PALEOENVIRONMENTAL AND PALEOBIOLOGICAL PERSPECTIVES ON THE CONTINENTAL END-TRIASSIC MASS EXTINCTION

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INTRODUCTION

The end-Triassic extinction (ETE) at 201.6 Ma (Blackburn et al., 2013), is one of the "Big Five" mass extinctions of the Phanerozoic (Raup and Sepkoski Jr, 1986). It is lesser in magnitude than the end-Permian extinction, but larger, by most measures, than that at the Cretaceous-Paleogene boundary [e.g., (Benton, 1995; Alroy et al., 2008; Kocsis et al., 2019; Marshall, 2023)] (Figure 1). This is true even when marine and non-marine taxa are treated separately (Benton, 1995; Kaiho, 2022). On the continents and in the oceans, the ETE extirpated many ancient lineages, with the survivors forming the basis of the modern biota (Sues and Fraser, 2010; Padian and Sues, 2015). On land, the ETE saw dinosaurs become the ecologically dominant land animals globally, a hegemony that would last 136 million years. Although Large Igneous Province (LIP) emplacements and eruptions are strongly implicated for three out of five of the Big Five mass extinctions, as well as lesser events (Green et al., 2022), the ETE stands out uniquely because evidence of the extinction is preserved in direct superposition with lava flows of the presumptive cause — the 15 x 10^6 km^2, Central Atlantic Magmatic Province (CAMP: Figures 2, 3) (Marzoli et al., 1999; Blackburn et al., 2013; Davies et al., 2017), Earth's aerially most extensive continental Large Igneous Province (LIP). Strata around the ETE and through the Triassic-Jurassic transition, especially in eastern North America, record the environmental changes that caused the extinctions and allowed the recovery. The Connecticut Valley Rift — the Hartford and Deerfield Basins (Figure 2) — are exemplary in this regard and are the focus of the field trip and field guide.

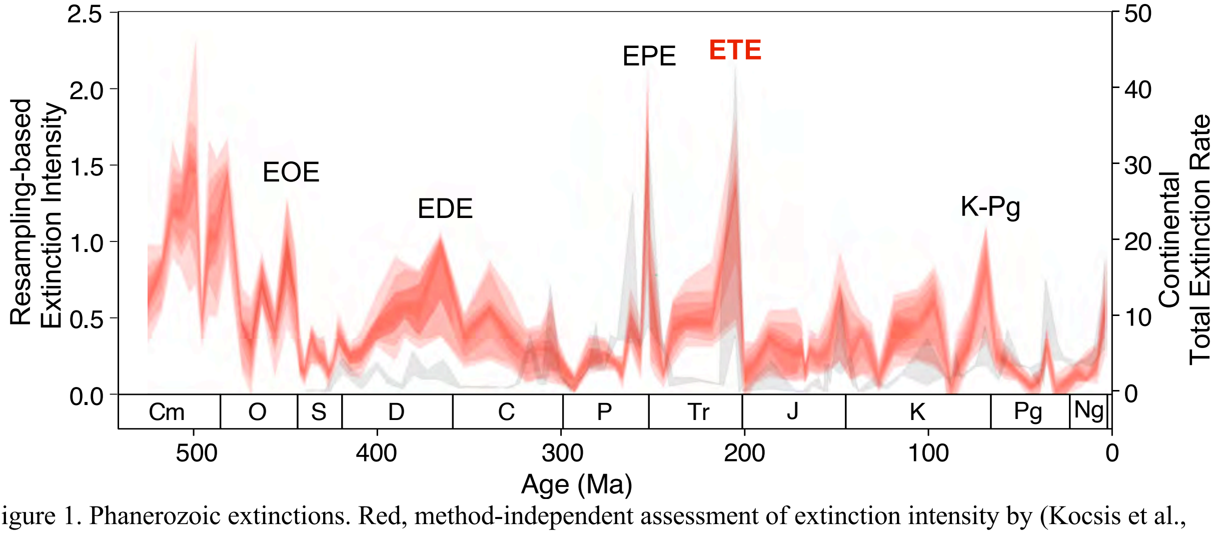

Figure 1. Phanerozoic extinctions. Red, method-independent assessment of extinction intensity by (Kocsis et al., 2019) based on data were derived from PaleoDB (https://paleobiodb.org). Gray, continental total extinction rate (numbers of families that died out in relation to the duration of each stratigraphic age) (Benton, 1995). Classic "Big Five" mass extinction events are: EOE, end-Ordovician extinction; EDE, end-Devonian extinction; EPE, end-Permian extinction; ETE, end-Triassic extinction; and K-Pg, Cretaceous-Paleogene (K-T) extinction. Of these five, only the EPE, ETE, and K-Pg are consistently outliers above background and the ETE is larger in magnitude than the K-Pg, with most methods. Data are on a common time scale from (Kocsis et al., 2019).

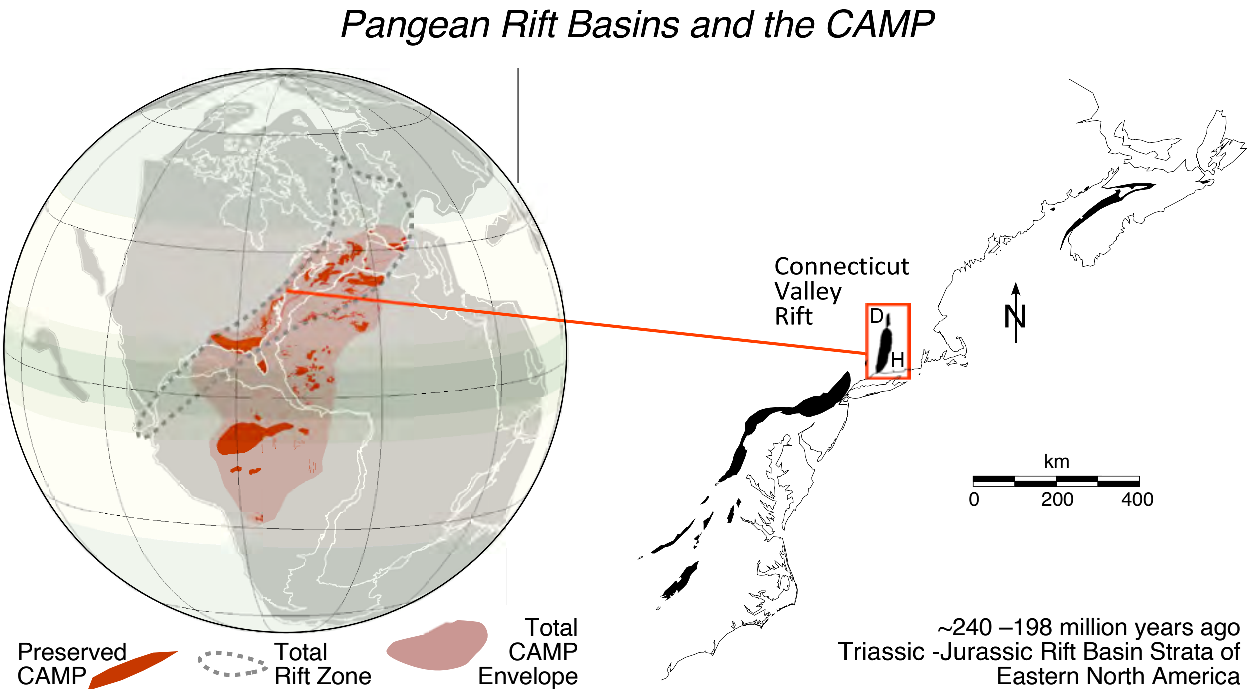

Figure 2: The supercontinent of Pangea, CAMP (Central Atlantic Magmatic Province), central Pangean rift zone, and eastern North American rift remnants. The Connecticut Valley Rift (**H**, Hartford; **D**, Deerfield Basins) is one of the larger remnants of the rift system sedimentary fill

This field trip examines outcrops and fossils spanning Late Triassic and Early Jurassic strata in the northern Hartford Basin and the Deerfield Basin in terms of a global view. Although some of this guidebook is drawn from previous field trip guidebooks, particularly (Olsen and Douglas, 2022) and (Olsen et al., 2024e) there is new material, particularly in the northern Hartford Basin and for the Beneski Museum and the Deerfield Basin. Here focus on, and debate, interpretations of CAMP volatile–modulated lacustrine cyclicity and ecosystem damage caused by volcanic winters and global warming associated with CAMP, which triggered the ETE. Safe road cuts, quarries, and natural outcrops will be visited, displaying lacustrine sedimentary cyclicity, dinosaur footprints, and CAMP lava flows. We will also visit the classic Edward Hitchcock fossil footprint collection at the Beneski Museum of Amherst College, which houses thousands of dinosaur footprints and other tracks that provide clues as to why dinosaurs were so successful through this otherwise catastrophic event. These stops will serve as venues for our discussions and debates on the paleontology and paleobiology of the Triassic–Jurassic transition. The goal of this field trip is to stimulate discussion on the overarching hypotheses that CAMP-related volcanic winters were the principal drivers of mass extinction on land, not global warming, while acidification and were the main drivers of extinction in the oceans.

Field Trip Begins: 9:00 AM: Metacom Drive, Simsbury, CT 06070: Park on road [41.890140°, -72.776880° (41°53'24.50"N, 72°46'36.77"W)].
Field Trip Ends: 5:00: Beneski Museum, Amherst College, Amherst, MA [42°22'19.1"N 72°30'51.5"W (42.371976, -72.514303)].

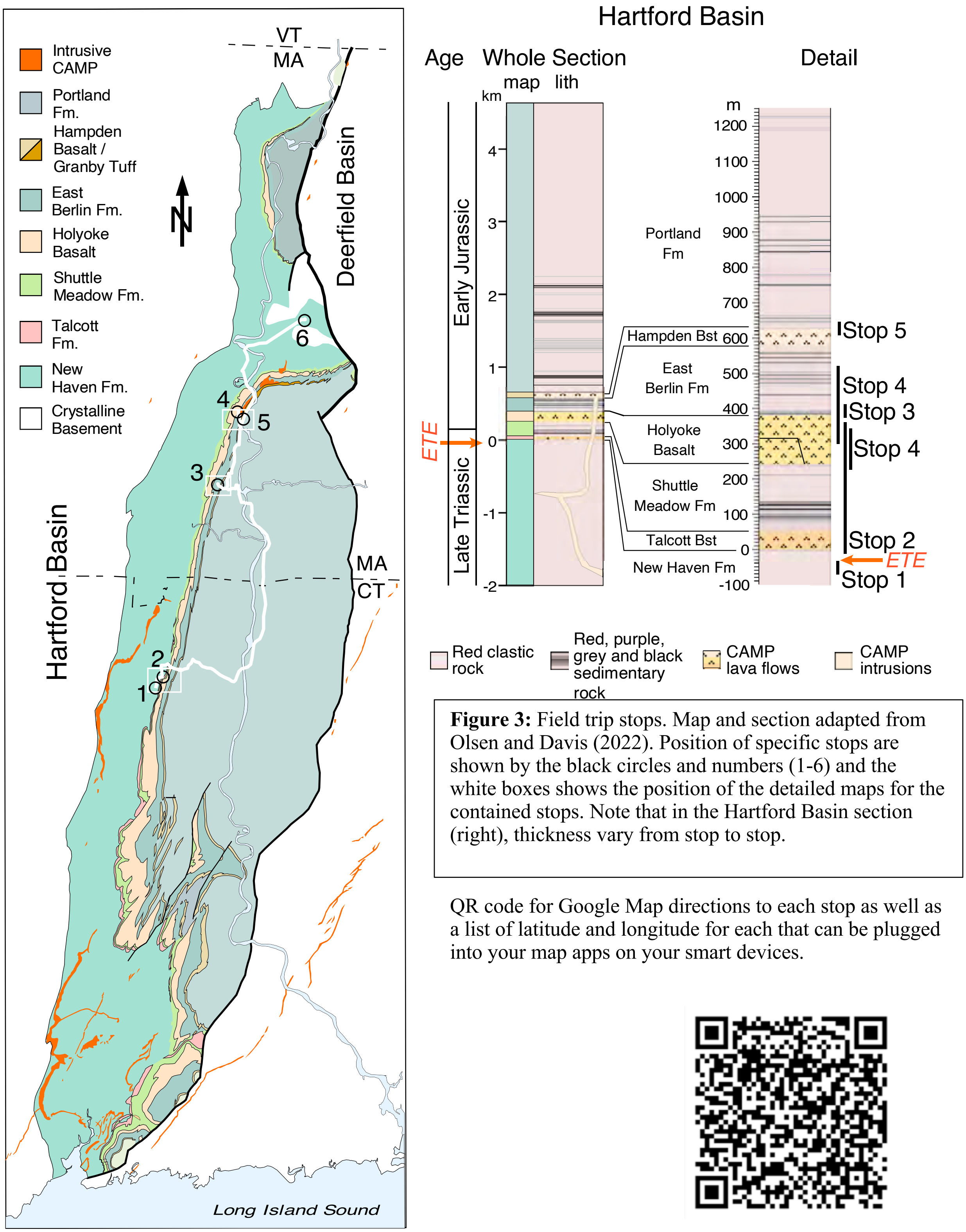

Figure 3: Field trip stops. Map and section adapted from Olsen and Davis (2022). Position of specific stops are shown by the black circles and numbers (1-6) and the white boxes shows the position of the detailed maps for the contained stops. Note that in the Hartford Basin section (right), thickness vary from stop to stop.

QR code for Google Map directions to each stop as well as a list of latitude and longitude for each that can be plugged into your map apps on your smart devices.

The Google Map directions can also be accessed via this link:
https://www.ldeo.columbia.edu/~polsen/nbcp/End_Triassic_Extinction.html

A RIFT WITH A VIEW

The Hartford and Deerfield Basins of the Connecticut Valley are linked erosional remnants of a continental rift that developed in the northern tropics of central Pangea (Figure 2) during the Late Triassic and Early Jurassic (~215-199 Ma). Assembled about 335 million years ago through multiple continental plate collisions during the Devonian-Carboniferous, Pangea began to develop an extensional system along the old sutures, plausibly as early as the Late Permian (Olsen and Et-Touhami, 2008; Kent et al., 2021; Ma et al., 2023). By the Late Triassic, the giant mountain belt was collapsing and the supercontinent was pulling apart creating Earth's largest known rift system, stretching from the proto-Arctic Ocean to Panthalassa, 8700 km long and 1000 km wide (Figure 2). Of the many, at least partly, interconnected basins, the Hartford and Deerfield Basins formed on the western edge of this giant rift system with its major eastern extensional bounding faults, following the preexisting, west-dipping, largely low angle, compressional fabrics and faults.

The scale of just the North American and African continents of this rift system is directly comparable to the largely Neogene East African Rift System (Figure 4), and similarly climatically situated, both being largely tropical. Together, the Newark though Culpeper Basins are about the size of Lake Tanganyika or Lake Malawi and the Connecticut Valley Rift is larger but close in size to Lake Turkana. Major differences between the two systems include that the East African rifts are bound by much higher-angle faults and broken up into many more sub-basins (Rosendahl et al., 1992) than the central Pangean rifts and that volcanism has characterized most of the 25-million-year history of East African rifts (Biggs et al., 2021) but was focused into a less than 1-million-year window (CAMP) in the central Pangean rifts.

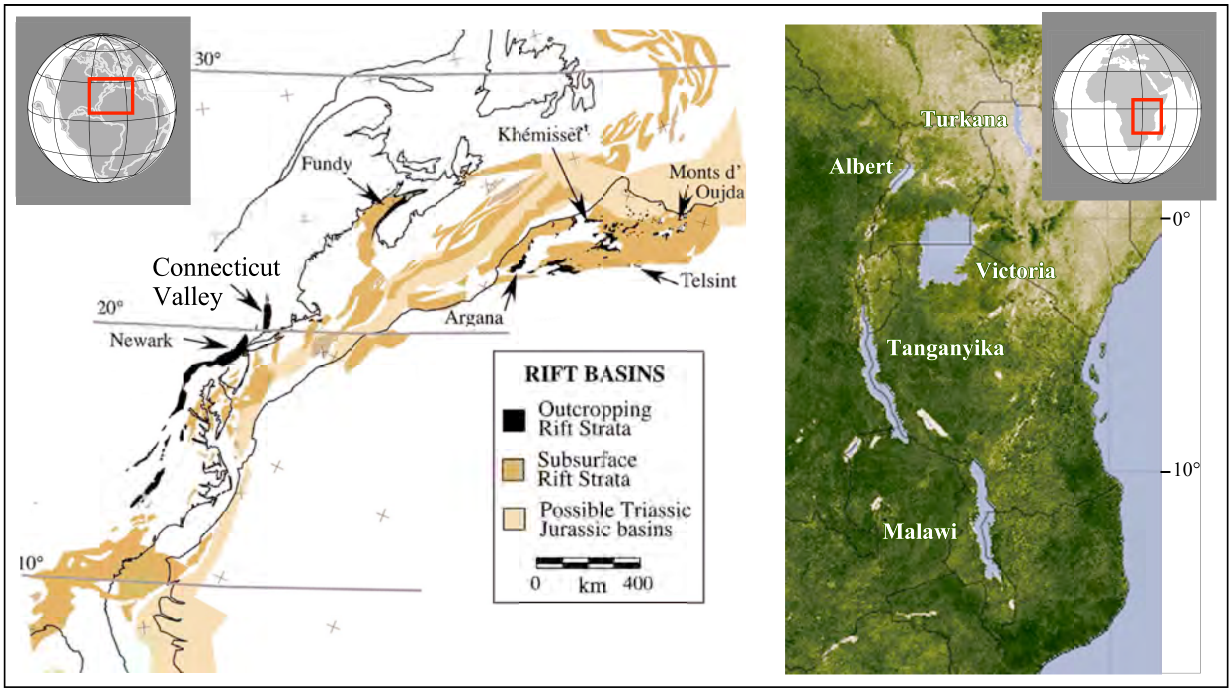

Figure 4: Triassic-Jurassic **Pangean Rifts (left)** compared to the Great Lakes of the **East African Great Rift today (right)**. The Connecticut Valley plus the three rift basins to the south (Newark, Gettysburg and Culpeper Basins) were located in the tropics and were filled with lakes, that at times, were bigger than today's Lake Tanganyika or Malawi. Image on right from Google Earth.

Pangean-extension ultimately resulted in half graben (Figure 5) for both Hartford and Deerfield Basins, with a major west dipping, eastern border fault system, towards which most strata dip, a central set of faults with apparent down to the west geometry, and smaller east dipping faults. However, in the absence of interpretable seismic reflection profiles or deep boreholes, the basic cross-sectional geometry of the Hartford basin is still not well constrained with interpretations being based on geophysical potential field methods (Wenk, 1984), extrapolations from surface stratal dips (Wise, 1992) and fault geometry (Schlische, 2003; Resor and DeBoer, 2005), seismic refraction profiles (Wenk, 1989), seismic receiver function analysis (Gao et al., 2020; Luo et al., 2021; Long, 2024), and analogy with the geometry of better constrained eastern US rifts (Withjack et al., 2024).

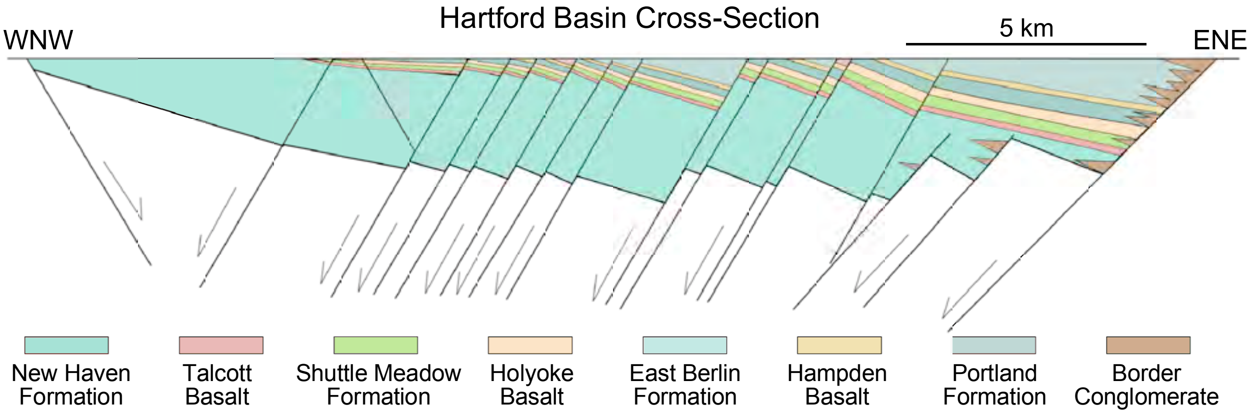

Figure 5: Conceptual cross-section of the Hartford Basin in the area of Meriden and Durham, Connecticut. Modified from (Olsen and Douglas, 2022) and consistent with modeling of (Phillips et al., 1988).

At least 5 or 6 kilometers of continental sedimentary strata, interbedded lava flows, and intrusions, accumulated over at least 18 Myr of the Late Triassic and Early Jurassic in the Hartford and Deerfield Basins. IN the Hartford Basins, the preserved record is constrained to begin around 217 Ma in the Norian of the Late Triassic (Cornet, 1977) and extend to at least 199 Ma in the Sinemurian of the Early Jurassic (Kent and Olsen, 2008) in the Hartford Basin. What is known about the Deerfield suggest a similar record. Apart from just below the oldest flows, the ~2 km-thick pre-CAMP interval in both basins is entirely fluvial. Profoundly cyclical, lacustrine, marginal lacustrine, and interbedded fluvial strata follow, in which CAMP flows are interbedded, which is succeeded by a much thicker post-CAMP cyclical lacustrine sequence in both basins. In the Hartford Basin a thick upper fluvial portion is present, which has very few temporal constraints. Strata accumulated in the growing half graben progressively tilting towards the east, plausibly linking up with depositional system of the Late Triassic Passaic Formation of the Newark Basin during later New Haven Formation time (Withjack et al., 2013; Withjack et al., 2020) resulting in a basin several times larger in area than the present basins.

Apart from basin onset and termination, the most impactful tectonic event in the Connecticut Valley Rift history was clearly the emplacement of the lavas and intrusions of the CAMP (Marzoli et al., 1999) (Figure 2). This event not only completely restructured the depositional environments of the basin from fluvial to dominantly lacustrine, it emplaced the lavas underlying the trap ridges of the Valley (LeTourneau and Pagini, 2017), accelerated growth on bounding and internal fault, and refocused deposition into smaller areas more closely approximating present basin depocenters. A remarkably similar pattern of lavas, cyclical lake strata and inferred events occur in the contemporaneous part of the Newark Basin section (Figures 6, 7), on which much of the geochronology of the basins depends.

CAMP and the ETE

Perhaps unique among LIPs thought to be related to mass extinctions CAMP flows (and at least two airfall ashes) are directly interbedded with the strata containing biological evidence of the continental ETE. This is true for the lacustrine rifts of eastern North America, northwest Africa, Iberia, and southern France, but is not true for studied marine sequence. Superposition trumps all inference which makes the lacustrine rifts uniquely suited as natural laboratories to study the relationship between a LIP and inferred extinctions. The rift strata also have orders of magnitude higher accumulation rates allowing much higher temporal resolution, especially for environmental proxies such as for pCO_2. Uniquely among strata reflecting mass extinction events there is also a brief and distinctive magnetic polarity interval E23r just before the ETE allowing sub-10,000-year-scale correlation. Potentially, this could be identified in marine strata, but as yet it has not. Finally, the CAMP itself is very unusual in having so many U-Pb-datable units, compared to other LIP, and as the CAMP dated flows are directedly interbedded with sedimentary strata displaying a lacustrine Milankovitch cyclicity, a highly corroborated, internally consistent, time scale has been developed (Figure 7).

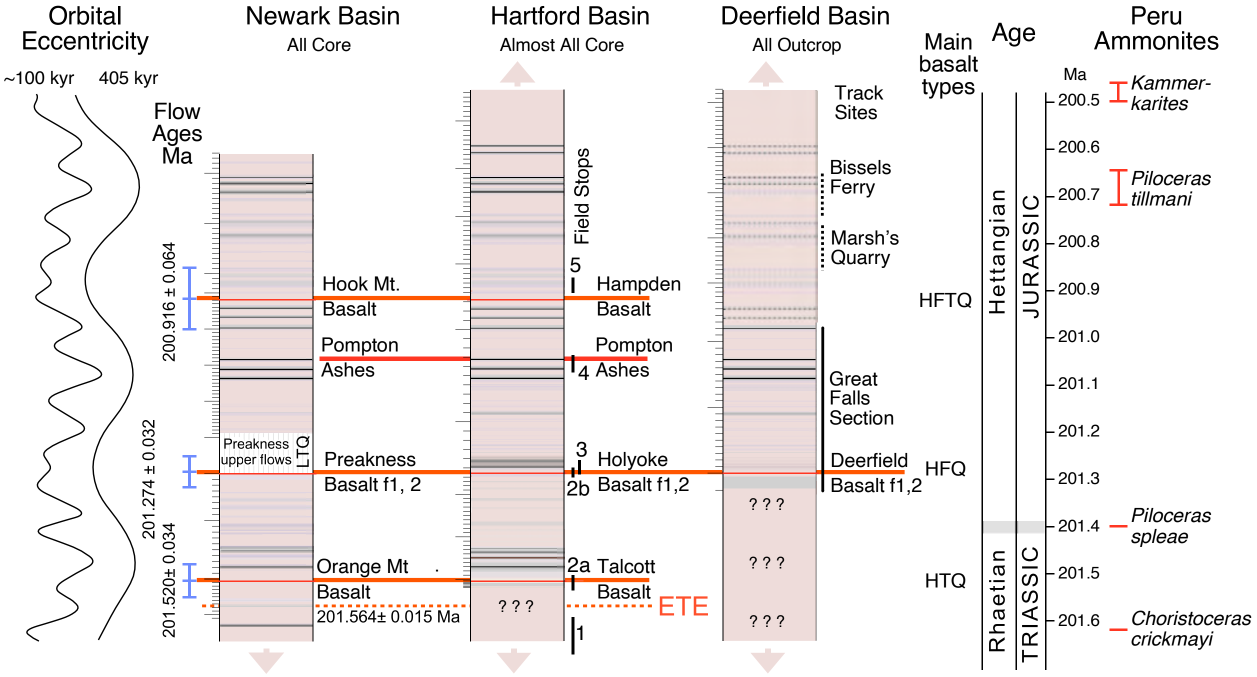

Figure 6: Correlation between the Newark and Hartford Basins shown with a U-Pb anchored, astrochronologically tuned time scale. Ticks are 10 m original measurements, mostly on cores. Arrows indicate there is more section in that direction. U-Pb dates are from Blackburn et al. (2013) and astrochronology from Olsen et al. (2019a). Basalt types from Weigand and Ragland (1970). Ammonites are from the marine Pucara Basin section (Peru) from Guex et al. (2012) using the zircon U-Pb CA-ID-TIMS time scale of Yager et al. (2017) and references therein. Colors very approximately are those of the sedimentary strata, but are shown dashed in the Deerfield Basin above the Great Falls section because very discontinuous outcrop to indicate the pattern is diagrammatic.

The temporal relationship between the CAMP and the ETE is well established (Figure 7). Based on a combination of high-resolution zircon U-Pb CA-ID-TIMS ages, paleomagnetic polarity stratigraphy (E23r), and biostratigraphy (sporomorphs and tetrapods), the oldest CAMP intrusions, predate the continental ETE (at 201.564±015 Ma) by about 100 kyr, and youngest known CAMP flows post-date the ETE by about 650 kyr. Peak CAMP activity seems to correspond closely to the continental ETE, and high-resolution zircon U-Pb CA-ID-TIMS ages from ashes interbedded with marine strata in Peru show that the marine ETE, as defined by ammonites is synchronous with the continental. Intercontinental correlation of ammonites and the GSSP of the base Hettangian (Austria), suggests that the Triassic-Jurassic boundary post-dates the ETE by about 180 kyr at 201.4 Ma and is basically a non-event. Thus, the timing of the initiation of the CAMP is consistent with it being the cause of the ETE thorough a scenario of volatile release, including CO_2 and SO_2 and consequent abrupt and drastically opposing radiative balance perturbations along with spikes in ocean acidity and anoxia.

