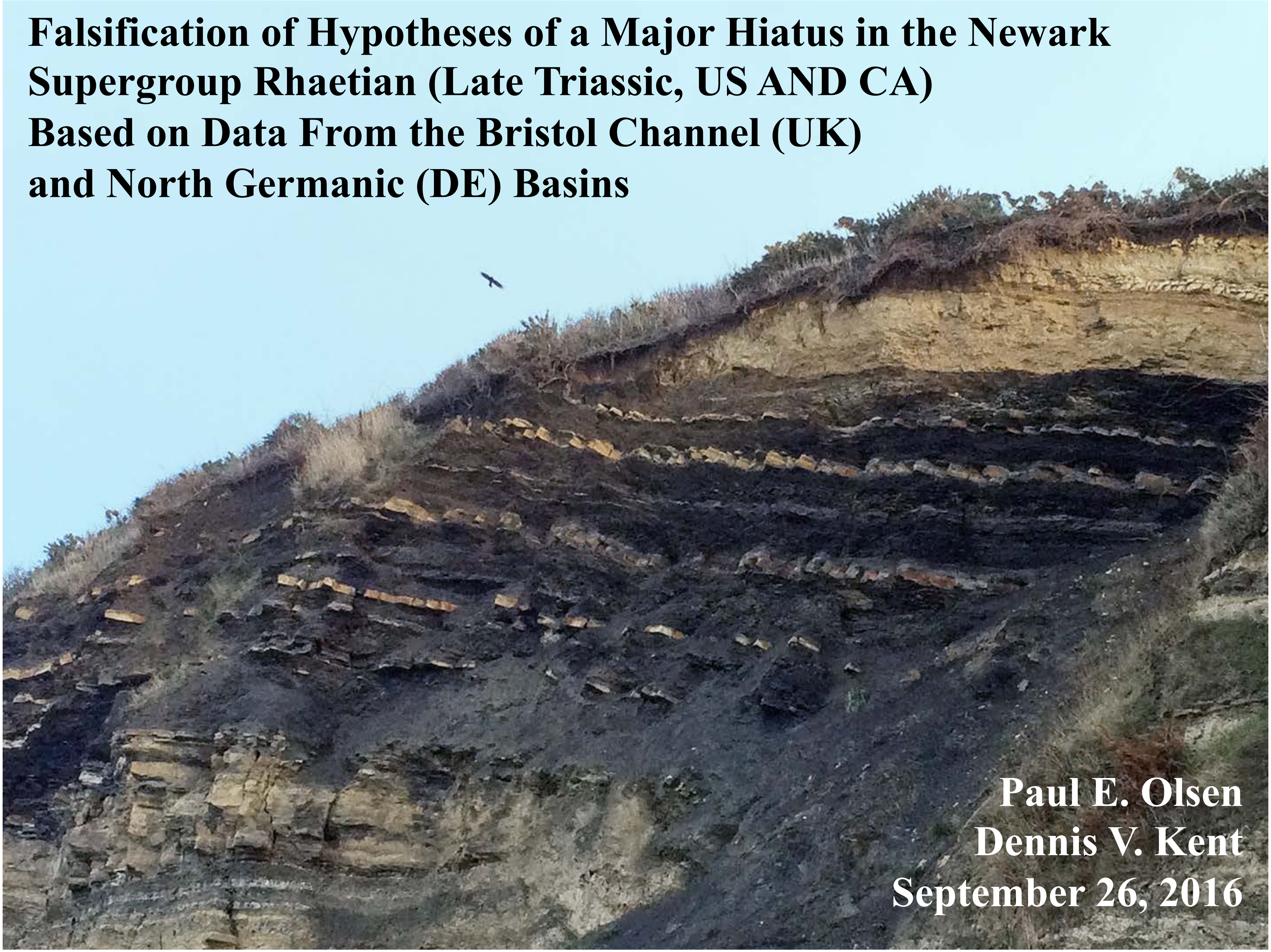
# Falsification of Hypotheses of a Major Hiatus in the Newark Supergroup Rhaetian (Late Triassic, US AND CA) Based on Data From the Bristol Channel (UK) and North Germanic (DE) Basins



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# FALSIFICATION OF HYPOTHESES OF A MAJOR HIATUS IN THE NEWARK SUPERGROUP RHAETIAN (LATE TRIASSIC, US AND CA) BASED ON DATA FROM THE BRISTOL CHANNEL (UK) AND NORTH GERMANIC BASINS (DE)

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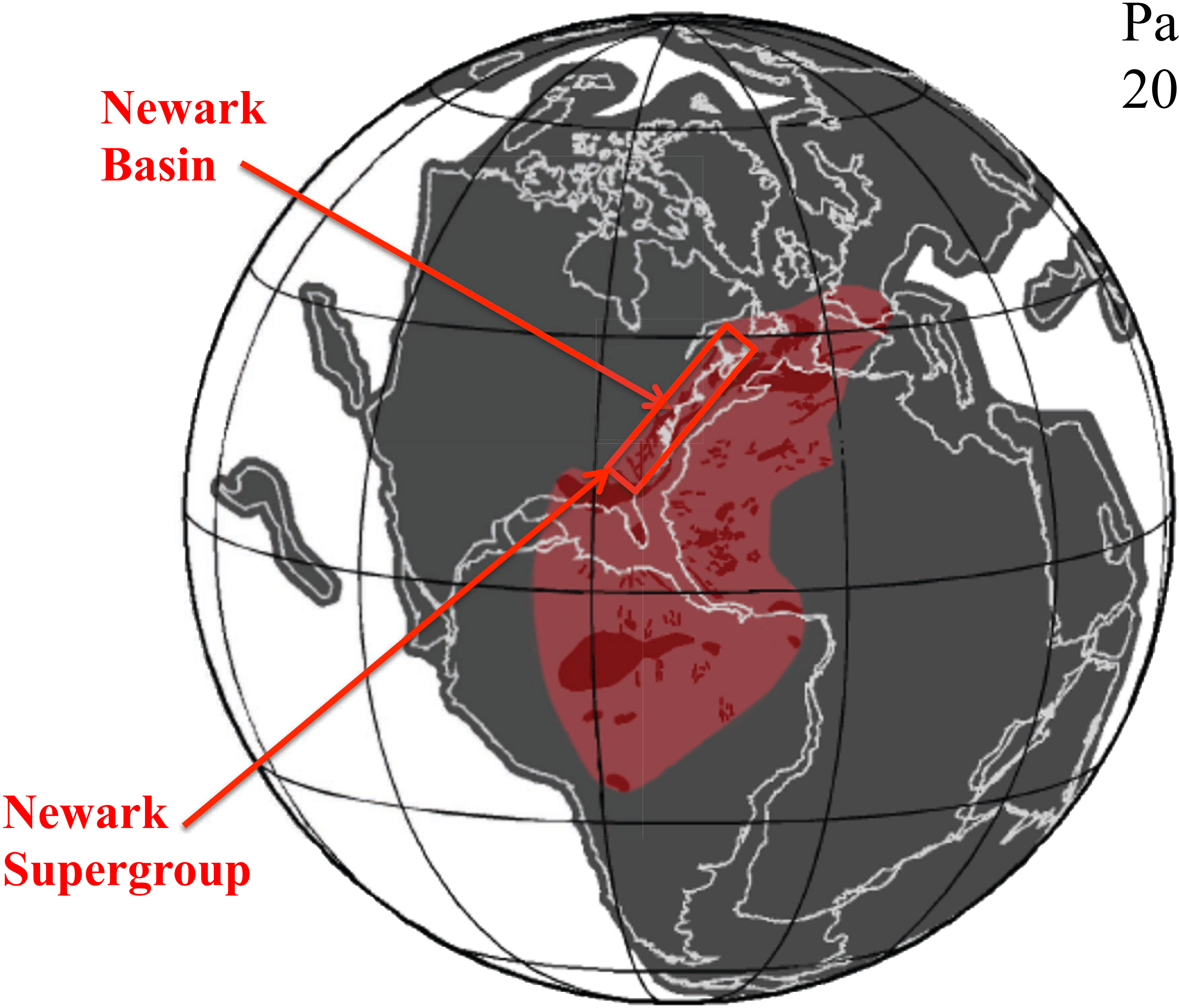
Rift basins of eastern North America and Morocco arguably preserve the temporally most tightly constrained record of abrupt continental biotic change through the end-Triassic mass-extinction (ETE) based on astrochronology and U-Pb dates (1). However, two biostratigraphic hypotheses have been proposed for these sections requiring a multi-million-year hiatus or unconformity spanning most of the Rheatian that we show here are falsified. Van Veen (2) hypothesized a hiatus based on European records where vesicate pollen (*Patinasporites-Enzonalasporites-Vallisporites* complex) disappear in the early Rhaetian while continuing up to the Newarkian ETE, and therefore implying the Newark succession is very condensed, consistent with a major hiatus. This is falsified by the presence of the vesicate forms in late Rhaetian strata of the Bristol Channel Basin (3). This pattern is more simply explained by a time-transgressive disappearance (in present geography) of the low-latitude vesicate pollen group as central Pangae translated north (4) prior to their ETE extirpation (5).

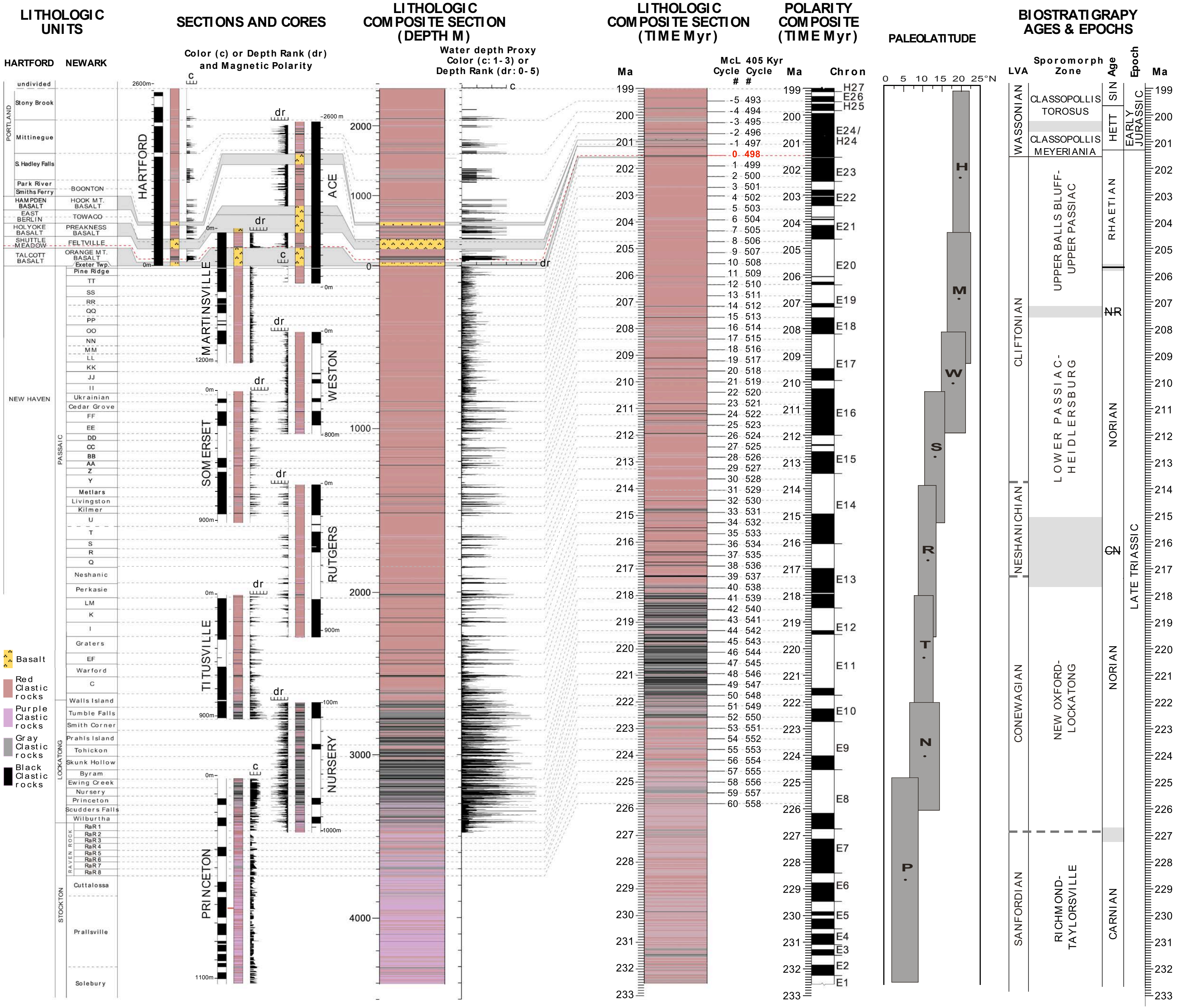
Similarly, Kozur & Weems (6) hypothesized that the absence of several Germanic basin clam shrimp zones in the Newark Supergroup indicate a hiatus spanning most of the Rhaetian. Their key observations are, "…the upper Norian faunas were dominated by very large conchostracans, while the Rhaetian (and Hettangian) conchostracan faunas are everywhere composed of very small forms." The lack of these zones and the presence of the large *Shipingia* just below the ETE in Newark Supergroup strata led to the hypothesis of a major hiatus. This hypothesis is falsified by our discovery of abundant large cf. *S. olseni*in late Rhaetian, largely marine strata in the North Germanic Basin.

Both hypotheses for a significant hiatus are thus falsified; moreover, no physical evidence for a significant hiatus at this critical level exists. There is instead compelling physical and magnetostratigraphic evidence of completeness at the 20 kyr level (e.g., chron E23r). The most parsimonious interpretation is that the Newarkian records through the ETE are continuous.

1, Blackburn+ 2013 Science 340:941; 2, Van Veen 1995 Tectonopysics 245:93; 3, Bonis+ 2010 JGS Lond 167:877; 4, Kent & Tauxe 2005 Science 307:240; 5, Olsen+2011 EESTRSE 101:201; 6, Kozur & Weems 2011 NMMNHS Bull 53:295.

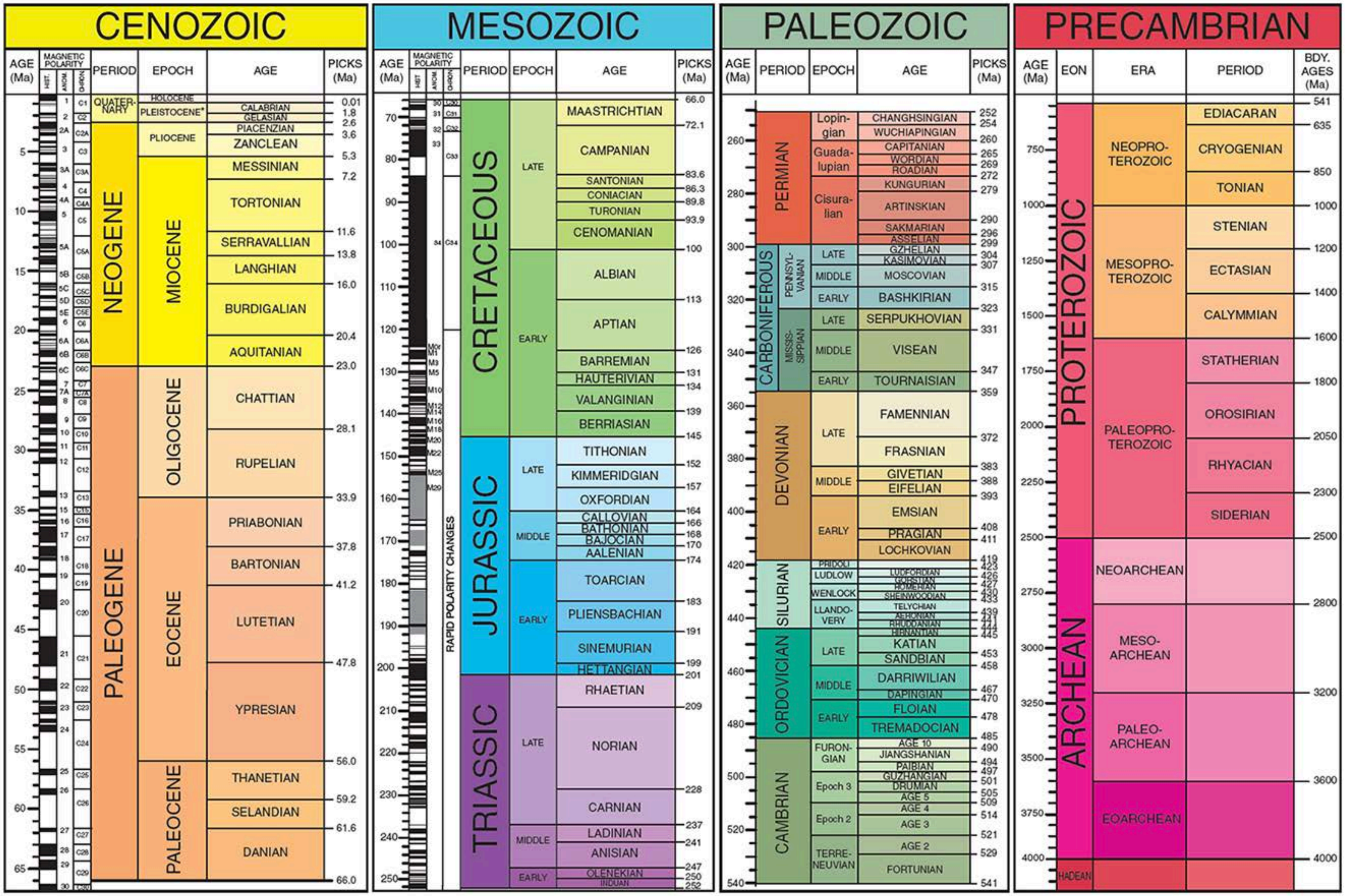
Pangea @
201.6 Ma





Kent et al., 2016

# 2012 GSA GEOLOGIC TIME SCALE v. 4.0



## CENOZOIC

| PERIOD | EPOCH | AGE | PICKS (Ma) |
|---|---|---|---|
| QUATERNARY | HOLOCENE | | 0.01 |
| | PLEISTOCENE* | CALABRIAN | 1.8 |
| | | GELASIAN | 2.6 |
| NEOGENE | PLIOCENE | PIACENZIAN | 3.6 |
| | | ZANCLEAN | 5.3 |
| | MIOCENE | MESSINIAN | 7.2 |
| | | TORTONIAN | 11.6 |
| | | SERRAVALLIAN | 13.8 |
| | | LANGHIAN | 16.0 |
| | | BURDIGALIAN | 20.4 |
| | | AQUITANIAN | 23.0 |
| PALEOGENE | OLIGOCENE | CHATTIAN | 28.1 |
| | | RUPELIAN | 33.9 |
| | EOCENE | PRIABONIAN | 37.8 |
| | | BARTONIAN | 41.2 |
| | | LUTETIAN | 47.8 |
| | | YPRESIAN | 56.0 |
| | PALEOCENE | THANETIAN | 59.2 |
| | | SELANDIAN | 61.6 |
| | | DANIAN | 66.0 |

## MESOZOIC

| PERIOD | EPOCH | AGE | PICKS (Ma) |
|---|---|---|---|
| | | | 66.0 |
| CRETACEOUS | LATE | MAASTRICHTIAN | 72.1 |
| | | CAMPANIAN | 83.6 |
| | | SANTONIAN | 86.3 |
| | | CONIACIAN | 89.8 |
| | | TURONIAN | 93.9 |
| | | CENOMANIAN | 100 |
| | EARLY | ALBIAN | 113 |
| | | APTIAN | 126 |
| | | BARREMIAN | 131 |
| | | HAUTERIVIAN | 134 |
| | | VALANGINIAN | 139 |
| | | BERRIASIAN | 145 |
| JURASSIC | LATE | TITHONIAN | 152 |
| | | KIMMERIDGIAN | 157 |
| | | OXFORDIAN | 164 |
| | MIDDLE | CALLOVIAN | 166 |
| | | BATHONIAN | 168 |
| | | BAJOCIAN | 170 |
| | | AALENIAN | 174 |
| | EARLY | TOARCIAN | 183 |
| | | PLIENSBACHIAN | 191 |
| | | SINEMURIAN | 199 |
| | | HETTANGIAN | 201 |
| TRIASSIC | LATE | RHAETIAN | 209 |
| | | NORIAN | 228 |
| | | CARNIAN | 237 |
| | MIDDLE | LADINIAN | 241 |
| | | ANISIAN | 247 |
| | EARLY | OLENEKIAN | 250 |
| | | INDUAN | 252 |

## PALEOZOIC

| PERIOD | EPOCH | AGE | PICKS (Ma) |
|---|---|---|---|
| | | | 252 |
| PERMIAN | Lopingian | CHANGHSINGIAN | 254 |
| | | WUCHIAPINGIAN | 260 |
| | Guadalupian | CAPITANIAN | 265 |
| | | WORDIAN | 269 |
| | | ROADIAN | 272 |
| | Cisuralian | KUNGURIAN | 279 |
| | | ARTINSKIAN | 290 |
| | | SAKMARIAN | 296 |
| | | ASSELIAN | 299 |
| CARBONIFEROUS – PENNSYLVANIAN | LATE | GZHELIAN | 304 |
| | | KASIMOVIAN | 307 |
| | MIDDLE | MOSCOVIAN | 315 |
| | EARLY | BASHKIRIAN | 323 |
| CARBONIFEROUS – MISSISSIPPIAN | LATE | SERPUKHOVIAN | 331 |
| | MIDDLE | VISEAN | 347 |
| | EARLY | TOURNAISIAN | 359 |
| DEVONIAN | LATE | FAMENNIAN | 372 |
| | | FRASNIAN | 383 |
| | MIDDLE | GIVETIAN | 388 |
| | | EIFELIAN | 393 |
| | EARLY | EMSIAN | 408 |
| | | PRAGIAN | 411 |
| | | LOCHKOVIAN | 419 |
| SILURIAN | PRIDOLI | | 423 |
| | LUDLOW | LUDFORDIAN | 426 |
| | | GORSTIAN | 427 |
| | WENLOCK | HOMERIAN | 430 |
| | | SHEINWOODIAN | 433 |
| | LLANDOVERY | TELYCHIAN | 439 |
| | | AERONIAN | 441 |
| | | RHUDDANIAN | 444 |
| ORDOVICIAN | LATE | HIRNANTIAN | 445 |
| | | KATIAN | 453 |
| | | SANDBIAN | 458 |
| | MIDDLE | DARRIWILIAN | 467 |
| | | DAPINGIAN | 470 |
| | EARLY | FLOIAN | 478 |
| | | TREMADOCIAN | 485 |
| CAMBRIAN | FURONGIAN | AGE 10 | 490 |
| | | JIANGSHANIAN | 494 |
| | | PAIBIAN | 497 |
| | Epoch 3 | GUZHANGIAN | 501 |
| | | DRUMIAN | 505 |
| | | AGE 5 | 509 |
| | Epoch 2 | AGE 4 | 514 |
| | | AGE 3 | 521 |
| | TERRENEUVIAN | AGE 2 | 529 |
| | | FORTUNIAN | 541 |

## PRECAMBRIAN

| EON | ERA | PERIOD | BDY. AGES (Ma) |
|---|---|---|---|
| | | | 541 |
| PROTEROZOIC | NEOPROTEROZOIC | EDIACARAN | 635 |
| | | CRYOGENIAN | 850 |
| | | TONIAN | 1000 |
| | MESOPROTEROZOIC | STENIAN | 1200 |
| | | ECTASIAN | 1400 |
| | | CALYMMIAN | 1600 |
| | PALEOPROTEROZOIC | STATHERIAN | 1800 |
| | | OROSIRIAN | 2050 |
| | | RHYACIAN | 2300 |
| | | SIDERIAN | 2500 |
| ARCHEAN | NEOARCHEAN | | 2800 |
| | MESOARCHEAN | | 3200 |
| | PALEOARCHEAN | | 3600 |
| | EOARCHEAN | | 4000 |
| HADEAN | | | |

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*The Pleistocene is divided into four ages, but only two are shown here. What is shown as Calabrian is actually three ages—Calabrian from 1.8 to 0.78 Ma, Middle from 0.78 to 0.13 Ma, and Late from 0.13 to 0.01 Ma.

