sampling of 371 Cambrian through Ordovician echinoderm genera. A morphospace was constructed using Principal Coordinate Analysis and disparity was calculated as the average distance between individuals and the overall centroid. The resulting morphospace recovered the major body plans commonly recognized within Early Palaeozoic echinoderms.

Overall, echinoderm disparity is consistent with the proposed pattern with a steady increase in disparity through the Cambrian paired with low biodiversity. Disparity stagnated during the Ordovician despite a large increase in generic richness during the Late Ordovician. However, this pattern breaks down as disparity is parsed between the constituent echinoderm groups. Both preradial (homalozoans) and pentaradial echinoderms expand in disparity through the Cambrian, but preradial forms contracted in the Ordovician while pentaradial forms steadily increased. Even within pentaradial forms, different body plans showed varied patterns in disparity. Edrioasteroids are morphologically conservative with a similar, though muted, pattern as homalozoans. Eleutherozoans and stalked echinoderms both show morphological diversifications within the Ordovician counter to the overall pattern. Within stalked echinoderms, eocrinoids and rhombiferans have Cambrian peaks in disparity, which diminish into the Ordovician. Crinoids show a large expansion in disparity in concert with their taxonomic diversification. Most crinoid subgroups expand in disparity through the Ordovician with the exception of the protocrinids and monobathrid camerates. Camerates contribute over half of the disparity within crinoids during the Ordovician, with diplobathrids representing 46% of the disparity within crinoids during the Late Ordovician.

Overall, Early Palaeozoic echinoderm morphologic disparity followed the hypothesized patterns. However, this is likely an amalgamation of distinctive and staggered morphologic diversifications within echinoderm groups rather than defining properties of the Cambrian Explosion and the Great Ordovician Biodiversification Event.

Siberian and Baltoscandian Ordovician depositional sequences and correlations

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The revised sequence stratigraphic scheme of the Ordovician of the Siberian platform consists of 12 depositional sequences. From the base to the top they are as follows: (1) Nya; (2) Ugor; (3) Kimai; (4) Baykit; (5) Muktey; (6) Volgino; (7) Kirensk; (8) Kudrino; (9) Mangazea; (10) Dolbor; (11) Nirunda; (12) Bur. Having in mind that two Hirnantian depositional sequences are not represented in the Siberian succession, the number of the Siberian Ordovician sequences coincides with the number of the Baltoscandian ones. That could be regarded as an indicator for a eustatic origin of sea-level fluctuations responsible for developments of these sequences. The problem however is that the ages of the sequence boundaries do not always coincide in Baltica and Siberia. For example, the two lowermost Baltoscandian sequences (Pakerort and Lower Latorp) correspond to one (Nya) Siberian sequence. On the other hand, Tallinn depositional sequence of Baltoscandia corresponds to three (Volgino, Kirensk and Kudrino) sequences of Siberia. The Mangazea depositional sequence of Siberia seems to correspond to Kegel, Lower and Upper Wesenberg sequences of Baltoscandia while Dolbor sequence of Siberia corresponds to Fjäcka and Lower Jonstorp sequences of Baltoscandia. It seems that on different palaeocontinents regional tectonic signals made the global eustatic signal obscure. Sea-level curve reconstructions for Baltica and Siberia are also different. The sea-level curve for the Ordovician of Siberia looks roughly the same as for the Laurentia. On both platforms a prominent sea-level drop and a long-term lowstand during the Middle Ordovician has been detected. On the other hand, sea-level curves for the Ordovician of Baltica and Gondwanan platforms (North Africa, Yangtze platform, South America, Avalonia) seem to share different patterns. The Middle Ordovician represents rather a highstand interval in these reconstructions. As a result, instead of one global sea-level curve for the Ordovician it would be probably more correct to suggest two semi-global curves for two big tectonic regions, one of which includes Siberia and Laurentia, and the other combines the Baltica and Gondwanan platforms. This subdivision probably reflects the position of the main Ordovician lithosphere plates. Long-term lithologic changes on these platforms also support such a model. In order to better understand the complex patterns and trends of different radiations and biotic immigration events constituting GOBE at local, regional and global levels a global correlation of the Ordovician depositional sequences is needed.

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Oxygen isotope ($\delta^{18}O$) trends measured from Early–Middle Ordovician conodont apatite using Secondary Ion Mass Spectrometry (SIMS): implications for ocean paleothermometry studies

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Oxygen isotopes ($\delta^{18}O$) in mineral phases are used as a proxy for ocean temperature based the temperature-dependent equilibrium fractionation effect between certain minerals and the ocean reservoir. Paleotemperature estimates are made by measuring the $\delta^{18}O$ from minimally altered minerals and fossils, which have the best potential to record primary seawater $\delta^{18}O$ if an invariant seawater $\delta^{18}O$ value is assumed. Phosphate is highly stable under low to moderate burial conditions and is ideal for reconstructing seawater temperatures because the P-O bonds are highly resistant to isotopic exchange during diagenesis. Phosphatic fossils such as conodont elements are used as a seawater temperature proxy based on the assumption that prior to the synthesis of biogenic phosphate, phosphate oxygen equilibrates with ambient waters via enzymatic reactions that are free to exchange with the environment in which the animal lived. Traditional methods used to measure conodont $\delta^{18}O$ involve bulk measurements of elements measured on a TC/EA device with an analytical precision of ~0.3‰ (V-SMOW). Because this method requires bulk collections of conodonts that can include elements from conodonts that lived in different environments and are potentially reworked into one sedimentary bed, this can yield a $\delta^{18}O$ value derived from a mixture of different water masses. This uncertainty can be minimized by measuring *in situ* spot analyses of individual elements using high-resolution microprobe techniques, which is also less sample destructive.

Here we present new $\delta^{18}O$ measurements using secondary ion mass spectrometry (SIMS) from conodont apatite collected from three Lower and Middle Ordovician stratigraphic successions and compare to a previously published Ordovician seawater $\delta^{18}O$ trend. Instrument precision on 10-µm wide spot analyses on an igneous apatite standard varies between 0.32–1.06‰ (average = 0.54‰, n = 37), similar to a gem-quality sample of the Durango apatite (0.35–0.73‰; average = 0.56‰, n = 4). Conodont samples with at least eight spot analyses show sample variability of 0.25 to 1.06‰ (average = 0.56‰, n = 72). Individual elements from the same species of sampled bed can vary by 0.94 to 2.55‰ (n=6). Conodonts that experienced moderate burial temperatures (up to ~150 ºC) have $\delta^{18}O$ values that are about 1–2‰ less than a published trend made from global compilation of conodonts measured using a SHRIMP ion microprobe. Conodonts with minimal burial temperatures (<50 ºC) have $\delta^{18}O$ values that are more similar to published values and generally less variable than more thermally altered conodonts. Overall, $\delta^{18}O$ values measured using SIMS can reproduce values similar to published trends with an analytical error twice the uncertainty of traditional techniques using bulk conodont sampling on a TC/EA device. Though the analytical error using SIMS is larger, this error is still less than the variability of $\delta^{18}O$ values from multiple elements from the same horizon. High-resolution stratigraphic sampling of conodont apatite using SIMS has the potential to be used as proxy for seawater temperature, particularly for sections with low conodont yields (e.g., 30 elements/kg rock) that were previously impractical to study using traditional conodont $\delta^{18}O$ methods.

Carbon isotope chemostratigraphy of the Cambrian Series 3-lowermost Ordovician on the Upper Yangtze Platform, Southwest China

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A set of hundreds to thousand meters thick carbonates is developed widely on the Upper Yangtze Platform from the Epoch 3 of Cambrian to the earliest Ordovician. The succession is extensively dolomitized and is poorly fossiliferous, which precludes any detailed biostratigraphic determinations and results that the further stratigraphic classification remains an unsettled issue. Herein, carbon isotope chemostratigraphy of the succession is studied from one drillcore and three outcrop sections. It shows that secular variations of $\delta^{13}C$ values of these four sections are similar and comparable. A distinct positive excursion in $\delta^{13}C$ is documented in the middle of the sequence, which could be correlated with the global Steptoean Positive Carbon Isotope Excursion, or SPICE excursion. A negative $\delta^{13}C$ excursion is also observed at the top of the carbonates, which we considered as the TOCE (Top of Cambrian Excursion). According to these $\delta^{13}C$ events, the boundary of the Furongian Series and the Paibian Stage, and the Cambrian-Ordovician boundary can be roughly identified in this sequence for the first time. The $\delta^{13}C$ baseline values are between -2‰ and -1‰ below the SPICE, but increase to -1‰ and zero above the positive excursion. It evidently reflects chemo-oceanographic changes from the Cambrian Epoch 3 to the Furongian. We think that sea-level change is an important reason for the $\delta^{13}C$ variations mentioned above.