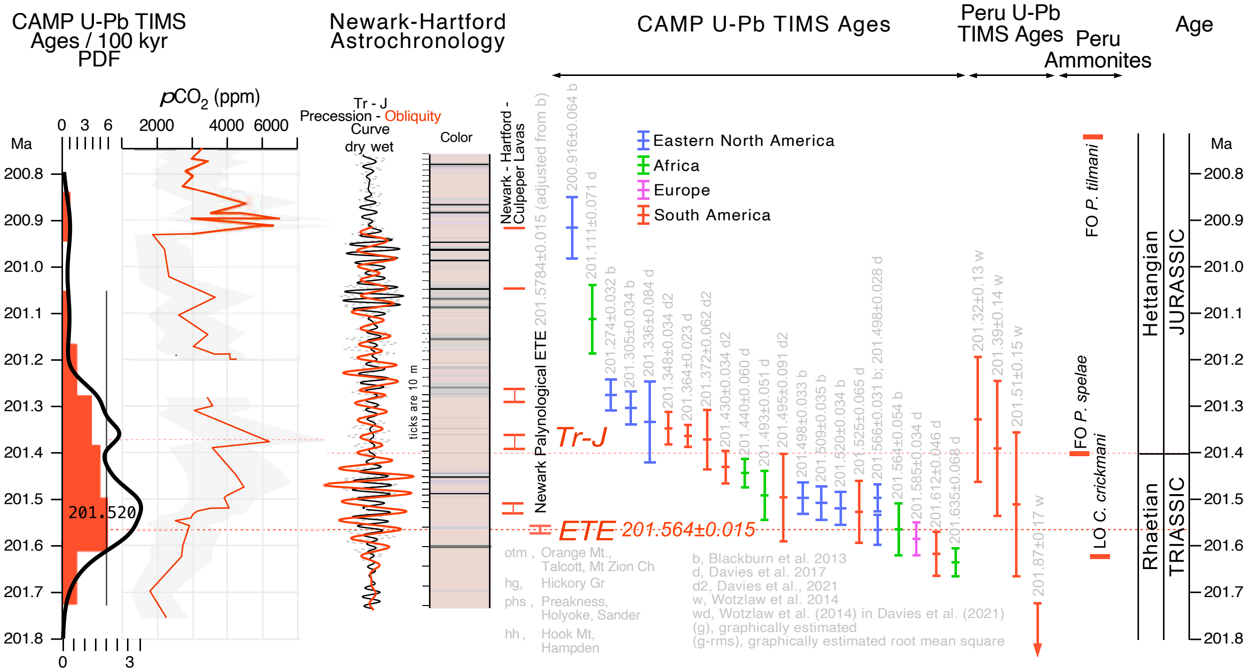

Figure 7. Zircon U-Pb, CA-ID-TIMS ages from entire area of the CAMP (Blackburn et al., 2013; Wotzlaw et al., 2014; Davies et al., 2017; Davies et al., 2021) compared to from the marine Triassic-Jurassic of the Pucara Basin, Peru (Guex et al., 2012; Wotzlaw et al., 2014) using the U-Pb time scale of (Yager et al., 2017), pCO_2 estimates based on the soil carbonate proxy [repositioned based on new stratigraphic and astrochronologic data from (Schaller et al., 2011; Schaller et al., 2012; Schaller et al., 2015)], and orbital pacing derived from the cores. Probability density function from Olsen et al. (2024c).

Basin sediment dispersal patterns and accommodation space growth changed dramatically around the onset of CAMP. During most of New Haven time, river and stream systems transported sediments predominantly from the east and north to the west and south (Hubert et al., 1978; McInerney and Hubert, 2003), largely from the eastern footwall and north. The basin was subsiding slowly enough that river systems left the basin with no clear indication of lake development[4]. But during latest New Haven Formation time, close to or at the ETE, paleocurrent data switched from axial and westerly to dominantly west to east flow from the hanging wall of the basin, with less significant eastern input (Hubert et al., 1992). This switch in the direction of sedimentary supply was accompanied by lake development in the basin close in time to, but before, the arrival of, the earliest Talcott lavas. By earliest Shuttle Meadow time, accommodation space growth so outpaced sediment supply, that even with the input of massive volumes of lava, deep lakes could form when climate permitted. Locally the accumulation rate may have increased by a factor of 6 or more into the post-Talcott strata. The contemporaneous increase in the Newark basin was similar, increasing by about a factor of 3 from the uppermost Passaic Formation to the Orange Mountain Basalt and the overlying Feltville Formation. Yet in both cases, accommodation space must have increased even faster than accumulation rates (even decompacted) because there was plenty of room for deep lakes at the same time. The accumulation rate increase and depositional milieu change from fluvial to lacustrine occurred during a time in which there is also significant evidence of syndepositional growth and tilting, not only on the major eastern boundary fault system, but also on at least some of the larger central basin faults. Evidence for syndepositional growth on the central basin faults consists of dramatic up-dip thinning and onlap of cyclical lacustrine strata between fault blocks on an east-west transect along with similarly dramatic along strike variations in thickness and onlap in the Shuttle Meadow Formation (Stop 2). This tilting must have happened extremely rapidly because the total amount of time from the top of the lavas of the Talcott Formation, to the base of the lavas of Holyoke Basalt was only ~250 kyr and most of the tilting during Shuttle Meadow time occurred in half that. Less tilting is seen between the Holyoke and Hampden Basalts (~330 kyr), based on scant, reliable thickness data, and none is yet detected for the Portland Formation.

We do not know if the abrupt acceleration in tilting and increase in accommodation space was a consequence of the CAMP event or an increase in extension rate was related to the cause of both, or some other combination of cause and effect. Working that out is a real challenge, but it might reveal some fundamental processes.

Although there was syndepositional tilting and accompanying growth, much if not most of the tilting postdates the preserved depositional sequence (Roden-Tice and Wintsch, 2002), which has been deeply eroded since the Early Jurassic, which is a pattern seen in other eastern North American rift basins (Withjack et al., 2024). Basin strata also exhibit transverse folds that increase in frequency and amplitude approaching the eastern border faults (Wheeler, 1939), but the degree to which these folds were syndepositional, influencing sedimentation vs. entirely post-depositional remains unconstrained (Schlische, 1995) (Stop 8). Most of this post-depositional tilting and folding was plausibly accompanied by erosion, although that need not have involved Mesozoic regional uplift, with the region still subsiding from the Paleozoic continental accretions and orogenies that formed Pangea. As with other eastern North American Basins this erosion was basically complete by the Early Cretaceous (Withjack et al., 2024).

Earth System Response to the CAMP

Eruptive products: At 15 x10^6 km^2, the CAMP is the largest large igneous province (LIP) by area on the Earth[1], equal to about 40% of the area of the Moon, and includes some of the thickest lava flow(s) from the last billion years (Olsen et al., 2024e). We can safely assume CAMP eruptions were beyond anything witnessed by humans — by several orders of magnitude. But we really know very little specific about the atmospheric and environmental effects. As described above, association in time between the CAMP and the ETE is clear (Schoene et al., 2010.; Guex et al., 2012; Blackburn et al., 2013; Wotzlaw et al., 2014; Davies et al., 2017; Davies et al., 2021) but the mechanism behind the extinctions, the climate changes driven by CAMP purported to have caused the ETE, and CAMP eruptive dynamics are, murky. North American CAMP eruptive rocks preserved in the Hartford Basin and Deerfield Basins and all are present in every basin with preserved strata of ETE and younger age. These CAMP extrusives all preserved as deeply eroded remnants in the rift basin fill on the northwestern periphery of the CAMP with much more in the way of eruptive CAMP buried beneath the coastal plain and continental shelves of the central Atlantic conjugate margins and in Iberia, Morocco and here and further east in North Africa and in South America. Even more of the CAMP preserved as intrusives, especially in Africa and South America. This is important because our view of CAMP is extremely biased to a relatively small part of the system and the original volume of CAMP eruptive is not well constrained. Estimates range from assuming the entire area underlain by intrusives, were previously overlain by flows (McHone, 1996) to the present remnants of flows is not vastly small than their original distribution (Kent and Muttoni, 2013). However, soil carbonate proxy and stomatal proxy data show that there was a doubling to tripling of pCO^2 during CAMP time [see review in (Schoepfer et al., 2022) and references therein].

Regardless of their original extent, the flows of the Hartford and Newark Basins, are is thus far the only place in which there is a sedimentary proxy record (in this case soil carbonate) of massively increased atmospheric CO$_2$ (pCO$_2$) in superposition with the lavas that are part of the eruptive events that led to the CO$_2$ input and subsequent proposed global warming (Schaller et al., 2011; Schaller et al., 2012; Schaller et al., 2015; Schaller et al., 2016) (Figures 7). In all other areas, the pCO$_2$ proxy records must be

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[1] This number differs from and is larger than previous passements, because PEO used Google Earth (projection on a sphere) and the "Latest Triiassic_Spgeog_994.kmz" from the Scotese PALEOMAP Project (2013) along with the map locations of Marzoli et al. (2018) for CAMP locations. Other estimates are assumed to have been on flat and hence inaccurate projections.

tied into the volcanic record by inferential means, so far without the independent high-resolution geochronology.

CAMP lava flows in the Hartford and Deerfield Basins are interbedded with thick, cyclical lacustrine strata composed of three major flow intervals, which are in ascending order, Talcott, Holyoke, and Hampden Basalts in the Hartford Basin, and the Deerfield Basalt in the Deerfield Basin (Figures 3, 6). These are quartz tholeiites lava formations with at least the Holyoke comprised of multiple flow units. The Hartford Basin is thus far the only place in the CAMP where specific feeder dikes are convincingly physically associated with specific vents and flows based on physical stratigraphy [i.e., Talcott Basalt – Fairhaven Dike (Philpotts and Martello, 1986) and Hampden Basalt – Black Rock Diabase (Foose et al., 1968)] and all three all three basalt flow formations can be tied to specific dike systems by petrology (Philpotts and Martello, 1986) including the Holyoke – Buttress–Ware Dike. Two very thin airfall ashes called the Pompton Ashes (or Tuffs) are also present in the Hartford Basin (Olsen et al., 2016) (as well as in the Newark Basin), and these are the only known airfalls in the CAMP (Figure 8). The Hartford basin, thus offers one of the best places to examine the eruptive processes and consequences of these globally impactful events.

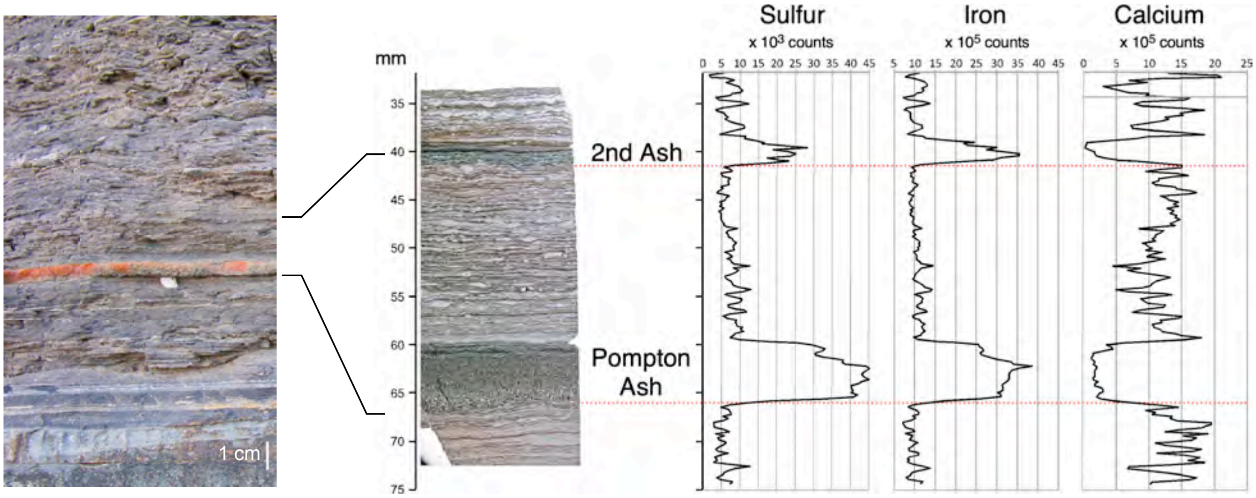

Figure 8: Appearance of the Pompton Ashes in outcrop at East Berlin, CT, in thin section, and in µ-XRF major element composition from a slabbed outcrop sample in Durham, CT.

Although there are strong similarities in CAMP stratigraphy between the Newark, Hartford, and Deerfield Basins, there are some major differences, the largest of which pertain to a trend of decreasing frequency of flow preservation from south to north (Figure 6). In the Newark Basin, there are three distinct cooling units in the Orange Mountain Basalt, the second of which tends to be pillowed. In the Hartford Basin there are either one or two flows in the correlative Taklcott Basalt, the lowest of which tends to be pillowed, with the Talcott being absent from the Massachuetts part of the basin — with no equivalent in the Deerfield Basin. In the Newark Basin, there are five distinct Preakness Formation flows; the lower two of which are of high-iron, quartz normative (HFQ) composition; while the upper three, separated from the lower two by a thin (~3 m) but laterally persistent red and gray sedimentary sequence, of are of low-titanium, quartz-normative (LTQ) composition (Tollo and Gottfried, 1992). There are no chemical or stratigraphic equivalents of these three flows in the Hartford Basin, and importantly, their stratigraphic position is taken by lacustrine strata of the lower East Berlin (see discussion below) that have no known counterpart on the Newark Basin, except the afore mentioned thin sedimentary bed in the Preakness. Instead, the HFQ Holyoke Basalt consists of two flows, the lower being discontinuous. A similar sequence of two HTQ flows comprises the Deerfield Basalt. The identity of the second HFQ flow being the same eruptive event in the Newark, Hartford, and Deerfield Basins seems fairly certain because of their matching but unusual paleomagnetic directions (Prévot and McWilliams, 1989). The high-iron, high-titanium, quartz normative (HTFQ) Hook Mountain Basalt in the Newark Basin is very similar to the chemically indistinguishable Hampden Basalt (Tollo and Gottfried, 1992), but the latter is replaced by the Granby Tuff in the northern Hartford Basin near its feeder system of the Black Rock Diabase (Brophy et al., 1967; Foose et al., 1968). There is no equivalent in the Hook Mountain-Hampden, in the Deerfield Basin.

***Competing Radiative Forcings from the CAMP**:* CAMP volatiles should have perturbed Earth's radiative balance in two opposing ways (Figure 9). Outgassed CO_2 would be expected to have caused global warming via the greenhouse effect, while SO_2 would be expected to cause increased albedo, dimming, and if large enough, volcanic winters.

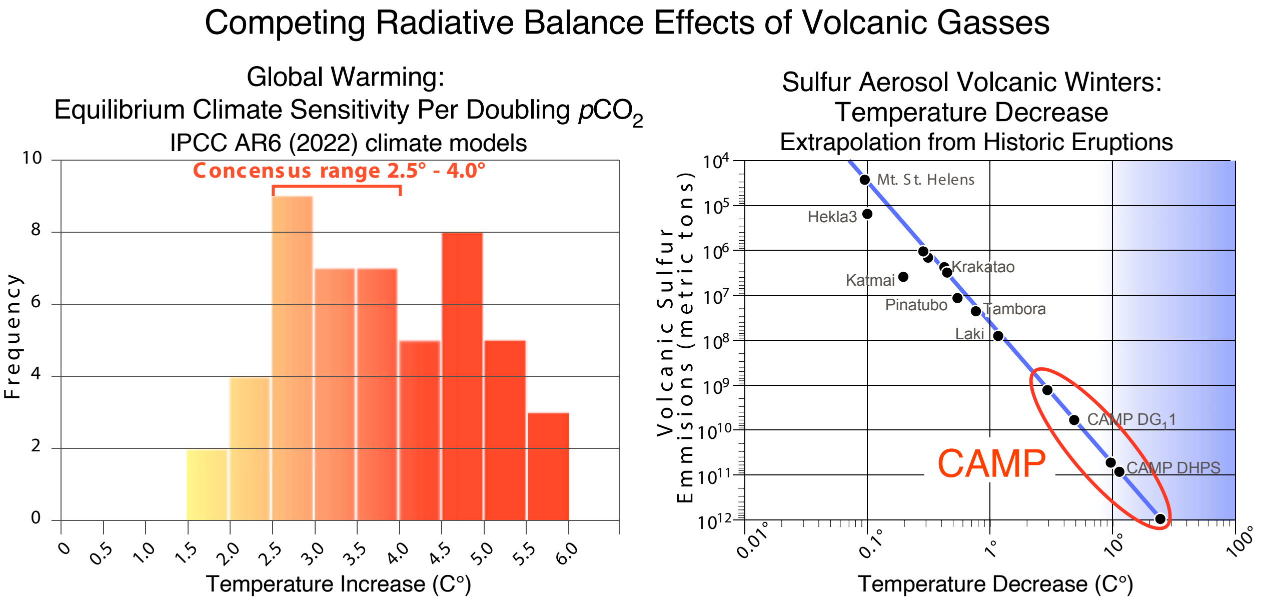

Figure 4: Volcanic eruptions produce both warmings and coolings, but volcanic winters are more dramatic than global warming, although much shorter in duration. Volcanic winters of the CAMP may have been the main drivers of mass extinctions on land rather than CAMP global warming. Modified from (McHone, 2003; IPCC, 2021). Measured CAMP sulfur concentrations suggesting 8 MT S release per km^2 are consistent with these numbers per eruption (Callegaro et al., 2014; Kent et al., 2024). CAMP $DG_1 1$ (NW Aftrica) and DHPS (Deerfield+Holyoke+Preakness+Sander Basalts) based on total area using sulfur estimates of (Callegaro et al., 2014).

The two forcings, however have very different recovery (e-folding) times by 5-orders of magnitude: modeled CAMP-related pCO_2 doubling takes about 300 kyr to return to base level (Schaller et al., 2012); but, once volcanic SO_2 input ceases, background levels return in 2-3, maybe up to 5 years (Robock, 2015; Brenna et al., 2020). Expected temperature changes for a doubling of pCO_2 by CAMP would be expected to be around the canonical 3° C. However this assumes unchanging Earth system sensitivity, which may not be the case, and it could be non-linear [e.g., (Bloch-Johnson et al., 2021)]. Models simulating sustained super-eruptions tend not to increase the maximum drop in temperature even with much larger sulfur loadings [e.g., (McGraw et al., 2024; Enger et al., 2025)], maxing out at about ~10° C change, with most results showing much less change. This may indicate extrapolation from historic eruptions to earlier much larger eruptions, as in Figure 9, may not be valid. This does, of course, ignore the possibility of ice-albedo feedbacks, which could be critical.

Evidence for doublings to triplings of pCO_2 directly associated with the CAMP LIP is strong (Figure 7) and there is similar evidence, perhaps less compelling tied to a LIP, for several other instances of abupt biotic turnover (Figure 10). It is noteworthy that the increase associated with the CAMP looks so large, not because peak concentrations were so high, but because pCO2 was declining for several million years prior to the CAMP, and kept declining afterward. After all, the Triassic continental biota seemed in relatively steady state for similar CO_2 concentrations during 20 million years of the Late Carnian and Norian. Is it possible that the opposing radiative balance forcing of CAMP sulfur aerosol-driven increase in albedo could have been the extinction driver?

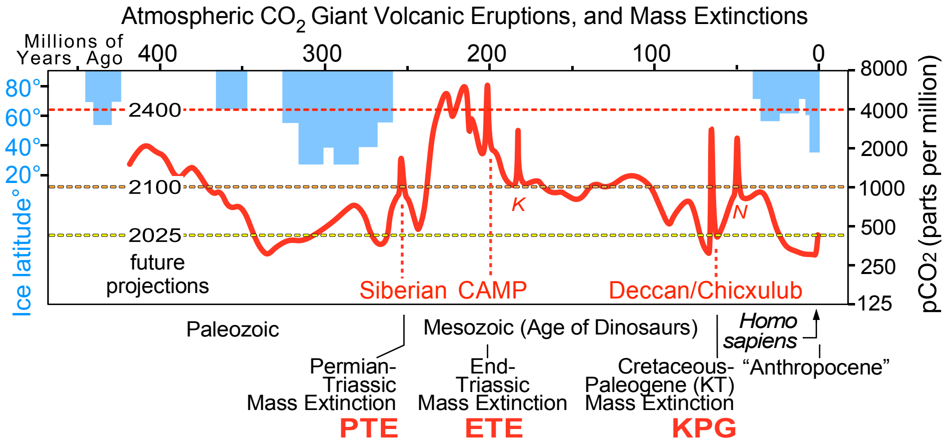

Figure 10: Conceptual history of atmospheric carbon dioxide (**pCO_2**) over the last 425 million years along with major volcanic events (Siberian, CAMP, Deccan, *K*-Karoo, *N*-North Atlantic), asteroid impact (Chicxulub), mass-extinctions (PTE, ETE, KPG), and ice ages (Ice Latitude). The Connecticut Valley record focuses on 200 million years ago. Based, but strongly modified from (Foster et al., 2017).

SO_2 from CAMP eruptions would be expected produce significant sulfate aerosol-driven global dimming and major volcanic winters, as discussed above. But is it reasonable to think volcanic winters from the CAMP could be sufficient to have global effects of sufficiently great magnitude that could overwhelm the pCO2-driven global warming? Modeling results show that it is possible. CAMP pulsed eruptions, unlike those experienced plausibly occurred over tens of years or longer, not months. This would allow time to develop strong convective plumes driving the eruptive products far higher than explosive short-lived eruptions, and allow for greater geographic transport away from their sources, possibly globally.

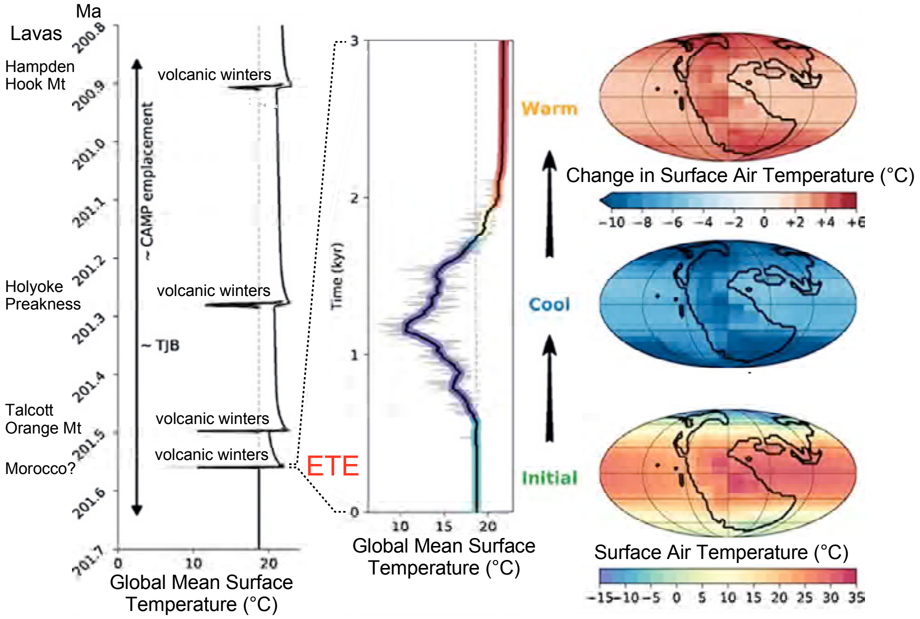

Figure 11: Modeled results of repeated, pulsed eruptions of CAMP lavas producing injections of sulfur aerosols causing volcanic winters that override the effects of global warming caused by CAMP CO_2. Modified from Landwehrs et al. (2020).

Landwehrs et al. (2020) show that repeated eruptions over 1000 years could produce an 8-10° C average annual global temperature drop, even taking into account for the 2-5° temperature increase caused by global warming from CAMP pCO_2-doubling (Figure 11). At times, global mean temperatures got within six degrees of freezing. However, this model may underestimate the effects of the sulfur injections. In this model, the aerosol pulses were short, ~10 years, from injection during explosive eruptions to return to background. As discussed, at least the largest CAMP eruptions had sustained plumes and the effect would have been much more intense, although this has yet to be modeled. Interannual temperature variations could be extreme. Both positive (global warming) and negative (volcanic winter) radiative balance-driven temperature changes were simulated as generally less for the lower latitudes and more for the higher latitudes for both the ocean and continental interiors (Figure 11).

In polar regions, summertime cooling from volcanic winters would be expected to be more intense than wintertime, simply because albedo increases from sulfate aerosols are only important when there is sunlight to reflect. A drop in polar summertime temperatures would be expected to drive the balance between wintertime sea ice development and summer melting towards less melting and higher sea ice albedo. Polar regions also experience the greatest climatic effects of obliquity, and the combined effects of the volcanic winters and sea-ice albedo feedbacks could result in amplification of the obliquity effects.

The Late Triassic-Early Jurassic continental Arctic was already experiencing wintertime freezing (Olsen et al., 2022b; Olsen et al., 2024f), and low-elevation mountain glaciers may also have been present (Figure 12). Reduced summertime snow melt during volcanic winters could have tipped the Arctic system into a period of glacial growth, perhaps resulting in a polar ice cap that, via reduced albedo feedback would last much longer than the volcanic winter itself.

Figure 12. Paleo-arctic lake-Ice rafted debris (L-IRD) from the Early Mesozoic, Junggar Basin, near Karamay, Xinjiang, northwestern China. A, Granule to small pebble sized L-IRD, Early Jurassic Badaowan Formation in laminated mudstone with abundant insects, arthropods and rare articulated fish. B-C, Large L-IRD in the form of *in situ* dropstones in laminated mudstone: B, Late Triassic Baijaintan Formation; C, Early Jurassic Badaowan Formation. Photos: A, Yanan Fang (NIGPAS), B and C, PEO.

The continental area of Arctic Asia during the Triassic-Jurassic transition was much larger than the area of Antarctica in the Miocene (Figure 13). Increased continentally may have exacerbated growth of ice sheets, all of which may have enhanced the effects of the volcanic winters.

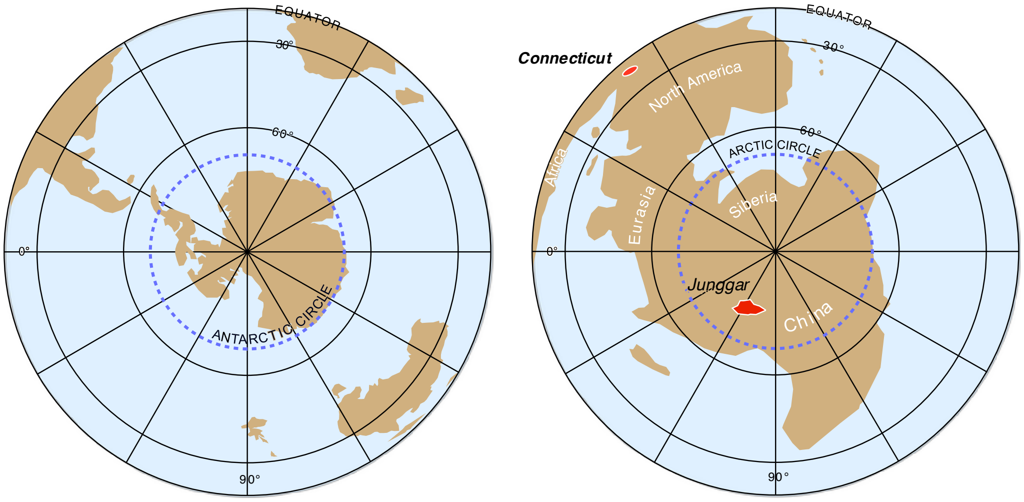

Figure 13. Comparison between Miocene (~18 Ma) Antarctic continental area with Triassic-Jurassic (202 Ma) Asian Arctic area. Miocene from Gasson et al. (2016) and GPlates Marcilly et al. (2021) and Triassic-Jurassic from (Olsen et al., 2024g). Much of Siberia adjacent to the proto-Arctic Ocean basin would have been submerged in the Lena Sea, but vast uplands were present as well (Frolov et al., 2024).

Increased polar ice-albedo feedback during CAMP volcanic winters may also have amplified Earth system sensitivity to obliquity forcing, driving the Earth System to a new albeit transient state, perhaps not unlike an abbreviated version of the "40 kyr" world of the Late Neogene [e.g. (Westerhold et al., 2020)] in which polar effects were exported globally. It may even be possible that, if the CAMP volcanic winters, especially during the first and largest pulse of eruptions around 201.5-201.6 Ma were sufficiently sustained, polar continental ice sheets could grow large enough to drive the observed, abrupt sea-level sea level fall most clearly seen in the European basins, as suggested by Schoene et al. (2010.).