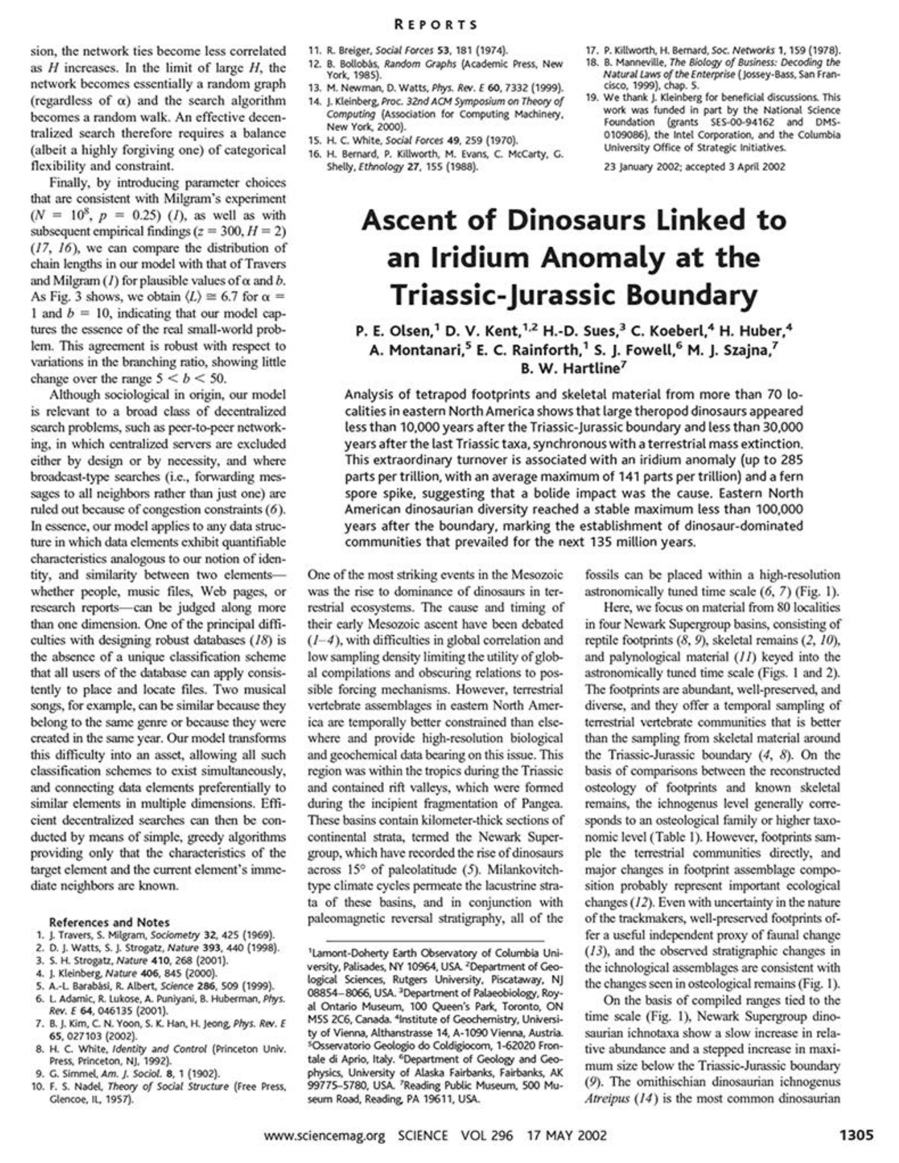
Walker, J.D., Geissman, J.W., Bowring, S.A., and Babcock, L.E., compilers, 2012, Geologic Time Scale v. 4.0: Geological Society of America, doi: 10.1130/2012.CTS004R3C.

The Cenozoic, Mesozoic, and Paleozoic are the Eras of the Phanerozoic Eon. Names of units and age boundaries follow the Gradstein et al. (2012) and Cohen et al. (2012) compilations. Age estimates and picks of boundaries are rounded to the nearest whole number (1 Ma) for the pre-Cenomanian, and rounded to one decimal place (100 ka) for the Cenomanian to Pleistocene interval. The numbered epochs and ages of the Cambrian are provisional.

REFERENCES CITED Cohen, K.M., Finney, S., and Gibbard, P.L., 2012, International Chronostratigraphic Chart: International Commission on Stratigraphy, www.stratigraphy.org (last accessed May 2012). (Chart reproduced for the 34th International Geological Congress, Brisbane, Australia, 5–10 August 2012.)

Gradstein, F.M, Ogg, J.G., Schmitz, M.D., et al., 2012, The Geologic Time Scale 2012: Boston, USA, Elsevier, DOI: 10.1016/B978-0-444-59425-9.00004-4.

# Olsen et al, 2002



sion, the network ties become less correlated as *H* increases. In the limit of large *H*, the network becomes essentially a random graph (regardless of $\alpha$) and the search algorithm becomes a random walk. An effective decentralized search therefore requires a balance (albeit a highly forgiving one) of categorical flexibility and constraint.

Finally, by introducing parameter choices that are consistent with Milgram's experiment ($N = 10^8$, $p = 0.25$) (*1*), as well as with subsequent empirical findings ($z = 300$, $H = 2$) (*17*, *16*), we can compare the distribution of chain lengths in our model with that of Travers and Milgram (*1*) for plausible values of $\alpha$ and *b*. As Fig. 3 shows, we obtain $\langle L \rangle \cong 6.7$ for $\alpha = 1$ and $b = 10$, indicating that our model captures the essence of the real small-world problem. This agreement is robust with respect to variations in the branching ratio, showing little change over the range $5 < b < 50$.

Although sociological in origin, our model is relevant to a broad class of decentralized search problems, such as peer-to-peer networking, in which centralized servers are excluded either by design or by necessity, and where broadcast-type searches (i.e., forwarding messages to all neighbors rather than just one) are ruled out because of congestion constraints (*6*). In essence, our model applies to any data structure in which data elements exhibit quantifiable characteristics analogous to our notion of identity, and similarity between two elements—whether people, music files, Web pages, or research reports—can be judged along more than one dimension. One of the principal difficulties with designing robust databases (*18*) is the absence of a unique classification scheme that all users of the database can apply consistently to place and locate files. Two musical songs, for example, can be similar because they belong to the same genre or because they were created in the same year. Our model transforms this difficulty into an asset, allowing all such classification schemes to exist simultaneously, and connecting data elements preferentially to similar elements in multiple dimensions. Efficient decentralized searches can then be conducted by means of simple, greedy algorithms providing only that the characteristics of the target element and the current element's immediate neighbors are known.

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19. We thank J. Kleinberg for beneficial discussions. This work was funded in part by the National Science Foundation (grants SES-00-94162 and DMS-0109086), the Intel Corporation, and the Columbia University Office of Strategic Initiatives.

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# Ascent of Dinosaurs Linked to an Iridium Anomaly at the Triassic-Jurassic Boundary

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B. W. Hartline[7]

Analysis of tetrapod footprints and skeletal material from more than 70 localities in eastern North America shows that large theropod dinosaurs appeared less than 10,000 years after the Triassic-Jurassic boundary and less than 30,000 years after the last Triassic taxa, synchronous with a terrestrial mass extinction. This extraordinary turnover is associated with an iridium anomaly (up to 285 parts per trillion, with an average maximum of 141 parts per trillion) and a fern spore spike, suggesting that a bolide impact was the cause. Eastern North American dinosaurian diversity reached a stable maximum less than 100,000 years after the boundary, marking the establishment of dinosaur-dominated communities that prevailed for the next 135 million years.

One of the most striking events in the Mesozoic was the rise to dominance of dinosaurs in terrestrial ecosystems. The cause and timing of their early Mesozoic ascent have been debated (*1*–*4*), with difficulties in global correlation and low sampling density limiting the utility of global compilations and obscuring relations to possible forcing mechanisms. However, terrestrial vertebrate assemblages in eastern North America are temporally better constrained than elsewhere and provide high-resolution biological and geochemical data bearing on this issue. This region was within the tropics during the Triassic and contained rift valleys, which were formed during the incipient fragmentation of Pangea. These basins contain kilometer-thick sections of continental strata, termed the Newark Supergroup, which have recorded the rise of dinosaurs across 15° of paleolatitude (*5*). Milankovitch-type climate cycles permeate the lacustrine strata of these basins, and in conjunction with paleomagnetic reversal stratigraphy, all of the fossils can be placed within a high-resolution astronomically tuned time scale (*6*, *7*) (Fig. 1).

Here, we focus on material from 80 localities in four Newark Supergroup basins, consisting of reptile footprints (*8*, *9*), skeletal remains (*2*, *10*), and palynological material (*11*) keyed into the astronomically tuned time scale (Figs. 1 and 2). The footprints are abundant, well-preserved, and diverse, and they offer a temporal sampling of terrestrial vertebrate communities that is better than the sampling from skeletal material around the Triassic-Jurassic boundary (*4*, *8*). On the basis of comparisons between the reconstructed osteology of footprints and known skeletal remains, the ichnogenus level generally corresponds to an osteological family or higher taxonomic level (Table 1). However, footprints sample the terrestrial communities directly, and major changes in footprint assemblage composition probably represent important ecological changes (*12*). Even with uncertainty in the nature of the trackmakers, well-preserved footprints offer a useful independent proxy of faunal change (*13*), and the observed stratigraphic changes in the ichnological assemblages are consistent with the changes seen in osteological remains (Fig. 1).

On the basis of compiled ranges tied to the time scale (Fig. 1), Newark Supergroup dinosaurian ichnotaxa show a slow increase in relative abundance and a stepped increase in maximum size below the Triassic-Jurassic boundary (*9*). The ornithischian dinosaurian ichnogenus *Atreipus* (*14*) is the most common dinosaurian

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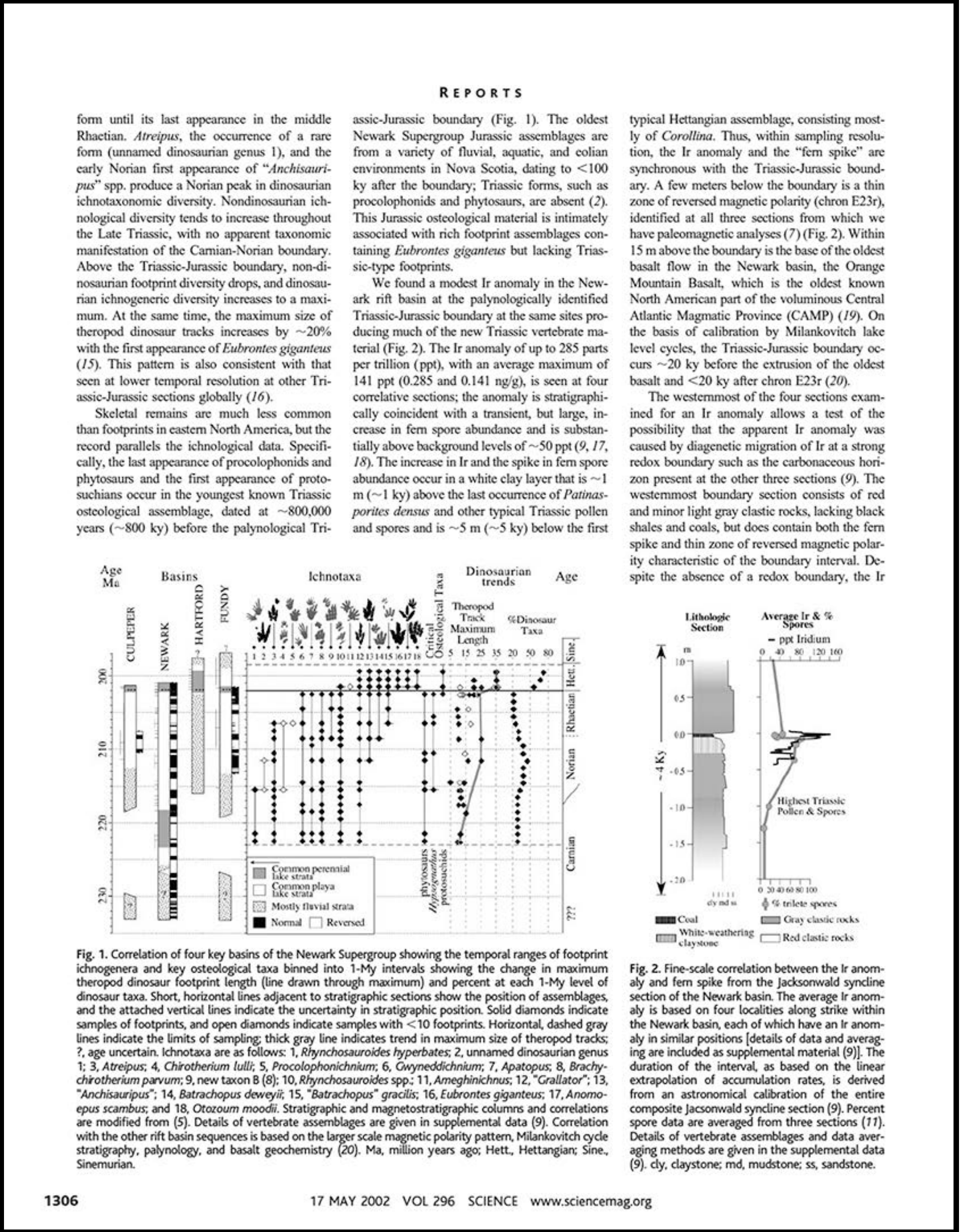


form until its last appearance in the middle Rhaetian. *Atreipus*, the occurrence of a rare form (unnamed dinosaurian genus 1), and the early Norian first appearance of "*Anchisauripus*" spp. produce a Norian peak in dinosaurian ichnotaxonomic diversity. Nondinosaurian ichnological diversity tends to increase throughout the Late Triassic, with no apparent taxonomic manifestation of the Carnian-Norian boundary. Above the Triassic-Jurassic boundary, non-dinosaurian footprint diversity drops, and dinosaurian ichnogeneric diversity increases to a maximum. At the same time, the maximum size of theropod dinosaur tracks increases by ~20% with the first appearance of *Eubrontes giganteus* (*15*). This pattern is also consistent with that seen at lower temporal resolution at other Triassic-Jurassic sections globally (*16*).

Skeletal remains are much less common than footprints in eastern North America, but the record parallels the ichnological data. Specifically, the last appearance of procolophonids and phytosaurs and the first appearance of protosuchians occur in the youngest known Triassic osteological assemblage, dated at ~800,000 years (~800 ky) before the palynological Triassic-Jurassic boundary (Fig. 1). The oldest Newark Supergroup Jurassic assemblages are from a variety of fluvial, aquatic, and eolian environments in Nova Scotia, dating to <100 ky after the boundary; Triassic forms, such as procolophonids and phytosaurs, are absent (*2*). This Jurassic osteological material is intimately associated with rich footprint assemblages containing *Eubrontes giganteus* but lacking Triassic-type footprints.

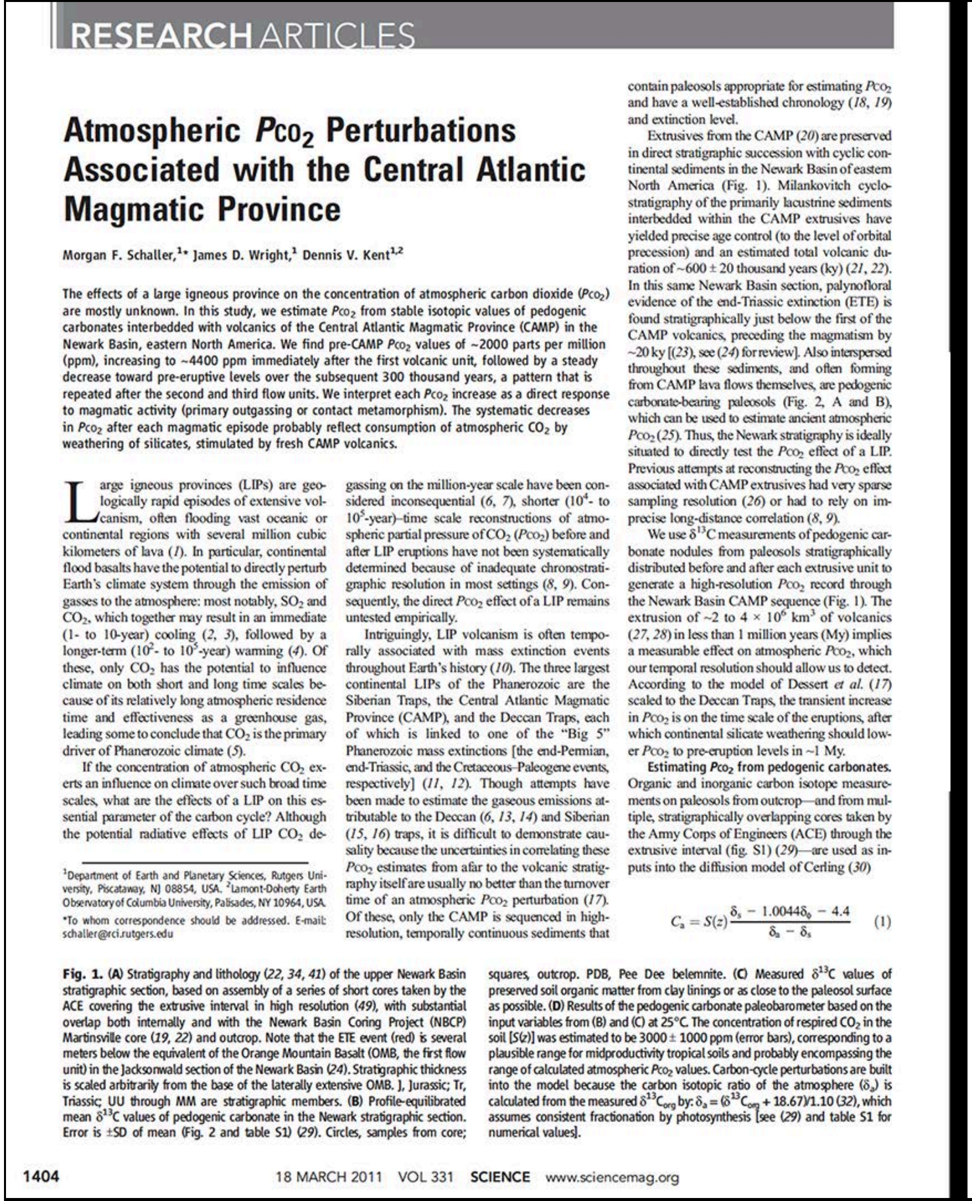
We found a modest Ir anomaly in the Newark rift basin at the palynologically identified Triassic-Jurassic boundary at the same sites producing much of the new Triassic vertebrate material (Fig. 2). The Ir anomaly of up to 285 parts per trillion (ppt), with an average maximum of 141 ppt (0.285 and 0.141 ng/g), is seen at four correlative sections; the anomaly is stratigraphically coincident with a transient, but large, increase in fern spore abundance and is substantially above background levels of ~50 ppt (*9*, *17*, *18*). The increase in Ir and the spike in fern spore abundance occur in a white clay layer that is ~1 m (~1 ky) above the last occurrence of *Patinasporites densus* and other typical Triassic pollen and spores and is ~5 m (~5 ky) below the first typical Hettangian assemblage, consisting mostly of *Corollina*. Thus, within sampling resolution, the Ir anomaly and the "fern spike" are synchronous with the Triassic-Jurassic boundary. A few meters below the boundary is a thin zone of reversed magnetic polarity (chron E23r), identified at all three sections from which we have paleomagnetic analyses (*7*) (Fig. 2). Within 15 m above the boundary is the base of the oldest basalt flow in the Newark basin, the Orange Mountain Basalt, which is the oldest known North American part of the voluminous Central Atlantic Magmatic Province (CAMP) (*19*). On the basis of calibration by Milankovitch lake level cycles, the Triassic-Jurassic boundary occurs ~20 ky before the extrusion of the oldest basalt and <20 ky after chron E23r (*20*).