Conodonts from the boundary interval of the Sandaogou and Pingliang formations (Middle and Upper Ordovician) in Pingliang, Gansu Province, China

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The Guanzhuang section (also known as the Pingliang section) located in Pingliang City of Gansu Province, is well-known for being the type locality of the Pingliang Formation, and for being previously selected as one of the stratotype candidates for the base of the Upper Series of the Ordovician System. Conodonts of the Pingliang Formation in this classic section have been extensively researched for decades. However, the lowermost few meters of this formation and the underlying Sandaogou Formation were not included in this research because of not being well exposed in the study section. It resulted in poor knowledge of biostratigraphy of the Pingliang-Sandaogou interval. Fortunately, a fresh outcrop of this interval was observed recently in a disused quarry, about 200m west of the classic location of the Guanzhuang section. At this new-found locality, the bottom of the Pingliang Formation consists of shale with intercalated limestone beds, and the top of the Sandaogou Formation is characterized by medium to thick bedded limestone. Conodonts from this interval are sampled and examined. It shows that fossils are not recovered from the bottom of the Pingliang Formation, but quite rich in samples collected from the top of the Sandaogou Formation. The fauna represents 17 species and 14 genera, mainly including *Pygodus anserinus*, *Erismodus typus*, *Microcoelodus asymmetricus*, *Periodon aculeatus*, *Spinodus spinatus*, *Protopanderodus varicostatus*, *P. robustus* and *Panderodus gracilis*. The *Pygodus anserinus* conodont biozone is recognized. This biozone occurs in the lower part of the Pingliang Formation as well according to previous studies at the classic locality. Therefore, it is evident that the Pingliang Formation conformably overlies the Sandaogou Formation in the study area.

Dynamic evolution of the Middle and Late Ordovician cephalopod faunas and provincialism in northeastern peri-Gondwana region

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The Middle to Late Ordovician is a critical period for the evolution of cephalopods, when they diversified rapidly by producing many new groups in the northeastern peri-Gondwana region. Based on the cephalopod occurrences in South China, two diversity peaks are recognized, one in the early Dapingian and the other in the early–mid Katian, separated by a decline in the Middle–Late Ordovician transition. Among the most significant evolutions is the replacement of the Middle Ordovician ellesmerocerids and endocerids faunas by the Late Ordovician orthocerids, oncocerids and tarphycerids faunas. Along with documentation of the replacement, we also conducted quantitative biogeographic analyses, including cluster analysis and non-metric multidimensional scaling, based on the occurrences of middle and late Ordovician cephalopods from South China, North China, Tibet, Sibumasu and Australia. The results indicate that during the Middle Ordovician three biogeographic provinces are recognized in northeastern peri-Gondwana region, i.e., the Australia, the North China–Tibet–Sibumasu, and the South China–Altun provinces. This provincialism lasted through the middle Ordovician, and retained largely a similar pattern in the Late Ordovician, with only the merging Tibet and Sibumasu regions with the South China–Altun Province to form a South China–Tarim–Tibet–Sibumasu Province. Based on the analysis of calcareous deposit characteristics of the different faunas in Middle and Late Ordovician and published paleogeographic reconstruction, the dynamic variation of cephalopod provincialism in the northeastern peri-Gondwana region is probably related to the differentiated paleoenvironments caused by changing paleolatitudes and locations of these terranes in the Middle and Late Ordovician.

Über shell beds: an integrated stratinomic model for the genesis and concentration of small shelly-style phosphatic microsteinkerns

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Small shelly fossils, predominately phosphatic steinkerns, are the dominant form of preservation across the late Proterozoic/Cambrian boundary. This same form of preservation extends across the GOBE into the Late Ordovician where carbonate fluorapatite (CFA) preserves internal molds of small shells and small parts of larger ones ("teilsteinkerns") in the limestone strata of the Kentucky/Ohio/Indiana area of the US. We propose a sedimentological process model for the formation and accumulation of these Cincinnatian (Katian) "small shellies" based on outcrop-to-thin section scale observations. We hypothesize that their formation is initiated by changing redox conditions during burial, and that the rate at which they are subsequently concentrated is controlled by sedimentation rate and reworking.

Carbonate fluorapatite (CFA) precipitates under suboxic conditions near the oxygen redox boundary. Microsteinkerns can form in more oxic sediments because appropriate redox conditions are localized to the inside of small cavities and porous particles depending on sediment redox conditions. Thus, CFA preferentially fills small shells and the smaller pores of larger shells. This phosphatic filling is more durable than the original calcareous shells. Disruption of the sediment by high-energy events, such as storms and tsunamis, enhances the destruction of shells while temporarily changing redox conditions and creating new redox microenvironments as new organic matter is buried. As the previously-formed steinkerns are subjected to the appropriate redox conditions, more CFA precipitates, resulting in an even more durable sediment grain. When sedimentation rates are low, this iterative reworking and burial process simultaneously enhances shell destruction while encouraging continued precipitation of CFA in previously formed steinkerns, along with the formation of new steinkerns. A point of equilibrium may be reached at which the rate of shell destruction is equivalent to the rate of shell growth, while phosphatic steinkerns continue to accumulate. Repeated burial and decay of organic matter during high-energy events may also serve as a source of phosphorus, enhancing CFA precipitation.

Our model predicts that beds with the highest degree of reworking, such as grainstones, yield the most abundant steinkerns, but that even lightly reworked beds may potentially preserve these fossils in smaller concentrations, as we demonstrate in Cincinnatian strata. It also predicts that grains at various stages of maturation, from heavily phosphatic to barely or not at all phosphatic should be found mixed together. Our model offers predictive power as to the settings in which this preservation might be most prevalent, and if correct, offers the prediction that these steinkerns may be more ubiquitous than previously recognized, and that conditions that encouraged the formation of the Proterozoic/Cambrian "small shelly faunas" are also potentially a common occurrence through geologic time.

The Geologic Time Scale 2020: integrating the stratigraphic range data from conodonts and other carbonate facies fossils

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The current Ordovician time scale (GTS 2012; Cooper & Sadler, in Gradstein et al., 2012) is derived from a global CONOP9 composite of graptolite first and last appearance events with interpolated radiometric dates. Local carbonate successions are correlated with graptolite zones derived from the composite using correlation charts in a subjective manner (tie points set by expert opinion on how the different sets of zones are related). During the past six years many new radiometric dates have been calculated from K-bentonites in carbonate strata, and these dates need to be incorporated into a revised Ordovician timescale. We suggest that the direct integration of the stratigraphic range data from carbonate facies fossils (e.g., conodonts and chitinozoans) into a global multi-clade CONOP9 composite Ordovician range chart will facilitate the interpolation of these dates, and significantly increase the precision and usefulness of the Ordovician time scale. The construction of a global multi-clade composite poses a number of challenges, such as analyzing a very large data set, integrating the North American Midcontinent and North Atlantic conodont successions, and finding enough sections that contain index species from both black shale and carbonate biofacies to effective link the disparate facies.

In this study we present several initial steps in constructing an integrated CONOP9 composite that may be used as the basis for the Ordovician GTS 2020. First, we constructed a feasible correlation matrix between separate global conodont and graptolite composite sequences and extracted a constrained initial sequence for an integrated CONOP solution. The correlation or "slotting" matrix delineates a channel through which any viable combination of the two composite sequences must pass. The width of the channel summarizes the level of constraint in the correlation. From this guided start, CONOP algorithms can find a best-fit sequence within this channel by minimizing the implied range extensions.

Second we present an example of a fully integrated graptolite, conodont, chitinozoan, and ostracod range chart from Baltoscandia that spans the Lasnamagi to Porkuni regional stages (Mid Darriwilian to Hirnantian), and show how this range chart can be used to project graptolite zonal boundaries into carbonate sections and correlate the regional chitinozoan zonation more precisely with the standard global stages. Finally, we note that a great deal of recently published chemostratigraphic data is derived from carbonate successions and investigate ways in which other types of stratigraphic data can be successfully integrated into automated graphic correlation networks.

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Upper Ordovician carbon isotope chemostratigraphy in Shitai, Anhui Province, East China

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The 'Great Ordovician Biodiversification Event' (GOBE) is one of the major macroevolutionary events during the Early Paleozoic, through which marine biodiversity substantially increased at relatively lower taxonomic ranks within the phyla established during the 'Cambrian Explosion'. Many case studies have been carried out on the GOBE in South China paleoplate. Up to now, quite a few researchers used the carbon isotope of carbonates to improve the correlation of sections from different facies and sedimentary environments. We select the lower Upper Ordovician of Shitai, Chizhou in southern Auhui Province to conduct stable carbon isotope chemostratigraphic study. The Ordovician succession at Daling includes the Zitai, the Kuniutan, the Datianba, the Pagoda and the Tangtou formations ascendingly. Forty-five carbon isotope and 27 conodont samples have been collected from the Datianba, the Pagoda and the lower Tangtou formations. The conodonts include *Baltobiodus variabilis*, *Baltobiodus alobatus*, *Costiconus ethingtoni*, *Yangtzeplacognathus jianyeensis*, *Hamarodus brevirameus*, *Protopanderodus liripipus* with the age ranging from the early Sanbian to early Katian. The $\delta^{13}C_{carb}$ curve shows a remarkable positive excursion in the lower and middle Pagoda Formation, which has been interpreted as the GICE (Gutenberg Isotope Carbon Excursion). The result shows a good correlation with the published isotope curves of South China and other areas around the world. It confirms that GICE can be used as an important tie-point for the regional and international stratigraphic correlation.

Occupation of Bryozoa growth-mode ecospace during the GOBE

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Because the fossil record for the phylum Bryozoa originates in the Early Ordovician (Tremadocian, 1b), their role in the GOBE provides an opportunity to document patterns of diversification at the phylum level in a clade with excellent preservation potential. Previous studies have explored the appearance and diversification of higher bryozoan taxa through the GOBE. The goal of this study is to document the first appearance and patterns of diversification of bryozoans as a function of their fundamental colony growth parameters (growth mode), and to eventually address questions of colony form's macroevolutionary and paleoecological significance.