CAMP Effects on lacustrine cycles

The CAMP eruptive volatile emissions plausibly caused linked, but competing, radiative balance disruptions and there is evidence of significant although transient changes to the Earth system translation of Milankovitch insolation cycles to climate cycles on Earth. The effects on warming have been famously modeled for the current increases in pCO_2, but also and specifically on the effects CAMP as revealed by Newark and Hartford Basin lacustrine cyclicity (Landwehrs et al., 2022) (Figure 14). Results are consistent with amplification of the hydrological cycle due to increased pCO_2 and consequent global warming. This follows the "dry gets drier, the wet gets wetter" (DDWW) paradigm, which is a simplified mantra for the idea that increasing warmth should intensify Hadley cell circulation as well as the capacity of the atmosphere to hold water vapor. State of the art modeling results based on the Newark-Hartford pCO_2 proxy record and lake level data strongly support concept the DDWW concept at orbital time scales (Landwehrs et al., 2022). New XRF elemental chemistry of Newark Basin cores provides a new perspective on these changes (Olsen et al., 2024a; Olsen et al., 2024b; Olsen et al., 2024c; Olsen et al., 2024e).

During the ~25 Myr of very high pCO_2 during the Late Carnian to Late Norian (based on the paleosol carbonate proxy) lacustrine strata of the Newark Basin were characterized by remarkably strong and obvious cyclicity with extreme variations in facies raging from deep, chemically stratified lakes to playas. Contemporaneous, similar sequences occur in the Gettysburg, Culpeper, Taylorsville, Dan River, and Deep River Basins (Olsen et al., 1989; Olsen and Kent, 2000; LeTourneau, 2003; Olsen et al., 2004; Olsen et al., 2015; Olsen et al., 2022a).

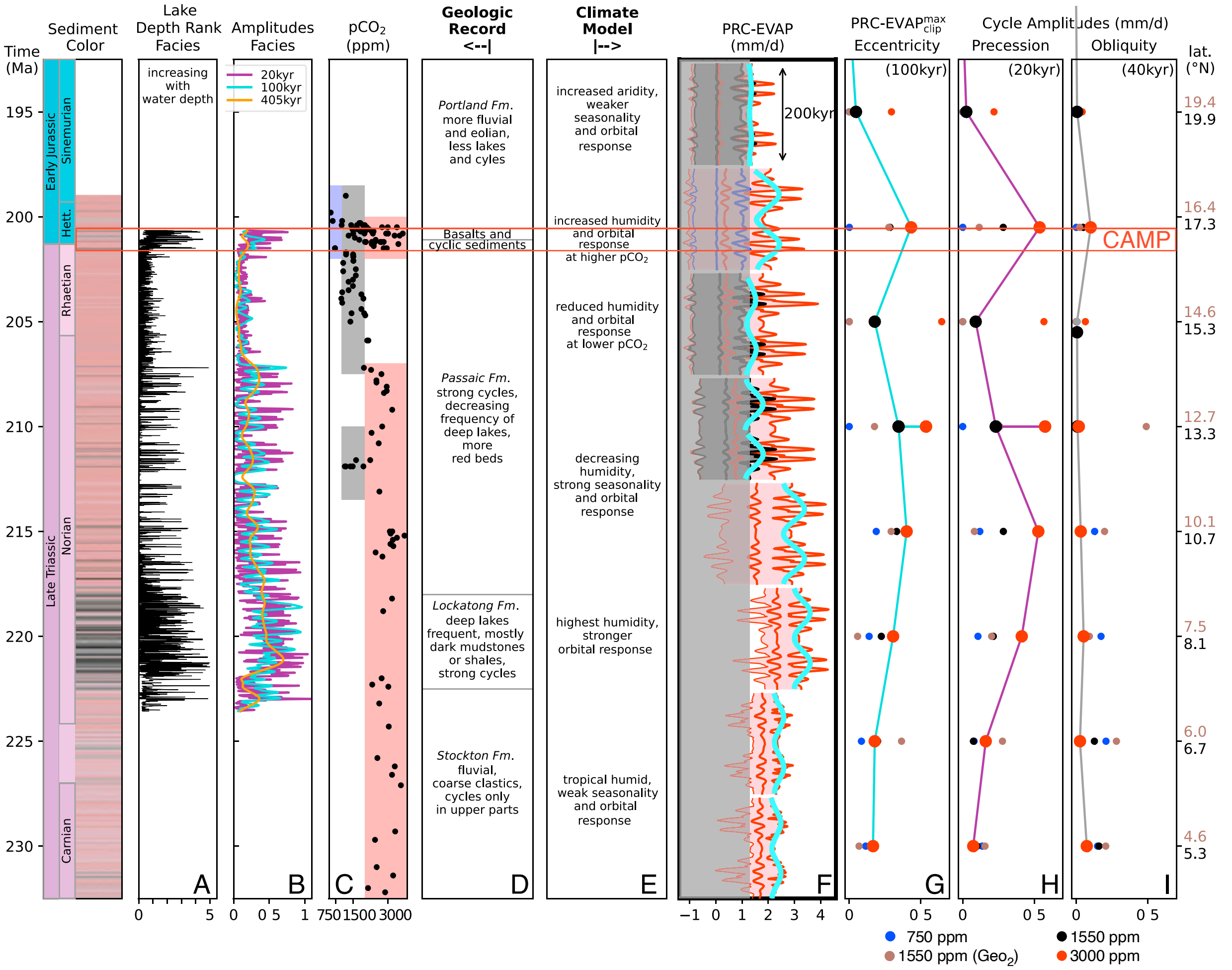

Figure 14: Modeled relationships between pCO₂ and modulation of cyclicity magnitude and precipitation minus evaporation [modified from (Landwehrs et al., 2022)]. A, Depth ranks from (Olsen et al., 2019a); B, Amplitudes of depth rank cycles in different frequency regimes; C, pCO₂, based on the soil carbonate proxy from (Schaller et al., 2015); D, Description of facies; E, Summary of results from the climate models; F, Modeled precipitation minus evaporation maximum, mean, and minimum values shown for transient 200-ky simulations at pCO₂ = 3,000 ppm (red) and additionally 1,500 or 750 ppm (black or blue) where lower pCO₂ values are suggested by proxy data. Turquoise lines indicate the amplitude of the eccentricity component. Darker gray areas indicate values below the humidity threshold required for persistent lakes – note that they occur during times of lowest pCO₂, while the highest magnitude fluctuations in precipitation occur during times of high pCO₂. Position the Norian-Rheatian boundary has been moved to conform with Wotzlaw et al. (2014) and (Maron et al., 2019).

This changed dramatically at about 207 Ma as pCO₂ dropped to about half the previous concentration. The dramatic extremes in facies within lake cycles disappears, replaced by a much more muted cyclicity, consistent with models (Figure 14). This is seen in all contemporaneous strata in exposed US rift basins. Despite being subtle, the lacustrine cyclicity displays remarkable fidelity to astronomical pacing in these strata as revealed by Newark Basin XRF and natural gamma data with strong precession and short eccentricity pacing and an apparent increase in the strength of the obliquity-related inclination cycle pacing (Margulis-Ohnuma et al., 2021b; Olsen et al., 2024e). All but the latest Rhaetian follows this pattern.

When pCO₂ increases in the Latest Rhaetian and Hettangian during CAMP eruptions back to Carnian early-middle Norian levels, the extreme expression of lacustrine cyclicity returns as well, a feature best seen in the middle to upper Towaco and East Berlin Formations of the Newark,, Hartford (Figure 15) and Culpeper Basins (Olsen et al., 2023a). However, the latest Rhaetian and earliest Hettangian age strata show a very strong deviation from the pattern seen in both older and younger strata — obliquity pacing becomes dominant over precession overlapping in time with peak CAMP eruptions (Figure 7).

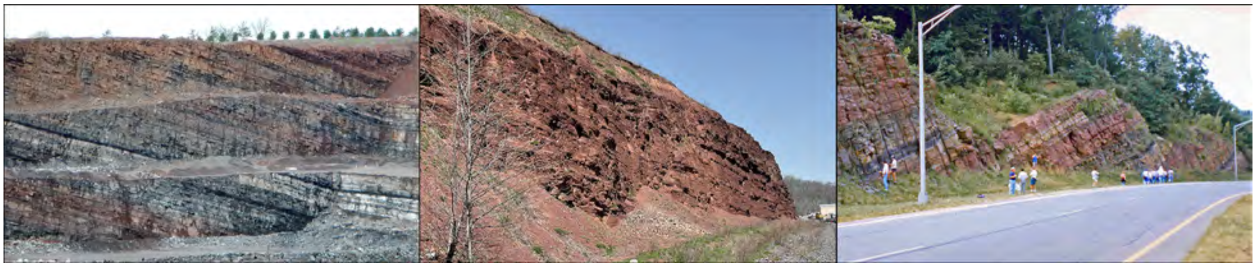

Figure 15: Examples of lake-level cyclicity under different pCO_2 levels. From left to right: Early Norian, Lockatong Formation at about 3000 ppm (H&K Skunk Hollow Quarry, Chalfont, PA); Late Rhaetian, upper Passaic Formation, at about 1500 ppm (Stavola Quarry, Bound Brook, NJ); and early Hettangian, East Berlin Formation at about 3500 ppm (East Berlin, CT). Cyclicity in the upper Passaic is almost not discernable.

Until 2024, the fundamental assumption guiding understanding of the relationship between the CAMP flows and climate and biotic change was that climatic precession modulated by eccentricity was the dominant pacemaker of background events as should be expected in the tropics. However, the new XRF data from the Newark and Hartford basins cores shows that this assumption is incorrect and obliquity and its modulator inclination, have a much larger role than previously suspected. This becomes extremely relevant to the Earth System perturbation caused by the CAMP and the consequent mass-extinction.

The first major change in interpretation involves the pacing of cyclicity at the ETE. The biotic record of the continental ETE is best seen in uppermost Passaic Formation of the Newark Basin, below the oldest CAMP flow, where it was first recognized on the basis of pollen and spores (Cornet, 1977; Cornet and Olsen, 1985; Fowell and Olsen, 1993; Fowell et al., 1994; Fowell and Olsen, 1995). Initially, as seen in the Newark Basin Martinsville no 1 core, it was assumed that the cyclicity of the upper Passaic Formation calibrated by the depth rank and lithologic expression of the 405 kyr long eccentricity cycle continued unchanged directly up to the Orange Mountain Basalt. Lacking evidence to the contrary this assumption was maintained even though the cyclicity was extremely muted in this interval, and the position of the palynological change had to be projected into Martinsville core from the fossiliferous outcrops in Exeter Township, PA, 120 km away using the ratio of thickness between reverse polarity chron E23r[35] and the basalt, known at both sites (Olsen et al., 1996a). Under this assumption, the thickness of E23r corresponded to about 26 ky and the 9 m interval between the ETE and basalt was assumed to be about 28 kyr, slightly more than one climatic precession cycle.

However, the Exeter site has much more obvious lithological variability than the Martinsville core, including dark to light gray laminated mudstones alternating with red mudstones. The main color alternation at Exeter was assumed to reflect the climatic precession cycle, which as noted above, was thought to dominate the entire sequence as seen in previous work [e.g., (Van Houten, 1962; Olsen, 1986; Olsen and Kent, 1996; Olsen et al., 2019a)]. The biggest-scale pattern of gray beds seemed a close match to what was seen in other parts of the section, including the Jurassic part of the Newark and Hartford sections. Projected onto Martinsville, this resulted in a doubling of the accumulation rate (Olsen et al., 2002) so that the time from the ETE to the basalt was now estimated at 14 kyr (Blackburn et al., 2013) and about halving of the duration of E23r (Figure 16).

The increase in accumulation rate approaching the basalt seemed plausible because it was already known that the cyclicity in the Feltville Formation overlying the Orange Mountain Basalt resembled that of Exeter and has much higher accumulation rate than in the Passaic, assuming the largest-scale cyclicity in the Feltville and Towaco ACE cores was paced by precession[36] (Olsen et al., 1996a; Olsen et al., 1996b). So, if the trend through the CAMP was for the accumulation rate to be increasing, presumably related to increased basin asymmetry, relief, and accommodation space, why would be not we expect to see that change starting just before the first CAMP erupted. Everything seemed to be in agreement.

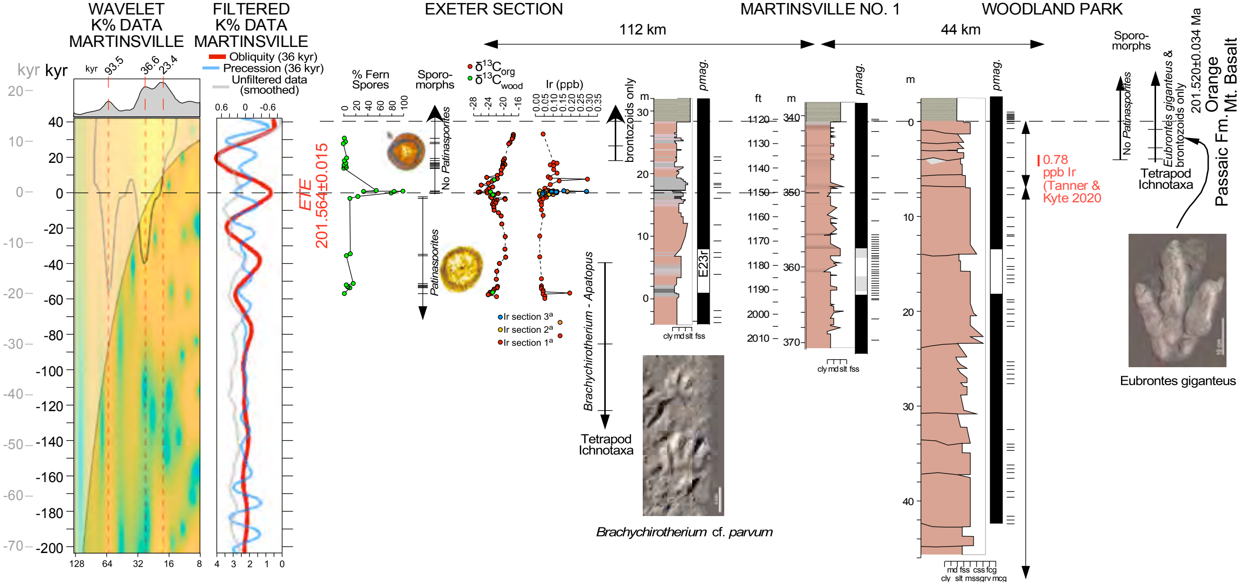

Figure 16: Data for the continental ETE in the Newark Basin. Old time scale based on supposed climatic precession on left in gray; new time scale based on elemental XRF data and [TimeOpt method (22.4851 cm/kyr (Meyers, 2015)] showing obliquity pacing on right. Data from Exeter section from Whiteside et al. (2021) and ages from Blackburn et al. (2013). Pollen grains shown are *Classopollis meyeriana* (above) and *Patinasporites* densus (below). Note order of magnitude increase in amplitude of filtered data at the obliquity frequency just where the Wavelet spectrum shows significance at the p = 0.05% level (black line) while the amplitude of filtered precession is unchanged from lower down.

The new elemental XRF data from the Martinsville core, forces a reinterpretation. The Mn/Fe redox proxy and the K clay proxy show an exceptionally clean orbital pacing pattern with accumulation rates staying remarkably constant through the entire upper Passaic of the core. But there is no sign of an accumulation rate increase towards the basalt (Hinnov and Cozzi, 2020; Olsen et al., 2024c; Olsen et al., 2024e) very much in line with the original 1995 interpretation. It had also already been shown by Hinnov and Cozzi (2020) using depth ranks and Margulis-Ohnuma et al. (2021a) using natural gamma radiation, that obliquity and inclination were unusually strong, in the almost entirely red upper Passaic Formation in the Martinsville core, and the 405 kyr long eccentricity cycle was unusually weak, even though the ~100 kyr short eccentricity cycle was very strong and spectacularly regular.

But the big surprise from the XRF data is that obliquity pacing dramatically increases in power towards the basalt becoming dominant in the interval containing E23r and the palynological ETE. Projecting back from Martinsville to the Exeter outcrops, what was thought to be an expression of climatic precession pacing, is actually obliquity. The precessional cyclicity is still there, just muted. This is why the accumulation duration for E23r and the time between the ETE and the basalt were robustly half of what was expected from relying on the Exeter interpretation.

This obliquity dominance is also characteristic of the overlying Feltville Formation in the Newark Basin and the equivalent Shuttle Meadow in the Hartford Basin as shown by the analysis of the Silver Ridge B-1 core in the Shuttle Meadow Formation recovered in 2002 (Whiteside et al., 2011). Prior to this core, the stratigraphy of the lower Shuttle Meadow Formation was basically unknown, and the various small, isolated, albeit very fossiliferous outcrops (McDonald, 1975, 1992) could not be assembled into a reliable composite stratigraphy. In broad strokes, the core stratigraphy turned out to be closely comparable to the lower Feltville Formation as seen in ACE cores (Olsen et al., 2024e). Although this clarified the stratigraphy of the various fossil fish localities in the Hartford Basin, it was confusing because there seemed to be twice as many well-developed dark-mudstone units as in the Feltville, although a one-to-one match of beds was still straightforward. The simplest interpretation of time series analysis of color, depth rank, total organic content (TOC), and bulk organic stable carbon isotopic ratios ($\delta^{13}C_{org}$), was that a ~20 kyr climatic precession paced cycle was indeed present, as was a ~10 kyr hemiprecession cycle, not unexpected in the tropics (Berger and Loutre, 1997). However, when compared to the Feltville, it was clear that the what was thought to be a reflection of the ~20 kyr climatic precession cycle demarcating the best developed, deep water, fish-bearing units could not be, and instead it had to be a cycle with about two times the period – in other words, obliquity. This implied very strong obliquity in the tropics — more pronounced than precession.

The East Berlin (Hartford Basin) and correlative Towaco (Newark Basin) Formations have long been interpreted as precession dominated (Olsen, 1986; Olsen et al., 1996b). It came as a major surprise, therefore that when Metropolitan District Commission (MDC) cores of the East Berlin Formation were revealed (Steinen et al., 2015; Conti, 2016; Olsen et al., 2019b), it turned out that not only was the lower one third of the East Berlin not represented by correlative strata in the Towaco, but that it was also obliquity pacing dominated (Figure 17) (Olsen et al., 2024b; Olsen et al., 2024c; Olsen et al., 2024d; Olsen et al., 2024e).

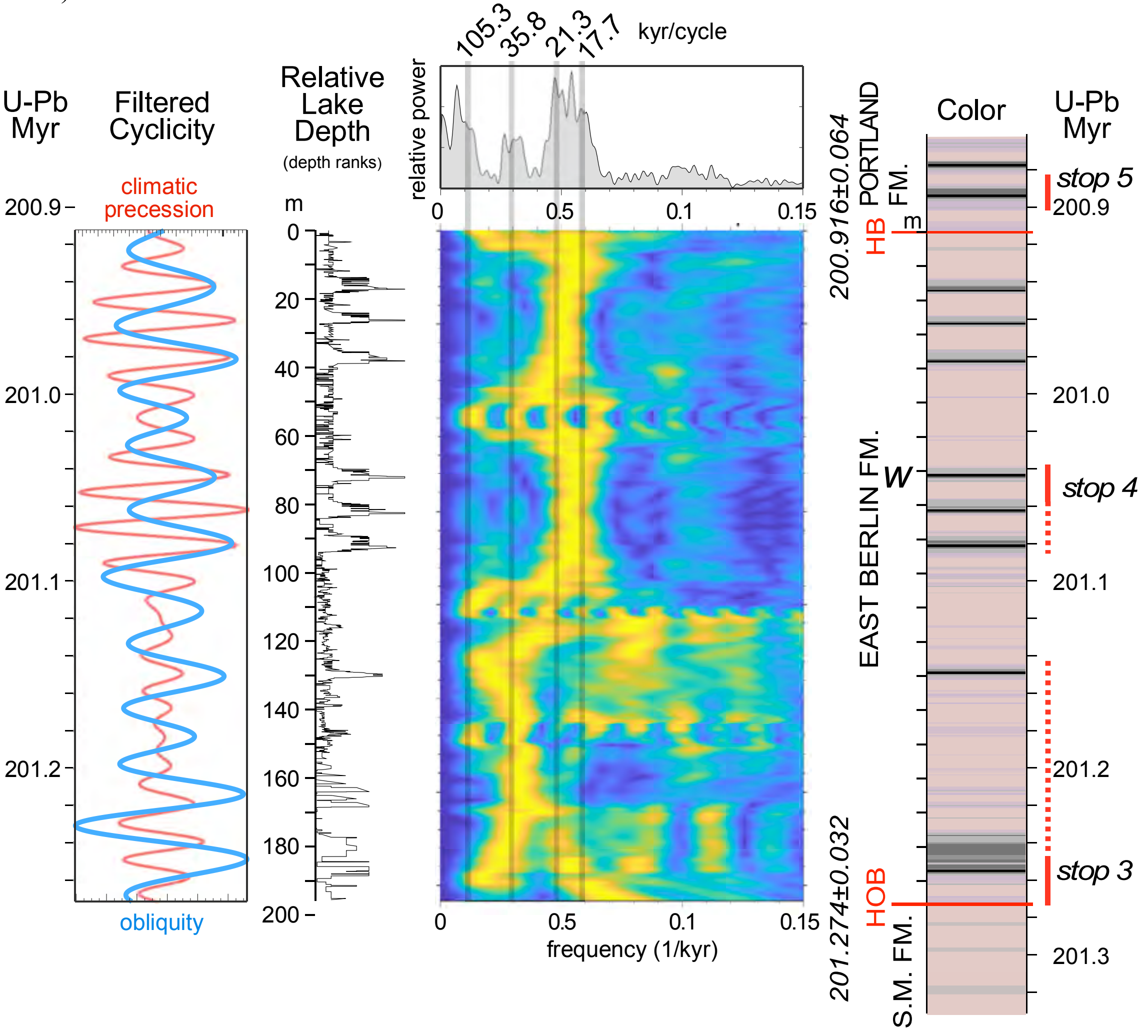

Figure 17: Composite stratigraphy and cyclicity of the East Berlin Formation based on (Olsen et al., 2019a). Thickness scale is based on MDC cores (Conti, 2016) and time scale is based on zircon U-Pb ages from correlative Newark Basin CAMP flows (Blackburn et al., 2013). Note the strong expression of obliquity compared to climatic precession in the lower East Berlin. Lava flows are shown as if they had no expression in time. HB, Hampden Basalt; HOB, Holyoke Basalt; S.M., Shuttle Meadow; W, Westfield Bed with Pompton Ashes.

Thus, obliquity dominates over climatic precession in the Pangean tropics from about 201.6 Ma, just before the ETE to about 201.1 Ma which overlaps with peak CAMP emplacement (Figure 7), and most of the duration of the CAMP. Could this amplification of the obliquity-related lake level cycles by high pCO_2 be the cause of the 500 kyr of obliquity dominance? The answer seems to be no, because although there is a small response predicted in the models (Landwehrs et al., 2022), there is never anything like these obliquity-paced cycles with dark gray to black mudstones predicted or present in the rest of the 21 million year Newark record. This includes the minimally 16-million-year-long interval of the of the Late Triassic with pCO_2 averaging as high as during the CAMP event (Figure 14). In addition, the two major obliquity-paced, whole-fish-bearing cycles in the Shuttle Meadow and Feltville Formations are completely unique in the entire Newark and Hartford Basin records and not a single fish-bearing, dark mudstone-bearing cycle is known from any other Mars-Earth, eccentricity low. If neither amplification of the hydrological cycle by high pCO_2, nor damping of the precession cycle during Mars-Earth, eccentricity lows explain the powerful CAMP obliquity-pacing, what could?

As discussed above, a plausible cause could be amplification of obliquity sensitivity by CAMP-triggered ice-albedo feedback. A potentially testable implication is that evidence of volcanic winters should be preserved in strata deposited during CAMP eruptions. In the Hartford Basin, these strata should include the basal East Berlin and the upper New Haven Formation, units deposited during upper flow sequence of the Preakness Basalt (Stop 3) and the Moroccan lower basalt flow sequences, respectively.

Testing the Alternative Scenarios

Two potentially testable predictions of the occurrence of volcanic winters would be direct evidence of a temperature drop and evidence of stratospherically transported sulphate aerosols, associated with CAMP products. Evidence of a temperature drop might be looked for using $\delta^{18}O$ or more reliably $\Delta 48$ and $\Delta 49$ (clumped isotopes) in carbonates. Impressions of ice crystals, glendonites, sailing rocks, and abundant ice-rafted debris could also provide evidence, but search for them might be unrealistic or difficult to interpret. Evidence of stratospherically transported sulphate aerosols would be sulfur mass independent fractionation ($\Delta^{36}S$, $\Delta^{33}S$) in gypsum, barite, or pyrite, although it is possible the signal could be diluted by indigenous lake sulfate.

Focused targets for testing the volcanic winter hypothesis should be sediments known to have been deposited during a CAMP episode or direct examination of a known eruptive product such as a flow or an ash. The interval around the ETE is apparently correlative to at least one major Moroccan flow sequence (the Tasquint Formation in the Argana Basin or lower basalt formation elsewhere) would be one key target. Other intervals would be the middle Shuttle Meadow and Feltville Formations that should have been deposited during the eruption of the Hickory Grove Basalt in the Culpeper Basin and the lower East Berlin Formation, deposited during the eruption of the upper Preakness and perhaps upper Sanders Basalt in the Newark and Culpeper Basins.

An additional, hitherto, completely overlooked source of information on volcanic winter aerosols (among other aerosols types), could the upper surface of the lava cooling units themselves, especially tops of the last cooling unit from an eruption. The exposed rough surface of fresh basalt flows, with innumerable blind cavities of many sorts may provide a potential place to trap aerosols with minimal dilution. The very first materials contacting the rough basalt surface would plausibly be aerosols and ash from the same eruption that produced the flow. Such material could reach the surface of the flow lobes as well, prior to burial by the advancing flow at timescales relevant to the eruption.

However, for chemical tests of the volcanic winter hypothesis to be viable, the mineral phases examined need to be a little altered as possible, especially by weathering. Not only can that remove soluble minerals such as calcite and gypsum, it can replace them with another mineral. The weathering from commonly extends to depths in excess of 50 m, sometimes hundreds of meters, and therefore coring is highly desirable, plausibly necessary except in unusual cases, such as the Pompton ashes, encased in carbonate rich, practically impermeable rock. To be serious about tests of the causes of the ETE, scientific coring projects are certainly necessary.

Although one might argue that coring projects in continental environments sample inherently local processes, that is not the case. Evidence of stratospheric volcanic sulfates, large-scale temperature changes, accelerated weathering due to high pCO_2, would by the nature of the processes themselves be evidences of very large scale or global processes. Furthermore, unlike marine strata, at least in venues thus far studied, coring in the rift basins with CAMP lavas removes the uncertainty that now plagues supposed proxy relationships with the LIP, in which the accuracy of the proxies are uncertain and the temporal relationships cannot be independently verified.

Biotic Consequences of the CAMP — the ETE on Land

The end-Triassic extinction on land was characterized by a major loss in biotic diversity, both in fauna and flora, in all the multifarious ways diversity can be defined (Figure 1). The details of timing leading up to the continental ETE, however, are blurry, first because of a relative dearth of rich Rhaetian (last age/stage of the Triassic) assemblages, especially in the low latitudes, and second because of a lack of temporal resolution. This preface is necessary, because, when we look at the ETE as a very granular level, our security drops in that actually went extinct at the level we are talking about here, i.e., what was the effect of the CAMP? Therefore, we are reduced to talking here in broad strokes, focusing on the continental biota but at least that allow us to frame hypotheses that might be direct us towards focused sampling campaigns.

All living groups of tetrapods appear in the Late Triassic, including amphibians (lissamphibians), turtles, lizards, sphenodontians (the Tuatara), crocodilians, dinosaurs (birds, today), and mammals. Many other tetrapods groups were also present in the Triassic, some having survived from earlier periods, others endemic to the epoch. Together their taxonomic, morphological, and ecological diversity both in marine and continental environments was enormous, especially among reptiles. There were many kinds of all stem-crocodilians, the remarkably diverse pseudosuchians. These included herbivorous forms, as well as the large low latitude top predators (the rauisuchians and large sphenosuchians), semiaquatic, very crocodile-like, carnivorous, forms the phytosaurs. And a very diverse assemblage of smaller reptiles including the procolophonids (looking like a cross between a horny toad and woodchuck), the drepanosaurs (sometimes called the monkey-lizards of the Triassic), the tanystropheiids (long-necked semi aquatic forms), vancleavids (large-fanged, semiaquatic heavily armored reptiles with tiny limbs, most of which were small), allokotosaurs (often bizarre, plausibly herbivorous forms). Noteworthy, is that many Late Triassic non-dinosaurian forms, especially among the pseudosuchians were convergent on much later dinosaurian forms. This included non-dinosaurs mimicking pachycephalosaurids (dome heads), ornithomimid (ostrich mimics), ankylosaurus (armored dinosaurs), and small gracile ornithischians (Stocker et al., 2016). All of these non-dinosaurian ecological precursors fail to survive the ETE. Of the Triassic forms that go extinct, the procolophonid *Hypsognathus fenneri* (Sues et al., 2000), the aetosaur *Stegomus arcuatus* (Marsh, 1896), the crocodylomorph *Erpetosuchus* sp. (Olsen et al., 2000; Foffa et al., 2020), and an indeterminant phytosaur ironically named "*Belodon validus*" (Marsh, 1893) are known from the New Haven Formation of Connecticut. One surviving group is represented by the sphenodontian *Colobops noviportensis* was found in the New Haven Formation (Sues and Baird, 1993; Pritchard et al., 2018; Scheyer et al., 2020).