The westernmost of the four sections examined for an Ir anomaly allows a test of the possibility that the apparent Ir anomaly was caused by diagenetic migration of Ir at a strong redox boundary such as the carbonaceous horizon present at the other three sections (*9*). The westernmost boundary section consists of red and minor light gray clastic rocks, lacking black shales and coals, but does contain both the fern spike and thin zone of reversed magnetic polarity characteristic of the boundary interval. Despite the absence of a redox boundary, the Ir

**Fig. 1.** Correlation of four key basins of the Newark Supergroup showing the temporal ranges of footprint ichnogenera and key osteological taxa binned into 1-My intervals showing the change in maximum theropod dinosaur footprint length (line drawn through maximum) and percent at each 1-My level of dinosaur taxa. Short, horizontal lines adjacent to stratigraphic sections show the position of assemblages, and the attached vertical lines indicate the uncertainty in stratigraphic position. Solid diamonds indicate samples of footprints, and open diamonds indicate samples with <10 footprints. Horizontal, dashed gray lines indicate the limits of sampling; thick gray line indicates trend in maximum size of theropod tracks; ?, age uncertain. Ichnotaxa are as follows: 1, *Rhynchosauroides hyperbates*; 2, unnamed dinosaurian genus 1; 3, *Atreipus*; 4, *Chirotherium lulli*; 5, *Procolophonichnium*; 6, *Gwyneddichnium*; 7, *Apatopus*; 8, *Brachychirotherium parvum*; 9, new taxon B (8); 10, *Rhynchosauroides* spp.; 11, *Ameghinichnus*; 12, "*Grallator*"; 13, "*Anchisauripus*"; 14, *Batrachopus deweyii*; 15, "*Batrachopus*" *gracilis*; 16, *Eubrontes giganteus*; 17, *Anomoepus scambus*; and 18, *Otozoum moodii*. Stratigraphic and magnetostratigraphic columns and correlations are modified from (5). Details of vertebrate assemblages are given in supplemental data (9). Correlation with the other rift basin sequences is based on the larger scale magnetic polarity pattern, Milankovitch cycle stratigraphy, palynology, and basalt geochemistry (20). Ma, million years ago; Hett., Hettangian; Sine., Sinemurian.

**Fig. 2.** Fine-scale correlation between the Ir anomaly and fern spike from the Jacksonwald syncline section of the Newark basin. The average Ir anomaly is based on four localities along strike within the Newark basin, each of which have an Ir anomaly in similar positions [details of data and averaging are included as supplemental material (9)]. The duration of the interval, as based on the linear extrapolation of accumulation rates, is derived from an astronomical calibration of the entire composite Jacsonwald syncline section (9). Percent spore data are averaged from three sections (*11*). Details of vertebrate assemblages and data averaging methods are given in the supplemental data (9). cly, claystone; md, mudstone; ss, sandstone.

# Schaller et al, 2011



## Atmospheric $P_{CO_2}$ Perturbations Associated with the Central Atlantic Magmatic Province

Morgan F. Schaller,[1]* James D. Wright,[1] Dennis V. Kent[1,2]

**The effects of a large igneous province on the concentration of atmospheric carbon dioxide ($P_{CO_2}$) are mostly unknown. In this study, we estimate $P_{CO_2}$ from stable isotopic values of pedogenic carbonates interbedded with volcanics of the Central Atlantic Magmatic Province (CAMP) in the Newark Basin, eastern North America. We find pre-CAMP $P_{CO_2}$ values of ~2000 parts per million (ppm), increasing to ~4400 ppm immediately after the first volcanic unit, followed by a steady decrease toward pre-eruptive levels over the subsequent 300 thousand years, a pattern that is repeated after the second and third flow units. We interpret each $P_{CO_2}$ increase as a direct response to magmatic activity (primary outgassing or contact metamorphism). The systematic decreases in $P_{CO_2}$ after each magmatic episode probably reflect consumption of atmospheric $CO_2$ by weathering of silicates, stimulated by fresh CAMP volcanics.**

Large igneous provinces (LIPs) are geologically rapid episodes of extensive volcanism, often flooding vast oceanic or continental regions with several million cubic kilometers of lava (*1*). In particular, continental flood basalts have the potential to directly perturb Earth's climate system through the emission of gasses to the atmosphere: most notably, $SO_2$ and $CO_2$, which together may result in an immediate (1- to 10-year) cooling (*2*, *3*), followed by a longer-term ($10^2$- to $10^5$-year) warming (*4*). Of these, only $CO_2$ has the potential to influence climate on both short and long time scales because of its relatively long atmospheric residence time and effectiveness as a greenhouse gas, leading some to conclude that $CO_2$ is the primary driver of Phanerozoic climate (*5*).

If the concentration of atmospheric $CO_2$ exerts an influence on climate over such broad time scales, what are the effects of a LIP on this essential parameter of the carbon cycle? Although the potential radiative effects of LIP $CO_2$ degassing on the million-year scale have been considered inconsequential (*6*, *7*), shorter ($10^4$- to $10^5$-year)–time scale reconstructions of atmospheric partial pressure of $CO_2$ ($P_{CO_2}$) before and after LIP eruptions have not been systematically determined because of inadequate chronostratigraphic resolution in most settings (*8*, *9*). Consequently, the direct $P_{CO_2}$ effect of a LIP remains untested empirically.

Intriguingly, LIP volcanism is often temporally associated with mass extinction events throughout Earth's history (*10*). The three largest continental LIPs of the Phanerozoic are the Siberian Traps, the Central Atlantic Magmatic Province (CAMP), and the Deccan Traps, each of which is linked to one of the "Big 5" Phanerozoic mass extinctions [the end-Permian, end-Triassic, and the Cretaceous–Paleogene events, respectively] (*11*, *12*). Though attempts have been made to estimate the gaseous emissions attributable to the Deccan (*6*, *13*, *14*) and Siberian (*15*, *16*) traps, it is difficult to demonstrate causality because the uncertainties in correlating these $P_{CO_2}$ estimates from afar to the volcanic stratigraphy itself are usually no better than the turnover time of an atmospheric $P_{CO_2}$ perturbation (*17*). Of these, only the CAMP is sequenced in high-resolution, temporally continuous sediments that contain paleosols appropriate for estimating $P_{CO_2}$ and have a well-established chronology (*18*, *19*) and extinction level.

Extrusives from the CAMP (*20*) are preserved in direct stratigraphic succession with cyclic continental sediments in the Newark Basin of eastern North America (Fig. 1). Milankovitch cyclostratigraphy of the primarily lacustrine sediments interbedded within the CAMP extrusives have yielded precise age control (to the level of orbital precession) and an estimated total volcanic duration of ~600 ± 20 thousand years (ky) (*21*, *22*). In this same Newark Basin section, palynofloral evidence of the end-Triassic extinction (ETE) is found stratigraphically just below the first of the CAMP volcanics, preceding the magmatism by ~20 ky [(*23*), see (*24*) for review]. Also interspersed throughout these sediments, and often forming from CAMP lava flows themselves, are pedogenic carbonate-bearing paleosols (Fig. 2, A and B), which can be used to estimate ancient atmospheric $P_{CO_2}$ (*25*). Thus, the Newark stratigraphy is ideally situated to directly test the $P_{CO_2}$ effect of a LIP. Previous attempts at reconstructing the $P_{CO_2}$ effect associated with CAMP extrusives had very sparse sampling resolution (*26*) or had to rely on imprecise long-distance correlation (*8*, *9*).

We use $\delta^{13}C$ measurements of pedogenic carbonate nodules from paleosols stratigraphically distributed before and after each extrusive unit to generate a high-resolution $P_{CO_2}$ record through the Newark Basin CAMP sequence (Fig. 1). The extrusion of ~2 to 4 × $10^6$ $km^3$ of volcanics (*27*, *28*) in less than 1 million years (My) implies a measurable effect on atmospheric $P_{CO_2}$, which our temporal resolution should allow us to detect. According to the model of Dessert *et al.* (*17*) scaled to the Deccan Traps, the transient increase in $P_{CO_2}$ is on the time scale of the eruptions, after which continental silicate weathering should lower $P_{CO_2}$ to pre-eruption levels in ~1 My.

**Estimating $P_{CO_2}$ from pedogenic carbonates.** Organic and inorganic carbon isotope measurements on paleosols from outcrop—and from multiple, stratigraphically overlapping cores taken by the Army Corps of Engineers (ACE) through the extrusive interval (fig. S1) (*29*)—are used as inputs into the diffusion model of Cerling (*30*)

$$C_a = S(z)\frac{\delta_s - 1.0044\delta_\phi - 4.4}{\delta_a - \delta_s} \qquad (1)$$

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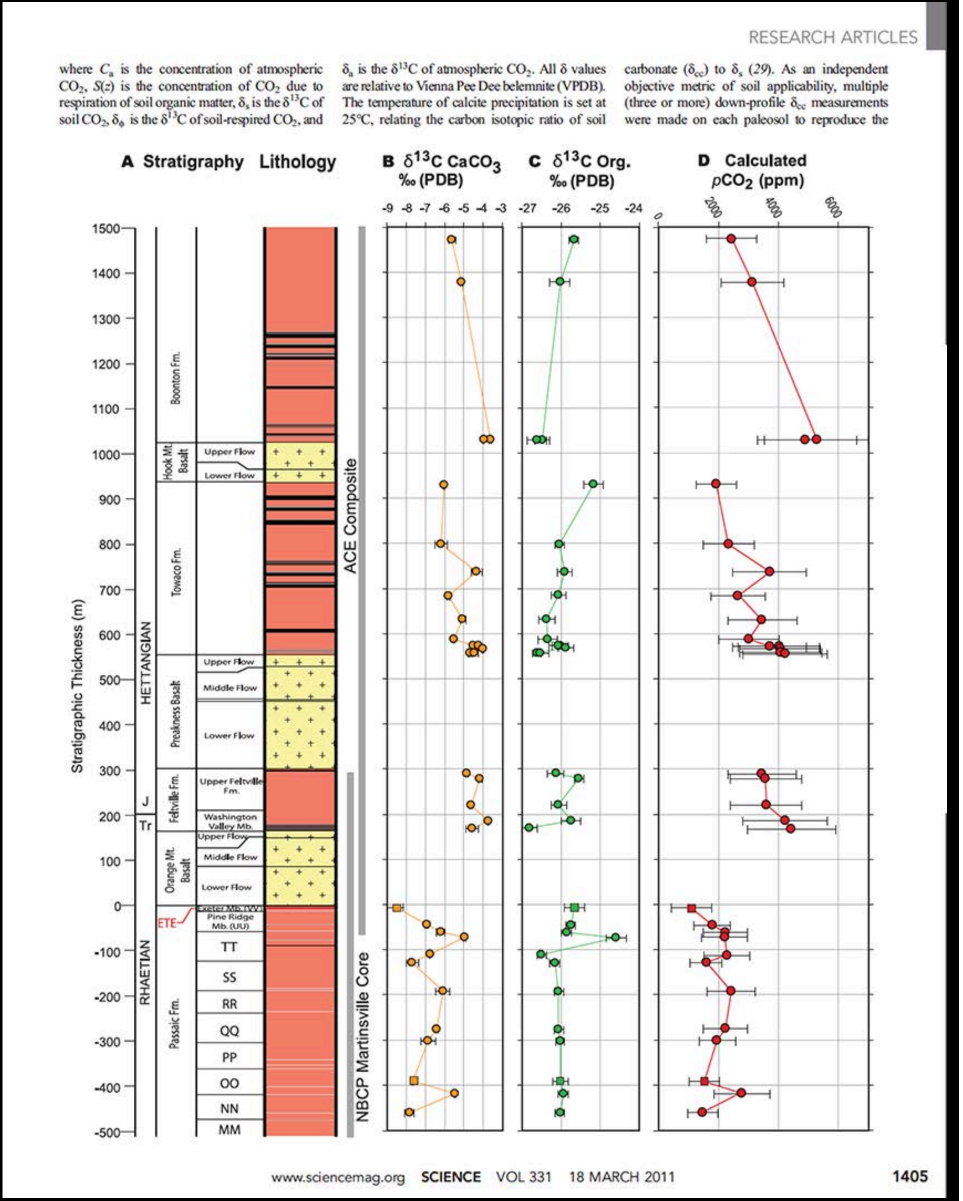
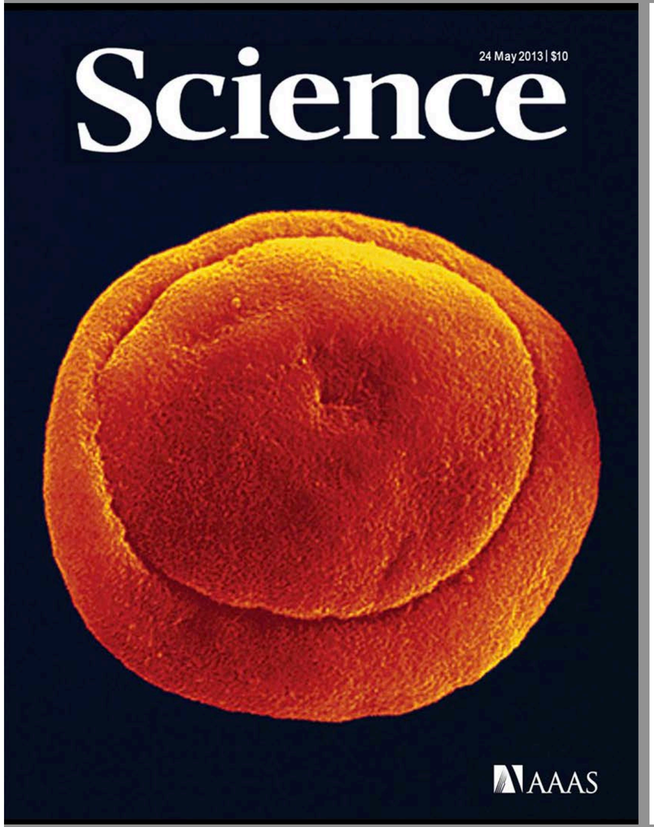
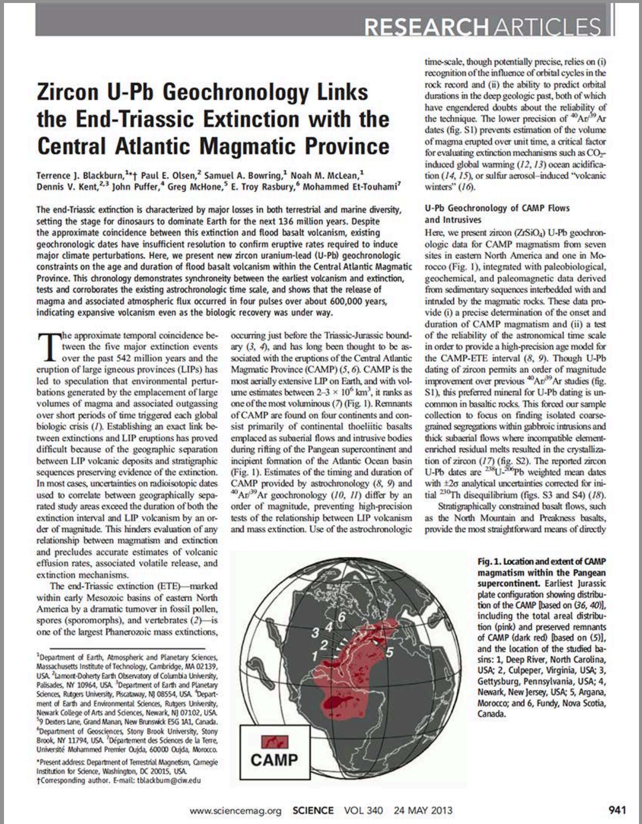
**Fig. 1.** (**A**) Stratigraphy and lithology (*22*, *34*, *41*) of the upper Newark Basin stratigraphic section, based on assembly of a series of short cores taken by the ACE covering the extrusive interval in high resolution (*49*), with substantial overlap both internally and with the Newark Basin Coring Project (NBCP) Martinsville core (*19*, *22*) and outcrop. Note that the ETE event (red) is several meters below the equivalent of the Orange Mountain Basalt (OMB, the first flow unit) in the Jacksonwald section of the Newark Basin (*24*). Stratigraphic thickness is scaled arbitrarily from the base of the laterally extensive OMB. J, Jurassic; Tr, Triassic; UU through MM are stratigraphic members. (**B**) Profile-equilibrated mean $\delta^{13}C$ values of pedogenic carbonate in the Newark stratigraphic section. Error is ±SD of mean (Fig. 2 and table S1) (*29*). Circles, samples from core; squares, outcrop. PDB, Pee Dee belemnite. (**C**) Measured $\delta^{13}C$ values of preserved soil organic matter from clay linings or as close to the paleosol surface as possible. (**D**) Results of the pedogenic carbonate paleobarometer based on the input variables from (B) and (C) at 25°C. The concentration of respired $CO_2$ in the soil [$S(z)$] was estimated to be 3000 ± 1000 ppm (error bars), corresponding to a plausible range for midproductivity tropical soils and probably encompassing the range of calculated atmospheric $P_{CO_2}$ values. Carbon-cycle perturbations are built into the model because the carbon isotopic ratio of the atmosphere ($\delta_a$) is calculated from the measured $\delta^{13}C_{org}$ by: $\delta_a = (\delta^{13}C_{org} + 18.67)/1.10$ (*32*), which assumes consistent fractionation by photosynthesis [see (*29*) and table S1 for numerical values].



where $C_a$ is the concentration of atmospheric $CO_2$, $S(z)$ is the concentration of $CO_2$ due to respiration of soil organic matter, $\delta_s$ is the $\delta^{13}C$ of soil $CO_2$, $\delta_\phi$ is the $\delta^{13}C$ of soil-respired $CO_2$, and $\delta_a$ is the $\delta^{13}C$ of atmospheric $CO_2$. All δ values are relative to Vienna Pee Dee belemnite (VPDB). The temperature of calcite precipitation is set at 25°C, relating the carbon isotopic ratio of soil carbonate ($\delta_{cc}$) to $\delta_s$ (*29*). As an independent objective metric of soil applicability, multiple (three or more) down-profile $\delta_{cc}$ measurements were made on each paleosol to reproduce the

# Blackburn et al, 2013





## Zircon U-Pb Geochronology Links the End-Triassic Extinction with the Central Atlantic Magmatic Province

Terrence J. Blackburn,[1*†] Paul E. Olsen,[2] Samuel A. Bowring,[1] Noah M. McLean,[1] Dennis V. Kent,[2,3] John Puffer,[4] Greg McHone,[5] E. Troy Rasbury,[6] Mohammed Et-Touhami[7]

**The end-Triassic extinction is characterized by major losses in both terrestrial and marine diversity, setting the stage for dinosaurs to dominate Earth for the next 136 million years. Despite the approximate coincidence between this extinction and flood basalt volcanism, existing geochronologic dates have insufficient resolution to confirm eruptive rates required to induce major climate perturbations. Here, we present new zircon uranium-lead (U-Pb) geochronologic constraints on the age and duration of flood basalt volcanism within the Central Atlantic Magmatic Province. This chronology demonstrates synchroneity between the earliest volcanism and extinction, tests and corroborates the existing astrochronologic time scale, and shows that the release of magma and associated atmospheric flux occurred in four pulses over about 600,000 years, indicating expansive volcanism even as the biologic recovery was under way.**

The approximate temporal coincidence between the five major extinction events over the past 542 million years and the eruption of large igneous provinces (LIPs) has led to speculation that environmental perturbations generated by the emplacement of large volumes of magma and associated outgassing over short periods of time triggered each global biologic crisis (*1*). Establishing an exact link between extinctions and LIP eruptions has proved difficult because of the geographic separation between LIP volcanic deposits and stratigraphic sequences preserving evidence of the extinction. In most cases, uncertainties on radioisotopic dates used to correlate between geographically separated study areas exceed the duration of both the extinction interval and LIP volcanism by an order of magnitude. This hinders evaluation of any relationship between magmatism and extinction and precludes accurate estimates of volcanic effusion rates, associated volatile release, and extinction mechanisms.

The end-Triassic extinction (ETE)—marked within early Mesozoic basins of eastern North America by a dramatic turnover in fossil pollen, spores (sporomorphs), and vertebrates (*2*)—is one of the largest Phanerozoic mass extinctions, occurring just before the Triassic-Jurassic boundary (*3*, *4*), and has long been thought to be associated with the eruptions of the Central Atlantic Magmatic Province (CAMP) (*5*, *6*). CAMP is the most aerially extensive LIP on Earth, and with volume estimates between 2–3 × $10^6$ km$^3$, it ranks as one of the most voluminous (*7*) (Fig. 1). Remnants of CAMP are found on four continents and consist primarily of continental thoeliitic basalts emplaced as subaerial flows and intrusive bodies during rifting of the Pangean supercontinent and incipient formation of the Atlantic Ocean basin (Fig. 1). Estimates of the timing and duration of CAMP provided by astrochronology (*8*, *9*) and $^{40}$Ar/$^{39}$Ar geochronology (*10*, *11*) differ by an order of magnitude, preventing high-precision tests of the relationship between LIP volcanism and mass extinction. Use of the astrochronologic time-scale, though potentially precise, relies on (i) recognition of the influence of orbital cycles in the rock record and (ii) the ability to predict orbital durations in the deep geologic past, both of which have engendered doubts about the reliability of the technique. The lower precision of $^{40}$Ar/$^{39}$Ar dates (fig. S1) prevents estimation of the volume of magma erupted over unit time, a critical factor for evaluating extinction mechanisms such as $CO_2$-induced global warming (*12*, *13*) ocean acidification (*14*, *15*), or sulfur aerosol–induced "volcanic winters" (*16*).