Many classification schemes for bryozoan colony growth forms/habits have been proposed, most of which rely on characterizing the geometry, function, ecology or sedimentary properties of the final form or construction. The method employed in this study aims to characterize how growth is achieved or limited by the process or mode of growth. Fundamental growth parameters are:

A) Zooecial budding vector: lateral only, lateral >> medial, medial : lateral, medial > lateral, medial >> base.
B) Primary growth dimensions: 1-D (linear), 2-D (area), 3-D (object).
C) Relationship to substrate: primary wall restricted to substrate, partially escapes substrate, rooted or articulated base.

Of the 45 morpho-eco space defined by these parameters, 24 of the options are topologically viable.

D) Width of colony unit (e.g. branch): narrow (1-3 zooecia), intermediate (4-12 zooecia), broad (≥13 zooecia).
E) Occupation of space: fully occupies space, explores space, mixed use of space, and systematically fills space.

All 3 x 4 = 12 morpho-eco space options by these parameters are viable. This bryozoan-morpho-eco space allows for 288 possible states, which efficiently characterizes both the morphological range and allows for detailed comparison among most known Bryozoa.

Building on data sets of taxonomic occurrences from previous workers (e.g. Taylor, Ernst, Koromyslova), a data set has been generated to code for this morpho-ecospace for 209 occurrences of 118 species (49 genera) from the Tremadocian through Darwillian. At least twenty fundamental growth habits had evolved in the Bryozoa by the end of the Darwillian, but a large proportion of species richness is restricted a relatively few (~4.0%) of the possible growth mode options in this model.

Assessing the quality of Baltoscandian chitinozoan biozones using quantitative stratigraphy

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Chitinozoans are one of the three most important groups in Early Paleozoic biostratigraphy, with well elaborated and widely adopted regional biozonal schemes in the Ordovician, and both regional schemes and a global standard in the Silurian. Baltoscandia is the region where chitinozoans were first described and where they have been actively studied since then. In the Ordovician succession of Baltoscandia, 26 chitinozoan zones and subzones have been established, and the most recent Silurian biozonal scheme contains 28 regional biostratigraphic units. However, the practical applicability of individual biozones varies due to different stratigraphic ranges and/or uneven geographic distribution of the key species, as well as their variable abundance and patchiness of the regional fossil record.

Here we apply quantitative stratigraphy to assess the quality and applicability of existing regional chitinozoan biozones and distinguish events that provide most promising additional correlation levels and hold potential for defining new formal biozones. We use the occurrence-level regional chitinozoan database CHITDB (http://chitinozoa.net), which was initially established for creating high-resolution diversity curves for the group in Baltoscandia (Hints et al., 2017). The database contains more than productive 6400 samples from 103 measured sections spanning from the Early Ordovician to Pridoli, altogether ca 35000 occurrence records of ca 300 taxa, including the zonal species.

Three different methods of quantitative stratigraphy were used to analyse the dataset by creating composite successions of events or associations (Hammer et al. 2001 and references therein): Constrained Optimization (CONOP9), Ranking-Scaling (RASC) and Unitary Associations (UAGraph). The most detailed composite succession was generated using CONOP9, providing opportunity to study how well the distribution of zonal species corresponds to the model. It appeared that FADs and LADs of most index species in the CONOP9 composite show below average misfit to the model and are thus stratigraphically well-constrained. It was revealed that the misfit values for zonal taxa are comparatively smaller in the Ordovician than in the Silurian. The RASC method also produced a reasonable composite succession, useful for assessing the individual biostratigraphic events and successions. On the other hand, the UAGraph composite, which is based on finding and ordering co-occurrences of taxa, strongly overestimated ranges of individual species and thus could not be readily used for analysing the current dataset.

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Diversity patterns and palaeoecology of the Pogonip Group (western US)

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The causes of the “Great Ordovician Biodiversification Event” (GOBE) are much debated. It has been proposed that extrinsic factors such as ocean water oxygenation and temperature, and the dissected paleogeography of the Early Paleozoic contributed to the global rise in marine biodiversity, but the role of ecological interactions, such as predation and competition, in the GOBE remains largely elusive. One way to detect such intrinsic drivers is to use the diversity partitioning approach in local sedimentary successions as archives of this event. Diversity partitioning allows for testing whether high gamma-diversity (regional diversity) is attained by a rise in alpha-diversity (local species richness), beta-diversity (differential diversity between sites or habitats), or a combination of both. Recently proposed models use trajectories of alpha- and beta-diversity to assess the role of competition in local diversification processes. With their nearly continuous depositional history and relatively diverse habitat architecture, shallow marine sections of the Pogonip Group (Utah, Nevada) provide ideal conditions for using quantitative paleoecological methods and diversity partitioning to test the impact of local-scale biological interactions on diversification events. Field observations and current analyses on newly collected macrofossils suggest that diversification across the GOBE in this region was structured. Low diversity assemblages dominate the Tremadocian and lower Floian part of the Pogonip Group, i.e. the House and lower Fillmore Formations. Alpha-diversity starts to increase in the upper Fillmore Formation and moreover in the succeeding Wah Wah Formation, but the assemblages are relatively uniform in terms of species composition. The Middle Ordovician Juab and Kanosh Formations record the most diverse and heterogeneous benthic ecosystems of the whole sequence. The higher beta diversity is most likely generated by the increasing restriction of articulate brachiopods to near-shore deposits, and the emergence of on- and offshore trilobite biofacies. These observations indicate a successive increase in alpha and beta-diversity which suggests that competitive exclusion became increasingly important and thus drove regional diversity. However, future investigations are necessary to tease these signals apart from external drivers such as substrate conditions, facies architecture, and taphonomy.

Katian carbon-isotope chemostratigraphy in the Neixiang area of central China

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Samples collected mainly from carbonate mudstone and wackestone rocks of the Katian (Upper Ordovician) Shiyanhe Formation at the Sigang section, Neixiang area, Henan Province, central China have been analyzed for stable carbon isotope ($\delta^{13}C_{carb}$) chemostratigraphy. The C isotopic data document the signal between the two major Ordovician positive shifts in $\delta^{13}C$, the early Katian Guttenberg and the Hirnantian excursions. Four $\delta^{13}C$ excursions, namely the Fairview (Ka2), Waynesville (Ka2/3), Whitewater (Ka3/4) and Elkhorn (Ka4) excursions are identified. Owing to having a well-defined and continuous conodont zonal succession, the Sigang section provides an integrated and high-resolution chemo-biostratigraphic framework for the mid-late Katian strata of China. A correlation between carbon isotope trends and relative sea-level changes based on gross conodont biofacies shows no clear relation and hence, this supports the idea that sea level to a great extent is not the main driver of $\delta^{13}C$ excursions during the Katian Age. A cross-basin correlation reveals that the Katian isotope zonations established in North America and northern Europe are quite useful for improving long-distance stratigraphic correlations, which suggests that these excursions represent global perturbations in the carbon cycle.

The "*Solenopora*" of the Cincinnati Arch: algae or sponges?

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Certain fossil algae and sponges can appear superficially similar, rendering them difficult to differentiate without microstructural analysis. Casual "field identifications" by non-specialists can easily be erroneous, resulting in misleading occurrence data, mislabeled museum specimens, and mistaken paleoecological or phylogenetic interpretations. One perennial victim of this confusion is *Solenopora* Dybowski, 1877. Originally described as a chaetetid sponge, the genus was widely regarded as a coralline-like red alga throughout the 20th century. More recent publications have reinterpreted the type species as a chaetetid once again. However, this revision did not include all species of *Solenopora* and further study is required to clarify the affinity of many taxa historically referred to the genus and its namesake family, Solenoporaceae, as some may actually be algae.

Notably, problematic calcareous nodular to branching or "brain-like" skeletal masses from the Upper Ordovician strata of the Cincinnati Arch region have been assigned to *Solenopora* for over a century. The most extensive occurrences of these fossils include biostromes in the Strodes Creek Member of the Lexington Limestone (lower Katian; Chatfieldian) near Winchester, Kentucky and beds of cerebriform, rhodolith-like nodules in the Grant Lake Formation (middle Katian; Maysvillian) south of Flemingsburg, Kentucky. Smaller nodules in the Whitewater Formation (upper Katian; Richmondian) around Richmond, Indiana have also been identified as *Solenopora*, though many of these are actually oncolites formed by the cyanobacteria *Girvanella*. Growth forms are typically lobate but vary somewhat from locality to locality, perhaps reflecting different paleoenvironmental conditions, different taxa, or both. Though locally abundant, well-preserved, and routinely found in situ, these Cincinnati Arch "*Solenopora*" are understudied and, due to the recent reclassification of *Solenopora*, lack taxonomic clarity.

Thus, we are engaged in literature review, first-hand inspection of museum specimens, extensive field sampling, and ongoing thin section work to better document these occurrences and resolve the question of their identity. Preliminary results support the work of previous researchers in suggesting that at least some of the Cincinnati Arch "*Solenopora*" are indeed red algae. If so, they are now in open nomenclature and require formal renaming. Furthermore, we have discovered likely cases of mistaken identity, which we hope to report and correct. For example, some specimens identified as the hexactinellid sponge *Pattersonia* in literature and museum collections have an appearance and provenance all but identical to the Flemingsburg "*Solenopora*". Furthermore, they have characters that differ from undoubted *Pattersonia*, leading us to believe they are in fact misidentified "*Solenopora*" (i.e. possible algae). Our findings highlight the importance of specimen-based taxonomic reappraisal: though onerous, such studies are necessary to improve the accuracy of our understanding of the fossil record.