Dinosaurs and their close relatives were present by the beginning if the Late Triassic. This includes a fairly diverse group of non-dinosaurian dinosauromorphs, the lagerpetidids, the lagosuchids, silesaurs, and the pterosaurs. Pterosaurs are the flying close relatives of the dinosaurs and definitely make it into the Rhaetian, and of course survive the ETE. Dinosaurs also survive the ETE, but the non-pterosaurian, non-dinosaurian forms do not, and may not have even made it into Rhaetian. As yet, there are no dinosaur or other dinosauromorph bones from Triassic strata of the Hartford Basin, and no definitive dinosaur bones of Triassic age from all of eastern north America. That said, the global dinosaurian record definitively shows that saurischian dinosaurs had diversified into carnivorous groups, mostly theropods (the group including *T. rex* and birds), and herbivorous sauropodomorphs (including the Triassic *Plateosaurus* and Jurassic *Brontosaurus*) by the late Triassic. Definitive ornithischian (e.g., Cretaceous duckbills and

Triceratops) dinosaurs are conspicuous by their absence in the Triassic (Irmis et al., 2007; Nesbitt et al., 2007; Olsen et al., 2011; Baron, 2017).

Because bones are so rare, footprints, which are orders of magnitude more common in eastern North America, comprise the main source of information on tetrapod diversity in the Late Triassic where we have good geochronology, leading up to the ETE. These will be discussed in reference to the Triassic-Jurassic transition itself. We will not discuss continental arthropods (including insects), or the rest of organismal diversity, except plants, or details of marine forms [see reviews of Hesselbo et al. (2020), Schoepfer et al. (2022), and Benton and Wu (2022)].

The pre-ETE Late Triassic flora was diverse comprised of various spore-bearing plants, including mosses and liverworts, horsetails, ferns, quillworts, and several extinct groups, and seed plants, including the cycads, conifers, gingkoes, gnetales, and many now extinct groups including seed ferns, cycadeoids, and czekanowskiales. There is evidence that flowering plants had evolved by the Late Triassic [e.g., Cornet and Habib (1992) and Cornet (1986)], but even if so, they comprised a small part of the floral communities and did not belong to crown group angiosperms [Benton et al. (2022) and references therein].

A remarkable and important feature of the distribution of Triassic continental tetrapods and plants is the exceptionally strong latitudinal provinciality (Whiteside et al., 2015; Kustatscher et al., 2018) (Figure 18). This despite the fact that an ambitious Late Triassic tetrapod could potentially walk pole to pole across Pangea, unimpeded by water or elevational barriers (Figure 18). Particularly conspicuous is the complete absence of even a scrap of herbivorous dinosaur from tropical Pangea (Nesbitt et al., 2007; Nesbitt and Sues, 2021). Another, aspect of this provinciality is the modest maximum size of tropical tetrapods, including the dinosaurs (with the exception of the semiaquatic phytosaurs). The largest tropical Late Triassic tetrapods topped out with a hip height of ~1 m for the largest carnivorous terrestrial pseudosuchian, *Redonavenator*, and about the same for another of the largest dinosaur, the carnivorous *Gojirosaurus*[62]. The herbivorous dicynodont synapsid *Placerias* was the most massive terrestrial animal with a shoulder height of 1.2 m for the largest individuals[63]. These are not giants, compared to the 1.6 m hip height of the late Jurassic *Allosaurus* or 2.6 m hip height for the Late Cretaceous *T. rex* (Dececchi et al., 2020).

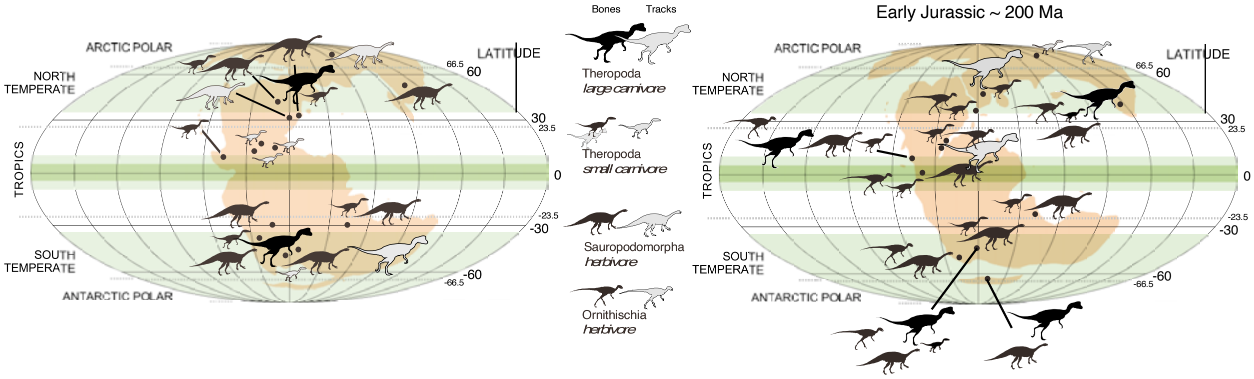

Figure 18: Late Triassic strong latitudinal provinciality compared to Early Jurassic relative homogeneity. Modified from (Whiteside et al., 2015) and (Olsen et al., 2024e).

In dramatic contrast, contemporaneous assemblages from mid- to high latitudes of both hemispheres have abundant, herbivorous, basal sauropodomorph dinosaurs. These were very large compared to tropical tetrapods, with *Plateosaurus* of the Northern Hemisphere being 0.8 to 2.2 m at the hips[64] and 4 to 10 m in length as adults (Sander and Klein, 2005), a leviathan compared to tropical dinosaurs. Over 100 skeletons have been found in Europe making one of the most common dinosaurs of any time period. There are associated theropods, some apparently much larger the largest in the tropics (Kirmse et al., 2024) rivaling the size of *Allosaurus* from the Late Jurassic. An association of pseudosuchians and other reptiles was present in the mid-latitudes similar to that in the tropics was also present. But there is a much higher diversity of large (temnospondyl) amphibians than in the tropics (Schoch and Moreno, 2024).

Southern mid- to high latitudes mirrored the north with abundant sauropodomorph dinosaurs some of which were giants of their time, such as the possibly sauropodian *Lessemsaurus* and *Ingentia* of Argentina, both at ~2 m at the hips and ~10 m in length (Apaldetti et al., 2018), respectively. And, the *Plateosaurus*-like *Melanorosaurus* was similar in size to its northern hemisphere counterparts (Barrett and Choiniere, 2024). Like the northern mid-latitudes pseudosuchians were abundant and diverse (Leardi et al., 2020; Pinheiro et al., 2024), and some top predators (Fawcett et al., 2024) but became rare further south (Tolchard et al., 2019), but very large forms were still present (Weiss et al., 2024). Phytosaurs were conspicuous by their near absence (Barrett et al., 2020).

In all the meanings of the term, diversity on the continents in the Late Triassic was very high (Pinheiro et al., 2024). Taxonomic, alpha diversity, was at a zenith with diverse reptile groups diversifying within the Triassic and groups surviving from earlier times (Payne et al., 2024). Geographic diversity, beta diversity, was also at a high, but the latitudinal biodiversity gradient (LBG) was not-like today, with lower diversity was lower in tropical regions than in mid-latitudes (Dunne et al., 2021), a pattern inherited from the Middle Triassic (Allen et al., 2020), perhaps reflecting dangerously high continental summer temperatures and otherwise violent chaotic weather due to extremely high pCO_2 (Whiteside et al., 2015). This may have been the reason high-metabolic-requirement herbivorous dinosaurs could not establish themselves in the face of pseudosuchian competition. Morphological diversity and expressed by metrics of disparity reflecting ecological diversity was also at a high (Stocker et al., 2016; Cawthorne et al., 2024). All this dramatically changed at the ETE.

Within 100 kyr of 201.6 Ma, the ETE devastated this diversity, causing one of the largest of these macroecological shifts in the Phanerozoic. On the continents, the extinctions decimated reptile diversity, including all non-dinosaurian reptiles bigger as adults than about a meter, and all large, low- to mid-latitude amphibians, as well as others too numerous to list here. It is unclear if the last of the large stem mammals (non-mammalian synapsids) went extinct earlier [e.g., (Kowal-Linka et al., 2019; Sulej and Niedźwiedzki, 2019)] . The great diversity of pseudosuchians was wiped out with only two linages of small, ~1 m long, cursorial forms survived, the protosuchians and small sphenosuchians. The former would give rise to modern crocodilians, and the latter would hang on until the Late Jurassic.

With the near total extirpation of the pseudosuchia, and perhaps because of it, herbivorous dinosaurs, immediately swept into the tropics, and the latitudinal taxonomic provincially characterizing the Late Triassic was swept away (Figure 18). At the same time, ornithischian dinosaurs make their first and very sudden definitive appearance, as if by special creation (Olsen et al., 2011; Baron, 2017). In addition, tropical theropod dinosaurs increase in size by about 20% in length, representing a near doubling of mass (Olsen et al., 2002), also seemingly geologically instantaneously. Compared to the Late Triassic continental diversity was very low, in all ways. With most of the highly level diversity of smaller reptiles also wiped out, and pseudosuchians decimated, the residue was the basis for modern continental communities.

Although the Early Jurassic had remarkable continental taxonomic homogeneity among tetrapods, there was still a size gradient from smaller tropical herbivores to larger in the mid- to higher latitudes. In the tropics, the newly arrived sauropodomorphs were relatively small compared to what is seen in southern Africa. Low latitude sauropodomorphs had hip heights in the range of around 1 m and a length of 4 m (Paul, 2016), but some southern African Early Jurassic sauropodomorphs notably *Ledumahadi* (McPhee et al., 2018) were the largest dinosaurs of their day, with a hip height of ~2.6 m and length of ~10 m and *Pulanesaura* (McPhee and Choiniere, 2017) with a hip height of ~2.7 m and length of ~11 m. They were as tall or taller than *T. rex,* and that was without lifting their long necks.

The tropical Triassic-Jurassic transition is particularly well displayed in eastern North American Footprint assemblages (Figure 19). The Hartford and Deerfield Basins and eastern North American Basins in general are justifiably famous for their quality and abundance of tetrapod footprints, especially those of dinosaurs (Stop 6). Footprints are orders of magnitude more common than bones in the shallow water and marginal lacustrine strata common in these rifts, and are abundant in the ETE transitional interval in the Newark Basin (Olsen and McDonald, 2025). Triassic aspect tracks, particularly *Brachychirotherium* are abundant (along with other ichnotaxa), restricted to below the pollen and spore change at the ETE (Figures 16, 19).

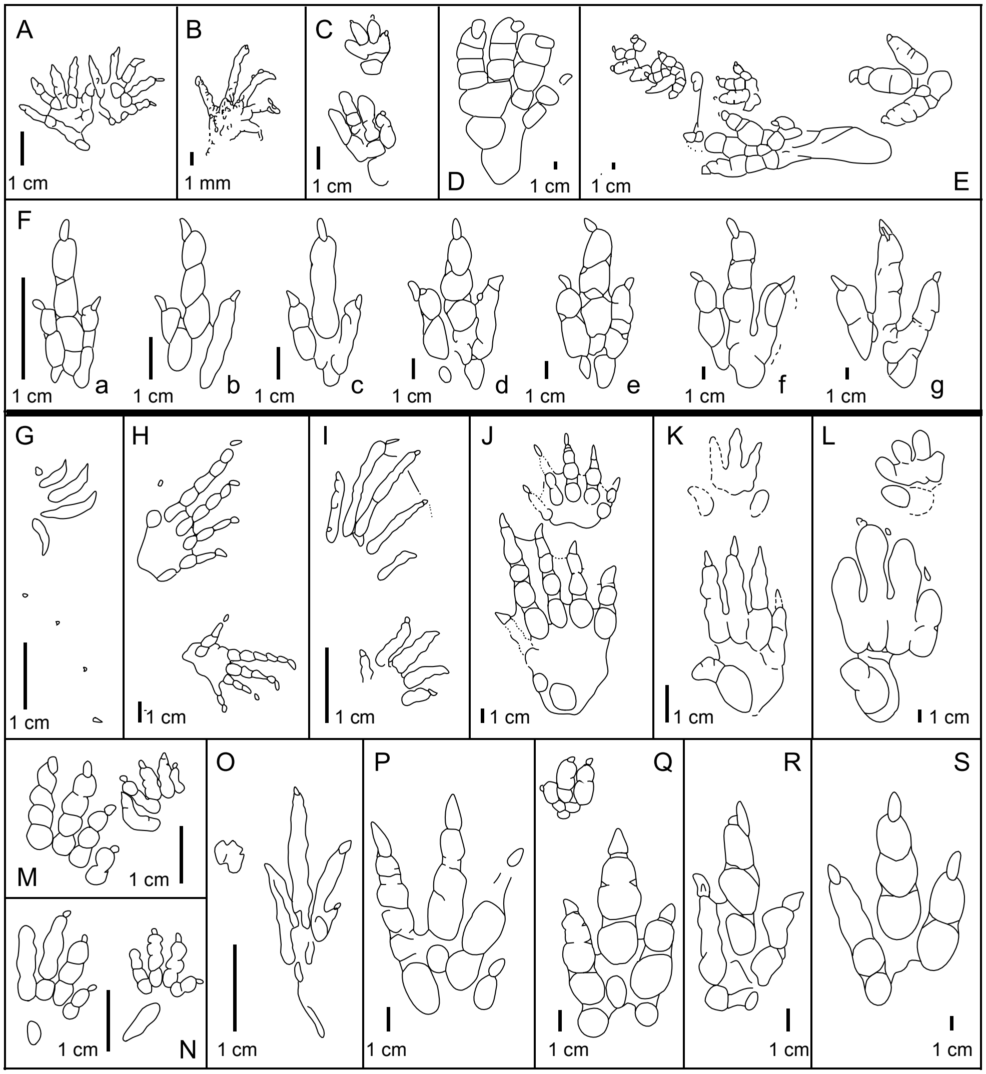

Figure 19: Examples of pre-ETE (below) and post-ETE (above) assemblages (separated by heavy black line). **A-F**, Connecticut Valley-type assemblages of latest Rhaetian to Sinemurian age. **G-S**, Passaic-type assemblages of Norian-Rhaetian age. All panels except **F** are shown as left manus-pes sets, or left pedes; the brontozoids in panel **F** are shown as right pedes. Individual specimens are: **A**, *Ameghinichnus* manus-pes set; **B**, *Rhynchosauroides* manus; **C**, *Batrachopus deweyi* manus-pes set; **D**, *Otozoum moodii* composite pes; **E**, partial trackway of *Anomoepus scambus*, pes and several manus; **F**, series of brontozoids from the Towaco Fm., Newark Basin (a-c, *Grallator*; d-e, *Anchisauripus*; f-g, *Eubrontes*); **G**, *Rhynchosauroides brunswickii* manus-pes set; **H**, *Rhynchosauroides hyperbates* manus-pes set; **I**, *Gwyneddichnium majore* manus-pes set; **J**, *Apatopus lineatus* manus-pes set; **K**, *Chirotherium lulli* manus-pes set; **L**, *Brachychirotherium parvum* manus-pes set; **M**, “new taxon B” manus-pes set; **N**, “new taxon A” manus-pes set; **O**, *Banistrobates boisseaui* manus-pes set**;** **P**, ?*Evazoum* pes; **Q**, *Atreipus milfordensis* manus-pes set; **R**, small brontozoid (*Grallator*) pes; **S**, medium-sized brontozoid (*Anchisauripus* c.f. *A. exertus*) pes [from Olsen et al. (2024e)].

Above the ETE in the Exeter section only small brontozoid tracks (*Grallator* and *Anchisauripus*), *Batrachopus*, and *Rhynchosauroides* have been found although the tracks were not abundant because of the very limited exposure. However, polarty chron E23r allows unambiguous correlation to what were much more extensive outcrops about 120 km to the northeast at Woodland Park. There, above the projected position of the pollen and spore ETE, are again brontozoid tracks, *Batrachopus*, and *Rhynchosauroides*, but abundant *Eubrontes giganteus* (another brontozoid) is also present, the oldest occurrence known in eastern North America (Olsen et al., 2002; Olsen and McDonald, 2025). These data that constrain the tetrapod transition to about 60 kyr.

In the succeeding strata, *Anomoepus* (tracks attributed to small ornithischians) and then *Otozoum* (plausible early-diverging sauropodomorph track) appear in the Hartford and Deerfield Basins. There is no apparent change in younger Newarkian strata, except perhaps in the larger maximum size of Anomoepus (Olsen and Rainforth, 2003; Olsen and McDonald, 2025).

With this dramatic extinction and revolution in continental fauna, the ETE ushered in the Real "Age of Dinosaurs". Afterwards dinosaurs would dominate virtually all large terrestrial ecospace until K-Pg mass extinction wiped out all large animals, including all but the avian dinosaurs.

Dinosaurs of the Midnight Sun

Polar areas have been nearly *terra incognita* with virtually no efforts having been made at prospecting and collection. The total described tetrapod skeletal inventory for the paleo-polar regions consists of two teeth, of possible plesiosaur affinities from lacustrine deposits with ice rafted debris from northwestern China (Olsen et al., 2022b; Olsen et al., 2024h). Previous reports of Triassic arctic continental fauna (Sues, 2017) turn out to be from paleo-mid latitude areas, accounting for continental drift.

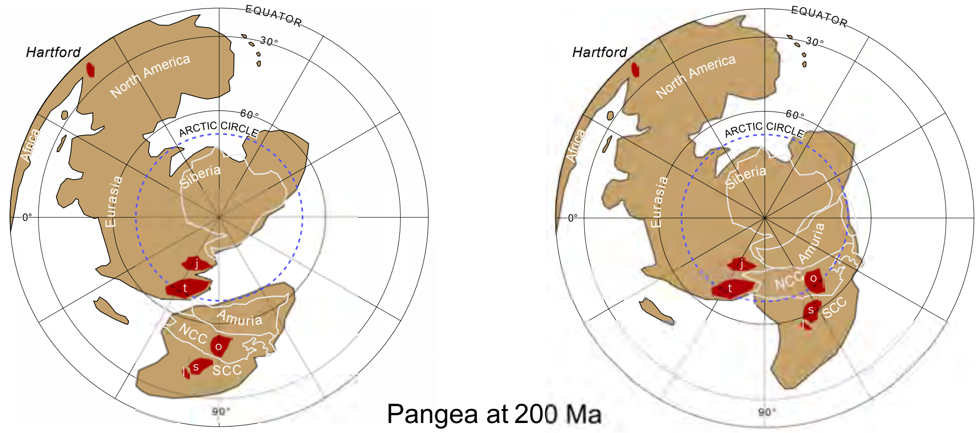

Figure 20. Comparison between north polar views conventional and revised configuration for major east Asian plates. Left, conventional configuration based on GPlates using Torsvik et al. (2012), Torsvik and Cocks (2017), and Marcilly et al. (2021). Right, same for Siberian plate and western Eurasia modified by data of Yi et al. (2023) (Olsen et al., 2024g). Basins are: l, Lufeng; j, Junggar; o, Ordos; s, Sichuan; t, Tarim. See also Figure 13.

The largest accessible paleo-Arctic continental area is in East Asia with the Late Triassic – Early Jurassic pole, basically being in northwest Siberia [e.g., (Muttoni and Kent, 2019; Frolov et al., 2024)]. Traditionally, the Amurian and North and South China blocks have been interpreted as hinged onto the rest of Asia on the west but widely separated on the east by a vast Mongol-Ohkhotsk Ocean [e.g., (Torsvik and Cocks, 2017)], spanning more than 45° of latitude on its eastern side in the early Late Triassic, that lasted into the Cretaceous before final, scissor-like closure. This would place North and South China blocks in the mid- to low-latitudes during Triassic though Early Jurassic while the Junggar Basin would be in in the paleo-Arctic (Figure 20). This paleogeographic scenario would be remarkable situation given that the stratigraphy of basic climate sensitive facies from Junggar to the South China block looking very similar from the at least the Late Triassic though the Early Cretaceous (Yi et al., 2019). However, recent paleomagnetic data suggest that Mongol-Ohkhotsk Ocean actually closed by the Late Triassic (Yi and Meert, 2020; Yi et al., 2023), with the major climate signature being due to a massive true polar wander event [Monster Shift of (Muttoni and Kent, 2019)] in the Late Jurassic swinging east Asia 30° south and then 15° north (Olsen et al., 2024g; Wang et al., 2024). Consequently, most of Central and East Asia were within the Arctic Circle, including the huge Junggar Basin, and most of the Tarim and Ordos Basins being in the paleo-Arctic in the Late Triassic and early, Early Jurassic. The area of available paleo-Arctic continental environments is much larger than previously known (Figure 13) give vertebrate paleontologists multiple prospective basins for new finds.

At the present, however, for the critical ETE interval including the Late Triassic and Early Jurassic very little is known in this paleo-Arctic region. Definitive ornithischian and theropod footprints are known from the from the Junggar and Tarim basins (Figures 20, 21) (Olsen et al., 2022b; Olsen et al., 2024h). A few tetrapod scraps have been found but there has been no systematic prospecting.

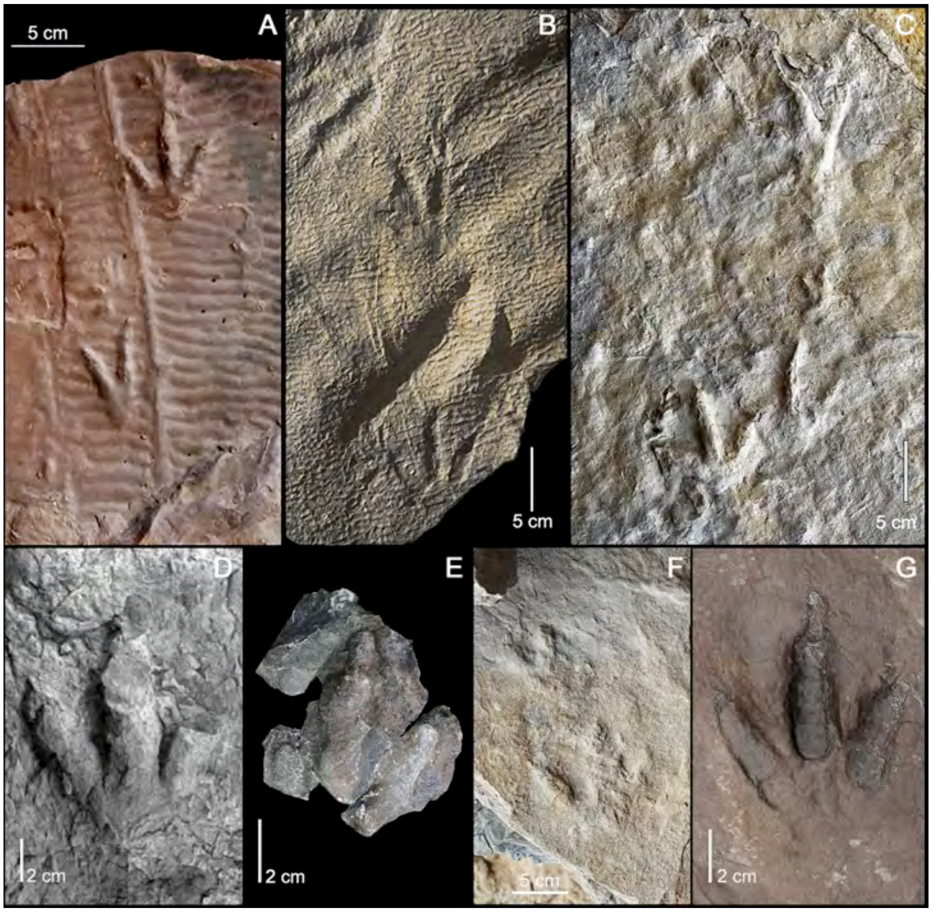

Figure 21. *Anomoepus* ispp. from Eastern US basins and paleo-Arctic of China: A, Feltville Formation, Newark Basin, early Hettangian, New Jersey, USA (AMNH 7639); B, Mount Toby Formation, Deerfield Basin, Massachusetts, USA, Hettangian (ACM ICH 16/5: holotype type *A. minor*); C, trackways, Xishanyao Formation, Junggar Basin, Xinjiang, China, Middle Jurassic (field photo); D, Badaowan Formation, Junggar Basin, Xinjiang, China, Middle Jurassic, Hettangian (Xing et al., 2014); E, Sangonghe Formation, Junggar Basin, Xinjiang, China, Middle Jurassic , ?Sinemurian (Olsen et al., 2024h); F, Yangxia Formation, Tarim Basin, Xinjiang, China, Middle Jurassic, ?Pliensbachian (field photo); G, Mount Toby Formation, Deerfield Basin, Massachusetts, USA, Hettangian (ACM ICH 48/1: type *A. intermedius* (Olsen et al., 2024h).

Given the absence of systematic prospecting, these footprint occurrences suggest that dinosaurs were common in polar tetrapod communities. Although, it has long been known that dinosaurs lived in paleo-polar regions [e.g., (Roehler and Stricker, 1984; Rich, 1996), the importance of these finds in particular is that the tracks occur in strata associated with deeper water lacustrine units with abundant and diagnostic ice-rafted debris from wintertime freezing not just in the Junggar Basins, but at least in the Tarim and Turpan Basins as well, in strata ranging from Late Triassic through Early Jurassic in age (Figure 12) (Olsen et al., 2022b; Chang et al., 2024; Olsen et al., 2024f). This suggests dinosaurs inhabited areas with wintertime freezing conditions and long periods of polar darkness early in their history. Combined with compelling evidence that diverse Cretaceous dinosaur bred and raised young in the paleo-Arctic

(Druckenmiller et al., 2021), it seems clear that dinosaurs inhabited polar environments for most of their history, as well as a myriad of other more clement environments.

Dinosaurs could live in freezing polar environments, because, as mounting evidence suggests, their common ancestor was insulated with protofeathers. This insulation would have given them serious competeive edge in surviving volcanic winters. Below, we compare the expected biological consequences of global warming from CAMP pCO_2 increase, compared to volcanic winters.

In addition to heat stress, the effects of global warming would be expected to include intensification of extremes in weather, and orbital cycle intensity. The latter is one of the mechanisms, in combination with competition from herbivorous pseudosuchians, by which herbivorous dinosaurs may have been excluded from the tropics (Whiteside et al., 2015). Statistical analyses by Dunne et al. (2022) support this and show that Late Triassic sauropodomorphs dinosaurs occupied narrower a niche space than theropods, and were excluded from the tropics. However, because the pCO_2 levels during the CAMP were not appreciably greater than the in the previously mentioned 16-million-year interval recorded in the Norian age part of the Newark Basin sequence, it is hard to see how those levels would, in the very latest Triassic and Early Jurassic, drive to extinction the very same groups of tetrapods that were thriving under those same pCO_2 levels eight million years before. In addition, if heat were a problem, poleward or elevational migration would be possible for both animals and plants, which is seen, for example, in poleward shifts of the pollen taxon *Classopollis* during the Jenkyns (T-OAE) warming event (Baranyi et al., 2024; Fang et al., 2025), but which is not seen for pollen or spore taxa during the CAMP — instead, the tropical vesicate pollen (such as *Patinasporites*) just go extinct. Poleward migration during the T-OAE event is also documented for various marine groups during the same event (Dera et al., 2011), but not for the ETE. And, of course it is happening now (Osland et al., 2021), although its complicated, with well-documented elevational migration for tropical species poleward (Melbourne-Thomas et al., 2021; Colwell and Feeley, 2024), shift to higher latitudes at a median rate of 16.9 km per decade in reptiles (Chen et al., 2011) and predictions of expansions of ranges of reptiles for the future [e.g., (Chiarenza et al., 2024), but there are hundreds more]. Yet there is no evidence for this at the ETE.