### U-Pb Geochronology of CAMP Flows and Intrusives

Here, we present zircon ($ZrSiO_4$) U-Pb geochronologic data for CAMP magmatism from seven sites in eastern North America and one in Morocco (Fig. 1), integrated with paleobiological, geochemical, and paleomagnetic data derived from sedimentary sequences interbedded with and intruded by the magmatic rocks. These data provide (i) a precise determination of the onset and duration of CAMP magmatism and (ii) a test of the reliability of the astronomical time scale in order to provide a high-precision age model for the CAMP-ETE interval (*8*, *9*). Though U-Pb dating of zircon permits an order of magnitude improvement over previous $^{40}$Ar/$^{39}$Ar studies (fig. S1), this preferred mineral for U-Pb dating is uncommon in basaltic rocks. This forced our sample collection to focus on finding isolated coarse-grained segregations within gabbroic intrusions and thick subaerial flows where incompatible element-enriched residual melts resulted in the crystallization of zircon (*17*) (fig. S2). The reported zircon U-Pb dates are $^{238}$U-$^{206}$Pb weighted mean dates with ±2σ analytical uncertainties corrected for initial $^{230}$Th disequilibrium (figs. S3 and S4) (*18*).

Stratigraphically constrained basalt flows, such as the North Mountain and Preakness basalts, provide the most straightforward means of directly dating the Triassic and Early Jurassic stratigraphy (Fig. 2). However, coarse-grained zircon-bearing flows in the CAMP are relatively rare. Therefore, we also have dated sills that are either physically connected to flows as feeders or can be geochemically linked with stratigraphically constrained flows (*18*, *19*). In both North American and Moroccan basins, stratigraphic superposition of basalt flows combined with trace element geochemistry provides a relative time scale for the geochemical evolution of CAMP basalts (*11*, *20*–*25*) (Fig. 3A). This same geochemical trend is also observed in the dated stratigraphically unconstrained units (Fig. 3A). The shared geochemical evolution in CAMP magmas permits correlation between units that share a common trace element signature, allowing the U-Pb date for a stratigraphically unconstrained intrusion to effectively date the horizon of a geochemically similar and stratigraphically constrained basalt flow. This composite geochronologically dated stratigraphic section is used to test the astrochronologic time scale for the Newark basin.

### Testing the Astrochronologic Time Scale for the Late Triassic

The quasiperiodic variations in Earth's orbit, axial direction, and tilt known as Milankovitch cycles result in corresponding variations in the amount and distribution of sunlight reaching Earth. The resulting forcing on climate and/or ocean circulation can influence the characteristics of sediments deposited within a basin, which may ultimately be preserved within the rock record as cyclical variations in rock lithology, chemistry, or isotopic composition (*26*). CAMP lava flows within the Newark basin of eastern North America (Fig. 2) are interbedded with strikingly cyclical lacustrine strata that have long been hypothesized to be paced by orbital forcing (*27*). Astrochronologic models for these sequences have been used to estimate the time represented by the sedimentary rocks between CAMP flows, placing high-precision [±20 thousand years (ky)] estimates on the total duration of the CAMP at between 580 and 610 ky (*9*, *28*). This proposed "floating" astronomical time scale (ATS) has been met with scrutiny because of the possibility that Earth experienced a different orbital forcing deep in geologic time due to differences in the state of the Earth-Moon system and solar systems dynamics. Further skepticism has focused on whether orbitally forced climatic effects are both accurately recorded and recognized in the geological record. The most straightforward test of the reliability of the ATS is to compare the time durations between basalt flows estimated by orbitally tuning the sedimentary rocks with differences between the zircon U-Pb dates of the flows.

The Orange Mountain Basalt flows are the oldest CAMP lavas in the Newark basin. Although authigenic zircons were not recovered from the Orange Mountain Basalt samples, the flow sequence is partly intruded and fed by an extension of the geochemically identical Palisade sill [201.520 ± 0.034 million years ago (Ma)] (*19*). Based on the ATS for the Newark basin, the overlying flows of the Preakness Basalt should be 250 ± 20 ky younger than the Orange Mountain Basalt (and Palisade sill) (*9*). The U-Pb date of the Preakness Basalt (201.274 ± 0.032 Ma) results in a difference of 246 ± 47 ky, consistent with the astrochronological estimate. A second interval within the Newark ATS, that again uses the Preakness basalt, can be tested by correlating the Butner diabase from the Deep River Basin (200.916 ± 0.064 Ma) to the stratigraphically highest and geochemically similar Hook Mountain Basalt (Fig. 3A). The ATS estimate for the time interval between the base of the Preakness and the base of the Hook mountain basalts is 350 ± 20 ky, a duration consistent with the difference between U-Pb dates for the Preakness Basalt and the Butner sheet of 358 ± 72 ky.

A more complete test of the ATS is provided by comparing the astronomical time scale to each of the CAMP flows and intrusions dated here. Using the relative stratigraphy of preserved CAMP flows and the geochemical correlations (Fig. 3A), each stratigraphically unconstrained CAMP intrusive can be correlated to the astronomically tuned Newark Basin. By correlating to the

**Fig. 1. Location and extent of CAMP magmatism within the Pangean supercontinent.** Earliest Jurassic plate configuration showing distribution of the CAMP [based on (*36*, *40*)], including the total areal distribution (pink) and preserved remnants of CAMP (dark red) [based on (*5*)], and the location of the studied basins: 1, Deep River, North Carolina, USA; 2, Culpeper, Virginia, USA; 3, Gettysburg, Pennsylvania, USA; 4, Newark, New Jersey, USA; 5, Argana, Morocco; and 6, Fundy, Nova Scotia, Canada.

**Fig. 2. Zircon U-Pb intercalibration of CAMP volcanism and Early Jurassic Late Triassic astrochronology.** Quasiperiodic precessional cyclicity (red) used to generate the ATS (*9*, *28*). Within the stratigraphic sections (right), black- and white-hatched regions mark depositional hiatuses, and error bars next to each basalt mark each unit's timing and uncertainty calculated from the ATS. Colored vertical bars (left) represent the $^{238}$U-$^{206}$Pb Th-corrected dates (*18*) for single-crystal zircon analyses at 2σ, where color indicates basalt chemistry (legend). Legend abbreviations: HTQ, high-titanium quartz normative, includes the lower (L), lower-intermediate (L-I), intermediate (I), and upper (U) units; HFQ, high-iron quartz normative; LTQ, low-titanium quartz normative; HFTQ-R, high–iron-titanium quartz normative or recurrent unit; and ON, olivine normative units. Grayed analyses are excluded from calculated mean dates (*18*). Sample numbers: 1, North Mountain Basalt; 2, Amelal sill; 3, Palisades sill; 4, York Haven intrusive; 5, Rapidan intrusive; 6, Preakness Basalt; 7, Rossville intrusive; 8, Butner intrusive. Reported dates and black horizontal line mark the weighted mean date, and the outer horizontal box marks the 2σ uncertainty. Tabulated data, including a second dated North Mountain Basalt sample, are reported in table S1 (*18*).

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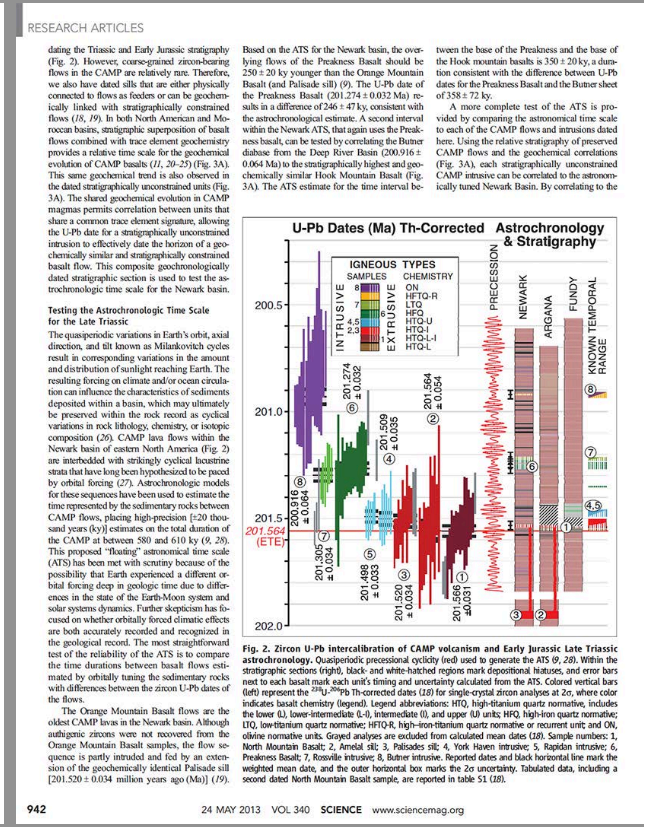
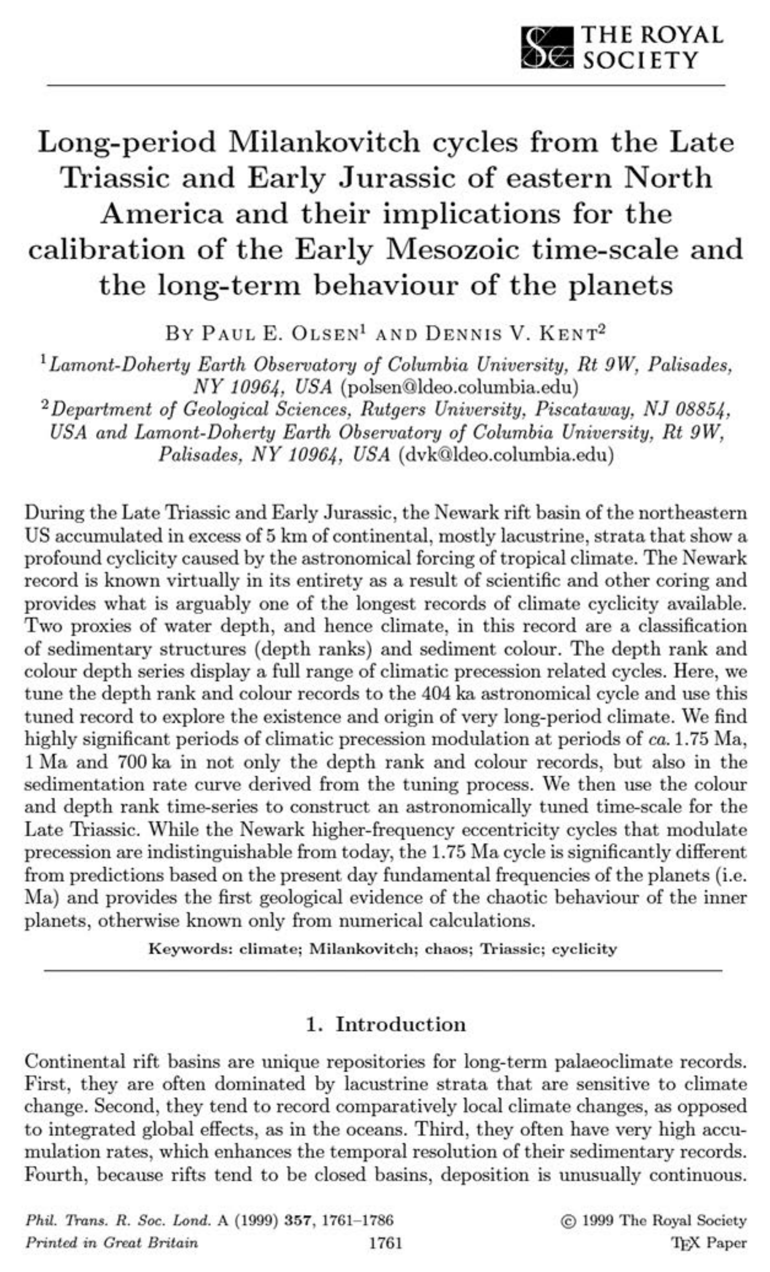


# Olsen & Kent, 1999



THE ROYAL SOCIETY

## Long-period Milankovitch cycles from the Late Triassic and Early Jurassic of eastern North America and their implications for the calibration of the Early Mesozoic time-scale and the long-term behaviour of the planets

By Paul E. Olsen[1] and Dennis V. Kent[2]

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During the Late Triassic and Early Jurassic, the Newark rift basin of the northeastern US accumulated in excess of 5 km of continental, mostly lacustrine, strata that show a profound cyclicity caused by the astronomical forcing of tropical climate. The Newark record is known virtually in its entirety as a result of scientific and other coring and provides what is arguably one of the longest records of climate cyclicity available. Two proxies of water depth, and hence climate, in this record are a classification of sedimentary structures (depth ranks) and sediment colour. The depth rank and colour depth series display a full range of climatic precession related cycles. Here, we tune the depth rank and colour records to the 404 ka astronomical cycle and use this tuned record to explore the existence and origin of very long-period climate. We find highly significant periods of climatic precession modulation at periods of *ca.* 1.75 Ma, 1 Ma and 700 ka in not only the depth rank and colour records, but also in the sedimentation rate curve derived from the tuning process. We then use the colour and depth rank time-series to construct an astronomically tuned time-scale for the Late Triassic. While the Newark higher-frequency eccentricity cycles that modulate precession are indistinguishable from today, the 1.75 Ma cycle is significantly different from predictions based on the present day fundamental frequencies of the planets (i.e. Ma) and provides the first geological evidence of the chaotic behaviour of the inner planets, otherwise known only from numerical calculations.

**Keywords: climate; Milankovitch; chaos; Triassic; cyclicity**

### 1. Introduction

Continental rift basins are unique repositories for long-term palaeoclimate records. First, they are often dominated by lacustrine strata that are sensitive to climate change. Second, they tend to record comparatively local climate changes, as opposed to integrated global effects, as in the oceans. Third, they often have very high accumulation rates, which enhances the temporal resolution of their sedimentary records. Fourth, because rifts tend to be closed basins, deposition is unusually continuous.

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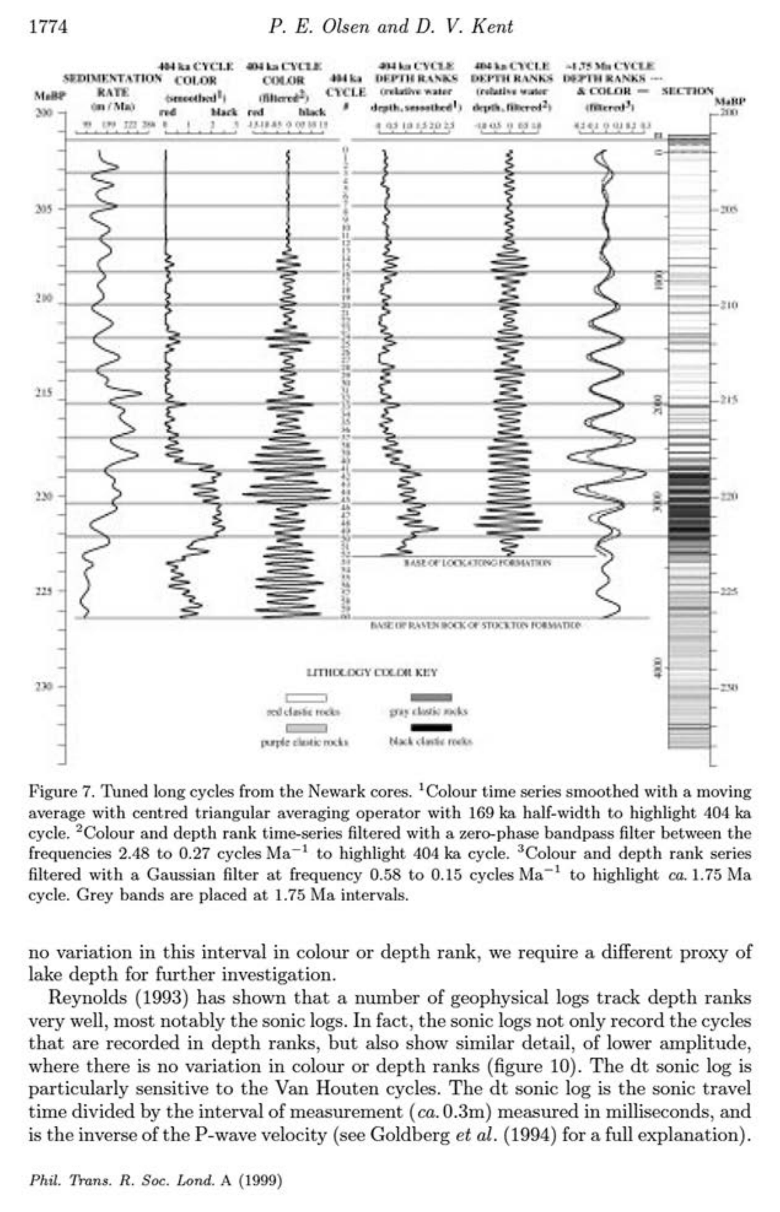
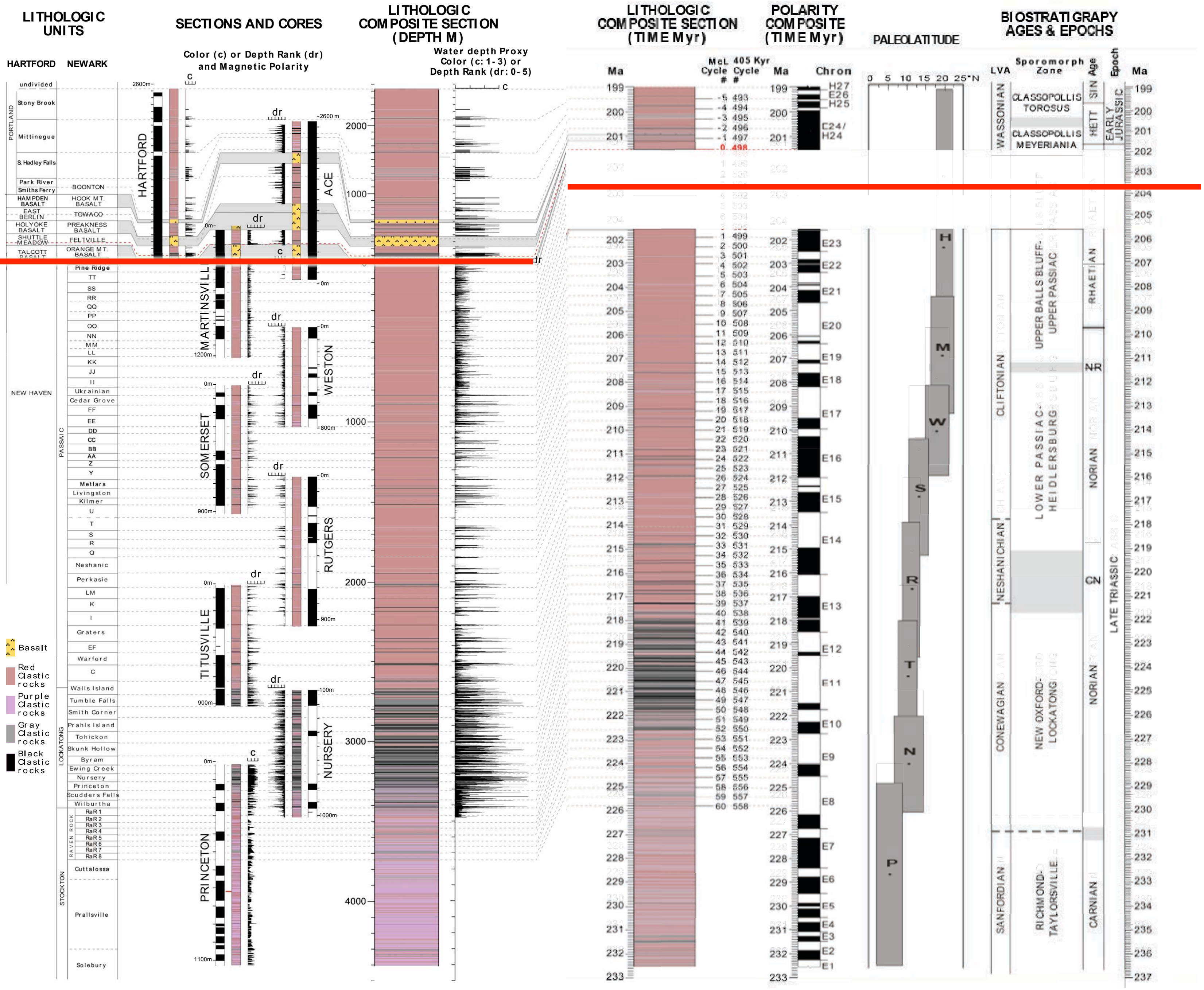


Figure 7. Tuned long cycles from the Newark cores. ¹Colour time series smoothed with a moving average with centred triangular averaging operator with 169 ka half-width to highlight 404 ka cycle. ²Colour and depth rank time-series filtered with a zero-phase bandpass filter between the frequencies 2.48 to 0.27 cycles $\mathrm{Ma}^{-1}$ to highlight 404 ka cycle. ³Colour and depth rank series filtered with a Gaussian filter at frequency 0.58 to 0.15 cycles $\mathrm{Ma}^{-1}$ to highlight *ca.* 1.75 Ma cycle. Grey bands are placed at 1.75 Ma intervals.

no variation in this interval in colour or depth rank, we require a different proxy of lake depth for further investigation.

Reynolds (1993) has shown that a number of geophysical logs track depth ranks very well, most notably the sonic logs. In fact, the sonic logs not only record the cycles that are recorded in depth ranks, but also show similar detail, of lower amplitude, where there is no variation in colour or depth ranks (figure 10). The dt sonic log is particularly sensitive to the Van Houten cycles. The dt sonic log is the sonic travel time divided by the interval of measurement (*ca.* 0.3m) measured in milliseconds, and is the inverse of the P-wave velocity (see Goldberg *et al.* (1994) for a full explanation).

## Supposed Hiatus of 3-4 Myr



Kent et al., 2016

# Two hypotheses for a hiatus:

1) The presence of vessicate pollen and the absence of key European Rhaetian sporomorphs in the latter Triassic of Eastern North America and Morocco directly below strata dominated by *Classopollis* indicates a Norian age in contact with Jurassic strata and therefore therefore a multi-million year hiatus must be present (Van Veen, 1995 etc).

2) The presence of large spinocaudatans in the latter Triassic indicates a Norian age and their absence indicate a Rhaetian age. This along with the absence of two supposedly latest Norian and early Rhaetian zones that are present in western US and Europe indicates a major hiatus in the eastern US where these zones are absent (Kozur, Weems, Lucas, Tanner, 2005, 2007, 2010, 2011, 2015 etc.).