Shells as a tiering boundary and a substrate for colonization in the initial stages of the Prague Basin, Czech Republic (Tremadocian to early Darriwilian)

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Shells of living or dead organisms represent a special substrate. Their colonization depends on many factors and reflects composition ecosystems in global as well as local scale. In the Prague Basin (existed from Early Ordovician to Middle Devonian; now situated in the central Czech Republic), especially in its early stages from the Tremadocian to the Darriwilian, the colonization of shells was strongly influenced by its development and colonization of the basin as a whole. The study of the shells is also affected by taphonomic processes in siliciclastic sediments of all studied formations; the shells are mostly dissolved. Thus, the colonization and biodegradation of the shell material such as microborings is beyond the scope of this research. However, two extensive ecospaces can be easily studied: above and below or inside. The former direction is occupied by epibionts, the latter offers space for hide but, especially, it is a source of food for (not only but especially endobenthic) feeders of decaying tissues of carcasses or microbial consortia of decompositors and their metabolites. It is also a special substrate of its own role in tiering.

Two basal formations (Třenice and Mílina fms.) of the Prague Basin are of a very low diversity of fauna. Only small cystoids cemented to convex surface of large trilobite shields were discovered there; no traces of activities along their inner surfaces or spaces have been found. First significant shell colonization in the Prague Basin was recorded in the Klabava Formation (Floian to Dapingian). Not only tubes of *Sphenothallus* are known from that unit but also their attachment disks on shells of trilobites, gastropods and cephalopods were found. Ichnofossils following the inner surface of flattened shells are exceptional but exist. The key overturn is traced in the Šárka Formation (early and middle Darriwilian). It is considered not only as a primary phenomenon but the 3D mode of preservation in siliceous nodules also contributed to it. Holdfasts of undeterminable echinoderms and thecae of edrioasteroids are occasionally preserved on shells, predominantly of hyolithids and molluscs. Shells of monoplacophorans *Pygmaeoconus* preserve often attached to conchs of hyolithids. Ichnofossils of *Arachnostega*-type and other simple and branched tunnels are very common inside or below shells. They are known from almost all fossil groups occurring in the Šárka Formation. Their usual preferential distribution in each shell testifies a topology of the tissues serving as a food. An effective feeding habit of consumers often preferred soft tissues of intestine, which is documented in some trilobites such as *Placoparia* and gastropods. However, some taxa appear to offer food only as wide-ranging remains (?organic membranes) on the inner surface of their exoskeletons: the ichnofossils are distributed randomly along the surface.

The gradual increase of faunal diversity and complexity of communities in the Prague Basin is reflected in a stuck use of shells as a substrate for colonization. It is considered to be related to development and changes of some environmental characteristics in the basin.

Pelmatozoan meadow attached to Early Ordovician stromatolites: hardground community at the dawn of the golden age for epizoans

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The Ordovician Period records remarkable changes of sedimentary systems in shallow-marine settings. Conspicuously, with a drastic decline of flat pebble conglomerates, Ordovician submarine hardgrounds (carbonate-cemented seafloors) achieve their peak of development within the Paleozoic Era. Owing in part to increased hardground cementation, the Ordovician also witnessed a great evolutionary radiation of epizoans on hard substrates. However, most of the previous studies mainly focus on the abiotic hardgrounds. Here we provide the first detailed description of a pelmatozoan community on Early Ordovician (middle Tremadocian) stromatolites in the upper Lunshan Formation from Biegongli in Jingxian, Anhui Province, South China. A 10-meter thick succession of cylindrical stromatolites is exposed in the outcrop. Sporadically, stromatolitic hardgrounds are encrusted by attachment structures of blastozoan echinoderms, likely paracrinoids or hemicosmitoids (Rhombifera). The holdfasts, overgrowing one another in a few cases, show a discoidal morphotype with slightly lobate margins. They are distinctive in showing rounded tri-lobate lumens similar to those seen in slightly later hemicosmitoids. A few fragments of echinoderm ossicles and stems, also with tri-lobate lumens, are present in stromatolites as bioclasts, but as yet no identifiable thecal plates have been recovered. In thin sections, the stromatolitic crusts are composed of well-preserved calcimicrobes (e.g. filamentous *Girvanella*) which reflect rapid calcification of photosynthetic cyanobacterial sheaths. Our findings suggest that lower Paleozoic microbialites were active hardground providers and autogenic engineers in subtidal ecosystems, which previously have been overlooked. Microbially induced hardgrounds may have been locally common during the Early Ordovician, providing micro-habitats for various epizoans at the dawn of the Ordovician Radiation.

Morphological variation of chitinozoans: a case study from the Upper Ordovician Viola Springs Formation, Arbuckle Mountains, Oklahoma, USA

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Chitinozoans are an extinct group of widely occurring, Lower to Middle Paleozoic organic-walled microfossils, commonly interpreted as eggs of unknown marine metazoans. The aim of this study is to analyze morphological variation exhibited by chitinozoans in order to detect any patterns supporting or contradicting the "egg hypothesis". Our study focuses on an exceptionally variable species Gen. et sp. nov. 1, specimens of which are abundant and three-dimensionally preserved in the Upper Ordovician Viola Springs Formation from SE Oklahoma. This species is characterized by a sub-conical to sub-cylindrical chamber with flaring short collar. It is also distinguished by very distinctive ornamentation: simple or multi-rooted spines distributed near the collar, low and multi-rooted longitudinal spines developed in the lower part of the chamber, and much stronger and more complex ones on the basal margin. The vesicle size of this species varies greatly, but the constriction and highly distinctive ornamentation provide solid evidence for presence of single species. Multivariate statistical analysis (PCA) shows also clearly single grouping of all specimens.

Morphological analyses are based on 331 specimens extracted from two samples from the Viola Springs Formation at the Fittstown auxiliary GSSP section. The vesicle length ranges from 93 to 318 µm, with median and mean values around 183 µm. The maximum/constriction diameter (Dcons/Dp) ranges from 55 to 120 µm and 40 to 99 µm, respectively. The frequency distribution plots of all parameters show nearly normal distribution, especially the Dcons/Dp ratio. Besides, the constrictions become stronger and the outlines become slenderer with the vesicles becoming larger in general.

Over three-fold variation in length detected in Gen. et sp. nov. 1 is far too large for the intraspecific variation usually observed in case of eggs, for instance, the insect and avian eggs. Moreover, the shape variation of the new species suggests longitudinal growth of vesicles during ontogeny of individuals rather than the variation of eggs. Growth-lines or other supporting evidence for that hypothesis are yet to be found. Considering that some egg-shaped desmochitinids usually show smaller intraspecific variation, our study suggests the egg hypothesis may not be suitable for explaining the nature of all chitinozoans.

Upper Ordovician oceanic red beds in northwest Tarim Basin and middle Yangtze region

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The ocean red beds are important for study of regional and global paleoenvironmental records. We have studied late Ordovician intervals from two sections (Dawangou section in Tarim basin and Puxihe section in Yangtze region), in which oceanic red beds were deposited overlying the Middle Ordovician black shale. The samples were measured using diffuse reflectance spectroscopy, and analysis of major, trace and rare earth element concentrations to discuss the formation mechanism of these oceanic red beds.

According to the results, the conclusions are drawn: (1) red beds from the Dawangou section are concentrated in the middle layer of the late Ordovician strata, which sandwiched between layers of the black siliceous oceanic deposits above and gray or gray-green nodular limestones below; while the red beds from Puxihe section are interbeded with marls and mudstone in other colors such as brown, yellow and gray, similar to the modern oceanic high-frequency cycle red sediment; (2) the Dawangou red beds are composed of hematite, which is the major mineral responsible for coloration of these red beds, while in Puxihe section it contains goethite and lower content of hematite, thus its color is clearly lighter than that in Dawangou section; (3) Th/U indicator, together with δCe and δEu anomalies, suggest that in the Dawangou section, the environment under which the red beds formed became more oxic . However, such transition with regard to redox state was not marked in the Puxihe section, as those parameters do not show large difference between the red beds and beds in other colors, thus their colors originate primarily from goethite minerals; (4) the relationship among Al, Zr, and Fe suggests a terrigenous detrital origin of the Fe for the formation of ferric oxides in red beds, this may be linked to the supply of land-sourced materials.

New bryozoans from Hubei Province (Central China) suggesting the onset of diversification of bryozoan in Early Ordovician

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Studies over the last 20 years have indicated both local and global factors playing crucial roles in the pattern and mechanism of the Great Ordovician Biodiversification Event (GOBE), and an increased interest in the palaeontology and palaeoecology of the Late Cambrian – Early Ordovcian in order to understand the GOBE further.

The earliest bryozoans appeared in the Nantzinkuan Formation (Lower Tremadocian) in the Upper Yangtze platform, South China. Recently, new bryozoan species were found in slightly younger deposits of the Fenghsiang Formation (late Tremadocian) deposits from South China, which could provide important implications of the mechanism of GOBE.

These new bryozoans include *Orbiramus* (Trepostomata), *Heminematopora* and *Prophyllodictya* (Cryptostomata) and Ceramoporidina indet. (Cystoporata). They reveal the first appearance of cystoporate and rhabdomesine bryozoans in late Tremadocian, and display developments of complex morphological characters in early bryozoans, such as, the development of polymorphisms, maculae composed by exilazooid and acanthostyles in trepostomes, and acanthostyles in *Prophyllodictya* cryptostome bryozoans. Five of the six orders of palaeostomate bryozoans appeared in Fenghsiang Formation, suggesting biodiversification of palaeostomate bryozoans at the high taxonomic level in Tremadocian which constructed genetically the framework of Ordovician, even Palaeozoic bryozoans. In addition, besides the formation of the earliest eumetazoan reefs formed by esthonioporate *Nekhoroshevilla*, the new bryozoans in the Fenghsiang Formation display complex palaeoecological characters, such as self-overgrowth, borings and epizoans, indicating extensive interaction between bryozoans and environment. The late Tremadocian was therefore a critical time for the evolution of bryozoans in when major lineages and ecological characters, which diversified later during Ordovician, appeared.