Some of the same papers that document poleward shifts in ranges discuss and document the ecological importance of rare extreme cold events [e.g., (Osland et al., 2021)] in limiting the ranges of warm adapted organisms. In the case of the ETE, virtually the entire low latitude continental biota would have no evolutionary experience with cold (except at high elevations). The key observation is that the tetrapods that go extinct at the ETE uninsulated and often large and the plants such as those producing vesicate pollen had a low latitude bias suggesting obligate thermophilus habitats. Modeling of thermal tolerances of Triassic tetrapods, accounting for heat and mass transfer into and out of organisms within microclimates, support this and shows that that large pseudosuchians were sensitive to the cold and would be unable to compensate behaviorally (Hartman et al., 2022). In addition, the groups that flourished at the extinction were plausibly insulted by protofeathers — dinosaurs and pterosaurs — and although many groups with smaller size also went extinct, those that did survive, such as mammals, lizards, sphenodontian, turtles etc., could have escaped could by burrowing. This would include the small protosuchians and sphenosuchians, the only pseudusuchians to survive the ETE. Insulated, ornithischian dinosaurs having evolved in the seasonally freezing polar regions, simply moved into lower latitudes, when their competitors were wiped out. In summary, ALL large continental animals that did not belong to insulated clades were wiped out at the ETE and their extinction is more consistent with effects of volcanic winters than global warming.

Mounting evidence from phylogenetic and biogeographic analyses suggest that survival and biogeographic patterns are inconsistent with a model in which CAMP-driven increases in pCO_2 cause extinctions in continental ecosystems. Rather, they support an alternative radiative balance hypothesis in which extinction and survival patterns resulted from repeated volcanic winters unfolding orders of magnitude faster than changes in pCO_2, despite clear evidence LIP emplacement caused pCO_2 change at anthropogenic time-scales. This leads to support for the competing hypothesis that the massive, and sustained, drop in apparent continental faunal and floral taxonomic diversity at the ETE reflected filtering of taxa with clade-specific characters by repeated volcanic winters, rather than primarily high pCO_2, driving multiple aspects of diversity in extinction and recovery. In this hypothesis, polar and high latitudes were incubators of dinosaurian life strategies and physiologies permitting survival of large-bodied animals through repeated volcanic winters. This post-ETE expansion of ranges in response to extinction of low latitude animals was the largest ecological shift on land until the K-Pg event. This hypothesis offers an explanation plausibly not unique to the ETE, and it may be more broadly applicable to other mass extinctions (e.g., end-Permian) and turnover events with paired and opposing radiative balance perturbations as well as anthropogenic change with geoengineered sulfate aerosol "solutions".

The afore mentioned *Anomoepus* in particular, from the paleo-Arctic of China (Figure 21), are exemplars of traces from dinosaurs from thriving polar communities that experienced freezing winters. This bears directly on what Baron (2017), "The Triassic Ornithischian Crisis". He points out that the absence of Triassic ornithischians (Olsen et al., 2011) presents a major conflict between the fossil record and the dominant paradigm for dinosaurian relationships established in 1887 which Ornithischia and Saurischia are separate groups (Seeley, 1888). This concept was revised and modernized in 1974 by Bakker and Galton (1974) in which the two groups arose from a common ancestor in the Triassic. But if the two groups split in in the Triassic, a missing "ghost" lineage of at least 30 million years is predicted, in which either forms with ornithischian traits were around but not found, or forms with traits of the common ancestor were around but not found. To reduce ghost lineages, Baron and Baron et al. (Baron, 2017; Baron et al., 2017) propose an alternative relationship for Ornithischia, in which the group arises either from the Theropoda or the Sauropodomorpha in the Early Jurassic. This is a modern version of Thomas Henry Huxley's Ornithoscelida hypothesis of 1870 (Huxley, 1870) which was intimately linked with his 1868 (Huxley, 1868) idea that dinosaurs were the "missing link" between reptile and birds, a view now considered essentially correct. However, the Ornithoscelida cause a slew of new problems. A different proposed solution is that the ornithischians closest relative are not saurischians at all, but rather what are now classified as non-dinosaurian dinosauromorphs, the silesaurids. Besides the problem of making the most obvious of all characters uniting the dinosaurs, the open acetabulum, be separately evolved in the two groups, there is no evidence of silesaurids in strata younger than Norian (205.7 Ma).

We think a much simpler solution to, "The Triassic Ornithischian Crisis", is that ornithischians evolved in polar areas and immigrated into the rest of Pangea at the ETE. This is basically the same thing as what happened with the sauropodomorphs and very large theropods except they lived in mid-latitudes (perhaps as well as polar) during the Late Triassic. We argue that the success of the dinosaurs at the ETE, especially relative to the near extirpation of the pseudosuchians, plausibly related to them being primitively insulated and therefor inured to volcanic winters.

In his once-page, prescient, (1973) Nature paper on the resurrection of Huxley's idea that birds descended from dinosaurs, Ostrom addressed the importance of feathers to bird and by extension dinosaur success,

> "The additional significance of this phylogeny is that "dinosaurs" did not become extinct without descendants and I suggest that feathers, as thermal insulators, could be the primary reason for the success of dinosaurian descendants." Ostrom (1973, p. 136)

Acknowledgments

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ROAD LOG

Overview

The ETE ushered in the dawn of the modern via the mass extinction of all large non-insulated animals including nearly all of the crocodile relatives, the pseudosuchians. In contrast, insulated animals, due to the presence of either protofeathers or fur insulation, were not only virtually unaffected, they expanded their ecological dominance from the higher latitudes into the entire Earth — and they still dominate as birds and mammals. We will examine the unexpected evidence, much from the Hartford Basin, that the ETE occurred during a period unique in the early Mesozoic where tropical climate pacing was very strong but dominated by axial obliquity (tilt) not precession (wobble), perhaps reflecting polar amplification by expanding ice-albedo feedbacks due to the CAMP-volcanic winters.

We will examine the Triassic-Jurassic transition in the tropics of Pangea as seen in the Connecticut portion of the Hartford and Deerfield Rifts at six stops (Figure 3) (including lunch). Our trip will begin at a superlative exposure of the upper New Haven Formation at Simsbury, Connecticut, in the Hartford Basin followed by five additional stops, including lunch, the last stop being at the Beneski Museum. Apart from the latter, the stops are arranged in stratigraphic order from oldest to youngest. Our stops will illustrate the tectonic and environmental changes in the Hartford Rift as well as the profound ensuing Earth system changes that led to the continental fauna as seen in the trace fossils of the Beneski Museum, from both the Hartford and Deerfield Basins.

From a Connecticut field trip standpoint, the last few years have been nearly disastrous given unprecedented rates of plant growth covering what used to be truly spectacular outcrops. However, some new construction has “refreshed” some previously completely overgrown exposures (e.g., Stop 2) and elsewhere plant growth has also closed off canopies in forests, with deer nearly clearing out the understory making some outcrops more accessible (e.g., Stop 3) — so there is some compensation. Be prepared, however, for walking though vegetation, including plants with thorns, and poison ivy, and there is the possibility (likelihood) of ticks, and especially at this time of year, yellow jacket wasps, and maybe other pesky wildlife. Be aware of moving vehicles, including bicycles and electric bikes. And, follow instructions. Depending on the weather and other exigencies, some field stops may be skipped or extended.

Field Trip Stops

Stop 1: Late Rhaetian Age, upper New Haven Formation (Figure 22), Simsbury, Connecticut
41.890140°, -72.776880° (41°53'24.50"N, 72°46'36.77"W)

Main Points:

1) Fluvial red bed sequence of late Rhaetian Age, ~202 Ma
2) Abundant bioturbation with many details of bedding obscured
3) Basin accommodation space growing more slowly than infill
4) Monotony of sequence may reflect lowered pCO_2 in Rhaetian

The main purpose of this stop is for comparison with younger strata deposited during the CAMP episode. These exposures reveal about 70 m of the upper New Haven Formation, beginning about 100 m below the Talcott Basalt (assuming 10° dip). This facies is typical of the upper New Haven Formation in this part of the Hartford Basin (Figure 23). It is characterized by monotonous appearance, intense bioturbation, poor preservation of depositional sedimentary structures (ripples etc.). There is no obvious cyclicity or periodicity. It is better cemented than the underlying parts of the formation and makes a distinct ridge. Based on the overlying Talcott Formation with a age derived from the equivalent Orange Mountain Basalt in the Newark Basin of 201.520 ± 0.034, the age of this sequence should be Late Rhaetian, although there are no indigenous corroborating fossils or other age-relevant data.

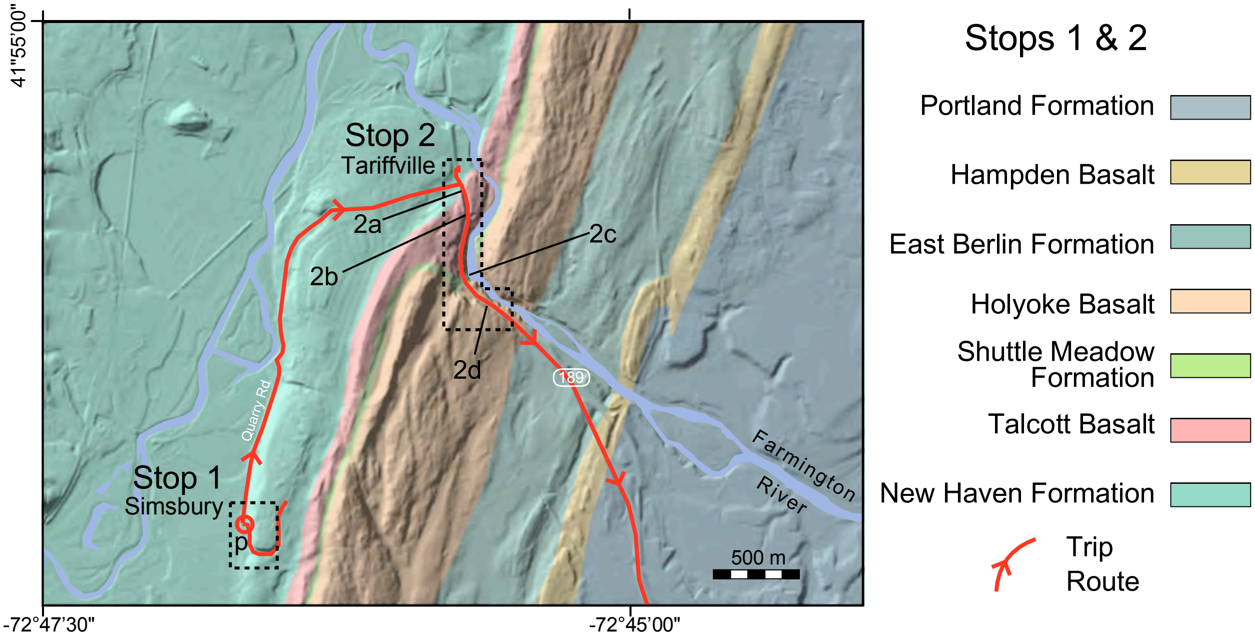

Figure 22: Bedrock geology and LiDAR Map of Stop 1 and Stop 2.

A fragmentary bone (scapula) of phytosaur was found about 3.25 km SW southwest of here in what is now downtown Simsbury in 1888 in middle New Haven Formation strata at about 680 m below the Talcott. It was named by *Belodon validus* Marsh in 1893 (Marsh, 1893, 1896), a taxon definitely representing a phytosaur, but not diagnostic to genus or species (Stocker and Butler, 2013). Although the crocodile-like phytosaurs were common members of Late Triassic, pre-end-Triassic-mass extinction (ETE) assemblages, no phytosaur, bone or track has ever been found in post-ETE strata.

Figure 23: A, Stop 1; Photograph of lower part of Metacom Drive section of upper New Haven Formation as it appeared ~1990. (Photo by Nicholas G. McDonald). B, type and only specimen (scapula) of the indeterminate phytosaur "*Belodon*" *validus* (Photo by Yale Peabody Museum).

The upper, but not uppermost, New Haven Formation appears to be entirely fluvial throughout the Hartford Basin, unlike the correlative upper Passaic Formation in the Newark Basin which is lacustrine in much of the basin. However, it shares with the upper New Haven a monotonous character, lacking any deep-water lake sequences. This may be because of muted extremes in the hydrological cycles due to comparatively low pCO_2, compared to older Norian and younger syn-CAMP strata (Wang et al., 2023). Compared to Hartford Basin syn- and early post-CAMP strata, accommodation space must have grown slowly because sedimentation evidently kept up with subsidence.

Return to vehicles.

Miles	Cumulative Miles	
0	26.15	Head back South on Metacom Dr toward Quarry Rd
0.35	26.5	Turn right onto Quarry Rd
0.6	27.1	Turn right onto CT-315 E
1.10	28.20	Turn left onto CT-189 N
0.01	28.21	Turn right onto Tunxis Rd
0.01	28.22	Turn left: PARK in parking lot: Stop 2

Stop 2: Latest Rhaetian Age, uppermost New Haven Formation, Talcott Basalt, Latest Rhaetian and Hettangian Age Shuttle Meadow Formation, and Hettangian Age (Early Jurassic) Holyoke Basalt (Figure 22), Tariffville, Connecticut (Figure 22).
41.909083°, -72.761500° (41°54'32.7"N 72°45'41.4"W) parking.

Main Points:

1) Change in facies in New Haven Formation before earliest CAMP flow
2) Pillowed and complex Talcott Basalt flow
3) Infiltrations of red mud- and sandstone into Talcott including one large fissure
4) Onlap of very much thinned (17 m), entirely red and purplish Shuttle Meadow onto Talcott, no sign of lower gray and black Durham Member
5) Only second flow of Holyoke here, with well-developed splintery fracture and characteristic shallow magnetic inclination.
6) Segregation veins in Holyoke, result of compaction of lower Holyoke crystal–liquid mush and dilation of middle of flow. Enriched in Zr and good candidates for crystallization-age zircons.

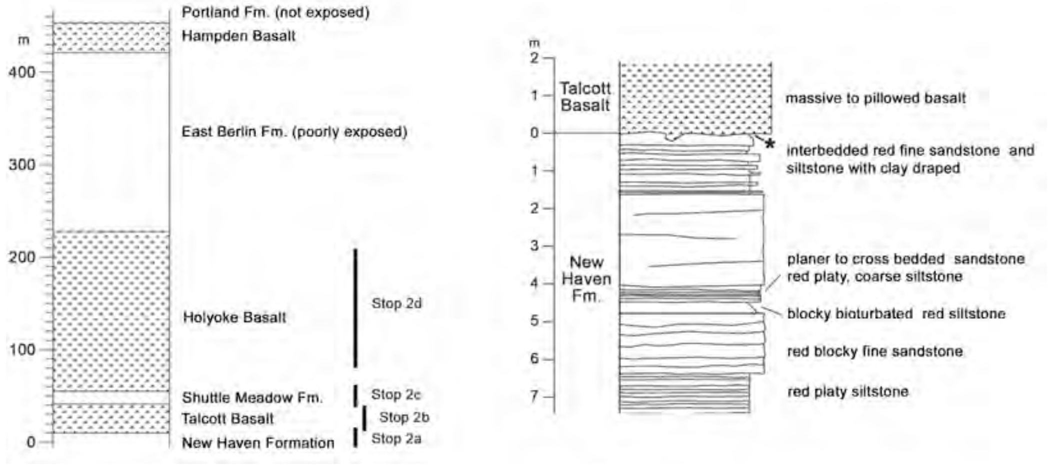

Figure 25: Left, overview of Stop 2. Right, uppermost New Haven Formation at Stop 2a. Section measured in 2002 prior to greenway installation. Modified from Olsen et al. (2003) (41.907689°, -72.761234°).

These exposures, along CT-189, the opposite side of the river on Tunxis Avenue and the Farmington River below, have been the topic of many guidebooks and studies (Rice, 1886; Gray, 1982; Philpotts and Reichenbach, 1985; Gray, 1987; Philpotts and Asher, 1992; Philpotts et al., 1996; Philpotts et al., 1997; Philpotts et al., 1999; Boudreau and Philpotts, 2002; Olsen et al., 2003b; Philpotts and McHone, 2003; Sheth, 2020; Holness and Neufeld, 2022) from at least 1886 to 2022, revealing a nearly complete section of the upper New Haven Formation through Hampden Basalt (Figure 24). This section is of considerable historical interest because Rice (1886) and Davis (1898) used observations from these outcrops to argue for an extrusive origin of the basalt flows rather than the generally assumed intrusive origin [e.g. Dana (1874)], but the section still yields new insights and controversies [e.g., Sheth (2020); Holness and Neufeld (2022)].

For over 20 years these exposures were more or less completely overgrown (Philpotts and McHone, 2003), but, fortunately for us, this cut was "refreshed" when a bike/pedestrian path was installed as part of the 3000 mile East Coast Greenway November 2022 – November 2023. We have divided this stop into four segments (Stops 2a-2d) (Figure 24) along CT-187 and the river. At 2a we will look at the Segment 2c is optional, and visitation will be governed by time, weather, and vegetation.

About 8 m of New Haven Formation and nearly all of the Talcott Formation are exposed in a cut for CT Route 189 and greenway trail. We will begin at the north end of the exposure in the uppermost New Haven Formation and walk south through most of the Talcott Formation at 2b. At 2a, the uppermost New Haven Formation (Figure 25) is entirely red. The lower 6.5 m of the section consists of heavily bioturbated red sandy mudstone and sandstone. Above that, there are numerous sandstone beds with clay drapes with much less bioturbation typical of footprint-bearing facies in the Shuttle Meadow through Portland formations (although we have yet to find any footprints here). The position of the ETE is not known at this section, but it should be possible to tell if it exposed here if reverse chron E23r can recognized. The main difference between this facies and what we saw at Stop 1 is the much better preservation of deposition sedimentary features and the change from the more massive, more heavily bioturbated facies to what we see here is characteristic of the New Haven Formation. This facies is transitional between New Haven Facies and the Shuttle Meadow Formation red beds.

Some point or points, during the deposition of the uppermost New Haven Formation, airfalls of from distant should have been deposited marking catastrophic drops in temperature leading to the ETE on land, at least according to the hypothesis outlined above. There is in fact at least one thin layer that based on hand sample examination, does seem to have highly altered ashy material in it within a cm or so of the contact with the overlying Talcott. However, as described for the Talcott pillow basalts and much better developed ash-like in the uppermost New Haven at Meriden (Olsen and Douglass, 2022), this could be hyaloclastite shed from the advancing lava flow. Hyaloclastite is a hydrated formed by granulation of the lava front due to quenching when the lava flowed into, or beneath water. That would be a local source, however, only obliquely related to airfalls associated with volcanic winters. How would we look for in these beds if they have been thoroughly mixed by sedimentation and bioturbation processes? We don't know where the ETE is this section so we don't even have a target and we don't have an idea what the accumulation rate is here. Finding E23r would be a start (see Stop 7).

Nearly the entire thickness (about 30 m) of the Talcott Basalt is exposed at this locality (Figure 22) where it described as consisting of two flows (Gray, 1982; Gray, 1987). The Talcott Formation is a HTQ-type basalt (high titanium, quartz normative basalt) identical in composition to the oldest flows in the Newark, Gettysburg, and Culpeper basins (Puffer and Philpotts, 1988) and in the Hartford Basin apparently derived from magma supplied by the Fairhaven-Higganum dike system (Philpotts and Martello, 1986). As described by Gray (1982) and Gray (1987) and Philpotts and Asher (1992) these exposures show the lower, pillowed 1.5 m of Talcott lying on unmetamorphosed New Haven Formation, with some pillows having sunk into the underlying sediment. This is followed by about 6 m of columnar basalt and then massive basalt near the top of the section where the basalt becomes vesicular passing upward into a flow-top breccia. An additional 15 m of vesicular basalt flow lobe units is exposed discontinuously along the road cut and better exposed along the river (Philpotts and Asher, 1992).

Figure 26: Stop 2b. Talcott Basalt along CT-189 (41.907444°, -72.761115°). Fracture fills (Neptunian dikes) and infiltrations at Stop 2b in Talcott Basalt (A, B) and Orange Mountain Basalt in Newark Basin C, D). A, Bedding in fissure fill in Talcott Basalt with hammer head resting on bedding plane. B, Infiltration of red sandy mudstone within Talcott Basalt. C, Very large Neptunian dike (1.5 m width) with bedding defined by basalt clasts (red arrows). Clasts come from above, not below). D, Flow-parallel mudstone is blister in crust of cooling unit and not at contact (red c) between chill cooling units defined by distinct light-colored chill zone. Units shown in C and D produced bones; location is active quarry (location on request). PEO photos.

There is a red bedding-parallel layer in the basalt to the north of the fissure which although could be interpreted as a sediment deposited on top of a cooled flow, is more simply interpreted as an infiltration (Figures 26 and 27). The presence of reddening at cooling unit contacts, even with the presence of sediments cannot be taken as evidence of a gap in time between flows. Post-cooling infiltrations are common and have to be excluded as an interpretation by other evidence, such as paleomagnetic [e.g. Kent et al. (2024)], before a hiatus in eruption should be supported. Thus, it is unclear if the apparent two or more cooling units in the Talcott as seen here represent one or more eruptions.

The observed structure of the flow systems in the CAMP as observed in outcrops as at this stop, quarries and cores does not translate easily into an understanding of the number or magnitude of eruptive events. First there is an important distinction between flows and cooling units. Cooling units have chill margins and normally vesicular tops and less vesicular bottoms. Based on the very well exposed Columbia River Basalts, as shown by Self et al. (1996), Thordarson and Self (1998), and others, large flows can grow by inflation overriding offshoots that were lobes of the advancing flow and extruding lobes formed the surface, with these lobes being cooling units, but not part of a separate lava eruption (Figure 27). These models have recently been applied to CAMP lavas (Puffer et al., 2018; Tanner et al., 2020). This is important because it is the magnitude and rate of the eruptions that matter most in terms of environmental impacts, many of which are rate-dependent [e.g., Hönisch et al. (2012); Landwehrs et al. (2020)].

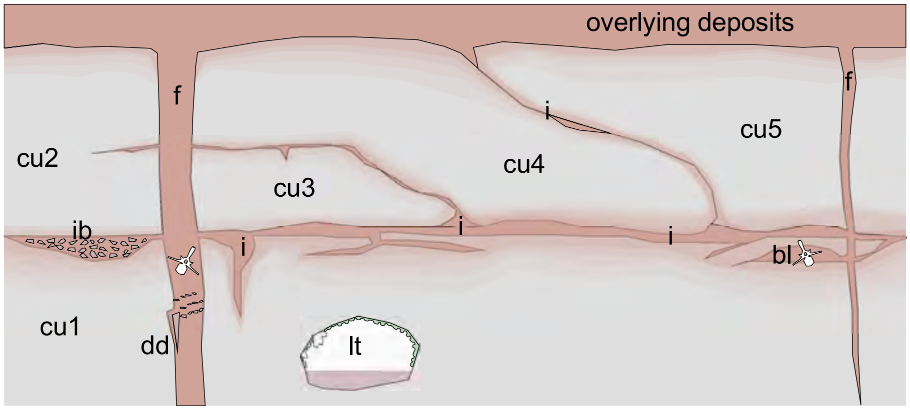

Figure 27. Conceptual model of lava lake and flow lobe complex from one eruption with infiltrations and asymmetrical reddening of vesicular cooling top (thick) and bottom (thinner): bl, bister infiltration with bones; cu1-cu5, cooling units 1-5; dd, downward displaced block of wall rock; f, fracture fill with bones and bedding with basalt fragments; i, inflitrations; ib, infiltration postdating breccia; lt, lava tube floored by rippled sediment with crystals on upper surface. Geometry of upper lobes from Thordarson and Self (1998).

Large CAMP flows of eastern North America should be expected, however, to exhibit significant differences from Columbia River Basalt, Deccan Trap, and exposed Siberian Trap flows. The latter were all emplaced on an extensive plain whereas eastern North American CAMP poured into rift basins where they could still grow by inflation, but reach enormous thicknesses. Consequently, the largest flows could have formed giant lava lakes with characteristics more like caldera-associated lava lakes rather than typical lava flows. This is the case with the second flow of the Holyoke and Preakness Basalts, the basal flow of the Sander Basalt, and the first flow of the North Mountain Basalt (East Ferry Member). The similarity of these units to lava lakes especially Kilauea Iki (Helz, 1980; Helz et al., 1989), along with their associated pegmatitic and gabbroic segregation veins was noted by Puffer and Husch (1996); Puffer and Hush (1996); Puffer and Volkert (2001) and Greenough and Dostal (1992), among others. Such lava lakes growing by inflation could expand over the rift floor against the regional paleoslope slope direction as described by Manspeizer (1980) for the Orange Mountain Basalt in the Newark Basin (Manspeizer, 1980; Puffer et al., 2018).

A common observation in CAMP sequences is that there are reddened vesicular contacts at the boundaries of cooling units, often with some intervening sediment, as seen here. These could be, and have been, interpreted as indicating soil forming processes and hiatuses of significant duration between flows in CAMP flows [e.g., Kontak (2008); Moumou et al. (2024)] and other large igneous provinces [e.g., Columbia River Basalt group and Deccan "red boles" (Schoene et al., 2019; Kasbohm et al., 2023)] and are therefore important for calibrating the number of eruptions and their concentration in time. However, these observations are not necessarily indicative of gaps between eruptions. Numerous additional observations indicate that the reddening of the basalt and presence of sediments are more often than not a consequence of infiltration of oxygenated water and sediment well after the lava pile has cooled (Figure 27). These include: Neptunian dikes, some very large, with internal bedding, cross-cutting cooling units that connect with the sediments at cooling unit contacts; as well as lava tubes floored with sediments; reddening of the base of the overlying cooling unit as well as the underlying cooling unit; consistent bedding orientation in siltstone and sandstone between breccia clasts; filled blisters and cracks in cooling unit tops; and presence of partial skeletons and bones in the Neptunian dikes and interconnected sedimentary beds between cooling units lacking in over- and underlying sedimentary formations. Many of these features are common to karst environments. The reddening indicating sub-surface weathering phenomena post-dating the cooling of the entire pile of cooling units.

Thus, large flows that grew by inflation with their overridden offshoot lobes and extruding surface lobes and thin cooling units arising from hornitos or rootless fissures, or pillowed sequences with their feeding lobes, while formed from one very large eruptive event, could have constituent cooling units with reddened contacts and intercalated sediments that could be misinterpreted as indicating separate lava flows from distinct eruptions separated by unknown but significant amounts of time. That said, real surface weathering surfaces on CAMP lavas do exist, with or without intercalated sediment, and they represent real hiatuses between separate eruptions. Discriminating between subsurface weathering surfaces or infiltrations in single eruptive units vs. significant pauses between eruptions is a major challenge in understanding process that drove CAMP as a world-changing event.

Secular variation of the Earth's magnetic field as recorded in lavas provides a completely independent way to discriminate between cooling units that belong to single eruptive events and eruptive events separated by significant time. Historical secular variation (Alexandrescu et al., 1997) suggests that paleomagnetic directions through cooling unit sequences that do not significantly change should represent at most a few decades to maximally a century. This methodology has been applied to the Deccan Traps [e.g., (Chenet et al., 2008)] and more recently CAMP lava sequences (Knight et al., 2004; Kent et al., 2012; Kent et al., 2023, 2024). In both cases, multiple cooling units separated by thin reddened units fall with single directional groups suggesting they represent a single eruptive pulse. However, some groups of cooling units in different directional groups are also separated by paleo-weathered surfaces, suggesting each direction group was separated by a longer period of time.

The many CAMP cooling units seems to fall into a much smaller number of directional groups, suggesting a relatively few gigantic eruptive events — more than the number of basalt formations — but, much less than the number of cooling units with reddened contacts or other evidence that could be construed as indicating temporal gaps. The Orange Mountain Basalt, of the Newark Basin, with at least 3 cooling units separated by well-developed red intervals, argued to be infiltrations and subsurface weathering, are within one direction group (Kent et al., 2023) and the individual cooling units are thus most simply interpreted as lobes of a single lava eruption beginning with a lava lake all emplaced in decades or less. The North Mountain Basalt, which also begins with a lava lake, has 18 or more cooling units (Kontak, 2008), almost all of which have reddened tops (Olsen et al., 2003a) often with small amounts of sediment, is comprised of only two directional groups (Kent et al., 2023, 2024). And, in Morocco, the Tiourjdal section (in the Central High Atlas) exposing 34 cooling units, has only 4 distinct directional groups (Knight et al., 2004; Kent et al., 2024). Thus, in the Hartford Basin where multiple cooling units with reddened tops and breccia intervals can be identified in the Talcott Formation, empirical paleomagnetic data will be needed to determine if more than one eruptive event is represented.