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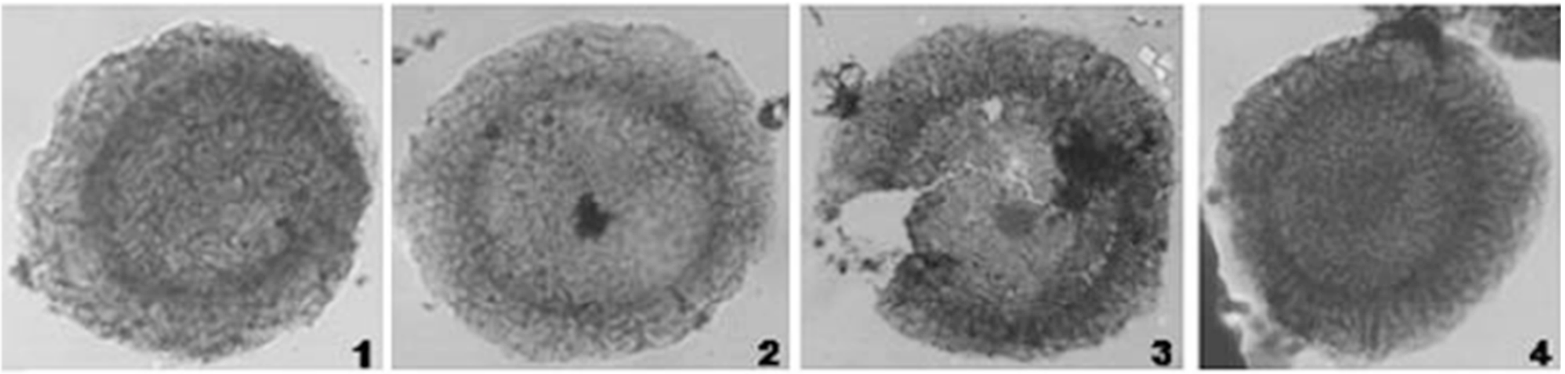
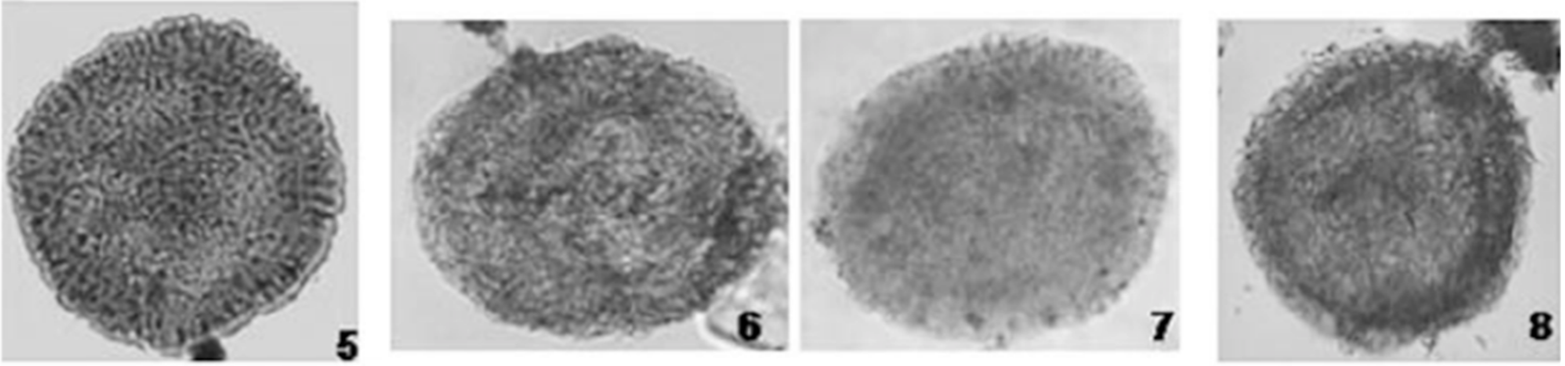
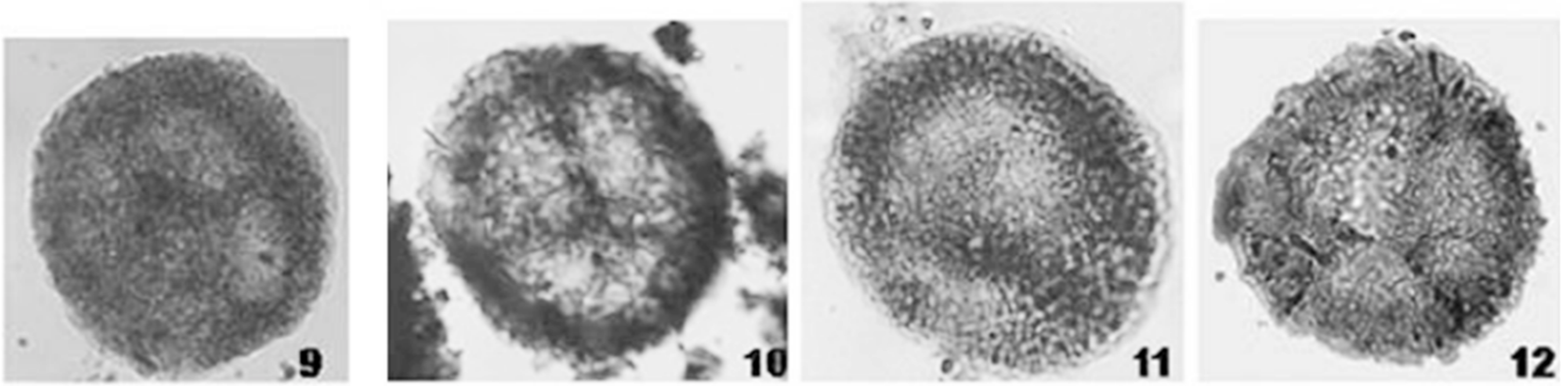
# Vessicate Pollen



*Patinasporites densus*

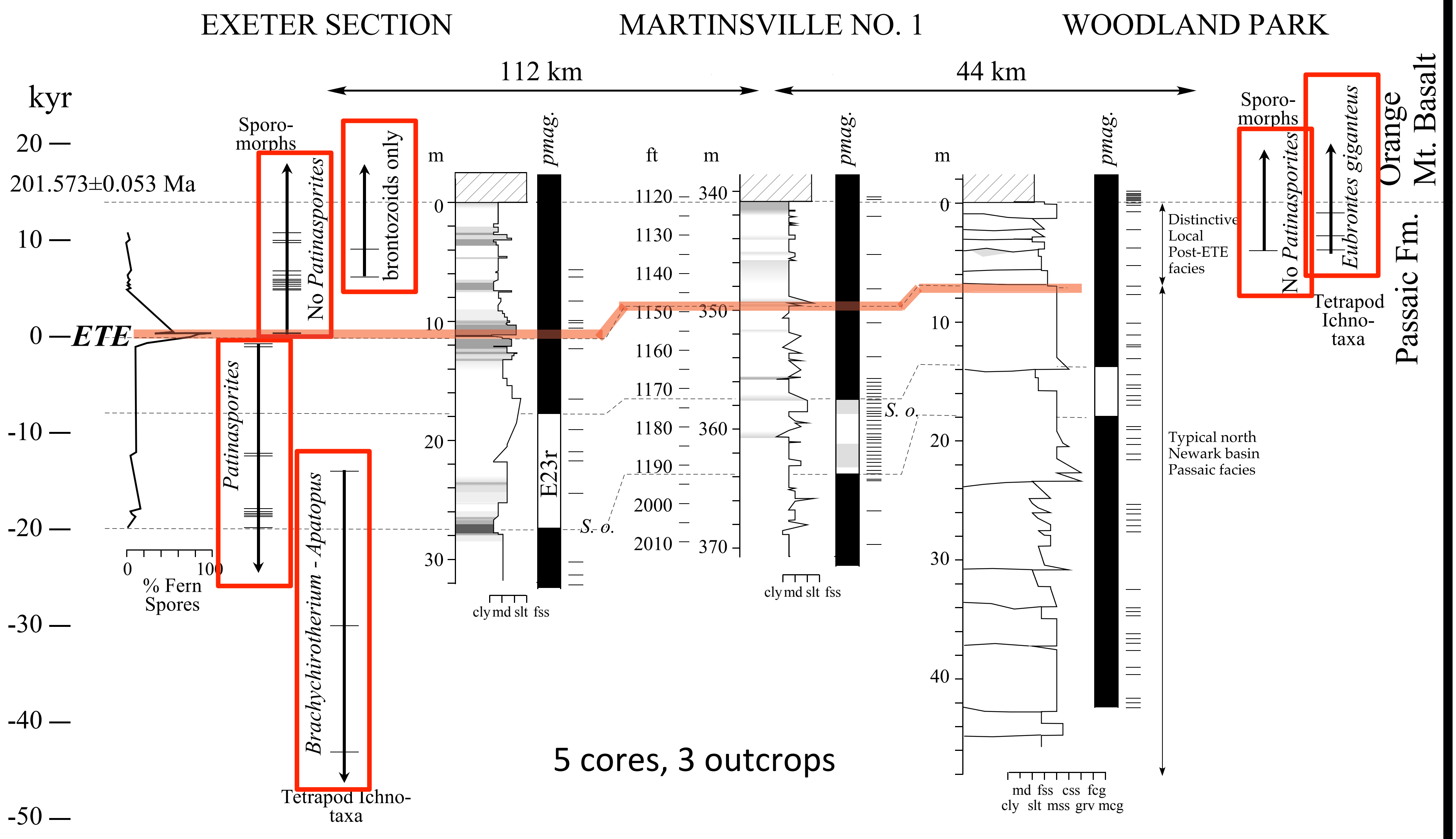


*Enzonalasporites vigens*



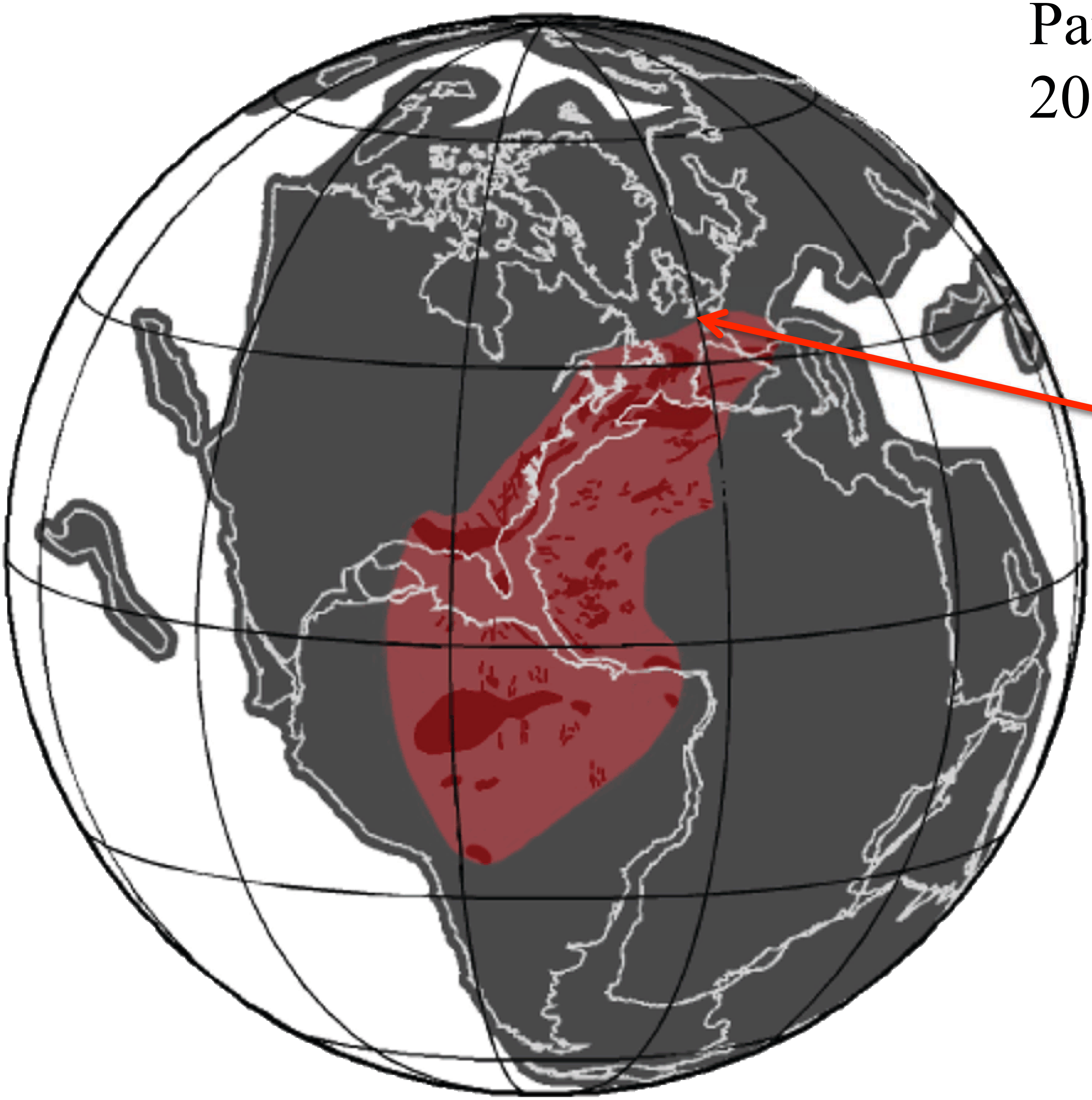
*Vallasporites ignacii*

Cirilli, 2010

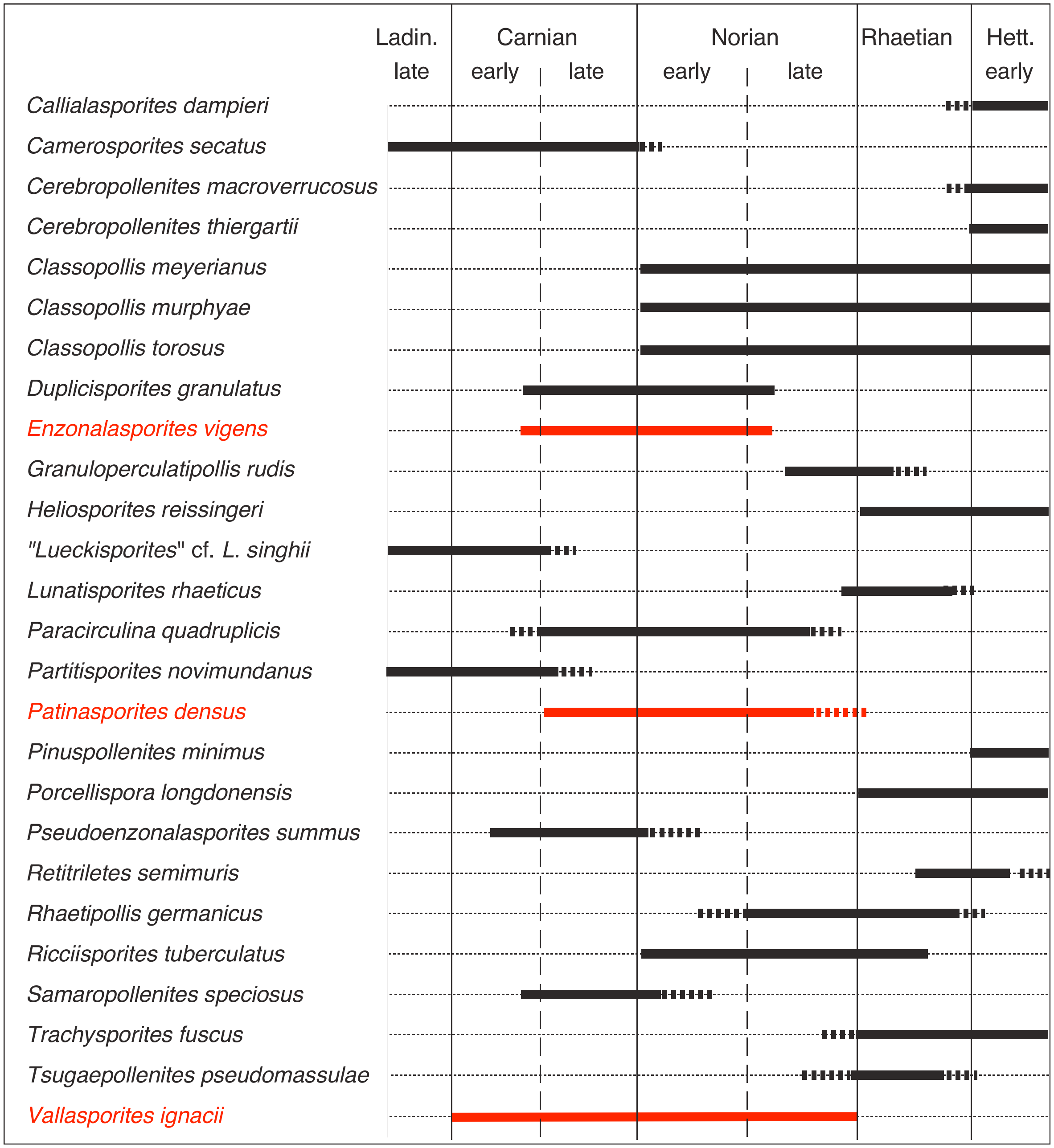


5 cores, 3 outcrops

Pangea @
201.6 Ma



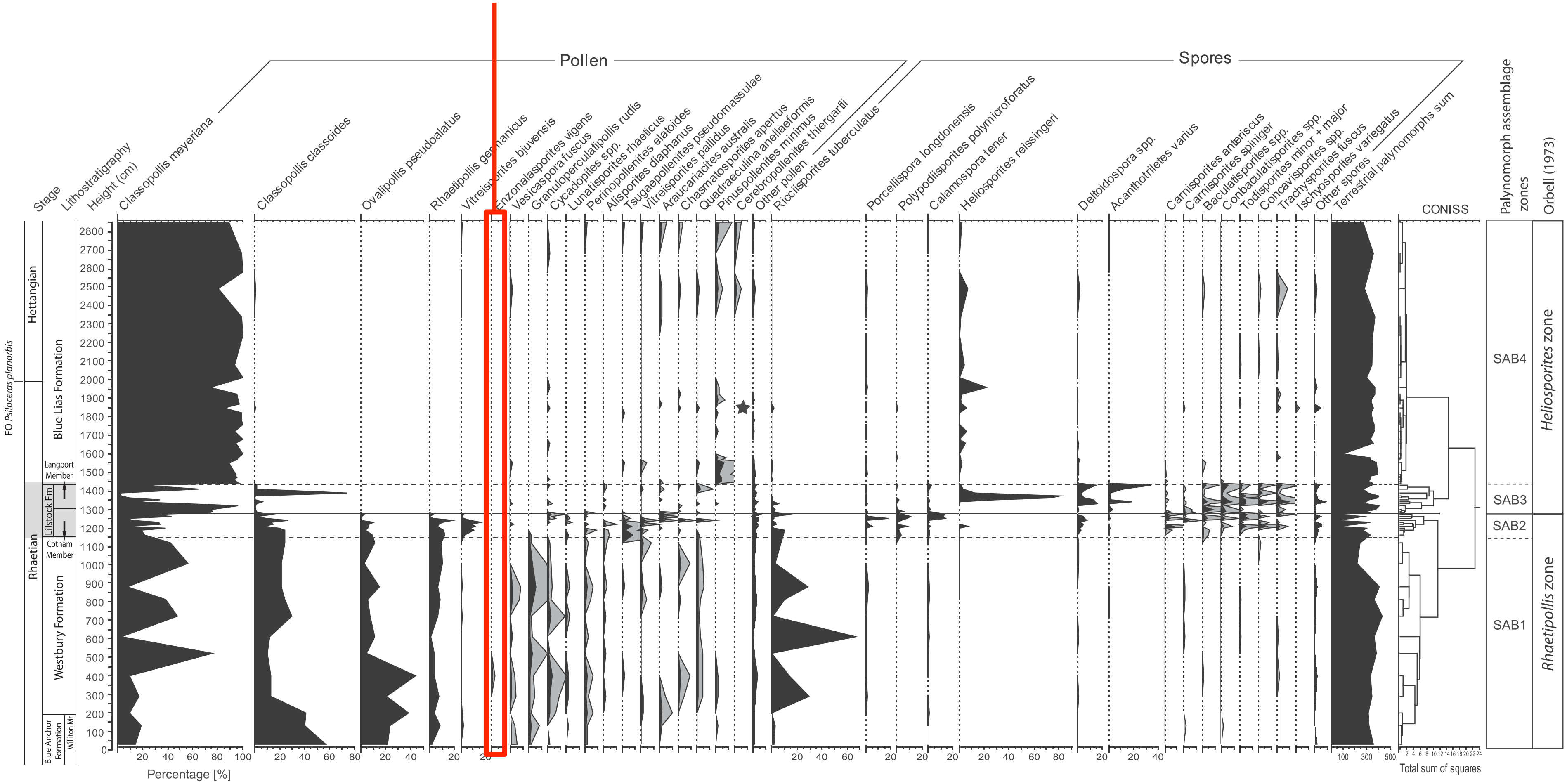
# Vessicate taxa missing from European Rhaetian