Cyclostratigraphy of the Katian Pagoda Formation, South China

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High resolution measurements of magnetism susceptibility (MS) in the Late Ordovician Pagoda Formation were performed at the Shatan Section in Sichuan Basin, South China. The MS variations and wavelengths of significant cycles correspond to long eccentricity, short eccentricity, obliquity and precession cycles among which long eccentricity reflects the strongest signal. This suggests that long eccentricity could be the main orbital forcing in the study area which affects isolation and sea-level fluctuations. These changes are related to the sedimentary environment of the Pagoda Formation and result in the coeval tectonic uplift which probably causes the widely known unconformity between the Pagoda Formation and the underlying strata in this area. The orbital tuning shows the deposition of the Pagoda Formation at this section lasts about 3.08Ma and the average accumulation rate is approximate 10.39m/Ma. This value of this duration is less than the one estimated based on International Community Stratigraphy (ICS) 2015. It indicates that the lower part of the Pagoda Formation is absent since the tectonic uplift stops when the Pagoda Formation began to deposit.

US midcontinent Upper Ordovician integrated chronostratigraphy project: introduction and advances

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The Late Ordovician, particularly the Sandbian and early Katian, represents the apex of diversity for many groups of organisms during the Great Ordovician Biodiversification Event. Establishing clear cause-and-effect evidence for those factors that drove diversification, versus those that inhibited it, is a daunting task. Development of a high-resolution regional chronostratigraphic framework is foundational for moving this work forward in eastern North America.

The Upper Ordovician chronostratigraphy of the US midcontinent is undergoing significant revision through collaborative efforts to integrate biostratigraphic ranges, chemostratigraphic patterns, and facies distributions within a sequence stratigraphic framework. New subsurface cores drilled in Wisconsin and Indiana, together with archived collections from Michigan, Iowa, Illinois, Ohio, Kentucky, Tennessee, Missouri and Arkansas, and targeted sampling of surface exposures across this region (~500,000 km^2), have yielded critical new material for study. New chitinozoan, graptolite. and conodont range data are being integrated with results of previous biostratigraphic studies in the region. High-resolution $\delta^{13}C_{carb}$ (N > 5,000) and $^{87}Sr/^{86}Sr$ isotope data from these sections and others, forming transects parallel and perpendicular to the basin axis, provide additional chronostratigraphic refinement and critical data for intervals barren of index fossils. Bounding surfaces of facies packages have been closely studied and their enclosed strata have been characterized texturally as well as compositionally using portable X-ray fluorescence (pXRF). Anomalies in the concentration of redox-sensitive elements (e.g., Mn, P, Zn, etc.), together with fossil epiboles, and distinctive event beds provide additional tie points for local correlation within portions of basins, particularly along strike. The pXRF results also provide rich data sets for time-series analysis, anchored by an expanding number of U-Pb $TIMS_{zircon}$ ages from bentonites sampled across the study area.

Integration of these many data sets is providing substantial new chronostratigraphic insights as our study reaches maturity. One of the most profound findings is that regional diachroneity is a clear pattern from the basin centers to the intervening arches, but even more so from the continental interior toward the margins (particularly from modern day north-to-south). Long-standing range uncertainties, sampling gaps, facies bias, and localized perspective are being resolved through this coordinated analytical campaign.

Paleoecology and ecosystem evolution of an Upper Ordovician echinoderm Lagerstätte from southern Ontario, Canada

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A mixed hard- and soft-substrate benthic community in the Kirkfield Formation (Katian, Mohawkian) of southern Ontario contains an exceptionally diverse and well-preserved assemblage of echinoderms, bryozoans, brachiopods, trilobites, and mollusks. The laterally extensive hardground, uncovered in a quarry in the Lake Simcoe District over a large (>1000 m^2) surface area, hosts obligate encrusters preserved *in situ*. "Pompeii-style" preservation of hard- and soft-substrate dwelling organisms provides a unique opportunity for detailed paleoecological study. High relief hardground mounds were exhumed after several successive burial events, prolonging the exposure time of the hard substrate through at least seven disturbance events. These episodic obrution beds record discrete "snapshots" of the community, allowing for examination of habitat and community evolution through millennial timescales.

The spatial distributions of taxa provide insights into the patterns of larval recruitment, microhabitat affinities, distance decay and barriers to dispersal on the heterogeneous substrate, pelmatozoan tiering patterns, population structures, and diversity comparisons between mound micropopulations. Comparisons of the community on each bed through a detailed microstratigraphic analysis indicate shifts through time in dominant taxa, here attributed to intermediate disturbance. The beds display complex patterns of deposition and localized erosion. Patchy exhumation of the lower hardground was controlled primarily by scour induced by obstruction of the prevailing current by topographically high mounds. This created a suite of microhabitats, including mound crests, channel-like erosional depressions, crater-like pits, sheltered overhanging mound ledges, as well as adjacent areas of variable substrate consistency (mud, silt, and sand). These microhabitats led to occupation of the ecosystem by a wide diversity of organisms with disparate autecologies. Unique biological interactions are represented, and a variety of organism attachment structures are assigned to identified species.

We compared this occurrence to similar North American echinoderm-dominated hardgrounds in the Upper Ordovician to assess the persistence of the "Kirkfield fauna" on a 100 kyr timescale, noting important differences and similarities among these occurrences, along a time-transgressive, shelf-parallel transect from Oklahoma to Ontario. Each occurrence coincides with local to regional hardground development, commonly with hardground mounds, indicating a consistent set of environmental parameters (sea level fluctuations, sedimentation rates, etc.) favourable to the proliferation of these communities throughout the Late Ordovician.

Sequence stratigraphy, chemostratigraphy, and correlation of the Upper Ordovician Nashville Group, Tennessee and Lexington Limestone, Kentucky

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The Upper Ordovician Nashville Group (Katian, Mohawkian) has long been known to correlate with strata of the Lexington Formation of the Cincinnati Arch, but a detailed microstratigraphic comparison has not yet been proposed. Outstanding new exposures near Nashville provide new details of stratigraphic architecture. Here, we document 4th order sequences in central Tennessee that equate to those previously documented in the Cincinnati Arch in Kentucky and Ohio. The upper Mohawkian (Chatfieldian) Hermitage, Bigby-Cannon, and Catheys Formations display striking similarities to the Lexington Limestone on a scale previously unrecognized. Internal divisions within these formations are correlated with members and submembers of the Lexington Limestone, and comparisons indicate the persistence of facies and fauna between these two regions. Divisions within the Hermitage Formation of Tennessee are correlated with the Curdsville, Logana, (Sequences M5A, M5B) and lower Grier members of the Lexington Limestone; divisions in the Bigby-Cannon Formation are correlated with upper Grier, the Macedonia bed, and the Faulconer, Salvisa, Cornishville beds (Perryville Member; sequence M5C); and divisions in the Catheys Formation are correlated with the Brannon, Sulphur Well, Stamping Ground, Strodes Creek, Greendale, Devil's Hollow, and Bromley Shale members (M6A, M6B). The uppermost Catheys Formation is recognized to correlate with the Peaks Mills, Gratz, Locust Creek, and Point Pleasant members of the uppermost Mohawkian to basal Cincinnatian Series (M6C-C1). Faunal epiboles previously known from more northern strata are recognized and documented for the first time in the Nashville Dome. These sequence stratigraphic correlations, corroborated by limited biostratigraphic data and similarities of facies stacking and faunal content are being further tested using patterns of $\delta^{13}C_{carb}$. The similarities of these patterns strongly suggest an overriding allostratigraphic control, as well as close connection between the Nashville Dome and Lexington Platform during Chatfieldian time. However, the detailed chronostratigraphic framework also provides insights into local and regional environmental fluctuations overprinted by active tectonic deformation.

Ordovician conodont biostratigraphy of deep water cherts from New South Wales, Australia and regional correlations

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A preliminary study on the biostratigraphic utility and biogeographic affinities of conodonts preserved in Ordovician cherts in parts of the Lachlan Orogen of central and southern New South Wales [NSW] (Percival 2006) recognised four zones:

1. *Paracordylodus gracilis* assemblage zone, of late Lancefieldian to early Bendigonian age, i.e. early Floian;
2. *Oepikodus evae* assemblage zone, late Bendigonian to late Chewtonian (late Floian);
3. *Paroistodus horridus-Spinodus spinatus* assemblage zone, early to mid-Darriwilian;
4. *Pygodus serra* assemblage zone, of late Darriwilian age.

In the ensuing 12 years, all known Ordovician cherts throughout NSW have now been examined, approximately doubling the area represented in the initial mapping program. These cherts typically occur as thin beds within thick intervals of poorly exposed siltstones and sandstones making up monotonous Ordovician turbidite successions in central, northwestern and southwestern regions of the state. Recognition of biostratigraphic zones based on conodonts has greatly contributed to field mapping by the Geological Survey of NSW in these areas by indicating younging directions and facilitating correlation of isolated fault-bounded outcrops. Results, now based on examination of over 6000 thick sections of cherts cut parallel to bedding planes (representing more than 1500 sample locations), confirm those assemblage zones identified in the original study. An additional *Pygodus anserinus* assemblage zone, of latest Darriwilian to basal Sandbian age, has also been recognized. This zonation supports Ordovician correlations state-wide and has enabled substantial simplification of Ordovician stratigraphic nomenclature in NSW and Victoria.