The presence of the pillows indicates some standing water at the time the flow system transgressed the sediment surface. At 41.903780°, -72.761558° there is a 0.5 m basalt breccia-filled fissure with an arkosic matrix in the middle of the road cut (Gray, 1987), originally observed by Rice (1886) and Davis (1898). As noted by all three authors, this fissure pausibly filled with sedimentary material from above. Bedding with regional dip orientation is fairly obvious. Such fissures are classically called Neptunian or clastic dikes and they are locally quite common in CAMP flows. Neptunian dikes were described in most detail by Schlische and Ackermann (1995) from the North Mountain Basalt of the Fundy basin in Nova Scotia, a correlative of the Talcott. They can be very useful for determining the local syndepositional state of stress and sometimes have fossils within them, including skeletal remains (Olsen et al., 2012b, 2023b).

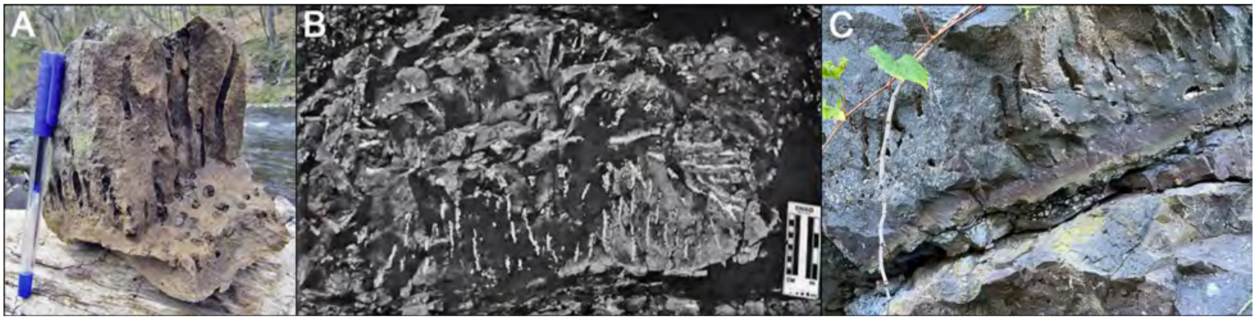

Figure 28. Pipe vesicles. A, Transported basalt block with pipe vesicles from Talcott Basalt [from Sheth (2020)]. B, Pillow in Talcott Basalt with radial vesicles, some with lambda-shaped coalescing amygdales at right and left sides of pillow, Farmington [from Philpotts and Lewis (1987)]. C, pipe vesicles at base of lava lobe in upper Talcott Basalt, Stop 2b. Note clear chill margin at base.

Some places along the contact have pipe vesicles suggesting flow of the base of the sheet moved northward or northeastward (Manspeizer, 1969; Gray, 1982) (Figure 28). Pipe vesicles are parallel-to-sub-parallel often downward-bifurcating cylindrical tubes classically interpreted by Waters (1960) as forming water vapor generated from the underlying sediment generated from the heat of the lava. The rising bubbles rising buoyantly into the overlying flow get dragged in the direction of the lava flow movement or bubbles nucleating at the contact. Philpotts and Lewis (1987) proposed different interpretation based on analogy with very similar looking radial tubes in pillow basalts and tubes in ice cubes, neither of which can possibly be from buoyantly rising bubbles, in which bubbles nucleate at the chill contact by exsolution of gas and advance into the cooling lava with continued exsolution causing the bubbles to grow normal to the solidification front as pipes. Bubble forming at base of sheets could then pulled in the direction of the moving sheet with the lower parts progressively frozen in place. Originating from lava volatiles, as opposed to the sediment is also consistent with a lack of bubbles in the sediment supposedly the source of the volatiles in the Waters model, and the fact that pipe vesicles and vesicle cylinders never extend down into the glassy base of a flow. The vesicles started only once the glassy selvage changed to a crystalline basalt.

Figure 29: Map view of Shuttle Meadow Formation showing apparent changes in thickness laterally. Map compressed NE-SW 400% to exaggerate lateral change. Geology from Schnabel (1960); Schnabel and Eric (1964, 1965) Simpson (1966), and Hanshaw (1968). The letters *h* and *n* are copper mines at the base of the Shuttle Meadow (h, is the Higley mine and *n* is the Old Newgate mine).

A yet more recent model by Sheth (2020) based largely on observations from the Deccan Traps, but including a Talcott example from Tariffville (Figure 28A) postulates that pipe vesicles are hollow trails left by droplets of dense, immiscible iron-rich silicate or sulfide melt sinking through a viscous thermal boundary layer just above the lower chilled margin of a flow unit with the downwardly branching caused by droplets breaking up as they sink in partially crystallized in the basal thermal boundary layer. Although, Sheth argues that the downwardly branching shapes are impossible to explain with any kind of solidification front as in the Philpotts and Lewis (1987). It seems to us that this model, which relies of gravitation settling of droplets, is falsified by the observed branching seen in the pillows here in the Talcott (Figure 28), that cannot be due to gravitational settling. Even more problematic is the lack the predicted immiscible Fe rich liquid at the bottom of each pipe. This is important because the Sheth model asserts that the direction of bending of the pipes does not indicate the movement direction of the flow.

The Talcott Basalt pinches out 2.4 km along strike to the north of here, reappears at 3.9 km, and pinches at 6.4, reappears at 7.9 km and out pinches out for good at 9.0 km. According to Schnabel and Eric (1964) it is replaced by 30-50 m of Shuttle Meadow formation with a "bleached" zone at base, mostly consisting of yellowish-gray to greenish gray arose and siltstone with reddish layers common. This is the unit hosting the ores at the Old Newgate Prison. Schnabel and Eric also note that the Talcott seems to drop to a lower stratigraphic level in the area north of Tariffville by about 50 m (150 feet) in a distance of 1.6 km (1 mile), which is another way of saying that the Shuttle Meadow Formation thickens from 17 m to 67 m over the same distance, a change readily apparent in map view (Figure 29).

STOP 2c. Shuttle Meadow Formation (41.903047°, -72.760584°).
(Because it involves getting down to the river, we will only visit these outcrops if time, weather, water level, and vegetation permit.

Only 17 m of Shuttle Meadow Formation is present at this location (Figure 30) (Gray, 1982; Gray, 1987) in contrast to its thickness in many other places (Figure 29) where it can reach over 200 m (Whiteside et al., 2011). Most striking at this locality is the lack of any indication of deeper water lacustrine units such as those that are microlaminated and rich in fish. Arguably, the section here represents only the uppermost part of the formation, thinning by progressive hanging wall onlap at this locality based on the lateral persistence of the sedimentary cyclicity (~200 ky) elsewhere between the Talcott Formation and Shuttle Meadow Formation. The observations suggest that significant tilting of the basalt occurred after eruption of the basalt, during (or less plausibly, before) deposition of the Shuttle Meadow.

The lake waters depositing the fish-bearing Van Houten cycles of the Durham Member could very well have extended over this area, but the sedimentary record of them was eroded during lake low stands. The lack of a corresponding thinning of the Talcott which represents a brief instant in time, implies accelerated tilting occurring over a few hundred thousand years amounting to differential relief of a couple of hundred meters in a couple of hundred thousand years.

Figure 30. View of Stop 2c as it appeared in Spring of 2018 from the right bank. A, overview photo mosaic. Red lines show contacts: H, Holyoke; SM, Shuttle Meadow; T, Talcott. B, Detail of A showing Shuttle Meadow, Holyoke contact. C, Detail of B showing splintery fracture typical of the lower part of Holyoke flow 2. PEO photos.

Figure 31: Rounded basalt beach cobbles directly above top of Talcott Basalt, Stop 2c. Above, surface as naturally weathered. Below cut of same block. Collected by P. Huber, N.G. McDonald collection

As described by Gray (Gray, 1987) red sandstones and mudstones at the base of the Shuttle Meadow Formation, contain rounded pebbles and cobble-sized fragments of basalt (Figure 31). Abundant calcite-filled evaporite crystal pseudomorphs up to 5 cm are abundant in some layers. Based on the outline shapes, Gray suggested glauberite was the original mineral. Smaller casts, become more abundant higher in the section but their shapes and hence original mineralogy cannot be determined. The upper half of the section consists of laminated gray soda-rich (sodium carbonate) mudstones form the upper half of the section, and Gray (Gray, 1987) suggests this is a consequence of the reaction between the original clay-rich sediment and hot soda-rich pore waters circulating from the overlying cooling Holyoke flow. We suppose the transition in color from red upwards though purplish to drab purplish gray color is also a consequence of the thermal and chemical effects of the Holyoke.

The laminated purplish siltstone beds have mudcracks but judging from its lateral continuity along this shore and the opposite, this interval is relatively shallow water lacustrine in origin and probably represents an expression of some of the wetter depositional environments at the top of the Shuttle Meadow Formation. Thus far no fossils have been found in this section.

As mentioned, the Shuttle Meadow lack the fish-bearing gray and black cycles present to the south (e.g., Stops 3 and 7). However, at least the lower cycle containing the Southington Limestone Bed outcrops 45 km to the north along I-91 at Northampton (Olsen et al., 2003b), where the climatic precession cycle must be in excess of 25 m thick, corresponding to a much thicker Shuttle Meadow Formation as well. Evidently, the Tariffville are was on a relative high area during Shuttle Meadow deposition. The abrupt thickening of the Shuttle meadow across some of the cross faults suggests at least some were active during sedimentation (Figure 29).

<u>STOP 2d.</u> Holyoke Basalt along CT-187 (41.901963°, -72.760026°): (20 minutes).

The Holyoke Basalt is about is 174 m thick (Philpotts et al., 1997; Boudreau and Philpotts, 2002) here and seems to consist only of the upper, second flow, not only based on the presence of the characteristic splintery fracture of the colonnade, but also the aberrant very low paleomagnetic inclination direction (Figure 44), this being site H2C of Prévot and McWilliams (1989). As prosaic as it may seem while we are looking at it, this is one of the thickest lava flows known on Earth.

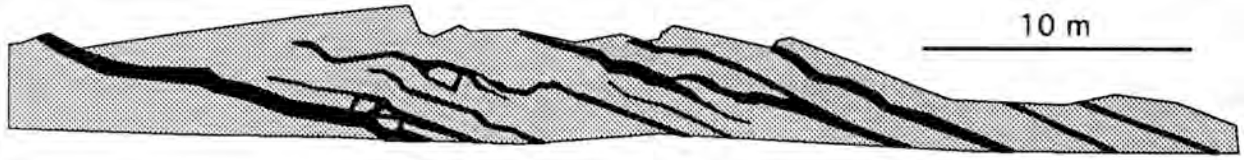

Figure 32: Vertical profile through zone of ferrodiorite segregation sheets in Holyoke Basalt mapped along north side of Farmington River along Tunxis Avenue using total stations. Similar sheets with similar geometries occur along cut at Stop 2d.

Philpotts and McHone (2003) note that the entablature/colonnade boundary is located 97 m above the base (exposed at the river edge but not here), which is 56% of the thickness of the flow. The splintery fracture, characteristic of this flow, cuts actual cooling columns of the colonnade that here are on the order of a meter in diameter. Vesicles are restricted to the top few meters and in the bottom decimeter of the flow; the rest of the flow being massive. This suggests to us that the magma may have largely degassed before the lava arrived at this site. Despite the flow's great thickness, the basalt is over all, fine-grained. Between 70 and 85 m above the base of the flow, however, sheets of coarse-grained ferrodiorite are spaced at ~1 m intervals. Most are a decimeter thick but the lowest is 2 m thick. Their cumulative thickness is 3.9 m, which is 26% of this central zone. They are laterally extensive, with the thicker sheets being traceable from one side of the gorge to the other, a distance of at least 400 m. A profile of these sheets was mapped using total stations on the right bank of the river along Tunxis Avenue before the outcrops became overgrown (Philpotts et al., 1997) (Figure 32). A Some thin and pinch out, but in such cases their stratigraphic position in the flow is marked by a horizontal fracture. Others bifurcate or connect with underlying or overlying sheets via short dikes. The matching of irregularities in the contacts on opposing sides of such dike/sheet intersections indicates that room for the segregation liquid was created by dilation of fractures in the host basalt. However, no angular corners are found on the contacts; instead, they are all rounded. Contacts on all but the lowest of the segregation sheets are sharp. The upper contact on the lowest sheet is also sharp, but the lower contact grades over a few decimeters. Fine-grained light-colored granophyric segregation sheets, which are typically about l cm thick, occur toward the tops of coarse grained ferrodiorite sheets, in the fine-grained basalt immediately overlying these sheets, and as extensions from the tapering ends of these sheets.

Similar coarse-grained segregation sheets the Preakness and North Mountain Basalts and multiple intrusions have yielded crystallization-age zircons that have provided the very high-precision ages for the CAMP (Schoene et al., 2010.; Blackburn et al., 2013; Davies et al., 2017; Marzoli et al., 2018; Davies et al., 2021), some of which have been critical in testing the lacustrine astrochronology. As yet, the Holyoke has not yielded such zircons, although only a few samples have been examined (see also Stop 3).

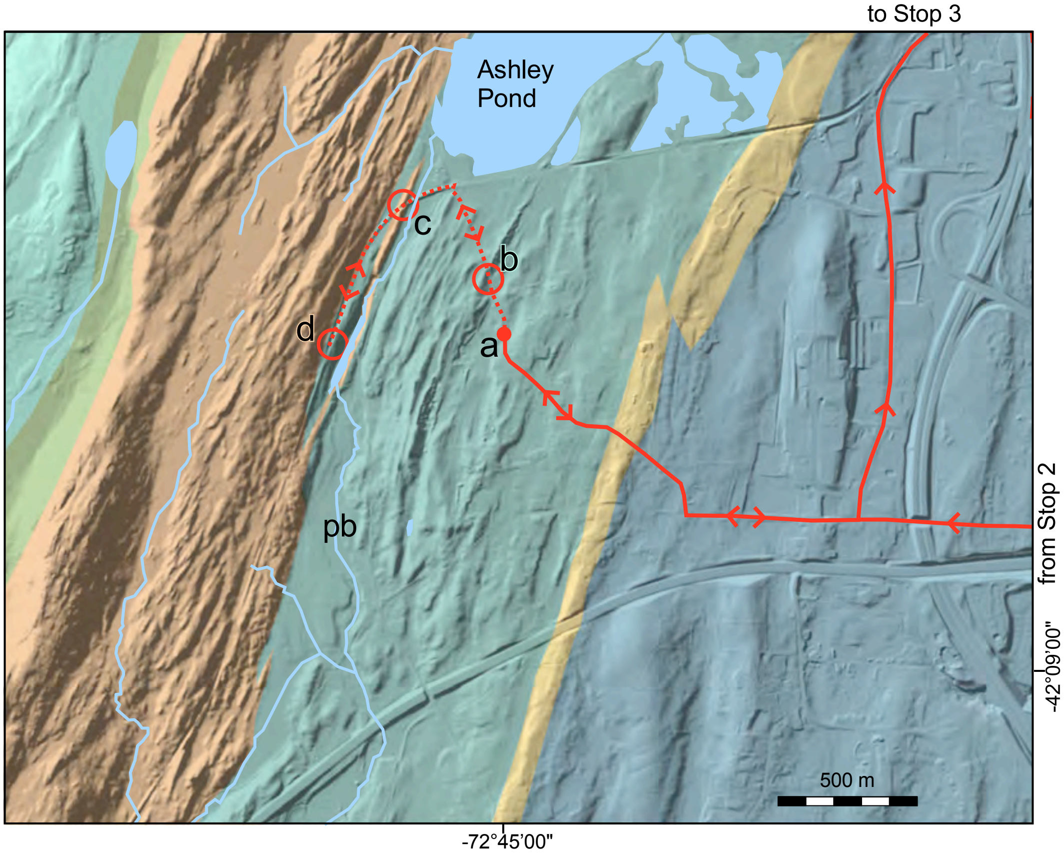

Figure 33. Bedrock geology and LiDAR for Stop 3. Sites are: **a**, parking area in cul-de-sac; **b**, Bosworth's Quarry's in lower East Berlin Formation; **c**, cut in uppermost Holyoke Basalt; **d**, basal East Berlin Formation. Abbreviation pb is for Paucatuck Brook. Key to units in Figure 22. Geology from Zen et al. (1983). Solid red line is driving route; dotted red is on foot.

Return to vehicles.

Miles	Cumulative Miles	
0.0	2.07	Head south toward Tunxis Rd, then, turn right onto Tunxis Rd
0.00	2.09	Right onto CT-189 N

0.90	2.99	Turn right onto State Hwy 540
1.40	4.39	Continue straight onto Seymour Rd
0.60	4.99	At the traffic circle, take the 1st exit onto International Dr
1.60	6.59	Use the right lane to turn right onto CT-20 E; stay on CT-20 E
4.00	10.59	Use two left lanes ramp to I-91 North toward Springfield
18.20	28.79	Use the left 3 lanes to turn slightly left to stay on I-91 N (signs for Greenfield)
0.70	29.49	Take exit 10A to merge onto US-5 N/Riverdale St
0.30	29.79	Merge onto US-5 N/Riverdale St, going North
1.60	31.39	Turn left onto Highland Avenue
0.10	31.49	Turn left onto Prospect Avenue
1.40	32.89	Turn right onto Quarry Road
0.60	33.49	Park at end of Quarry Road at cul-de-sac

Stop 3: Early Hettangian, basal East Berlin Formation (Figure 33), West Springfield, Massachusetts
Parking at 42.160755°, -72.666378° (42°09'38.7"N 72°39'59.0"W)

Main Points:

1) Contact between uppermost Holyoke Basalt and basal East Berlin Formation of early Hettangian Age, ~201.2-201.3 Ma
2) Infilling of complexedly porous uppermost second Holyoke Basalt flow with gray sediment
3) Basal East Berlin lacustrine and carbonate-rich and laminated, but with abundant dinosaur tracks
4) Basal East Berlin deposited during eruption of CAMP lavas elsewhere
5) Lower East Berlin Formation characterized by dominant obliquity pacing.

Lacustrine strata of the lower East Berlin Formation or their contact with the underlying Holyoke Basalt have received virtually no attention in the geological literature, perhaps because all of the known outcrops are along streams or other somewhat remote (by Connecticut standards) locations. This stop is one of the most assessable of lower East Berlin sites, but nonetheless requires a minimum 1.6 mi round trip walk. Our access route is along a trail and railroad tracks that traverse the middle though lower East Berlin Formation into the upper Holyoke Basalt.

At roughly 215 m north-northeast of our parking area, we will be at the southern edge of the surface expression of one of the Bosworth Quarry pits (42.162614°, -72.667181°), which during the 1840s was a supplier of stone for the Holyoke canals and produced 79% of the building stone produced in the Connecticut Valley during that time (Anonymous, 1982). A significant find of dinosaur footprints was made here in 1890 attracting national attention. The Naturalist, Kansas City, MO, volume IV, no 78 for 1890, reported,

> "A great discovery of fossil footprints has just been made at Bosworth's quarry in Holyoke. Here is a clean surface of shale about 100 by 40 feet, on which are seen about 200 tracks. Nearly all of them are in rows, the longest row containing seventeen tracks. The tracks are from six to eight inches in length, and were probably made by a reptile, that, if it had front feet seldom used them. 'this is without doubt the largest uncovering of tracks since the days of President Hitchcock'."

Lull (1904a, 1953) provides the only scientific mention of the site known and said exactly the same thing twice.

> "A quarry worked for commercial building stone situated to the west of the river in the town of Holyoke near Ashley Pond is said to have produced many footprints, quantities of which have been built into the foundations of the various mills in the city of Holyoke. One

> slab was shown me bearing two impressions which I identified as *Eubrontes giganteus* or *approximatus.* Of the other species no record is extant to my knowledge, as the locality has never been exploited scientifically, and as a rule when the commercially less valuable footprint layer is reached it is removed as speedily as possible."

Strata presently exposed at the northwestern edge of Bosworth's Quarry make a prominent, narrow ridge, enhanced by berm to the north of the trail and consist of at least on meter of thin-bedded, purplish to gray mudstone overlain by a thick bedded tan-to-brownish-weathering sandstone, plausibly the target of the quarrying. There are overlying red thin-bedded mudstone and fine sandstones underlying a ridge to the east, in between which there is no exposure. However, there is also no sign of any gray-black rubble that might indicate one of the deeper-water perennial lake sequences. What is exposed is very similar to the gray-purple unit at 60 m in the composite section in Figure 34. However, scaled to the whole formation, Bosworth's Quarry has to be stratigraphically lower in the section, perhaps near 120-130 m.

Walk along the side of the railroad tracks to the west and south, spotters will be alert for trains, although they are very uncommon. At about 0.12 mi (200 m) west there are is a cut through the upper contact of the Holyoke Basalt and very basal overlying East Berlin Formation (42.164762°, -72.670843°). As evident from the topography visible in LiDAR (Figure 33), there are many faults and fractures in this area. The exposures at this cut terminate to the west abruptly because of one of these faults, in this case with down-dropping to the west separation. Smaller faults in the exposure have well-developed near-horizontal slikenlines, and although the attitude of the fault cannot be determined, it trends NNE based on the abrupt termination of topography.

Because of microbial and lichen colonization, details of the contact are difficult to see which is exacerbated by the fact the abundant and often quite large voids in the basalt are filled with sediment that is a similar color to the basalt and which can have a large fraction of basalt debris. We will be able to see this more clearly at the next stop, albeit deeper with the flow.

Unlike the void fillings at Stop 2 in the Talcott Basalt which are red, these infillings are gray and presumably deposited in water-saturated basalt. Evidently, shortly after cooling, the basalt surface in this area was inundated by lake waters with lacustrine sediment infilling the ragged surface of the basalt. Note the thin vesicular decimeter-scale sheet underlain by sediments. This is plausibly the roof of a blister where vapors beneath the crust accumulated, exerting pressure, pushing the crust upward to form a dome, which later infilled with sediment. The true top of the Holyoke is higher than these sediments. We have not looked very hard, but thus far we have not seen not scraps of fish or other bone fragments in the sediment, and it is plausible that it was not a good place to live.

As we walk south, to our main destination, we will pass at least two other small exposures of the Holyoke Basalt and East Berlin Formation, similar to the one we just saw. At 0.4 miles south, southwest from the main Holyoke-East Berlin contact, there is a low cut along the tracks exposing laminated carbonate-rich strata of the basal East Berlin Formation — our primary target (42.160550°, -72.673975°).

The exposed section consists largely of laminated, oscillatory-rippled, calcareous siltstone and some limestone. The oscillatory ripples are generally very flat, generally not visible or barely visible in outcrop cross section. Desiccation cracks are rare. Scattered plant debris can be abundant and small dinosaur footprints are very abundant. There are many small to large slabs scattered along the west side of the cut, pried loose by avocational paleontologists on which many features can be seen, including the occasional small footprint. These slabs are particularly useful for seeing sedimentary structures and fossils.

Note: if you are moving slabs be aware that this is the season that yellow jacket wasps are active and can be especially aggressive as food supplies diminish. They especially like loose piles of rocks as nesting sites and PEO has been dissuaded on more than once from going through the rubble by then swarming when disturbed (although not on PEO's mid-September 2025 visit).

Identifiable fossils found so far include small (<20 cm) brotozoid (*Grallator* and *Anchisauripus*) and *Anomoepus* footprints, attributed to theropods and early diverging ornithischians, *Brachyophyllum* shoots and related male and female cones and bracts (chirolepidaceous conifers), and, importantly, partial leaves of the fern *Clathropteris*.

The section is especially important because it is one of the very few available sections of the basal East Berlin. The combination of significant, nearly bedding-strike-parallel faults and very discontinuous outcrops makes it impossible to compile a reliable section through the lower East Berlin anywhere that connects to the very well-known middle to upper East Berlin sections [e.g., Stop 4; Hubert et al. (1976), Hubert et al. (1978), Olsen et al. (1989), Olsen et al. (2024e)]. In fact, prior to the description of the MDC cores by Conti (2016) and Steinen et al. (2015), PEO had assumed that the gray lacustrine sequences in the lower East Berlin correlated to the lower Towaco Formation as seen in the Passaic River Diversionary Tunnel cores (Olsen et al., 1996b). The MDC cores showed that, although there was an remarkably close match in the stratigraphy between the upper three quarters of the East Berlin and all of the Towaco, the lower one quarter of the East Berlin had no counterpart in the Towaco. In astrochronology, that amounted to about 60 kyr predicted to be represented by the Preakness Basalt (Figure 6). Specifically, MDC core BD 255 (and BD 228) spans what is "missing" in the Towaco Formation (Figure 34).

The lowest gray sequences evident in East Berlin stand out as unusually well-developed for their position in the astrochronology. The interval is also unusual in tending have significant carbonates. Some are prominent enough to support the limestones are well developed enough to have supported a small cement industry in the so-called Jarvis limestone (Starquist, 1943). Edward Hitchcock was aware of these limestones and wrote (Hitchcock, 1858, p. 8),

> "I have recently traced this limestone with more care, and find it laid open in four places in West Springfield, besides the north bank of Chicopee River, namely, at what is called the Bear's Hole, Paine's Quarry, Meacham's Quarry, and a quarry two miles south of the north line of the town, and two and a half miles west of the river; so that I cannot doubt that it forms a continuous bed, at least ten feet thick, and six miles long. Much of it is a blue compact limestone, much resembling the lias of England. It lies near the base of that series of rocks-sandstones and shales-to which the preceding reasoning applies, having the same easterly dip of about 20°, as the including sandstone and shale, and not far above the trap of Mount Tom."

However, on the hand-colored versions Hitchcock's (1858) famous "Ichno-geological Map" we have seen, the color code for the limestone units and the "Volcanic Grit" seems confused.

The map of "Ireland", 3rd Parrish of Springfield depicted as 1827 in Everts et al. (1879)(p. 918-919) show "hydraulic cement" manufacturing at the Grist Mill on Paucatuck Brook about 272 m north-northeast of this exposure, and the dwelling of Rufus S. Paine just to the south (? Paine's Quarry). The remains of the mill are still present (42.162466°, -72.671935°). Walls of the mill are on the upper contact of the Holyoke and the section is truncated to the west apparently by the same fault that truncates the basalt as we walked along the tracks and follows the valley of Paucatuck Brook south of the mill location. There are clear signs of quarrying in this area, especially along the east side of Millville Road immediately east of the mill site, as well as along strike to the south- southwest. The thin-bedded units at the railroad cut are far too impure to make cement from, and it is unclear exactly which lake cycle in the basal East Berlin the quarried limestone is in, although they must be close. Thin carbonates are also present in the basal East Berlin along Spruce Brook, Pistol Creek Park, Berlin, Connecticut (Olsen et al., 2024e), and a brook draining into Quonnipaug Lake, Guilford, Connecticut.

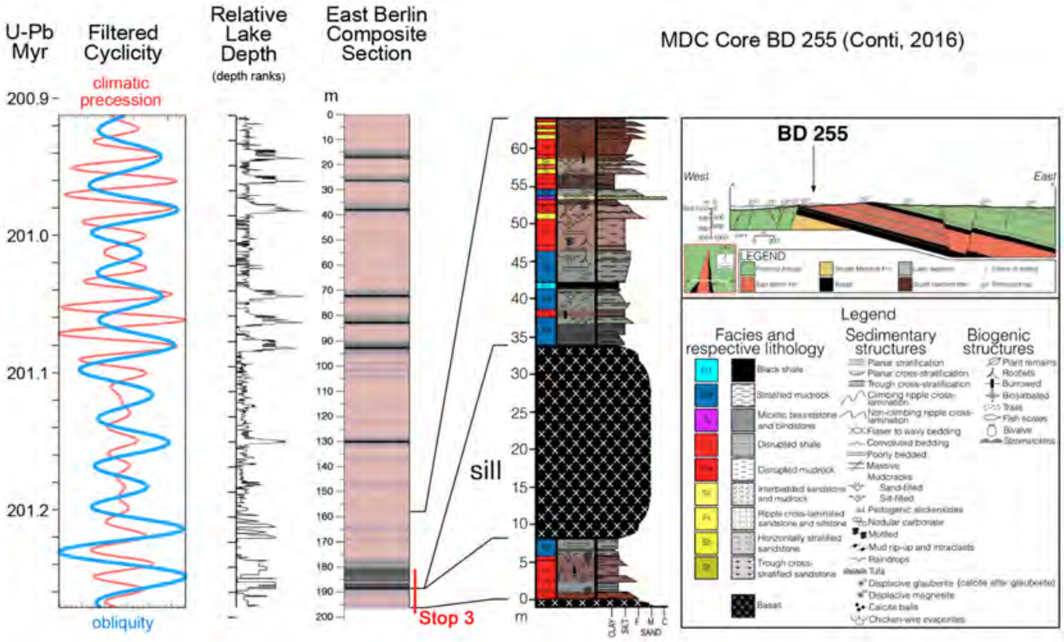

Figure 34. MCD core BD 255 in relation to East Berlin composite stratigraphy and orbital pacing.