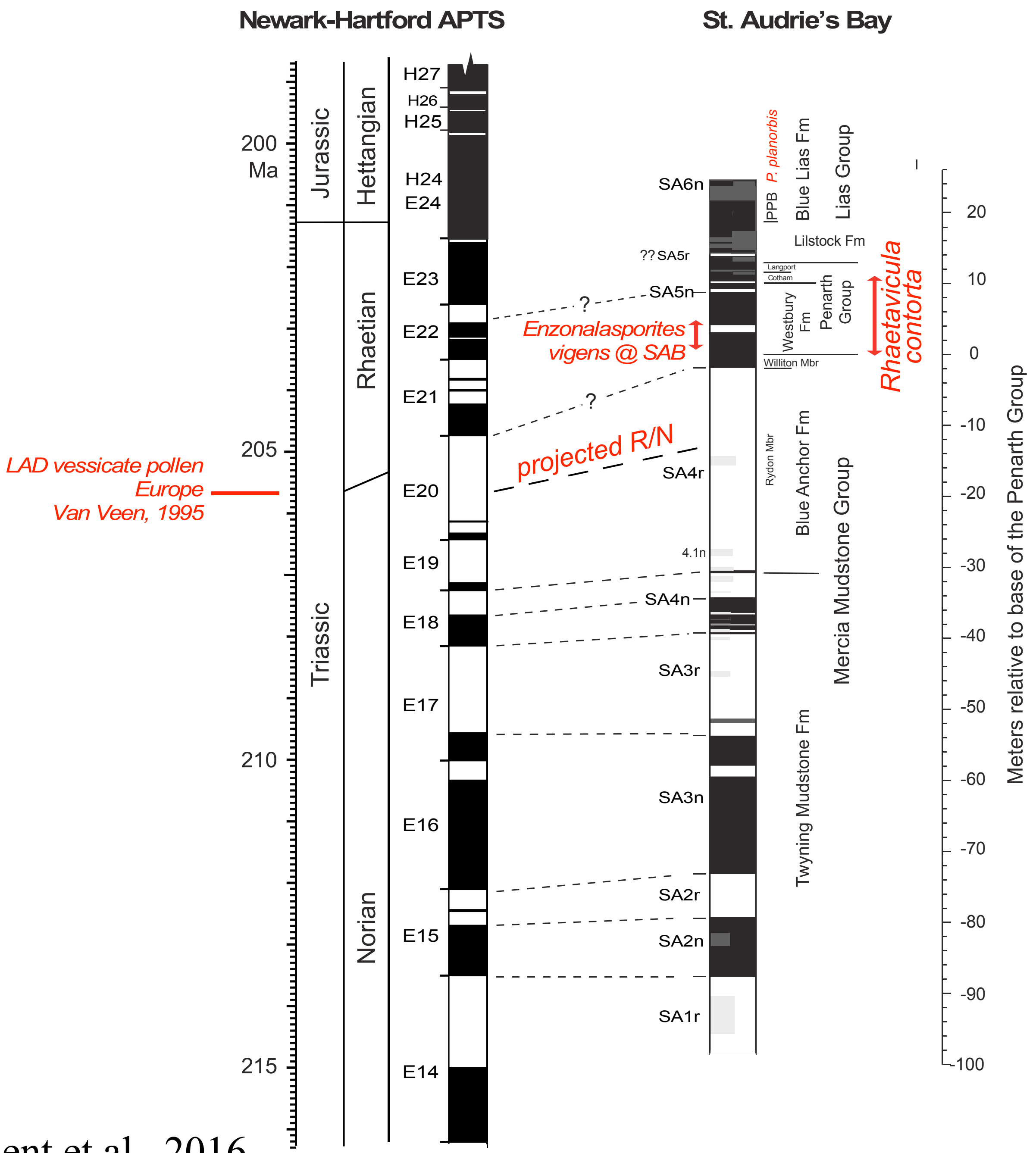
Cirilli, 2014

# Triassic-Jurassic, Bristol Channel Basin, St, Audrie’s Bay, Somerset, UK

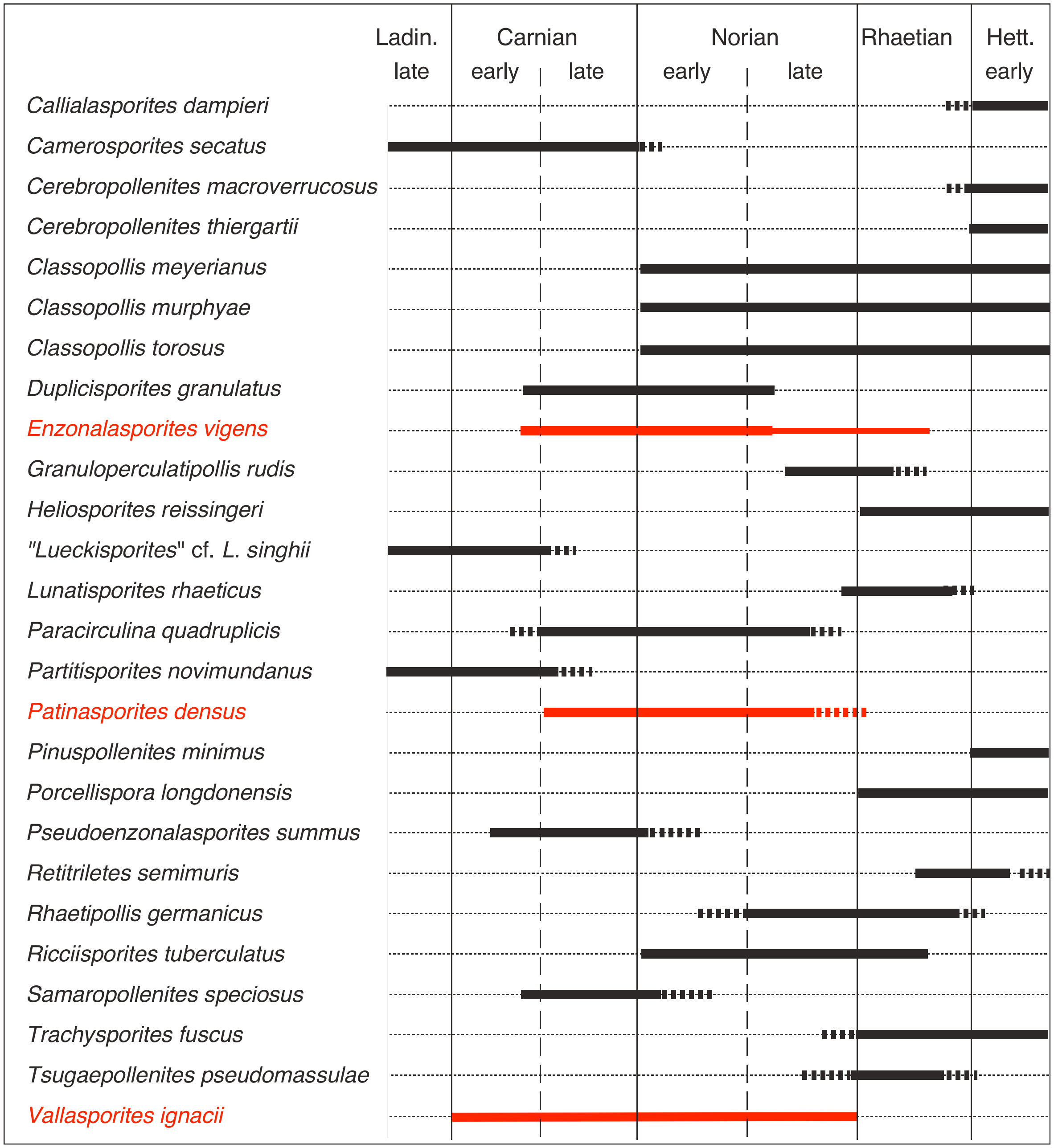
# Enzonalasporites vigens



Bonis & Kürschner, 2010

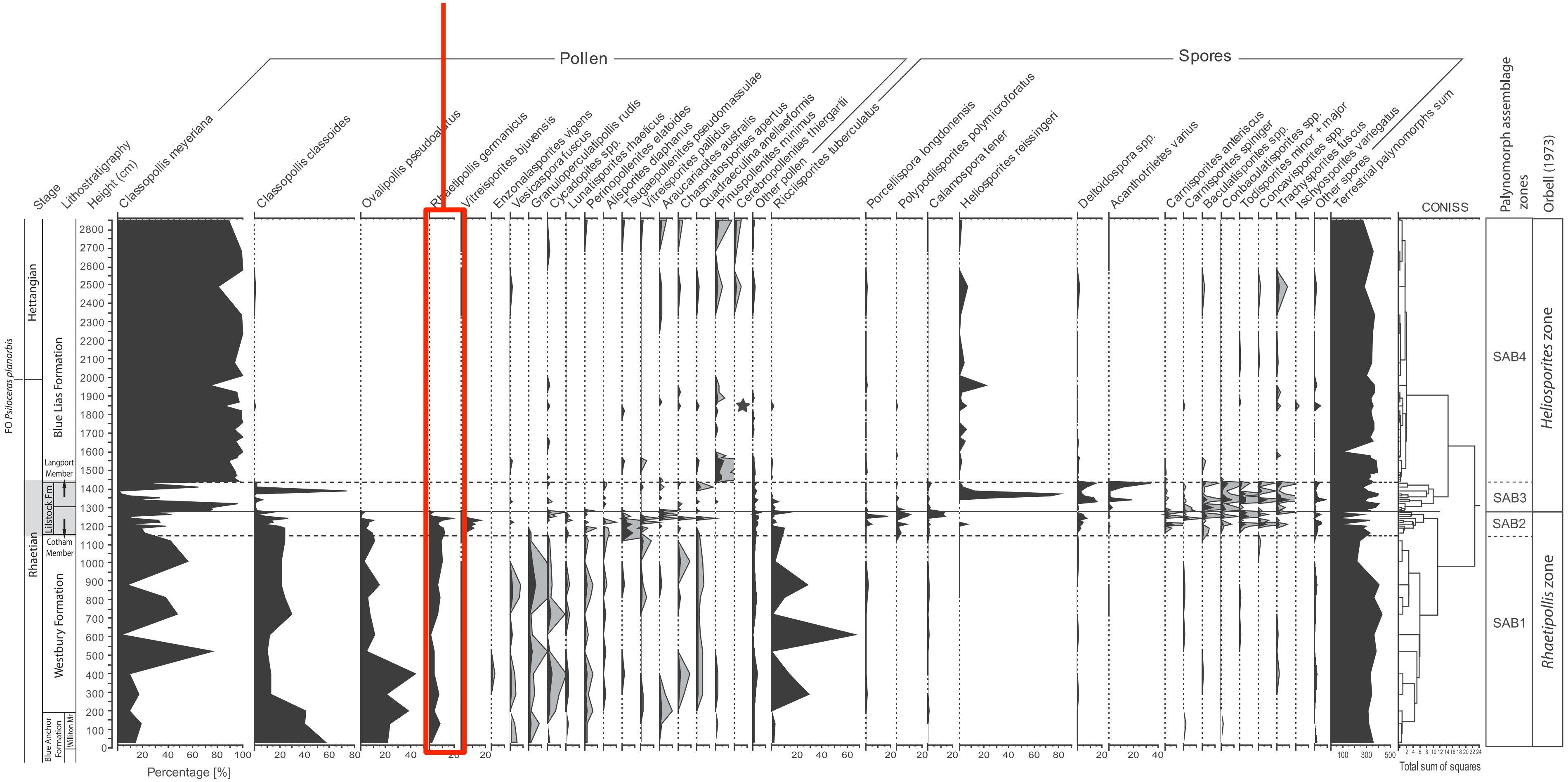


Modified from Kent et al., 2016



Cirilli, 2014

## *Rhaetipollis germanicus*



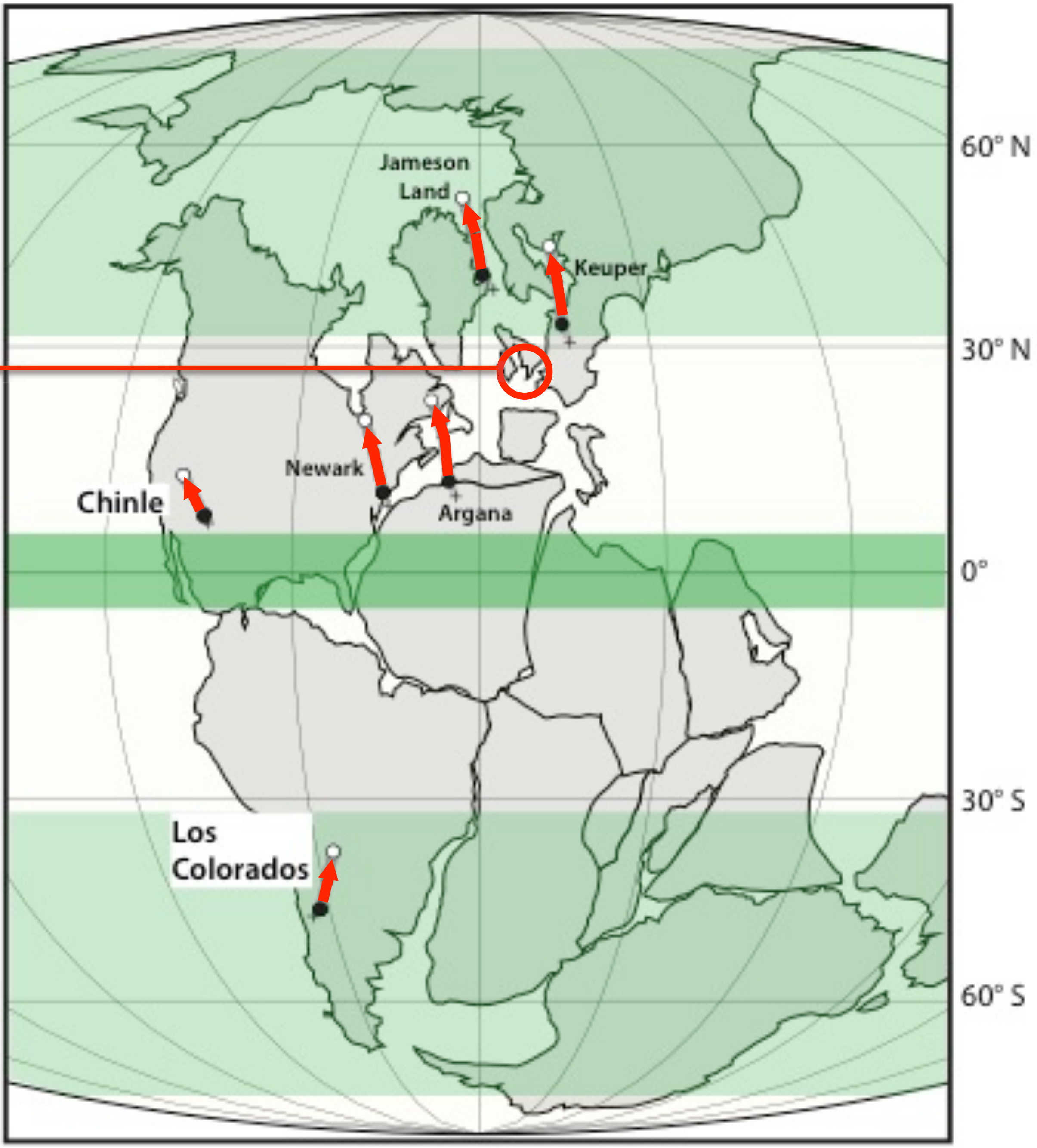
Bonis & Kürschner, 2010

# “Typical Rhaetian” taxa missing from Newark Supergroup

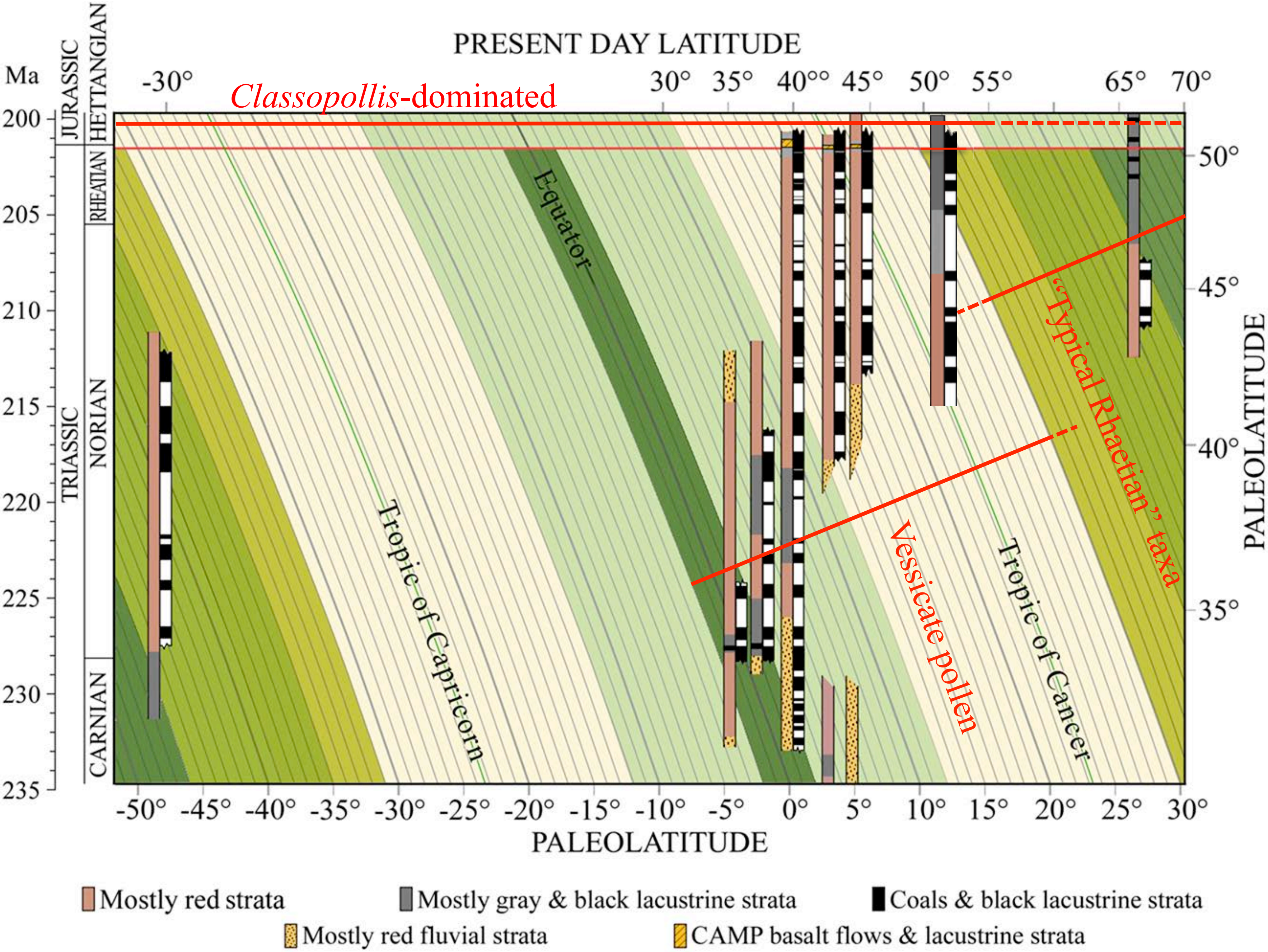
Cirilli, 2014

# Translation of Central Pangea Northward Through Late Triassic

St. Audrie's Bay:
Bristol
Channel
Basin



Kent et al., 2016


PRESENT DAY LATITUDE
Ma
JURASSIC
HETTANGIAN
TRIASSIC
RHEATIAN
NORIAN
CARNIAN
200
205
210
215
220
225
230
235
-30°
30°
35°
40°°
45°
50°
55°
65°
70°
Classopollis-dominated
Equator
"Typical Rhaetian" taxa
Vessicate pollen
Tropic of Capricorn
Tropic of Cancer
50°
45°
40°
35°
PALEOLATITUDE
-50°
-45°
-40°
-35°
-30°
-25°
-20°
-15°
-10°
-5°
0°
5°
10°
15°
20°
25°
30°
PALEOLATITUDE
Mostly red strata
Mostly gray & black lacustrine strata
Coals & black lacustrine strata
Mostly red fluvial strata
CAMP basalt flows & lacustrine strata

# Two hypotheses for a hiatus:

1) The presence of vessicate pollen and the absence of key European Rhaetian sporomorphs in the latter Triassic of Eastern North America and Morocco directly below strata dominated by *Classopollis* indicates a Norian age in contact with Jurassic strata and therefore therefore a multi-million year hiatus must be present (Van Veen, 1995 etc).

2) The presence of large spinocaudatans in the latter Triassic indicates a Norian age and their absence indicate a Rhaetian age. This along with the absence of two supposedly latest Norian and early Rhaetian zones that are present in western US and Europe indicates a major hiatus in the eastern US where these zones are absent (Kozur, Weems, Lucas, Tanner, 2005, 2007, 2010, 2011, 2015 etc.).

# Two key assertions:

1) The presence of large spinocaudatans in the latter Triassic indicates a Norian age and their absence indicate a Rhaetian age; therefore, the presence of large spinocaudatans up to the level of last spinocaudatan zone of (late Rhaetian age) in the eastern US indicates a hiatus.