New results from this project include firstly, a marked increase in the diversity of this Open-Sea Realm fauna (which is relatively poorly represented in the Ordovician biota) as additional conodont genera have been identified, particularly among coniform taxa. Also preserved within the cherts are various fauna and flora (algae) occupying pelagic and infaunal deep-water habitats (Percival 2012) whose fossilized remains are often overlooked in biodiversity studies. Secondly, geochemical analyses of the cherts (Bruce & Percival 2014) support reinterpretation of the tectonic regime in which the cherts and associated turbidite sediments were deposited, from an island arc to a back-arc basin setting.

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Aberrations in the infrabasal circlet of the cladid crinoid genus *Cupulocrinus* (Echinodermata) and implications for the origin of flexible crinoids

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Flexible crinoids (subclass Flexibilia) are considered to have originated from the cladid crinoid genus *Cupulocrinus* or one of its immediate ancestors in the Middle to Late Ordovician. A remarkably constant and clade-defining character of flexible crinoids is the possession of three plates in the infrabasal circlet of the calyx. This character was a significant morphological modification for the origin of the flexible clade, resulting from the reduction of the number of infrabasal plates from five plates in the ancestral cupulocrinid.

From a total of 615 museum specimens of *Cupulocrinus* sp. for which the number of infrabasal plates could be determined, 21 specimens, or 3.4%, displayed a deviation from the normal five infrabasals. Of the aberrant specimens, fifteen have four infrabasal plates, and six have six infrabasal plates. An additional aberrant specimen has five infrabasals, with one being significantly reduced in size. Although the number of infrabasals is typically thought to be constant within a species, this trait appears to have been variable in the immediate ancestor of flexible crinoids, in the time period just before the number of infrabasals became fixed at three for the Flexibilia. This paper documents the range of aberrations within the infrabasal circlet of *Cupulocrinus* and considers the implications for the origin of the flexible crinoids.

Onset and duration of the Great Ordovician Biodiversification Event

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Most researchers agree that the Great Ordovician Biodiversification Event (GOBE) signified a fundamental change in the history of life. Yet, there is less agreement regarding when it precisely started and for how long the radiation continued. Biodiversity estimates—that usually are compiled with a Phanerozoic scope—exhibit great discrepancies during the Early Palaeozoic. Was the GOBE initiated during the latest Cambrian or during the Middle Ordovician? And was the GOBE only a small part of a much longer diversification peaking during the Devonian, or was it mainly confined to the Middle Ordovician? These discrepancies make it difficult to reach any agreements as to the timing of the event, and it further complicates identification of causal mechanisms, be they biotic or abiotic drivers. Focus has instead been on discussing whether or not to retain the original definition of the GOBE coined by Webby (2004), stating that the event is the sum of all diversifications throughout the entire Ordovician. Although this all-inclusive definition may be convenient, it was based on the data available at the time of publication. Since then, a wealth of new data on biodiversity and taxa ranges has surfaced, and a plethora of plausible causal mechanisms have been proposed. Thus, a more detailed scenario now emerges, suggesting that some clades, notably within the phytoplankton, originated during the latest Cambrian (Furongian), and that conodonts, for instance, radiated during the earlier parts of the Ordovician (Floian). However, the main phase of the GOBE event, as indicated by high-resolution data on both graptolites and brachiopods, seems to have occurred during the early parts of the Middle Ordovician, possibly with a major diversity pulse during the earliest Darriwilian. Later in the Ordovician a phase of global dispersal caused biodiversity levels to rise regionally, but not globally. So, should all of these phases be included in just one event called the GOBE? Or, would it be more appropriate to view this as a composite event comprising 1) a long late Cambrian–Early Ordovician phase with slow diversity accumulation where some new clades also originated, 2) a Middle Ordovician, confined phase that may actually be characterized as a major speciation phase on a global scale, and then, lastly, 3) a time of global dispersal, where taxa migrated to new regions, but without contributing to an overall global biodiversity increase. Resolving this question would allow for a more thorough test of *when* the GOBE occurred, and, not least, *what* might have caused it.

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Significance of the lower Katian $\delta^{13}C_{carb}$ Guttenberg Excursion (GICE) in the Ottawa Embayment, Eastern Canada

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A new record of the GICE is recognized at a superbly exposed Sandbian-lower Katian (Turinian-Chatfieldian) section in Gatineau Park, near Ottawa, eastern Canada. This section (about 100 m thick) comprises a lower facies assemblage of muddy limestone (Lowville and Watertown formations) with abundant euryhaline taxa that is disconformably overlain by an upper facies assemblage of open marine rhythmically- bedded grainstone, packstone, and wackestone (Rockland and Hull formations). This succession has marked similarity to the classic “Trenton-Black River” boundary interval of the Mohawk Valley of New York (~250 km to the south). A broad range of environments are recorded within the Gatineau Park section. At the base of the outcrop, muddy limestones represent inner-ramp sediments deposited in a range of environments above the fair-weather wave base (FWWB): tidal flat, lagoon, and semi-restricted shallow subtidal shoals. The grainier limestones represent storm-dominated mid-ramp facies and the interbedded calcisiltites and shale represent outer-ramp facies deposited below the FWWB. Facies assemblages and sharp bounding surfaces suggest the presence of at least three decameter-scale depositional sequences. In addition, several meter-scale cycles form a distinctive cyclic stratigraphic motif within sequences 2 and 3 (Rockland and Hull formations).

A positive $\delta^{13}C_{carb}$ excursion, tentatively identified as the globally recognized GICE, is recorded within our sequence 2. The base of the section (Lowville and Watertown formations) contains $\delta^{13}C_{carb}$ values that range from -1 to +1‰. Values demonstrate a stair-stepped rise through the Rockland and into the Hull Formation, peaking at +3‰ in the lower Hull. This $\delta^{13}C_{carb}$ record shows great similarity to the New York State composite record of Barta et al. (2007).

Overall, our preliminary data suggests our sequences 1 and 2 are correlative with the classical Mohawkian M4 and M5 composite sequences of New York and Kentucky, suggesting a strong allocyclic control on the Ottawa Embayment stratigraphic architecture during the early Katian despite significant basin morphology changes induced by the Taconic orogeny and foreland basin. The present study documents short-term and high- amplitude cyclic sea-level fluctuations suggestive of glacio-eustasy. This glacio-eustatic signal typifies a timespan coeval with the $\delta^{13}C_{carb}$ isotopic excursion (GICE) that potentially played a significant role in intensifying the Late Ordovician (Katian-Hirnantian) glacial interval. Ongoing work on chemostratigraphy and conodont biostratigraphy is aimed at further testing these hypotheses.

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An acritarch assemblage from the Fenghsiang Formation of Gudongkou section, Yichang, South China

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An acritarch assemblage is for the first time described from the Early Ordovician Fenghsiang Formation of the Gudongkou section (Yichang, Hubei province, South China). More than 35 species attributed to 20 genera are identified, including some easily recognizable and biostratigraphically important acritarch taxa, such as *Coryphidium, Dactylofusa velifera*, *Peteinosphaeridium* and *Rhopaliophora*. These four taxa have previously been considered to have their first appearance in the upper Tremadocian Stage (Tr3). However, the material investigated in this study comes from the lower to middle parts of the Fenghsiang Formation which correlates to the *Paltodus deltifer* conodont Biozone, indicating the middle Tremadocian Stage (Tr2). Therefore, these four taxa possibly indicate their earliest occurrences in South China. In addition, the discovery of *Peteinosphaeridium* might be its first appearance at a global level. Furthermore, the assemblage is dominated by the genera *Polygonium*, *Baltisphaeridium* and *Rhopaliophora*. Since *Rhopaliophora* has been regarded as an indicator of offshore marine habitats and *Polygonium* and *Baltisphaeridium* as taxa common in open sea environments, our study suggests that the middle Fenghsiang Formation in the Gudongkou section belongs to an outer shelf environment.

Upper Katian cyclostratigraphy of the Vauréal Formation, Anticosti Island (Gulf of St. Lawrence, Canada)

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Anticosti Island (Gulf of the St. Lawrence, Canada) has some of the most complete, thickest and most richly fossiliferous carbonate successions in the world containing the Ordovician-Silurian boundary. This study focuses on the cyclostratigraphy of the upper Katian Vauréal Formation. Data from both continuously exposed coastal sections (West End) and complete stratigraphic drill cores (NACP and Laloutre cores) contains high-resolution (dm-scale) proxy profiles of natural gamma ray (NGR) profiles, handheld X-Ray Fluorescence (pXRF) measurements and bulk carbonate stable isotope values of oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$). Outcrop and core data are correlated using the high-resolution lithological logs and $\delta^{13}C$ profiles. Time-series analysis of the proxy series demonstrates meter-scale periodicities in lithological alternations (carbonate versus clay content), which are hypothesized to result from sea-level variations or variations in the supply of detrital material. Similar periodicity patterns can be seen in the $\delta^{18}O$ stable isotope data. The available age constraints (bio- and chemostratigraphy), indicate that the primary observed periodicities are in the order of the astronomical periods of precession and obliquity. The main periodicity (5-9 m) is on a larger scale than the typical tempestite alternations (dm-scale) and is thus probably not representing single events (e.g. storm deposits) or pure diagenetical features, but long term changes in carbonate versus clay in the local paleodepositional system. One working hypothesis is that astronomical changes in insolation were driving sea-level variations by the waxing and waning of the Late Ordovician ice sheets. An alternative hypothesis suggests changing detrital input into the basin (e.g. driven by a monsoonal system) altering the carbonate versus clay content. Ongoing signal processing investigations can shed light on long-term amplitude modulations of the proxy records – which can help determining the precession and/or obliquity driven nature of the records. Our results demonstrate the potential for constructing a high-resolution age model (down to the order of ten thousand years) for the Vauréal Formation and other similar formations on Anticosti Island. Such an astronomically based age model and corresponding climatic interpretations should shed more light on the dynamics of the Late Ordovician glaciations and the mass extinction event.