The basal East Berlin stands out as being unusual in the abundance of carbonate and resembles in that aspect the lower Shuttle Meadow Formation, which also supported an early hydraulic cement industry (Andrews, 1924; Olsen et al., 2024e). The pattern could represent a facies syndrome associated with the ETE and the CAMP, perhaps from weathering of a large watershed with abundant basalt under super-greenhouse conditions alternating with volcanic winters, supplying waters enriched in both calcium (Ca2+) and bi-carbonate (HCO3-) ions compared to background conditions. The prevalence of carbonates and the presence of the fern *Clathropteris* suggest an unusual climate. *Clathropteris* is otherwise known from much of the Late Triassic and Early Jurassic of higher paleolatitudes, and perhaps its transient excursion south near the ETE reflects an equatorward migration due to volcanic winters and related larger scale climate change.

As shown by time series analysis of the East Formation, based on cores, the lower East Berlin Formation was paced by obliquity (Figures 17, 34), and like the lower Shuttle Meadow and Feltville, the lower East Berlin has much more limestone than any other part of the formation. This part of the East Berlin was deposited during the eruption of the upper Preakness Basalt flows. Presumably, some airfall or aerosol record of these eruptions are within this sequence. What would we look for?

Return to vehicles.

Miles	Cumulative Miles	
0.00	33.49	Head south on Quarry Rd toward Tiara Ln
0.60	34.09	Turn left onto Prospect Ave
0.40	34.49	Turn left onto Interstate Dr
0.80	35.29	Continue onto Bobala Rd
0.40	35.69	Turn left onto Whitney Ave
0.10	35.79	Continue onto Homestead Ave
0.20	35.99	Turn right onto Lower Westfield Rd
0.30	36.29	Merge left I-91 N toward Greenfield/Brattleboro VT

2.40	38.69	Take exit 15A to merge onto MA-141 E/Easthampton Rd toward Holyoke
0.40	39.09	Turn left onto Northampton St
1.60	40.69	Turn left onto Mt Park Rd
0.60	41.29	Turn right past gate onto Mt Tom Ski Rd (restricted usage MA DCR)
0.30	41.59	Continue onto Mt Park Rd
0.70	42.29	Park on left in large open area, Stop 4.

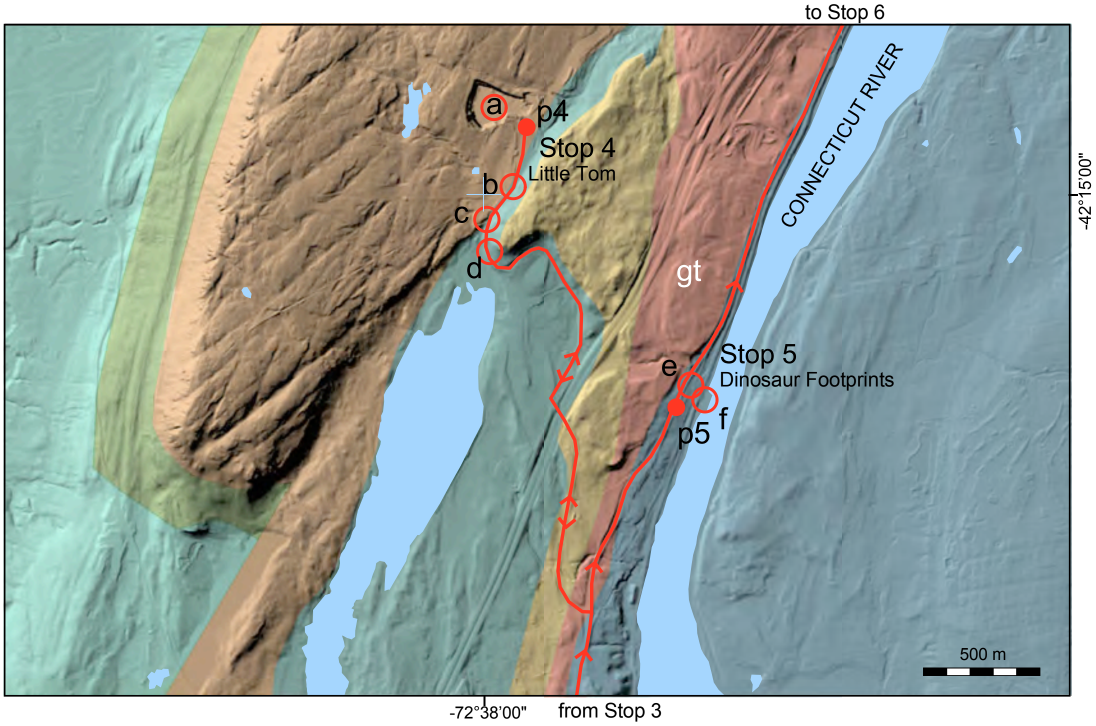

Figure 35. Map for Stops 4 (**a-d**) and 5 (**e**, **f**): **a**, Holyoke Basalt Quarry; **b**, dark gray laminated mudstone in precession-paced cycle below that with Westfield bed; **c**, vesicular interval of upper Holyoke Basalt; d, location of Westfield Bed and Pompton Ashes; **e**, main surface at Dinosaur Footprints; **f**, gray and red track bearing strata ~65 m above main track bed; **gt**, Granby Tuff; **p4**, parking for Stop 4; **p5**, parking for Stop 5. Geology modified from (Zen et al., 1983).

Stop 4: Little Tom Mountain. Hettangian, Middle East Berlin Formation and Holyoke Basalt, Holyoke, Massachusetts (Figure 35)
Parking at 42.252332°, -72.631151° (42°15'08.4"N 72°37'52.1"W)

Main Points:

1) Upper one-half of second flow of the Holyoke Basalt and Middle East Berlin Formation of early Hettangian Age, 201.274 ± 0.032 Ma and 200.0 – 201.1 Ma
2) Gabbroid veins in basalt
3) Infilling of cracks and fissures in second Holyoke Basalt flow with gray sediment
4) Giant Lake deposit of middle East Berlin Westfield Bed with dephosphatized fish
5) Pompton Ashes

The 73-acre Little Tom Mountain was secured by the Trustees of Reservations in 2002 from the former Mt. Tom Ski area. Mountain Park Road and the old Mount Tom Ski Road provide access the site and have exposures there are outcrops and exposures of Holyoke Basalt, East Berlin Formation and intrusive sills of Black Rock Diabase near the top of the hill to the north and east. A now-abandoned trap rock quarry in the Holyoke Basalt is at the north end of the preserve. Outcrops along Mount Tom Ski Road and the quarry are controlled by the Massachusetts Department of Conservation and Recreation (DCR). Much of this text is derived from a PEO contribution to (Getty and Thomas, 2017) and (Olsen et al., 2024e).

Stratigraphy. The sedimentary section at Little Tom Mountain was briefly described by Olsen et al. (1989) and Getty and Thomas (2017) and correlated with two other major sections in the Hartford Basin (Figure 36). The Middle and upper East Berlin Formation is exposed along the road, which in the summer time is barely visible because of the brush and trees that have grown since the 90s. The section at Little Tom was particularly challenging because of the considerable relief, intermittent outcrops, and sills intruding in the red beds above the section along the road. The contact between the East Berlin Formation on the southeast side of the road is separated from the Holyoke Basalt on the northwest side of the road by a significant fault that is down-on-the-southeast. These sections are the only ones we will see on this field trip that provide some larger environmental context.

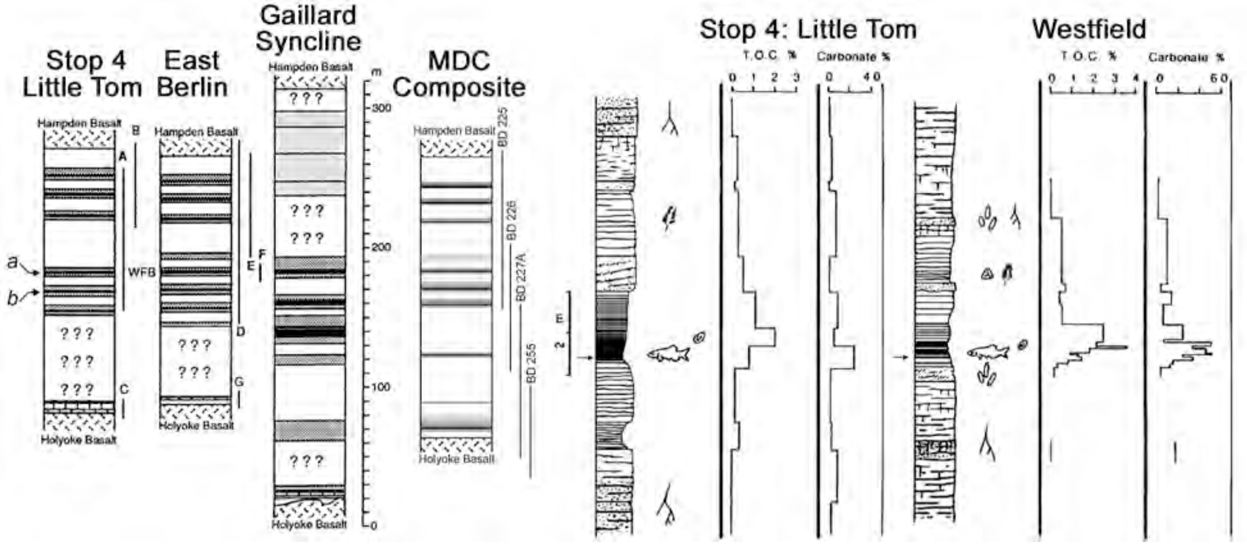

Figure 36. Correlation of the East Berlin Formation at three major areas of exposure and organic carbon and carbonate carbon, Westfield fish Bed: MDC composited based on Steinen et al. (2015). Stop 4 section is a composite north west side Little Tom, the 1-91 cut, Mountain Park, MA (Hubert et al., 1976); and the railroad cut south of Ashley Pond, Holyoke, MA, as hypothesized in 1989. The East Berlin section is a composite of the US 9, Ct 15, Ct 72 cuts, East Berlin, CT, the 1-91, US 9 cuts, Cromwell, CT and the, Spruce Brook outcrops, East Berlin, CT , as hypothesized in 1989. The Gaillard Syncline section is highly diagrammatic and also, as hypothesized in 1989. Right: details of correlative cycles at Stop 4). Arrows indicate position of Pompton Ashes. Modified from Olsen et al. (1989) and Getty et al (2017).

Best exposed are two lake level cycles in the middle East Berlin (*a* and *b* of Figures 36, 37, 38, 39), on the southeast side of the road. Both have black laminated mudstone sequences and the upper of the two is the Westfield Fish Bed. PEO first correlated this bed with the section that takes its name at Westfield CT along Miner Brook about 74 km south. Confidence in this correlation was based on its stratigraphic position with a thick red sequence above it, its specific microlaminated sedimentary fabric, and the presence of fossil fish (Figure 36-39) and small clam shrimp (spinocaudatans). There is also a prominent ~2 cm turbidite that was speculated to correlate with a wide spread similar turbidite at several localities to the south (Olsen, 1988a). The importance of this correlation at the time was that it implied that the lakes that produced the black microlaminated mudstones were very, very large, perhaps hundreds of kilometers long and that the lake-level oscillations represented basin-wide event, in fact isochronous intervals, not local ponds or flood-plain lakes. This was very important to the Milankovitch hypothesis for these cycles [e.g., (Olsen, 1986)].

Great lakes and lake cycles: There was, and still is in some quarters, a strong resistance to the idea that one can correlate meter-scale beds in continental sequence over distances greater than 100 km in what is in fact an area of notoriously poor outcrop. However, this correlation was recently highly corroborated, in fact as close to as proved as possible, by the discovery of the Pompton Ashes, first seen without being recognized as such in the Newark Basin Army Corps of Engineers cores in the 1980s, and then recognized in the well-known East Berlin Formation exposures along CT-9 East Berlin, CT (thanks to Tony Philpotts) (Olsen, 2017; Olsen and Douglass, 2022; Olsen et al., 2024e). Since then, it has been found at all but one of the Hartford and Newark Basin localities at which the Westfield Fish Bed and its correlative in the Newark Basin (the Colfax Bed) were hypothesized to exist (Olsen et al., 2016), making a total so far of four cores (2 Newark, 2 Hartford) and six outcrops (1 Newark, 5 Hartford) spanning 200 km and two basins. Not only does this ash unequivocally demonstrate that the cycles are correlatable basin-wide, but it also demonstrates, because the fish-bearing microlaminated bed in which it is interleaved is varved, that the lakes in the Newark and Hartford basin experienced the same climate signal – at the *seasonal* level!

Figure 37. Exposures of the cycles bearing the Westfield Fish Bed (*a* in Figure 35) as it appeared in 1989. On right is PEO for scale, looking for fish (photo courtesy of N.G. McDonald). PEO was unaware of the Pompton Ashes at that time.

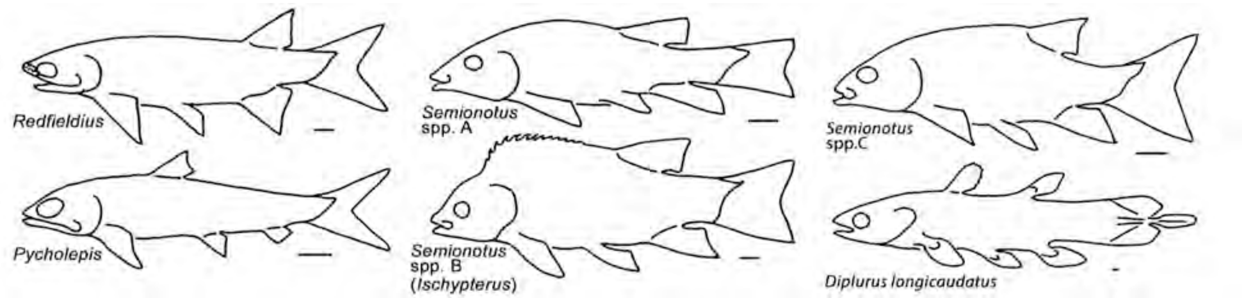

Figure 38. Fishes of the East Berlin Formation. There appear to have been many species of the stem gar, *Semionotus*, comprising species flocks like those of cichlids of the African Great lakes (McCune, 2004).

The sections as presented in Figure 36 were pieced together from smaller sections and the composite sections have recently been tested and corroborated by the MDC cores as reported by Steinen et al (2015). These cores also filled in a critical gap in the lower East Berlin as previously described. It is clear now that lakes in the Newark and Hartford basins fluctuated to climate rhythms synchronously and that the lakes, when at high stand, were huge and may even have been connected by open water. In fact, what is known about cyclical sequence in the Culpeper Basin in Virginia is consistent with correlative lake sequence there (Olsen et al., 2023a), and if the lakes connected though the Gettysburg Basin, the lake would be in excess of 700 km long, considerably larger than any lake in the world other than the Caspian and Black seas.

Cycles of the middle East Berlin Formation. The upper two of the middle triplet of lacustrine cycles are exposed along the road on the NW side of Little Tom (Figure 35). The upper cycle contains the Westfield Fish Bed (Figures 37, 39). This bed has a calcareous, organic-rich, microlaminated interval containing the Pompton Ashes (see below), articulated fish, and *Bulblimnadia* sp. clam shrimp (spinocaudatan crustaceans).

In order of abundance, the Westfield Fish Bed has produced *Semionotus* spp. (holostean gar relatives), *Redfieldius* spp. (paleonisciforms), *Diplurus* cf. *longicaudatus* (a coelacanth), and *Ptycholepis* (another paleonisciforms). The Westfield Fish Bed produced the one of the very first recorded articulated fossil fish in North America, a *Redfieldius* from Westfield, CT, mentioned by Silliman in 1816 [in Cleaveland (1816)] (Brignon, 2017). The *Semionotus* species from this bed have a very wide range of body forms and scale shapes and comprised species flocks, similar to the cichlid fishes of the East African great lakes (McCune et al., 1984). Only *Semionotus* and perhaps *Redfieldius* have been found at this locality, however, and their preservation style makes them hard to identify. The fish here, as at most localities of the Westfield Fish Bed, are to varying degrees "dephosphatized" (Figure 39E); that is, the phosphate mineral matter of the bone has been mostly or completely dissolved early in diagenesis by microbially mediated post-burial processes (McDonald and LeTourneau, 1989; Leonard, 2013; LeTourneau et al., 2015). This has led to complete disappearance of the fish or just the faintest of "ghost fish". This is almost certainly a very much more widespread phenomena than generally realized [e.g., Meacham (2016)] and in fact may be the norm rather than the exception.

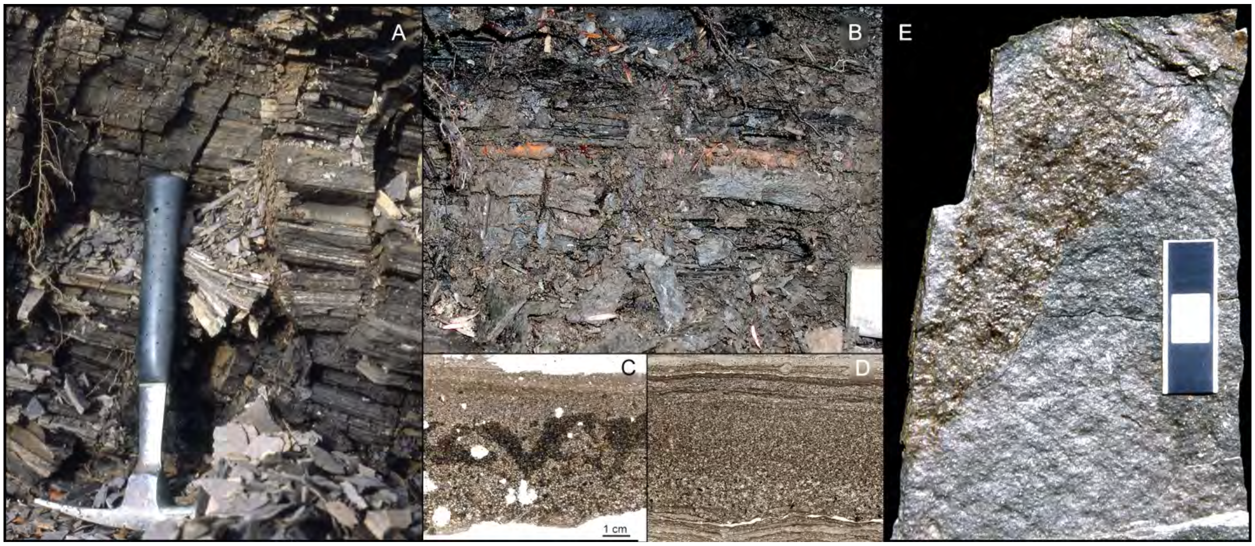

Figure 39. Facies, ash, and fish of the Westfield Fish Bed at Stop 3: **A**, laminite of the fish bed, the facies that produces the fish and clam shrimp (hammer is ~28 cm); **B**, the orange-weathering Pompton Ash (hammer head is 2.5 cm deep); **C**, thin section of Pompton Ash from Stop 3; **D**, thin section of Pompton Ash from Parmellee Brook, Durham, CT; **E**, dephosphatized indeterminate fish (?*Semionotus*) from Stop 3 (scale is cm, courtesy of N.G. McDonald). (Both thin sections courtesy of A. Philpotts).

What seems to be the next cycle down section (*b* in Figure 36) is exposed to the north, opposite the old buildings for the former ski area. This cycle has yet to produce any fish, although as suggested above, they may have vanished (!). This cycle is notable for having what look like stromatolites (Figure 40). They are in an appropriate position within the lake-level cycle, lying in the transgressive part, but they also look like some types of penetrative footprints in cross section. PEO favors stromatolites. Which are they?

Figure 40. Left, are these stromatolites or penetrative footprints (from *b* in Figure 36, left)? Right, *Palamopus clarki,* the tracks with more than 3 toes. Pl XLIV, fig 2 of Hitchcock (1858).

Dinosaur tracks from Little Tom Mountain. Hitchcock (1858) refers to what is probably this locality in naming a new species of a penetrative track, *Palamopus clarki* (Figure 40, right). In regards to ACM ICH 12/1, Hitchcock (1858; p. 127) states that the locality, is, "Northampton [now Holyoke], back side of Mount Tom, where it was discovered by Professor WILLIAM S. CLARK, whose name, therefore, it seems proper, should be attached to it, even though I exclude another name, which I have always delighted to honor. … But the tracks of the hind feet are too distinct to be mistaken, and too unlike any others to be confounded with them." In fact, footprints abound in these strata and are literally lying around. *Batrachopus deweyii* ACM ICH 26/5 and 26/6 (Stop 6) are also plausibly from this locality (Olsen and Padian, 1986), possibly from near the sills high in the bluff.

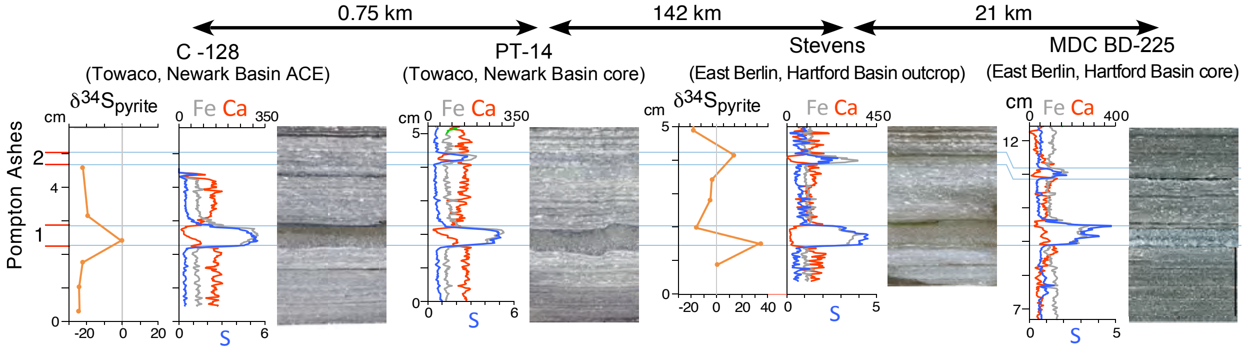

Figure 41. Pompton Ashes from four localities in the Newark and Hartford Basins showing variations is µ-XRF major element composition and $\delta^{34}S$. Note the lack of thickness changes in the ashes laterally.

Pompton Ashes. The two thin (lower ~5mm and upper ~1mm) Pompton Ashes are the only definitive CAMP airfall ashes in the entire $15x10^6$ km^2 extent of the province, and as such are presently the only known source of direct information on the potential atmospheric effects of ash rich eruptions of the CAMP. Weathering of the ashes results in a bright orange mineral, presumably a jarositic mineral derived from the pyrite, that in outcrops often makes the lower ash brilliant red-orange, but when fresh the ash is steel gray to dark gray. Because of the high pyrite content, the ashes show up very clearly in micro-XRF scans (Figure 41). When fresh, the ashes consist of euhedral plagioclase laths of many sizes, with no signs of rounding and (at least in the lower ash). There are minute spherules with what appear to be quench textures. Based on analyses of Philpotts [in (Olsen et al., 2024e)], pyrite and calcite fills interstices, along with what may be chert. The plagioclase laths are An46-An22 and therefore the ash appears basaltic-andesitic in composition, as are some CAMP flows and intrusions (Marzoli et al., 1999). There is no quartz or mica unlike surrounding microlaminated mudstone. The ashes show no systematic change in thickness over a distance of 200 km suggesting that it is a distal product of a mega-eruption very far away.

The Pompton ashes have thus far been found at 10 sites total stretching over roughly 200 km: two cores and five outcrops in the Hartford Basin and two cores and one outcrop in the Newark Basin. The ashes are always in a microlaminated calcareous mudstone with fishes in the same position in the deep-water phase of the same precession-paced lake level cycle – the Westfield Bed in the Hartford Basin and the Colfax Road Bed in the Newark Basin. Despite the very long distance over which these ashes occur, no clear trends in grain size or thickness of the ashes have been detected. Compositionally the ashes are very distinct from the surrounding microlaminated mudstone. The lower and thicker (~5 mm) ash has anomalously high platinum-group-element (PGE: including Ir) and Hg concentrations, and mafic appearing εNd (as opposed to adjacent sediments which look appropriately continental). Both ashes have unusually positive δ^{34}S isotopic ratios for pyrite (0 to >30‰) (Stüeken et al., 2019).

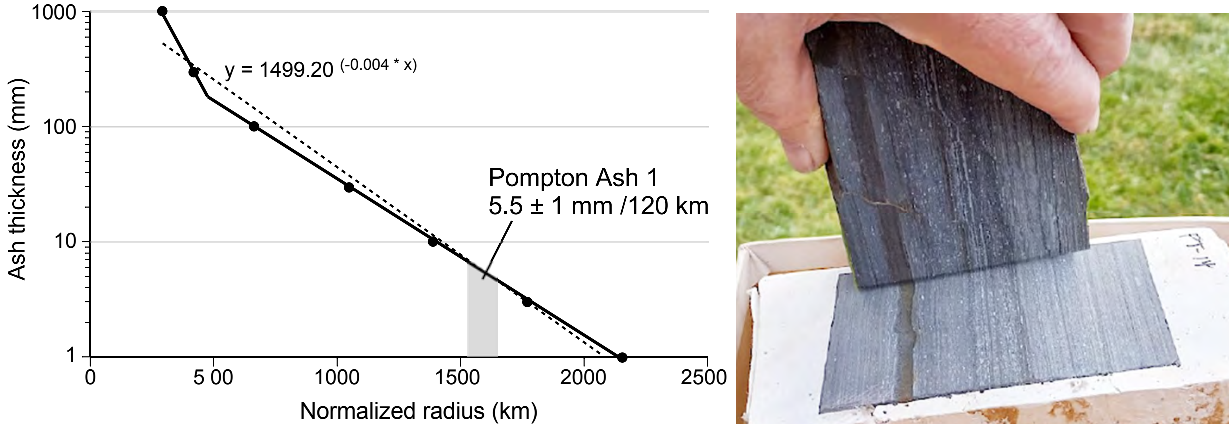

Figure 42. Left, modeled ash thickness from Yellowstone-scale eruption with thickness of lower Pompton Ash. (ash 1), based on Mastin et al. (2014). Right, reality check! Slab containing the Pompton Ashes from outcrop at the Stevens Locality, Durham, Connecticut, placed up against a segment of slabbed ACE core PT-14 from Wayne, New Jersey separated by about 140 km and in different basins.

The very long distance over which both ashes retain consistent thickness is very unusual and calls for an explanation related to their source or sources – which is extremely uncertain. One explanation is that the source was a basaltic-andesitic, Yellowstone-scale eruption very far away. Ashes decrease in thickness exponentially[19] from their sources and thus to get no discernible change over such a distance requires being at the tail of the thickness curve where the rate of thickness change would be at a minimum, but yet large enough to still produce a ~5 mm ash (Figure 42). A Yellowstone-scale eruption from south Florida, 1800 km away might do it. A second explanation is that the source(s) were not a distant point source, but rather was an enormously long fissure eruption from a dike parallel to the trend of the basins erupting simultaneously (at a year-scale) over a significant part of its length. We presume that CAMP eruptions were from fissures from feeder dikes, but known dikes in eastern North America would be so close that they would produce a very uneven thickness distribution of ash.

Interesting, there is at least one candidate dike in Morocco, the +400 km Foum Zguid Dike and associated Bas Dra Sills. This compound, chemically diverse dike ranges in composition mostly along the Talcott-Higganum-Palisade-Orange Mountain to Hampden-Bridgeport-Pelham-Black Rock-Hook Mountain trend in terms of major elements and along a similar trend in the incompatible rare earths and transition metals. It has produced one U-Pb zircon CA-ID-TIMS age of 201.111 ± 0.071 Ma (Davies et al., 2017) and thus falls within tight uncertainties of the astrochronological age of the Pompton Ashes at 201.040 ± 0.020 Ma, almost halfway between the Preakness/Holyoke and Hook Mountain Hampden ages (Figures 6, 7, 17). About 1500 km distant, Pangean trade winds are oriented the right way to carry ash from the Foum Zguid Dike to eastern North America and also far enough away that it might not be necessary for a major part of the dike to be active along its length. Of course, there might be other candidates dikes as well on the conjugate continental margins as well. However, we note, that if the chemistry of these rocks is a proxy of time (see below) then this dike was active through much of the history of the CAMP.