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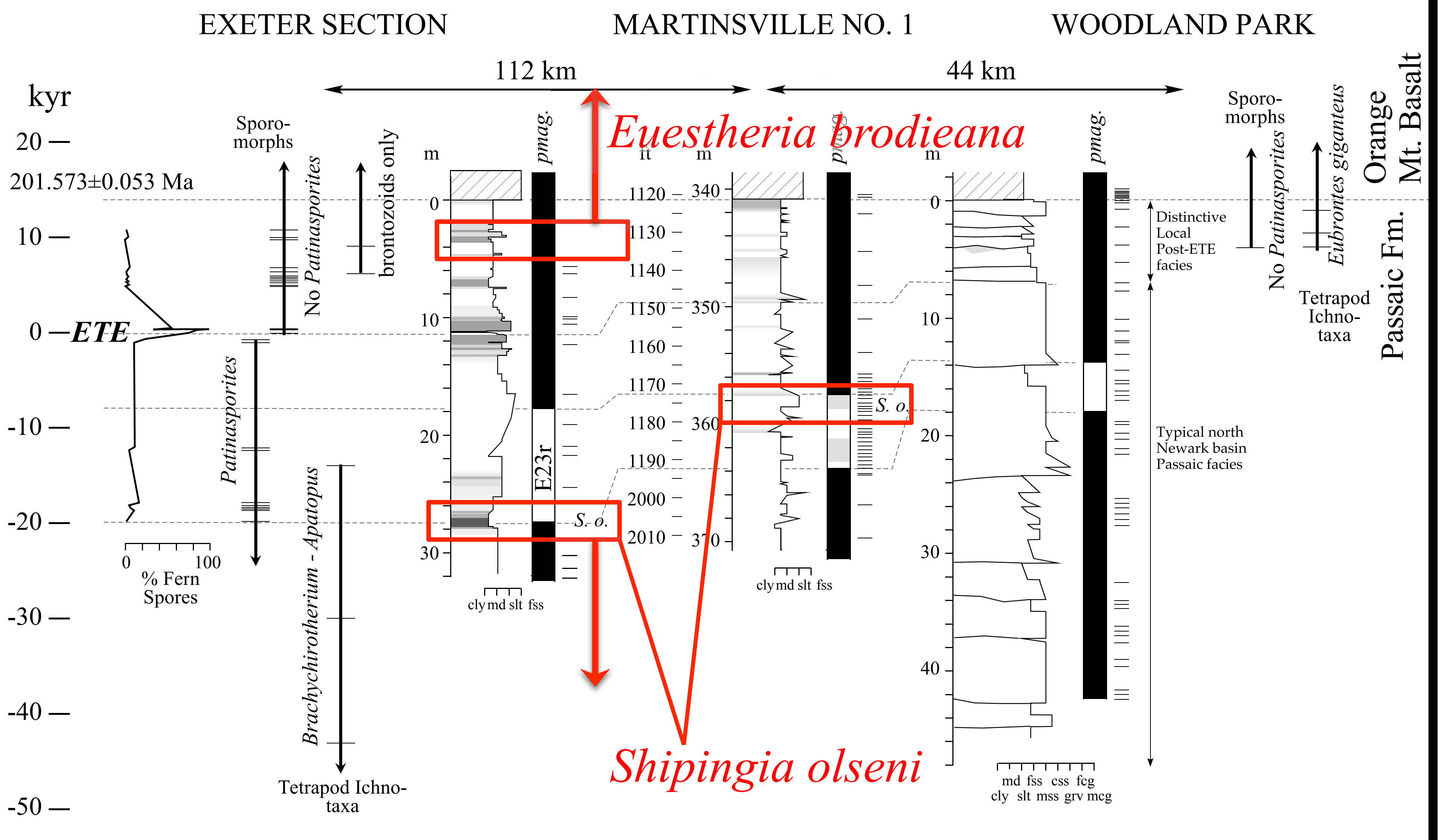
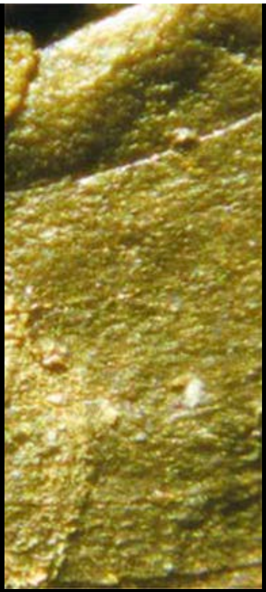


*Euestheria brodieana*

*Shipingia olseni*

*Euestheria brodieana* Midland Fm (Kozur & Weems, 2005)

*Shipingia olseni* holotype ♀
Passaic Fm (Weems & Kozur, 2005)



detail microsculpture

*Shipingia olseni* ♂
*Bull Run (Weems & Kozur, 2005)*

detail microsculpture

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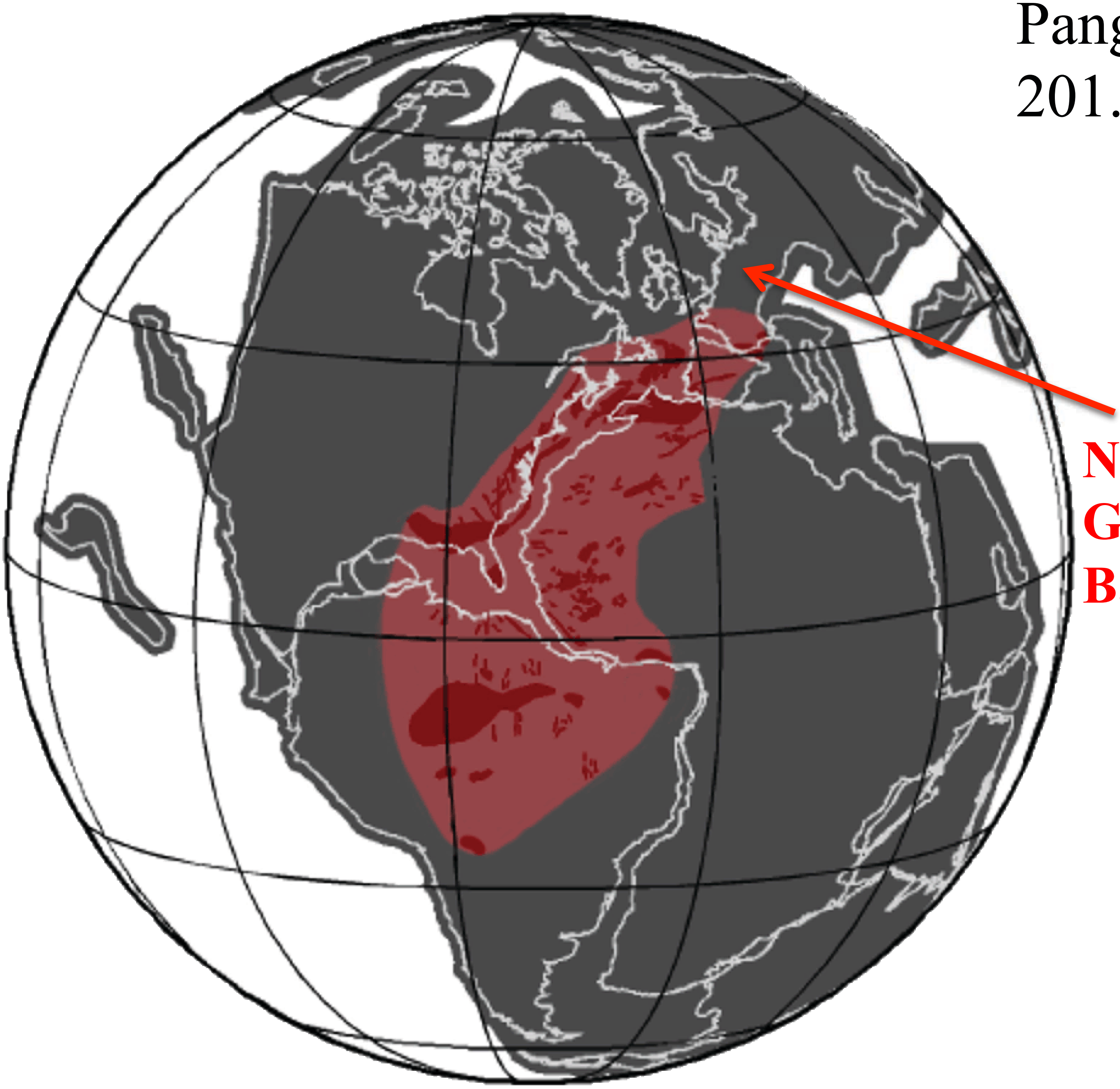
“The beds immediately below a distinct sporomorph spike, documented a few meters below the oldest lava flow (Orange Mountain basalt) in the Newark Basin in Exeter, Pennsylvania and previously assigned to the TJB, instead belong to the Sevatian (late Norian) rather than the Rhaetian as previously assumed. This is indicated by the abundant occurrence of *Shipingia olseni* nov. sp., which is found throughout the entire Sevatian section of the Newark Supergroup and in the Sevatian Stubensandstein 3 of Baden-Württemberg in the Germanic Basin. No species belonging to the Norian conchostracan genus *Shipingia* is known to range as high as the Rhaetian anywhere in the world.”

Kozur & Weems, 2005 p. 21

"…the upper Norian faunas were dominated by very large conchostracans, while the Rhaetian (and Hettangian) conchostracan faunas are everywhere composed of very small forms." (Kozur & Weems, 2011, p. )

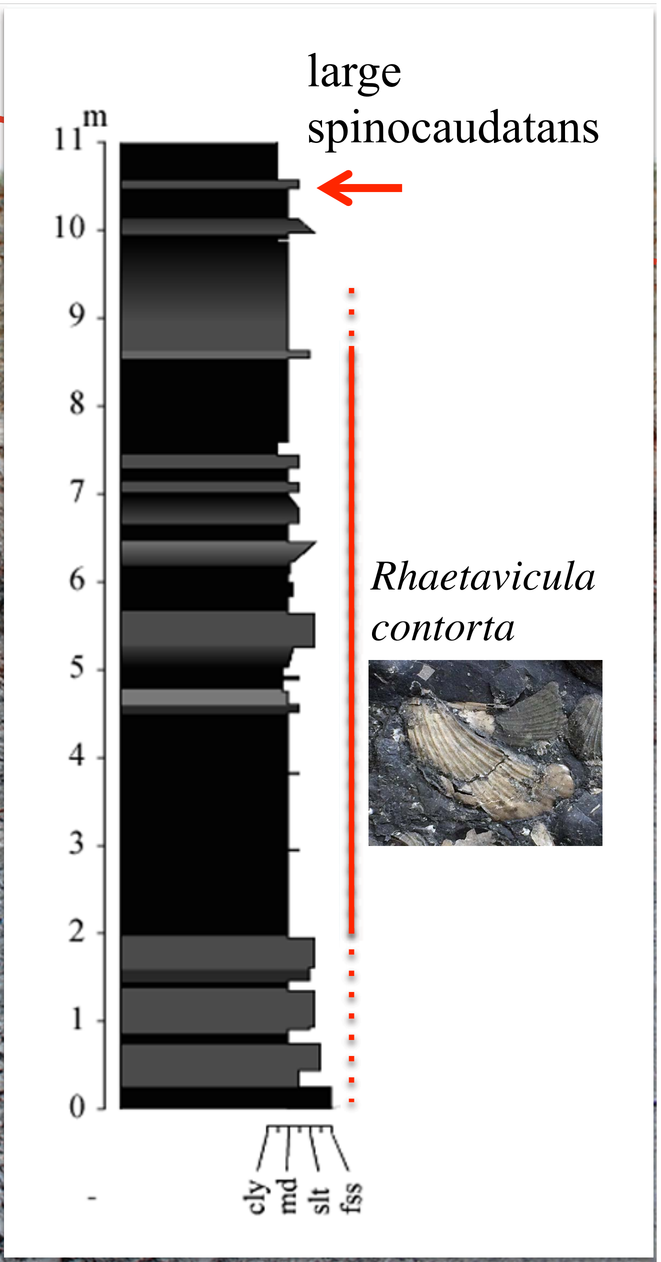
"No species belonging to the Norian conchostracan genus *Shipingia* is known to range as high as the Rhaetian anywhere in the world." (Weems & Lucas, 2015, p. 315)

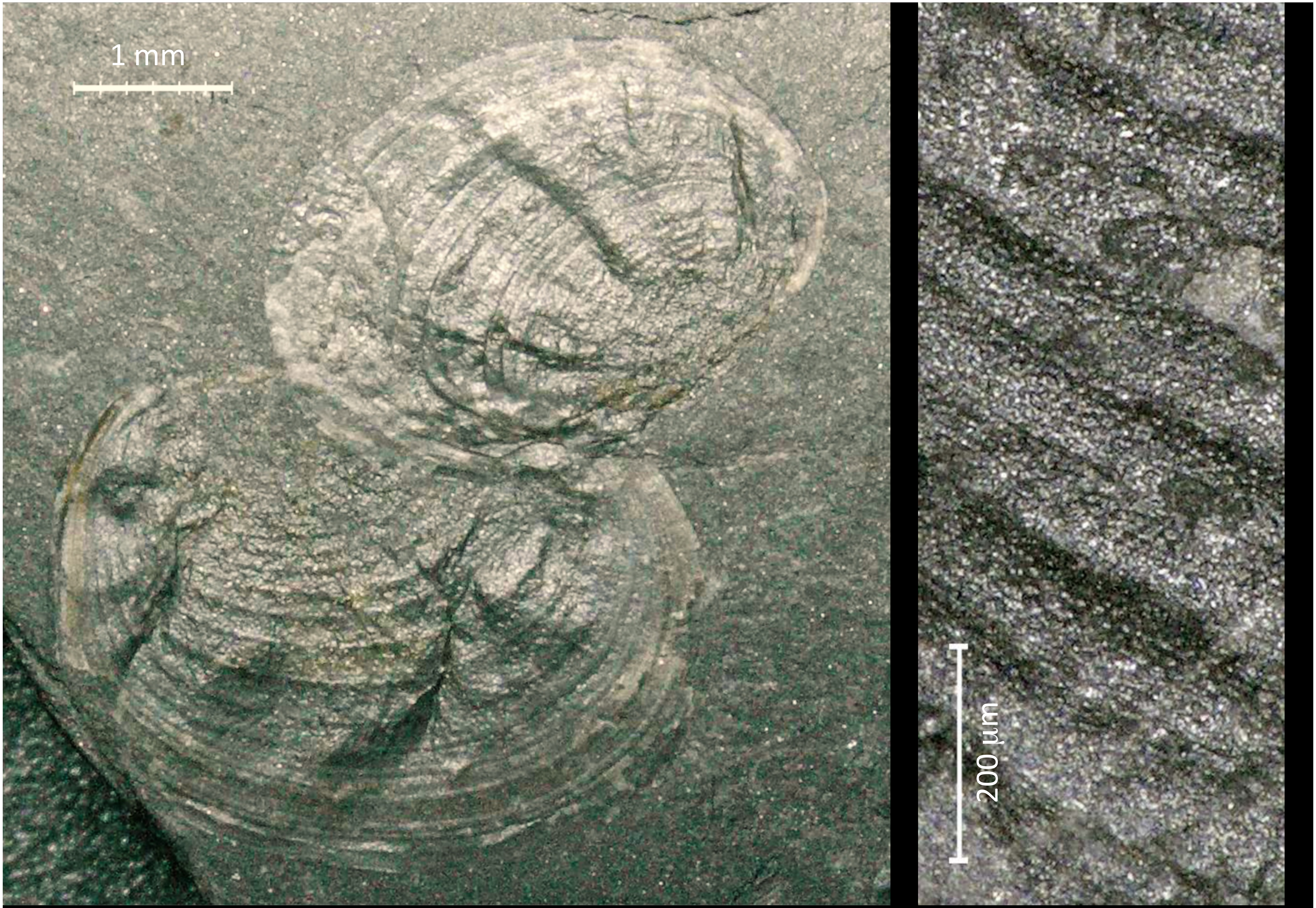
Pangea @
201.6 Ma



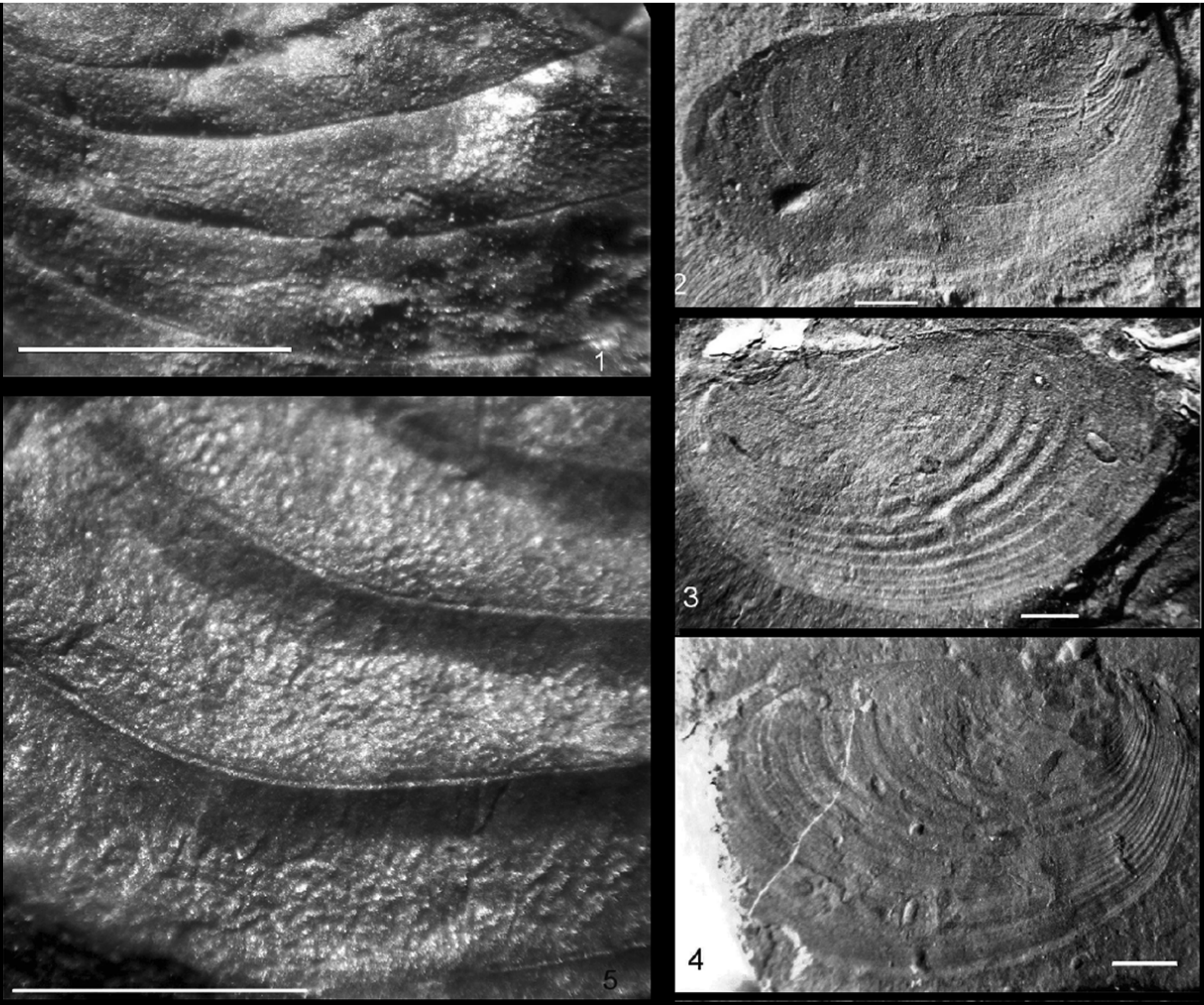
**North Germanic Basin**

# “Westbury equivalent” Bonenburg, Germany





Bonenburg (Late Rhaetian) *Shipingia* cf. *S. olseni*



*Shipingia olseni*, Passaic Fm. (Kozur & Weems, 2007)