Ephemeral invasions, epiboles, and biotic immigration events: contrasting ecosystem impacts of biotic invasions in the Type Cincinatian Series (Late Ordovician, Katian)

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The fossil record comprises a rich record of species with geographic ranges that began in one geographic area and later expand across geographic or climatic barriers to encompass multiple regions. Both demographic and geographic expansion of populations from the initial speciation site into additional geographic areas is a hallmark of successful speciation events, and thus characterizes all species known from the fossil record. However, the temporal duration of expansion and persistence of populations at specific geographic range size fluctuates through time. Likewise, the relative ecological impacts of short vs. long term colonization of geographic space differ.

Invasion events, in which species immigrate into a geographic area distinct from their area of origin, are particularly noteworthy because invasion events provide evidence of temporally-limited physical connectivity between otherwise isolated geographic areas. The ecological and evolutionary impact of the invasion on the recipient community varies with the scale of the invasion, in terms duration, number of taxa, and ecology of the taxa involved. Herein, we compare the pattern and impact of two types of invasion preserved in Katian rocks of the Cincinnatian Series: ephemeral and long-term invasion.

Ancient invasions preserved in the fossil record can (and should) be considered in light of current invasion biology. The outstanding preservation and exposure of Late Ordovician (Katian) strata in the Cincinnati, USA region provides a natural laboratory to explore the patterns and processes operating during ancient invasion events. In particular, three types of invasions will be examined and compared: ephemeral invasions, ecological epiboles, and a regional biotic immigration event (BIME).

The transition from Maysvillian to Richmondian age strata is marked by a dramatic influx of over 80 genera native to surrounding Laurentian basins into the Cincinnati Basin. This event, known as the Richmondian Invasion, produced substantial ecosystem turnover as evidenced by changes in community structure and niche occupation. During the early phases of this invasion, epibole beds, in which certain taxa occur in great abundance, occur and are useful as regional marker beds. Intensive collecting has revealed that some of the classic “Richmondian Invasion fauna” are also present at low population abundances in pre-Richmondian. If these species occurrence records are accurate, then there must have been pathways for immigration available at least intermittently during the Edenian interval, which precedes the Richmondian Invasion proper by nearly five million years.

Neither epibole beds nor the rare “Richmondian type” invaders that occur in the Kope Formation produced a marked or lasting impact on ecological relationships within Cincinnatian communities. Conversely, the Richmondian Invasion was an event that included multiple waves of invasion over tens of thousands of years minimally. Immigration pathways would have remained open for much of this time resulting in substantial propogule pressure, which facilitated the establishment of a new ecosystem structure that was dominated, in terms of both abundance and biomass, by the invasive species. Thus, the duration of potential immigration and the flexibility of the native communities to undergo niche partitioning and niche evolution are key factors in determining whether invasion events will be ephemeral or manifest as major ecosystem changes.

Ecosystem dynamics and the consequences of invasive species

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Although a leading cause of extinction in modern ecosystems, the effects of biotic invasions on ecosystem structure and functioning remain poorly understood. Food web data before invasion are rare, and without direct comparisons before and after invasion, differences in overall network structure are difficult to identify. The fossil record contains intervals of dramatic ecosystem changes, and can thus provide insights into persistent ecosystem conditions over evolutionary timescales, particularly before and after invasions.

Shallow marine food webs from the Late Ordovician (Cincinnati Arch, USA) were compared before and after the Richmondian Invasion, a well-documented influx of invasive species. Invasions may trigger significant ecosystem restructuring and major changes in energy transfer pathways, such as patterns of interactions and the distribution of taxa among trophic levels. Network structure and functioning was therefore examined using descriptive metrics and Cascading Extinction on Graphs models. We observed a loss of richness which corresponded with a decrease in the number of functional groups, but few differences in link density, average path length, modularity, and trophic levels. Despite the similarity in overall structure, the post-invasion community was less stable and resistant suggesting that functional richness may play a more critical role in ecosystem stability than biodiversity.

These results, therefore, are consistent with functional homogenization, and thus have important implications for conservation and management efforts, which typically focus on preservation of biodiversity. A better understanding of biotic invasions on multiple spatiotemporal scales will prove useful in ecosystem management, for preventing invasions and predicting their long-term effects.

Middle Ordovician (Darriwilian) chitinozoans from the Qaidam Basin, China

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For a long time, the Qaidam (Chaidam/Chiadam) Basin also known as the Qaidam Paleoplate, has been the focus of research because it is a microcontinent that is currently part of central Asia Plateau (Central Asian Orogenic Supercollage). Although all reconstructions agree that the Qaidam Paleoplate was at low latitude during the Ordovician, its position relative to other continental blocks is currently contentious. In order to find more clues which may help to solve the uncertainty of its position during the Ordovician, palynological study of Middle Ordovician (Darriwilian) Chitinozoans was conducted in the Qaidam area, in the hope of providing new materials from the biological affinity side.

Ordovician microfossils such as chitinozoans have not previously been reported from the Qaidam Paleoplate. Chitinozoan samples were collected from the Dameigou section in the northern margin of the Qaidam Platform, which can be independently and adequately dated by means of graptolites (Darriwilian *Undulograptus austrodentatus* and *Archiclimacograptus confertus* graptolite biozones).

The chitinozoan fauna includes several biostratigraphically and paleogeographically important chitinozoan species, such as *Lagenochitina langei*, *L. pirum*, *Rhabdochitina magna*, *Rh. usitata*, *Conochitina turgida*, *Co. subcylindrica*, *Co. decipiens*, *Clavachitina poumoti*, *Belonechitina nevillensis*, *Be. cf. uniformipunctata* and *Be. chydaea*. The assemblage contains a specimen in which the collarette of a specimen of *Eisenackitina* sp. is attached to the aboral pole of a specimen of *Lagenochitina* sp., indicating that a single organism could produce more than one chitinozoan morphospecies. The *Co. turgida–Co. subcylindrica* Biozone is indicated by the recovered chitinozoan assemblage.

Biostratigraphically important species from the Qaidam microfauna suggest faunal affinities with Laurentia (north America), eastern Gondwana (Australia) and the peri-Gondwana area (southeast China). The chitinozoan paleogeographic data indicate that the Qaidam region was at low latitude during the Middle Ordovician, and that area was near South China rather than North China. The paleogeographic information deduced from chitinozoans is consistent with that from graptolites and paleomagnetic analysis in previous studies.

Quantifying and comparing fossil type and abundance at the nationally renowned fossil collection site of Caesar Creek State Park, Warren County, OH

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This experimental study measured the overall fossil type and abundance at the emergency spillway of Caesar Creek Park, Warren County, OH, which is a famous collecting site that has been heavily visited by geologists since 1978. An additional purpose was to determine if there are quantitative differences in fossil type and abundance between heavily collected areas and lightly collected areas of the spillway.

The emergency spillway was divided into six (6) rows with nine collection sites per row. Three rocks were collected at each site for a total of 162 rocks. The heavily collected area of the spillway versus the lightly collected area was observed and estimated. The rocks were cleaned and viewed to determine the qualitative abundance of fossil types (super abundant, abundant, present, minimally present, and not present) at each collection site.

Fossils were less abundant in heavily collected areas of the spillway versus lightly collected areas, but, there was no difference in diversity between heavily and lightly collected areas. Also, for the entire spillway, there is a high diversity of fossils including bryozoans and other fossils such as echinoderms, and a good overall abundance of fossils despite forty years of intensive collection efforts.

Bayesian modeling of a comprehensive genus-level informal supertree reveals the diversification and evolutionary dynamics of Ordovician crinoids

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The ability to estimate hypotheses of evolutionary relationships (i.e., phylogenies) and the development of tree-based comparative methods to study character evolution and lineage diversification has greatly expanded research programs in paleontology. An especially fruitful avenue of current research in phylogenetic paleobiology concerns methods of time-scaling cladistic hypotheses to absolute geologic time that integrate information regarding ancestor-descendant relationships (i.e., “budding” divergence of morphotaxa), incomplete sampling/preservation, and general diversification dynamics.

The Crinoidea (Echinodermata) are one of five major clades of living echinoderms and have a rich fossil record spanning nearly a half billion years. Because crinoids were significant constituents of Ordovician paleocommunities and have a well-sampled fossil record, crinoids form an ideal group for dissecting patterns of lineage diversification during the GOBE and assessing the magnitude and selectivity of the late Ordovician extinctions.

Based on results from recent quantitative phylogenetic analyses of early crinoids (and their geologically younger subclades), we assemble the first comprehensive genus-level informal supertree of Ordovician crinoids. Using this robust phylogenetic framework, we present results of a Bayesian analysis utilizing a time varying birth-death-sampling model to generate a posterior distribution of time-calibrated phylogenies to assess temporal patterns of lineage diversity and estimate rates of origination, extinction, and sampling parameters. Preliminary results indicate crinoids underwent a major global radiation during the middle to late Ordovician, reaching maximal genus-level diversity during the Katian, whereas the end-Katian is characterized by clade-specific patterns of extinction selectivity.