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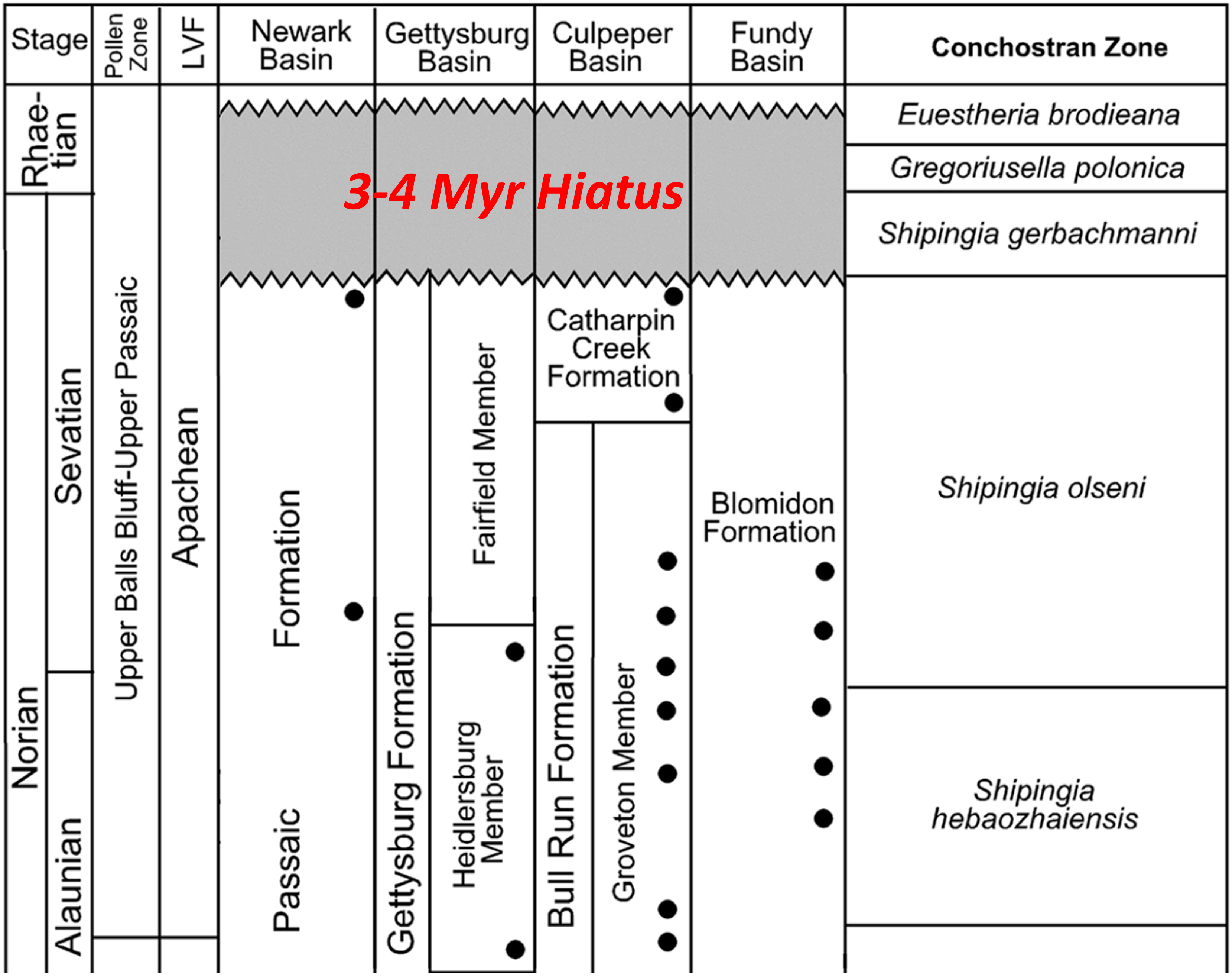
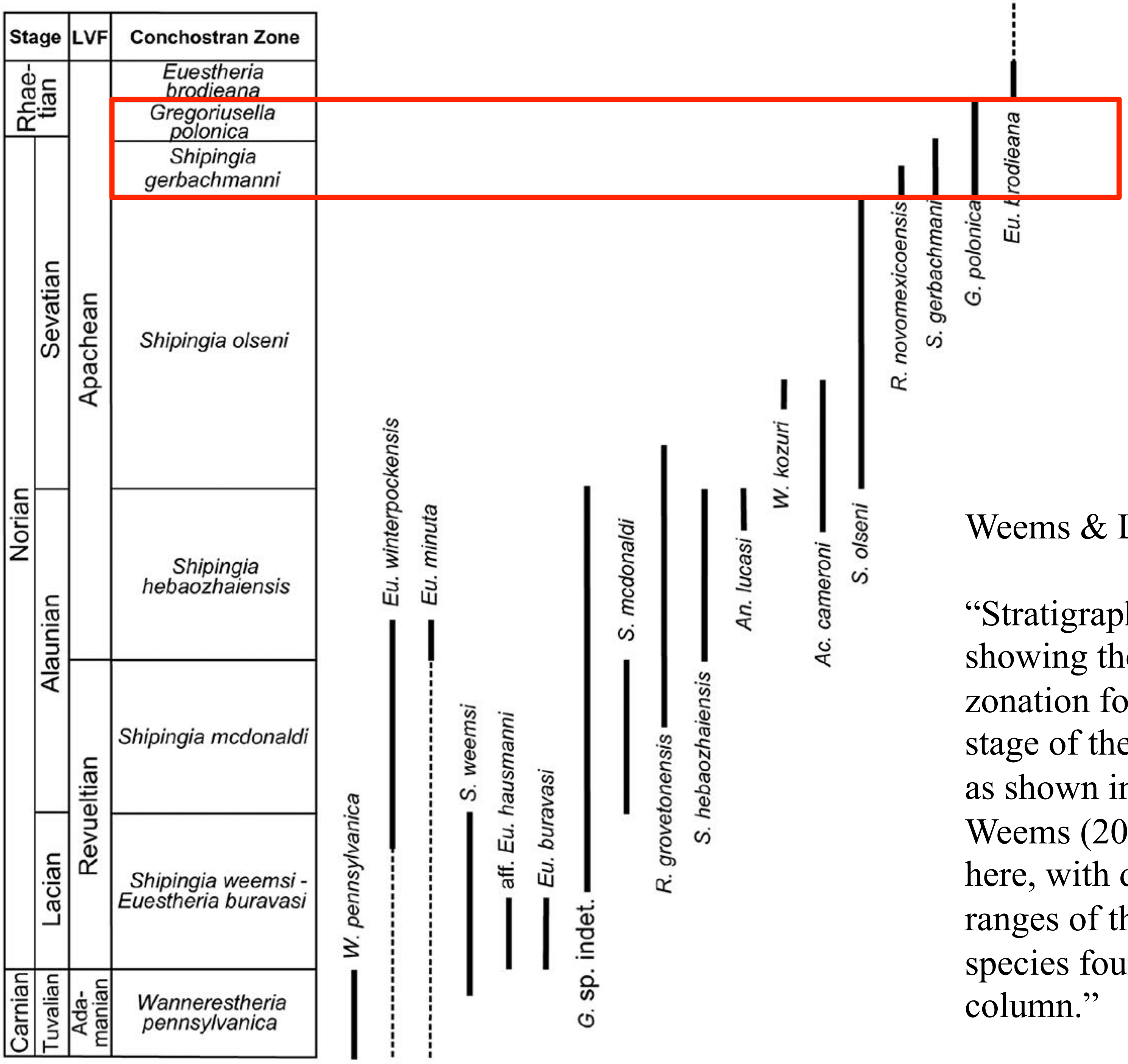
Weems & Lucas, 2015



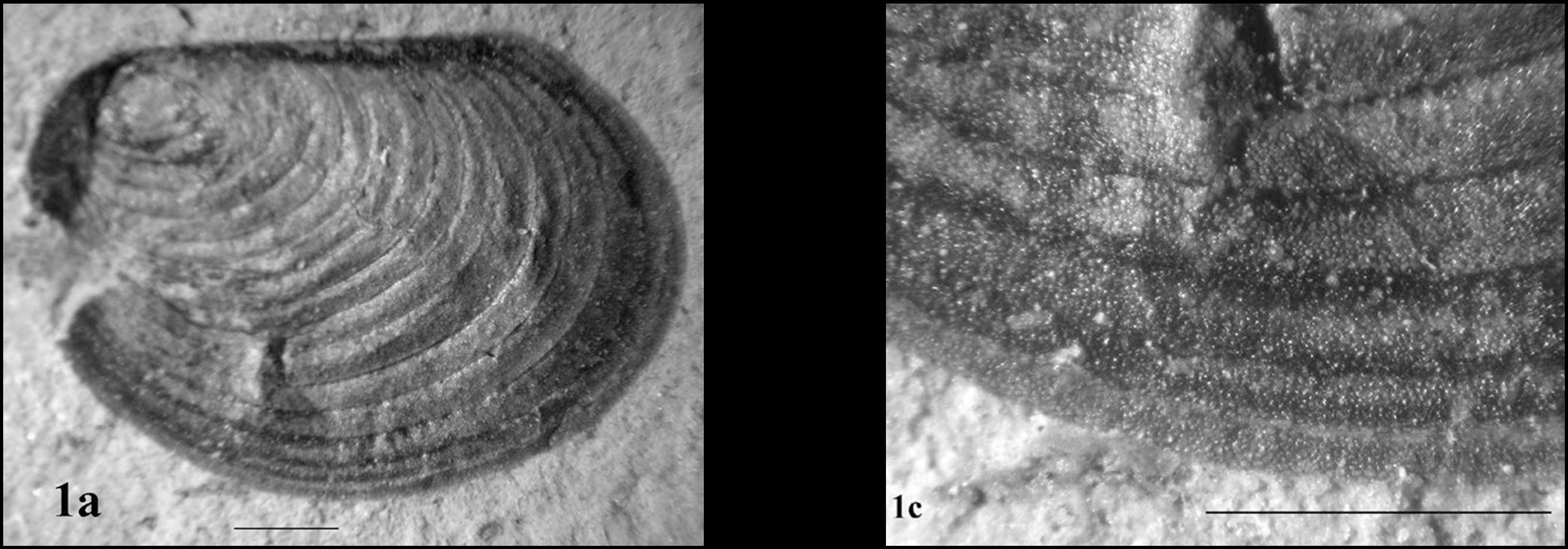
“The co-occurrence of these two species [*S. gerbachmanni* nor *G. polonica*] is characteristic of the uppermost Norian (upper Sevatian).” (Weems & Lucas, 2015, p. 308)

It remains notable that neither *S. gerbachmanni* nor *G. polonica* have ever shown up in the Newark Supergroup, even though both species occur abundantly in uppermost Norian strata in Europe (Kozur and Weems, 2011). Conchostracans collected by Paul Olsen (Lamont-Doherty) from the Bigoudine Formation in Morocco and provided to us for identification now document the presence and co-occuence of *S. gerbachmanni* and *G. polonica* in northwest Africa. Therefore, the absence of both of these upper Norian-lower Rhaetian conchostracans in the Newark Supergroup continues to support the conclusion that a significant unconformity of 3-5 million years duration separates the Norian strata of the upper Chatham Group from the upper Rhaetian strata of the basal Meriden Group.” (Weems & Lucas, 2015, p. 315)

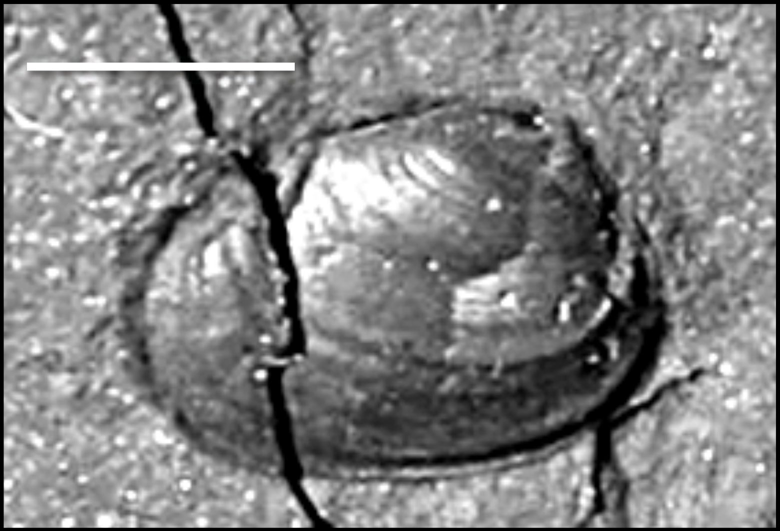


Weems & Lucas, 2015

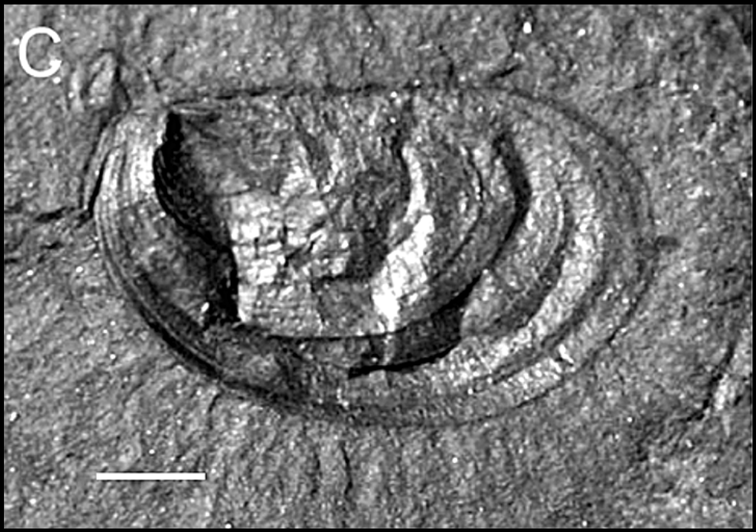
"Stratigraphic column showing the conchostracan zonation for the Norian stage of the Upper Triassic as shown in Kozur and Weems (2010) as updated here, with demonstrated ranges of the conchostracan species found in the Norian column."



*Shipingia gerbachmanni* “upper Norian” (Hauschke & Kozur, 2011)



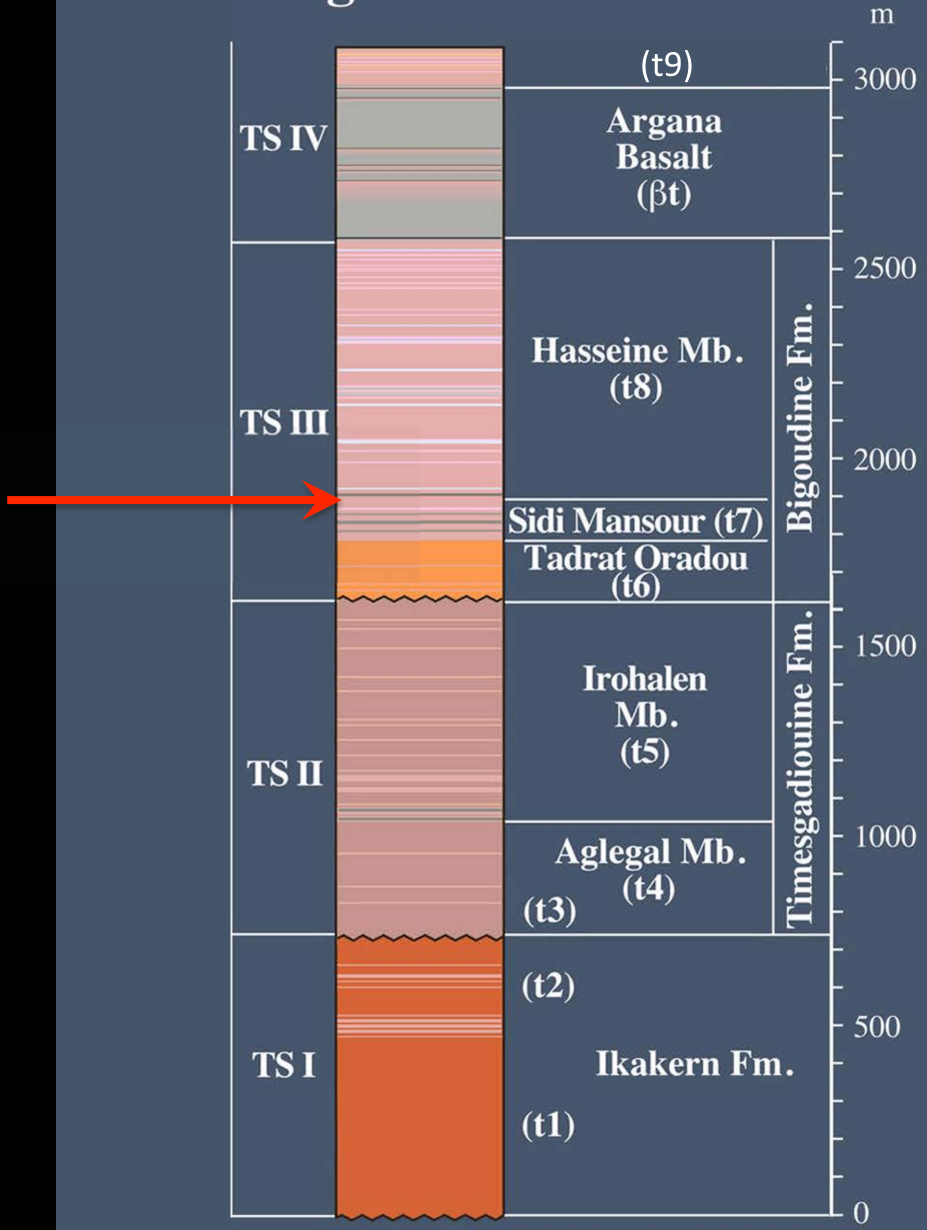
*Gregoriusella polonica* Bigoudine Fm (Weems & Lucas, 2015)



*S. gerbachmanni* Bigoudine Fm (Weems & Lucas, 2015)

Pangea @
201.6 Ma

# Argana Basin

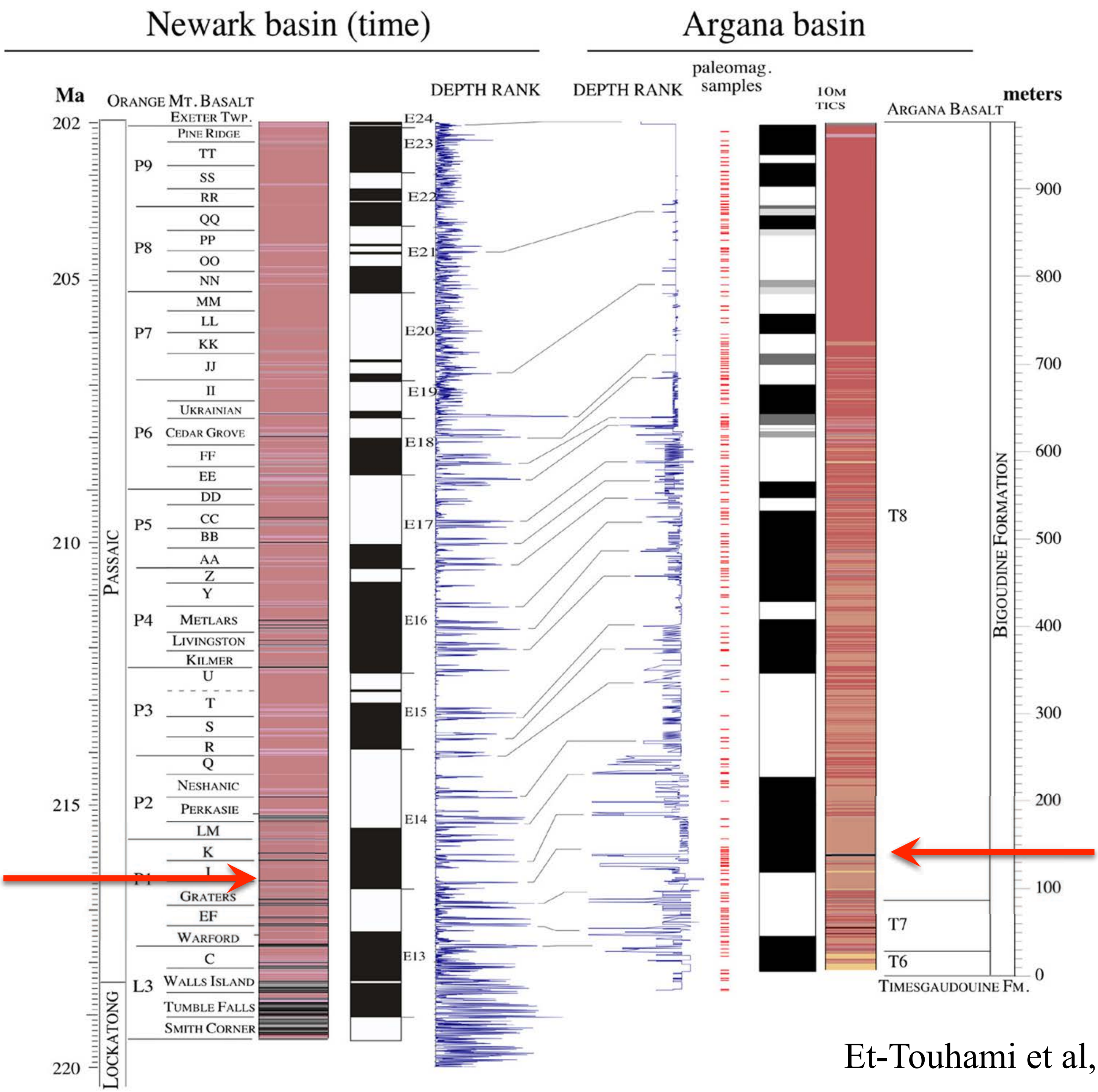


Middle Bigoudine Fm., near Argana

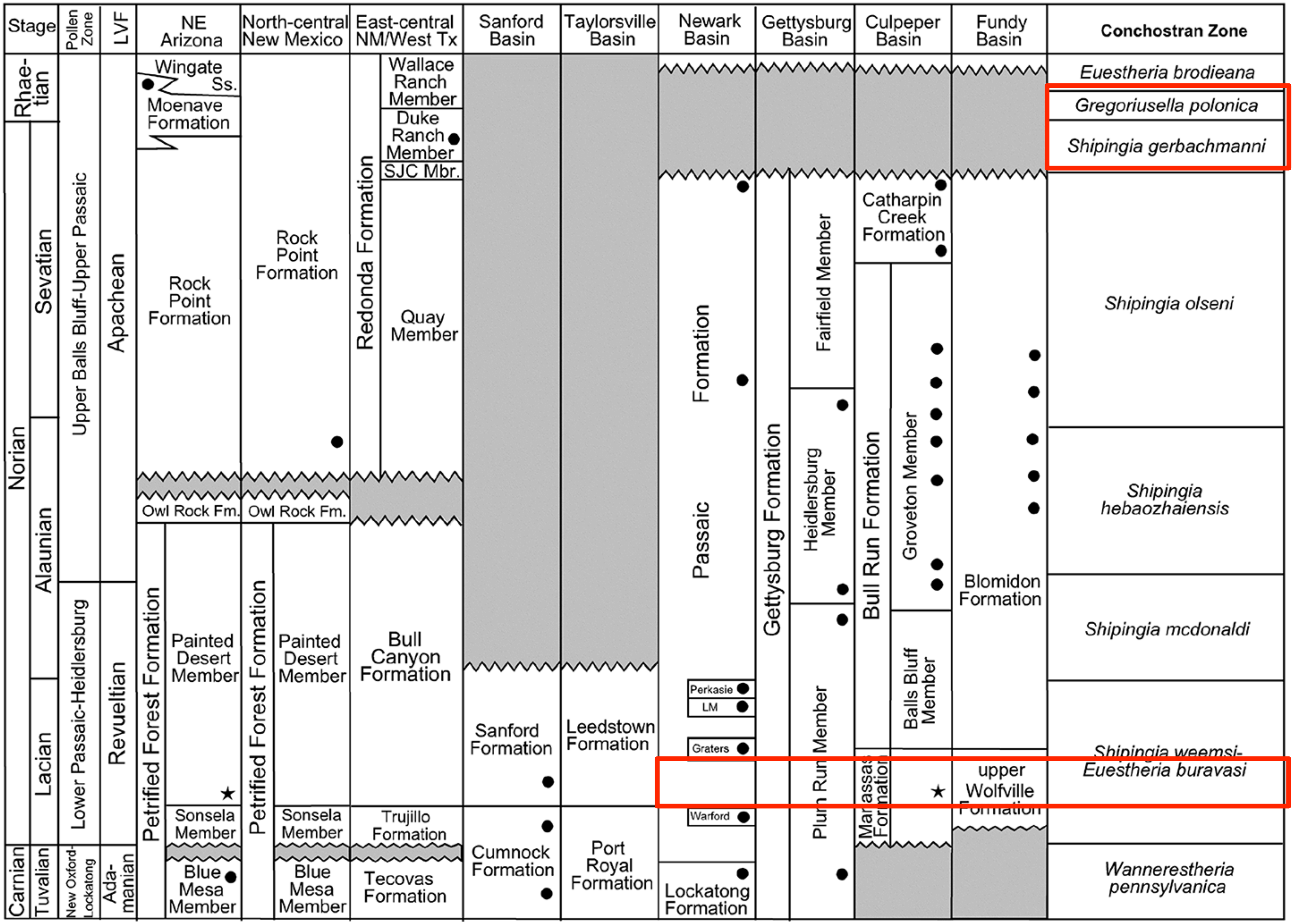
*Lower Bigoudine Formation, Hassein Mb., Argana Basin*

Near Argana, Morocco


40
30
20
10
0



Et-Touhami et al, in prep.



Weems and Lucas, 2015

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