A Tremadocian acritarch assemblage at Xiangshuidong, southwestern Hubei Province: biodiversification and palaeogeographical implications

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The IGCP 653 project "The onset of the Great Ordovician Biodiversification Event" has been accepted and focuses on the onset of the Great Ordovician Biodiversification Event (GOBE). As the primary producers during the Paleozoic, acritarchs are very important in the GOBE. Most acritarchs are considered to be the cysts of phytoplanktonic unicellular algae and thus the primary produces of the marine trophic chain in the Palaeozoic.

Most Ordovician acritarch studies focused on the Floian to Darriwilian, and rarely on Tremadocian from South China. Fortunately, a new Tremadocian acritarch assemblage have been discovered from the Xiangshuidong section, Songzi, southwestern Hubei Province. The Xiangshuidong section is subdivided in the the Nantsinkuan, Fenhsiang, Hunghuayuan, Zitai, Kuniutan and Pagoda formations in ascending order, representing sediments from the upper Cambrian to the Upper Ordovician.

Moderately well preserved but diverse acritarch assemblages were recognized in the Nantsinkuan and Fenhsiang formations attributed to the Tremadocian. The acritarch assemblage from the Tremadocian Xiangshuidong section contained 50 species assigned to 32 genera. The Nantsinkuan Formation contains 39 species assigned to 26 genera acritarchs, dominated by *Cymatiogalea*, *Polygonium* and *Aryballomorpha* while the Fenhsiang Formation contains 35 species attributed to 22 genera acritarchs, dominated by *Lophosphaeridium*, *Polygonium*, *Cymatiogalea*/*Stelliferidium* and Peteinosphaeridium.

The acritarch diversity in Tremadocian is fairly low from South China in the previous studies. Our new study showing moderate acritarch diversities during the Tremadocian implies that a diversity increase during the late Cambrian possibly indicated the onset of the GOBE in South China.

The present of the Volkova's 'warm water' *Aryballomopha-Athbascaella-Lua* assemblage, for the first time recorded in South China, together with *Coryphidium*-Diacromopha possibly shows a mixed acritarch assemblage in South China during Tremadocian.

Revised stratigraphy of the Late Ordovician Early Katian Lexington and Point Pleasant Formation on the margin of the Point Pleasant Basin, northern Kentucky and Ohio

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The Upper Ordovician (Mohawkian; lower Katian) Lexington and Point Pleasant Formations display rapid lateral facies changes along the margin of the Lexington Platform in northern Kentucky and Ohio, USA, in cross sections due to regional water depth variation into the Point Pleasant Basin. Facies changes make identifying sequences (or drawing timelines) in the exposed record difficult and have resulted in a complex lithostratigraphic nomenclature. This study further builds on sequence stratigraphy developed in the Lexington Platform, and extends correlations of the Katian 3rd and 4th order sequences into the Point Pleasant Basin utilizing high resolution carbon isotope analysis, faunal epiboles, and an expanded comparison with the subsurface record of Ohio, USA. Prominent positive carbon isotope excursions (~1-3‰ $\delta^{13}C_{carb}$) allow for direct comparison of sections using time specific signatures of the Logana Excursion, Macedonia Excursion, and others. High resolution sampling of both core and outcrop, and a wider region of study have led to further revisions of the Lexington and Point Pleasant Formation allostratigraphy. The lower parts of the type Lexington Formation (sequences M5A, M5B, M5C, M6A TST and lower HST) can be readily identified in the subsurface. In particular, the Macedonia Member (M5C; previously Macedonia "Bed") comprised of two divisions, a basal grainstone overlain by interbedded shales and calcisiltites, with abundant *Prasopora*, displays a strong positive carbon isotope excursion (Macedonia Excursion), which has been recognized in both outcrop and core of Kentucky and Ohio. The Point Pleasant Formation in the Ohio subsurface is age equivalent to the upper Lexington Formation of central KY and is comprised of sequences M6A (HST) M6B, M6C and C1, in part, i.e., Brannon through "River Quarry beds". The latter, interpreted as TST of C1, has sometimes been termed "Point Pleasant Member" *sensu stricto*, but review of the type locality indicates that the original definition of the Point Pleasant Member included primarily strata below this level; hence the broader definition of the Point Pleasant used in the subsurface is more appropriate. The Point Pleasant Formation is offset at its base by a sharp discontinuity (probably a maximum flooding surface) into the highly organic rich Brannon Member, and offset by another discontinuity at its top by another major flooding surface that marks the base of the Kope Formation. Hence, as presently defined, the Point Pleasant approximates a large scale genetic sequence (bounded by MFS). A revised terminology will help in communication between surface and subsurface stratigraphers. Improved, high-resolution correlations provide a framework for examining the environmental and biotic changes both vertically and laterally, as well as basin dynamics of the Point Pleasant Basin and Sebree Trough.

A review of Konservat-Lagerstätten in upper Cambrian and Ordovician shales in South China: biodiversity, facies and taphonomy

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The later Cambrian to Ordovician rocks of South China contain many shales that yield diverse faunas and Konservat-Lagerstätten. These shales are developed intermittently and contain exceptionally-preserved faunas in the Furongian, Tremadocian–Floian transition, Darriwilian–Sandbian transition, and late Katian to Hirnantian deposits, combining to reveal a rich record of community development. The Sandu Formation of Jiangshanian (Furongian, Cambrian) age yields the Guole Lagerstätte, a Burgess Shale-type fauna containing arthropods, echinoderms, brachiopods, cnidarians, graptolites, hyolithids, palaeoscolecids and algae, and representing a marginal platform to slope facies. The upper Tremadocian Fenghsiang Formation, typified by intercalated shale and limestone, contains exceptionally-preserved linguloid brachiopods (with pedicles), black corals, conodonts, bryozoans, the cnidarian *Sphenothallus*, conulariids, graptolites and a putative scalidophoran embryo, which together comprise the Fenxiang Biota. The formation represents a marginal platform facies. The Floian Tonggao Formation yields conulariids, palaeoscolecid worms, a possible nematode worm, pelmatozoans, graptolites, brachiopods, gastropods, bryozoans, non-biomineralized arthropods and algae, which comprise the Tonggao Biota. The Sandbian Miaopo Formation, lithologically typified by black shale intercalated with a few layers of limestone, represent deposits of an intra-platform depression in the Yangtze Region, South China. The shale of the formation contains abundant, sometimes exceptionally preserved, graptolites, brachiopods, trilobites, nautiloids, chitinozoans, echinoderms and algae. Some largely contemporaneous shale (upper Darriwilian to Sandbian) also occurs in the North China and Tarim blocks, indicative of a likely global transgression event at the Darriwilian–Sandbian transition. The upper Hirnantian Wenchang Formation is characterized by a thick succession of sandstones and siltstones with a few layers of shale, and represents deep-water, dysaerobic deposits of a basin adjacent to the Cathaysian Land. In a 9-m-thick, deeper-water black shale interval of the formation, the Anji Biota (Konservat-Lagerstätte) occurs, which is dominated by extremely diverse sponges, with abundant soft-tissue preservation, and graptolites, and less common non-biomineralized arthropods, cephalopods and echinoderms. These exceptionally-preserved faunas from upper Cambrian and Ordovician shales in South China are related to various facies, including marginal platform-slope facies, intra-platform depression or foreland basin with anoxic–dysoxic sea water, but all appear to be associated with global or regional transgression events, suggesting a general causative phenomenon. In the Anji Biota in particular, exceptional preservation by rapid sedimentation was generated by post-glacial transgression over weathered land masses, and similar processes may have operated at other times. The combined record of these (and potential further faunas in the region) provides a key window for understanding the development of Ordovician ecology, beyond the normal shelly assemblages.

A hypothesis for facies differentiation of Late Ordovician carbonate rocks in the Central Tarim Uplift (NW China)

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In the Central Uplift of the Tarim Basin, northwestern China, the Katian (Upper Ordovician) limestones of the Lianglitag Formation extend from outcrops in the Bachu area to the subsurface in the Tazhong Oil Field (TZOF) area. Reefs and inner platform deposits are the dominant facies throughout the formation. The reef composition illustrates a palaeoecologic gradient from microbial-dominated buildups on the northwestern margin to metazoan-dominated reefs on the eastern and southern margins of the platform. Between these areas no outcrops are present. In the present study, data including litho- and biofacies logs and correlations from eight wells are presented, six of them of the region between Bachu and Tazhong, and two wells along the former platform margin from the TZOF. Calcimicrobial carbonates are common in core from the inner platform part. Benthic biota documented here resemble that of the microbial mounds and bioclastic limestones in the Bachu outcrop area, and thus is considered as the eastward extension of this realm. However, metazoan-dominated boundstones formed by corals, stromatoporoids, sponges together with calcareous algae are abundant along the southern platform margin, and are similar in composition to the reefs of TZOF in the easternmost part of the platform. The palaeoecologic differentiation between microbial- and metazoan-dominated reefs suggests a strong environmental gradient from a well-oxygenated windward eastern and southern side of the platform, which favoured the open ocean and which was dominated by metazoan reefs, and the inner platform as well as the northwestern, leeward margin of the platform with warmer, less-oxygenated water, which favoured the growth of microbial carbonates. Assuming the trade winds as cause for the contrasting facies on both sides of the platform a palaeo-position of Tarim south of the ITCZ seems probable because a position north of it would require a post-Ordovician clockwise rotation of Tarim of about 90° which is possible but less probable.

Trekking Across the GOBE

From the Cambrian through the Katian

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