Spherules, some 100µm, with apparent quench textures including inwardly-radiating textures and partially hollow centers are one of the most striking aspect of thin sections of the lower ash (Figure 43), plausibly indicating very rapid cooling from melt from a vapor cloud. These resemble some impact spherules, although we do not imply an impact origin. They imply a very high and hot vapor plume for the eruption.

It is often said that basaltic eruptions should not result in high plumes and widespread ash transport because of the low viscosity which inhibits fragmentation favoring gas escape and fountaining (Polacci et al., 2006) as opposed to violent explosions. Although, explosive basaltic eruptions do occur (Arzilli et al., 2019), it is not the explosive forces that drive the plume height, in theory, it is the column buoyancy due to local atmospheric heating in response to successive eruptive pulses that has the potential to transport the ash and gases to the stratosphere (Kaminski et al., 2011). This convective transport could have been responsible for transporting a vapor plume into the stratosphere which then reentered as spherules and other ash products.

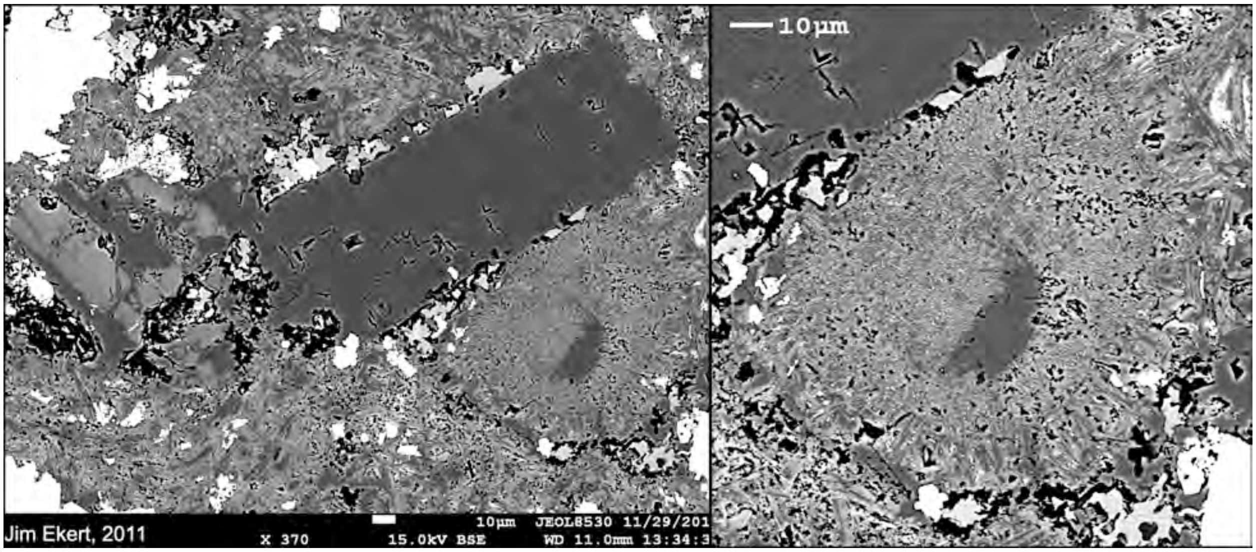

Figure 43. Backscattered electron image of thin section of Pompton Ash 1 (Stevens locality, Hartford Basin) showing primary plagioclase crystals and spherules the most prominent of which is in the lower right of the left image and shown enlarged on the right. Note the radial crystals suggesting a quench texture and the hollow interior that could be a shrinkage bubble from the cooling and crystallization of the sphere. Imaging by Jim Ekert and Anthony Philpotts.

Among the eruptive products that may have entered the stratosphere during the eruptions that produced the Pompton Ashes would be sulfur dioxide (SO_2). Combining with water in the atmosphere it forms sulfuric acid (H_2SO_4) and sulfate salt aerosols that are highly reflective, increasing atmospheric albedo resulting in dimming and cooling, the most dramatic episodes of which are termed volcanic winters (Rampino and Self, 1992). Injection into the stratosphere is important for volcanic winters because it allows very long distant transport, potentially globally. The hypothesis that the Pompton Ashes sulfur from eruptive plumes reached the stratosphere suggests that the sulfur should have undergone mass-independent fractionation (MIF). This most common scenario in which this would occur is by photochemical reactions by high frequency UV light above the tropopause and above the ozone shield which has blocked the highest frequency UV since the Great Oxygenation Event at 2.5 Ga (Farquhar et al., 2000). There is evidence that sulfur MIF (S-MIF) did occur due to injection of sulfur from target rocks above the tropopause at the K-Pg boundary (Junium et al., 2022) and similar evidence may show that Pompton Ash eruptive plumes did as well.

There is already sulfur isotopic evidence that Pompton Ashes were accompanied by large amounts of sulfur input into Eastern North American lakes. Stüeken et al. (2019) showed that the high pyrite sulfur concentrations in the Pompton Ashes were accompanied by positive anomalies (0‰ to >40‰), while the adjacent and surrounding microlaminated sediments are much more negative (~ -20‰) as would be expected for sulfur reducing bacterial fractionation, and this is exactly what is seen at the K-Pg boundary (Junium et al., 2022; Rodiouchkina et al., 2024). The search for S-MIF should test the hypothesis that this pattern was a consequence of stratospherically modified volcanic sulfur. These ashes are weathered at this locality, and as is true at most outcrops of the unit, the lower, thicker ash has weathered a bright orange probably from jarositic hydrous sulfates of potassium, sodium, or aluminum and iron resulting from the degradation of pyrite.

Were these really the only CAMP airfall ashes? We think a far more parsimonious argument is that nearly all thin CAMP ashes mixed into the sediments by bioturbation and current action in the non-microlaminated intervals and are now "cryptotephras", but without the glass. The sediments produced by chemically stratified lakes that preserve of the microlaminae and whole fish comprise a minor fraction of the sequence and that accounts for the rarity of airfalls. It is a preservational phenomenon.

As yet, no CAMP lava flows have been attributed to the eruptions that produced the Pompton Ashes. A candidate, however, is the “Recurrent Basalt Formation” in Morocco, which is geochemically nearly identical to the Hampden-Hook Mountain Basalts which it is usually assumed to be its equivalent (Marzoli et al., 2019). However, the Recurrent Basalt is in geographic proximity to the Foum Zguid Dike and at least part of the dike appears chemically similar to that Moroccan Flow (as well as the Hampden-Hook Mountain) and the dike is significantly older (201.111 ± 0.071) than the Hampden-Hook Mountain Basalts (200.916 ± 0.064) (Blackburn et al., 2013; Davies et al., 2017). An attempt by PEO to find the Pompton Ashes failed, possibly because the ashes are replaced by the flow. However, it is also possible that the ashes are not preserved in a visible form because there are no microlaminated units in the Moroccan sequence, although they would be expected to be quite thick given the proximity of the feeder intrusions.

Volcanism, lava lakes, and Mega eruptions. As seen at Little Tom and elsewhere, The East Berlin Formation is sandwiched between lava flows of the CAMP - the giant Holyoke Basalt below and the Hampton Basalt and its pyroclastic equivalent the Granby Tuff above. In addition, this is one of the very few places that a dike system of the CAMP, the Bridgeport-Pelham dike and its local name the Black Rock Diabase, can be seen, especially along I-91, directly “feeding” the flow and pyroclastics as well as sending numerous sills and irregular plutons into the East Berlin (Foose et al., 1968; Philpotts and Martello, 1986).

The former Mt. Tom Quarry just to the north of the Ski slope buildings has spectacular and important exposures of the Holyoke Basalt. The Holyoke Basalt was extruded into the basin and filled the lowland like water filling a lava lake - in many ways more like a caldera than a typical lava flow. Well-developed pegmatitic sheets are present low in quarry section, but still well above most of the thickness of the sheet. According to Philpotts et al. (1998) these formed from the expulsion of residual liquids from compaction of the underlying cooling crystal mush. As such, they are rich in incompatible elements, and it is from these kinds of pegmatitic sheets that datable zircons can be recovered (Blackburn et al., 2013), although that has yet to be done here.

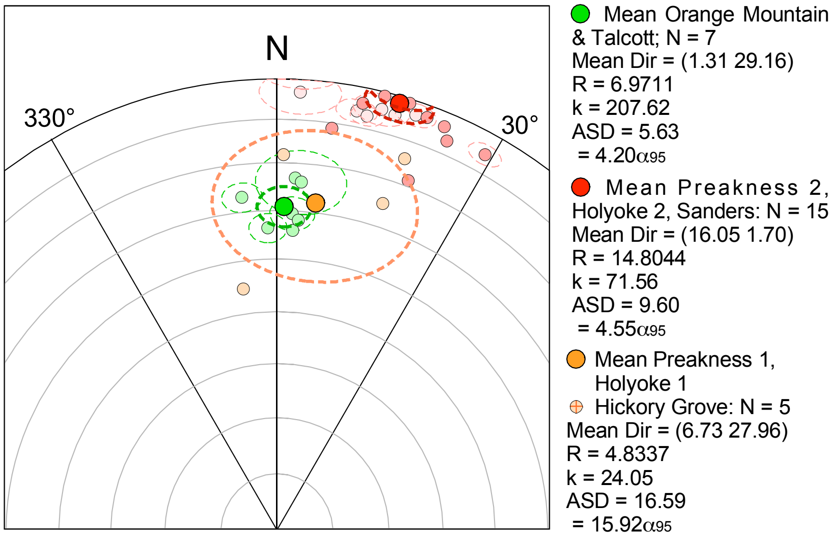

Figure 44: Comparison of bedding corrected directions for Talcott and Holyoke flows 1 and 2 (Hartford Basin); Orange Mountain Basalt, Preakness flows 1 and 2 (Newark Basin); and Hickory Grove Basalt and flow 1 of the Sander Basalt (Culpeper Basin). Light red, orange and green are data with the lightest colored dots plotting on upper hemisphere. Data are from Irving and Banks (1961), Prévot and McWilliams (1989), Hozik (1992).

The quarry also exposes numerous fissures that are filled with gray and drab sediments and basalt breccia spalled off the sides similar to what is seen higher in the sheet at Stop 3. In as much as these fissures were connected to the surface and filled from above, they actually comprise the locally oldest East Berlin Formation. In many places, such as the Ashley Pond are to the south, within Holyoke, the East Berlin Formation sediments in with contact and overlying with the Holyoke are gray and lacustrine. The sediment fill of these Holyoke fissures were likely deposited in water infiltrating and saturating the basalt. The contact with the East Berlin cannot be seen here however, because of down-to-the east fault separating exposures of the two formations between the quarry and the hill. Similar fissures in Basalt, albeit filled with red sediments have produce bones in the Fundy Basin (Olsen et al., 1989). One needs to be alert for such things as bones, even in such an unusual setting.

Only one flow of the Holyoke Basalt is present at Mount Tom, and vicinity. Ther are two flows however, in the Holyoke. the lower of which does not extend into Massachusetts. In Connecticut, the two flows are separated by a reddened vesicular surface with only a tiny amount of sediment (Davis and Whittle, 1889), which might be suggestive of a single eruptive (cf., Figure 27). However, it has long been recognized that each cooling unit has decidedly different paleomagnetic directions (Prévot and McWilliams, 1989), with the upper cooling unit having very shallow inclinations (Figure 44), indicating these do represent separate flows from separate eruptions. The upper flow, as previously mentioned, also has very distinctive splintery prismatic jointing (Stop 5) which is maintained laterally and even outside the Hartford Basin in the Newark and Culpeper Basins. The simplest explanation of the consistent directions in the upper unit is that it represents a single enormous eruption the products of which span ~800 km. It is worth noting, however, that the second flow of the Holyoke and its correlatives, are so thick that they may have taken over a century to cool (Moumou et al., 2024) beyond the magnetic carrier's Curie point and this might capture secular variation as the top and bottom cooled earlier than the middle, as has been suggested (McIntosh et al., 1985; Hozik, 1992). Systematic and repeated study through this amazingly thick flow is needed to test this hypothesis.

There are thus only four eruptive events definitively recorded in the lavas of Hartford Basin: one for the Talcott, two for the Holyoke, and one for the Hamden. Two more distant eruptions are recorded in the two Pompton Ashes. It is unclear how many eruptive events are recorded by the three cooling units above the second flow of the Preakness Basalt. They could have resulted from only one eruption as there is some continuity of chemistry (Tollo and Gottfried, 1992); however, it is clear they are not represented in the Hartford Basin and must have been emplaced during early East Berlin Formation time (Stop 6). Perhaps they are represented as visually obscured cryptotephras.

Even more flows contemporaneous with lower East Berlin sedimentation have been reported from the Culpeper Basin. In addition to the lower thickest flow of the Sander Basalt, there are at least four different chemistries described as comprising two major flow sequences and numerous individual flows (Lee and Froelich, 1989; Tollo et al., 1989). Apart from the lowest, how many of these are actual cooling units or flows remains to be determined, but importantly, the upper units at least do not have counterparts in the Hartford Basin and may be represented by cryptotephras in the lower East Berlin (Stop 6) along with records of environmental disturbances caused by the eruptions.

Hampden Basalt and Granby Tuff. Because of time considerations we will not examine the third and youngest lava formation in the Hartford Basin, the Hamden Basalt, but we passed it on the way in and will pass it on the way out of this site. It a high-iron, high titanium basalt (HFTQ). It was emplaced about 358 kyr after the Holyoke, based on U-Pb dates (Blackburn et al., 2013) from the intrusive proxy for the Hook Mountain Basalt in the Newark Basin to which it correlates based on cyclostratigraphy and geochemistry. There is no clear evidence that the Hampden Basalt consists of more than a single flow in Connecticut. Reports of multiple flows [e.g., (Chapman, 1965; Moumou et al., 2024) appear to be largely based on vesicle-rich segregation veins. According to Gray (1982), the base of the flow is almost everywhere characterized by tilted pipestem vesicles indicating a southwesterly source. Gray also notes the presence of fragments and meter thick layers of vesicular basalt locally at the base. However, in Massachusetts, two flows have been reported (Colton and Hartshorn, 1966) but without details. Again, we suspect the presence of two flows was inferred on the basis of vesicle-rich segregation veins.

The Hampden is the only CAMP lava other than the Talcott that is securely tied to a vent and that relationship can be seen in this immediate area. In this region, the Hampden Basalt merges with the Granby Tuff in a complex arrangement. Breccias and ash fed by the Black Rock Diabase Dike and associated sills, related thin cooling units overlie the Hampden flow. Exposures of the vent complex were documented by Brophy et al. (1967) and Foose et al. (1968) where five flows emanate from a diabase plug. These thin flows and Granby Tuff lie below the Hampden Basalt towards the south according to (Emerson, 1898a; Emerson, 1898b) but lie on top of the Hampden according to (Bain, 1941; Balk, 1957) but in the vicinity of the plugs the Hampden cannot be traced and it seems plausible the entire complex represents a single eruption with multiple lobes interbedding with ash at the vent. Despite the lack of recent volcanological or geochemistry analysis of this vent complex, there is little doubt this feeder is part of the Bridgeport-Pelham dike system (Philpotts and Martello, 1986). We will pass several outcrops of Granby Tuff going toward Stop 5.

Return to vehicles.

Return to vehicles.

Miles	Cumulative Miles	
0.00	42.29	Head southwest onto Mt Park Rd
0.30	42.59	Continue onto Mt Park Rd
0.40	42.99	Continue straight onto Mt Tom Ski Rd
0.30	43.29	Turn left onto Mt Park Rd
0.60	43.89	Turn left onto Northampton St
0.60	44.49	Turn right into parking are for Dinosaur Footprints, Stop 5

Stop 5: "Dinosaur Footprints", Hettangian, Basal Portland Formation (Figure 35)
Parking at 42.241740°, -72.623510° (42°14'30.3"N 72°37'24.6"W)

Main Points:

1) Basal Portland Formation of Hettangian Age, 200.9 Ma
2) Location of holotype of *Eubrontes giganteus* the first dinosaur footprint described
3) Shallow water lake environment with breif periods of emergence
4) Although trackways look like herding, movements of the dinosaur may have followed shoreline instead.

In 1891, the Massachusetts legislature established the "Trustees of Public Reservations" for the explicit purpose of safeguarding land and historic sites for public benefit. The word "Public" was formally dropped from the organization's name in 1954 to distinguish it from government-owned properties. As the world's oldest regional land trust, it continues to serve this mission. The properties at Stop 5 (Dinosaur Footprints) and Stop 4 (Little Tom) are under the stewardship of the Trustees, while adjacent land is largely managed by the Massachusetts Department of Conservation and Recreation. The eight-acre Dinosaur Footprints preserve, acquired in 1935, represents one of the few locations where tracks remain in situ much as Hitchcock originally observed them, and is almost certainly the site of the type specimen of *Eubrontes giganteus*. Numerous trackways of *Eubrontes*, smaller brontozoids, *Anomoepus*, *Batrachopus*, plant remains, and diverse sedimentary structures are documented here. The visibility of these tracks is heavily influenced by ambient light conditions, which at times can render them nearly invisible.

Stratigraphy. Strata at Dinosaur Footprints belong to the Smith's Ferry Member of the Portland Formation (Kent and Olsen, 2008), which is the lowest division of the formation (Figures 6, 7, 17). The back slope hill to the immediate west of the site is comprised of Granby Tuff, Hampden Basalt and, intrusions of the Black Rock Diabase that in part were feeders to the tuff and flows. This site is shown on Hitchcock's 1858 "Mt. Tom section" in Figure S21 along with the "Little Tom" (Stop 3) site. This part of the Portland Formation is cyclical, but as the individual cycles cause by climatic precession are 20 m thick, that cyclicity is not easily visible at this site. However, there is a dark mudstone at the western water's edge overlain by gray then red siltstones and sandstones that comprise the projection of outcrop extending into the river. Based on astrochronology, itself based on the orbitally paced (Milankovitch) lake-level cycles, U-Pb zircon dating of basalts in the Newark Basin correlative to those in the Hartford (Blackburn et al., 2013), the age of these strata is 200.9 Ma, which is about 660 ky after end-Triassic extinction.

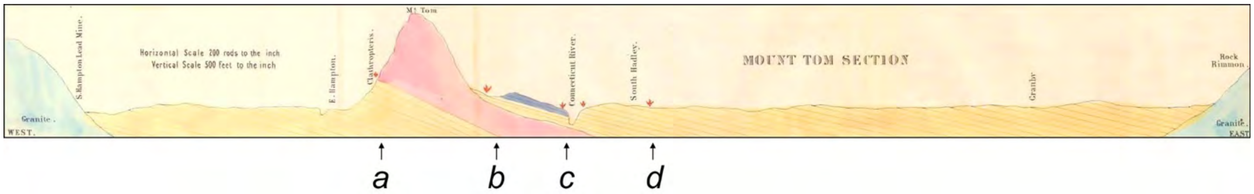

Figure 45. The "Mt. Tom Section" from Hitchcock (1858, Pl. III) extending approximately from 2 km west of Southampton to 3 km east of Ludlow, Ma showing Stops 2 and 3 with crystalline basement in teal, sedimentary rocks of the Hartford Basin in yellow, Holyoke Basalt underlying Mt. Tom in pink, and Hampden Basalt, Granby Tuff, and sills of Black Rock Diabase in indigo: *a*, Bassett's Quarry (overgrown) in the upper Shuttle Meadow Formation; *b*, position of Stop 4 at Little Tom in the East Berlin Formation; *c*, position of Stop 5 at Dinosaur Footprints preserve on the west bank of the Connecticut River, Smiths Ferry Member of the Portland Formation; and *d*, projection of the Moody quarries in South Hadley, in the Park River Member of the Portland Formation.

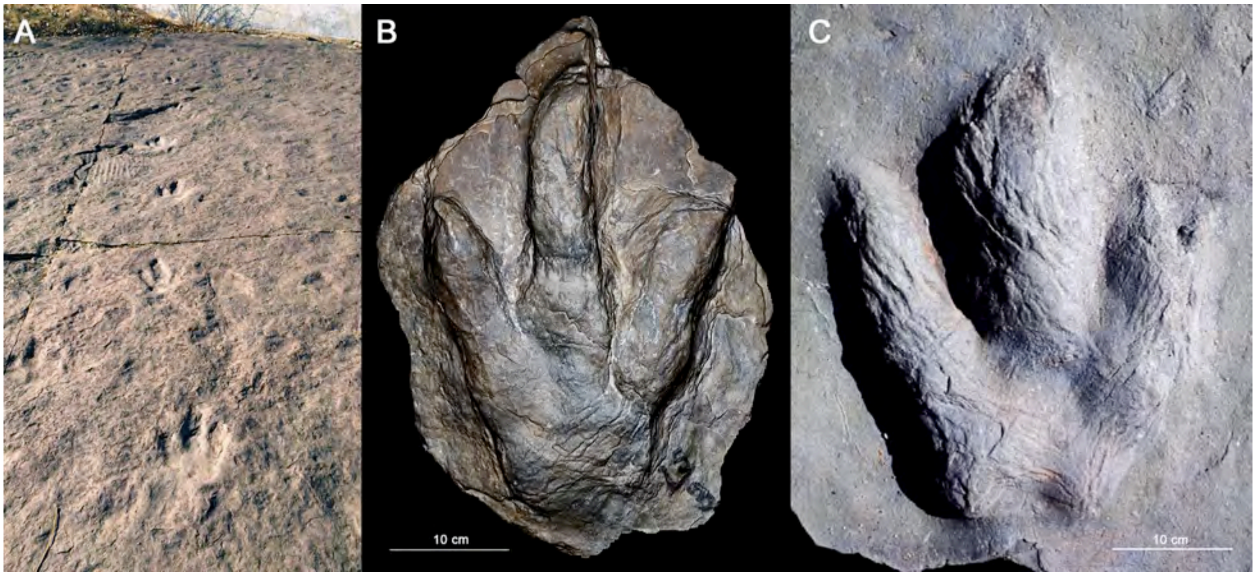

Figure 46. *Eubrontes giganteus*. A, trackway in good light at Dinosaur Footprints. B, holotype of *Eubrontes giganteus* ACM ICH 15/3, from the Dinosaur Footprints site described by Hitchcock (1836). C, Natural Cast in sandstone of a typical *Eubrontes giganteus* from Dinosaur State Park, Rocky Hill, Connecticut (outside the Exhibit Center). A and B are from the basal Portland Fomation and C is East Berlin Formation. We regard the differences between the morphology of the relatively narrow-towed holotype and the broader-toed Dinosaur State Park example as due to a combination of substrate firmness (the holotype was in softer mud) and the thickness of the microbial mat on the surface (the Dinosaur State Park example was imprinted on a thick mat).

Type specimen of *Eubrontes giganteus*. The principal evidence that this is the locality where the type specimen of *Eubrontes giganteus*, ACM ICH 15/3 (Figure 46), was collected derives from Hitchcock's 1836 paper in which he first described it. Hitchcock (1836, p. 308) states, "These stones were obtained from a quarry in the southeast part of the same town [Northampton, now Holyoke], on the east side of Mount Tom: and on resorting thither, I found numerous examples, some of them very fine, of several kinds of tracks. The strata at this spot, dip to the east, not more than 10°, and pass directly beneath Connecticut river, by which they are washed.", and then referring to the ichnospecies (p. 317), "Occurring only at the quarry in Northampton, on the east side of Mount Tom, where it is abundant.". The larger brontozoids at this site indeed bear a close resemblance to ACM ICH 15/3, and since the holotype is a natural cast while the tracks in the main area (against the retaining wall for CT 5) are molds, it is entirely plausible that its counterpart is still preserved among the visible in situ tracks.

In later works [e.g., Hitchcock (1865)], the locality is referred to as "Smith's Ferry". The ferry itself was located some 2.5 km north-northeast of the track site. However, neighborhood of Smith's Ferry (Mountain Division East Lots of Northampton), was annexed by Holyoke in 1909. Prior to its transfer to the Trustees of [Public] Reservations, the land on which the track site is located was owned by George D. Pellissier of Holyoke who brought the Thermite welding technique to use commercially in the United States for welding rails. Pellissier used it for the first time on a stretch of the Holyoke Street Railway. According to contemporary newspaper reports he was actively engaged in promoting the transfer (Transcript-Telegram Oct 14, 1936, p. 16).

Parallel trackway orientations: evidence for gregariousness? [this section is largely derived from Getty in Getty and Thomas (2017)] The "Dinosaur Footprints" site is notable as where dinosaurs were first interpreted as exhibiting gregarious, or social, behavior. Hitchcock (1836) initially advanced this idea after observing that numerous trackways of *Eubrontes giganteus*, which he attributed to giant birds, ran parallel to one another. Over a century later, Ostrom (1972) revisited the hypothesis and conducting a detailed survey and producing the first comprehensive map of the track surface. He documented 134 individual prints, which he assigned to 33 animals; 28 of these individuals were represented by trackways, while five were single tracks. Of these, 22 trackways and four isolated footprints were assigned to *Eubrontes giganteus*. Significantly, 19 (86%) of the *Eubrontes* trackways trended westward, whereas four of the five non-*Eubrontes* trackways showed differing orientations. Because no natural barrier could be identified as a cause for the directional pattern, and given that the orientations appeared taxon-specific, Ostrom inferred that the *Eubrontes* trackmakers had traveled together as a group. Later, Smith et al. (1996) noted similar parallel trackways with a comparable westward preference on surfaces situated 69 m stratigraphically above the main track bed, implying that such behavioral patterns persisted over extended time intervals.

Getty et al. (2012) and Getty et al. (2015) remapped the "Dinosaur Footprints" main slab exposure, raising the track count to 805, about six times Ostrom's tally, and identifying many other tracks including small brontozoids (*Grallator* and *Anchisauripus*), *Anomoepus* (early diverging ornithischians), and *Batrachopus* (protosuchian crocodylomorphs) in addition to *Eubrontes giganteus*. Of these, 222 tracks in 39 trackways and 14 isolated impressions were attributed to *E. giganteus*, which showed a statistically significant, bimodal orientation (75% westward, remainder eastward). Rather than interpreting this as evidence of gregariousness, however, Getty et al. (2012) suggested that parallel orientations reflected shoreline-following behavior, supported by associated oscillatory ripple marks and sedimentary indicators of a stable northeast–southwest shoreline. Similar results were obtained from higher strata at the river's edge, where *E. giganteus* trackways again showed significant northeast–southwest alignment. While shoreline influence was favored, the possibility of group movement could not be excluded.

Theropod diet: what were they eating? Researchers [e.g., Olsen et al. (2003b)] have long known that the tracks of carnivores (brotozoids) are more abundant than those of herbivores (*Anomoepus* and *Otozoum*) in Early Jurassic age ichnofaunas. Furthermore, large herbivores tracks, such as *Otozoum*, tend not occur in association with those of *Eubrontes* (Rainforth, 2003), although the tracks of presumed small carnivores (*Grallator* and *Anchisauripus*) often cooccur with *Otozoum* and *Anomoepus*. McDonald et al. (2025) revisited the topic providing a survey of Connecticut Valley Rift basin data, supporting both the numerical dominance of brontozoids the and extreme rarity of cooccurrence of *Eubrontes* and *Otozoum*. This suggests an inverted ecological food pyramid structure, with only a few herbivores, as can be seen at Dinosaur Footprint Reservation (Getty et al., 2012) (Figure 47). Even adding the 18% of tracks that Getty et al. (2012) considered indeterminate to the number of herbivore tracks would still result in less than half of the tracks being made by herbivores.

McDonald et al. (2025) and Getty in Getty and Thomas (2017) suggest a number of possibilities why carnivore tracks of might be found in higher proportions than those of herbivores. In addition to the possibility of inaccurate attribution of tracks to track makers [e.g., Weems (2003)] it is possible that big theropods may have been more active in their pursuit of prey or had larger home ranges than herbivorous dinosaurs, thus leaving more tracks or that there was a habitat-based preservation bias. Assuming that the proportions of tracks ascribed to herbivores is representative of their actual abundance in the fauna suggest the terrestrial communities may have had an aquatic food chain base (Olsen, 2010; Getty and Thomas, 2017; McDonald et al., 2025)

Body and trace fossils support this hypothesis. Milner and Kirkland (2007) pointed out that *Dilophosaurus*, which is a possible trackmaker for *Eubrontes giganteus* has possible fish-eating adaptations and that theropod teeth with piscivore adaptations occur with the tracks and fish at the St. George Dinosaur Discovery site in Utah (Hettangian, Moenave Formation). In addition, fish have been found on surfaces with *Eubrontes* at another lower Portland locality [Nash site: McDonald et al. (2025) and theropod teeth similarities to those described by Milner and Kirkland (2007) occur in Hartford basin lacustrine deposits. Additionally, the brontozoids at Dinosaur Footprint Reservation exhibit two preferred orientations correlated with the size of the trackmaker. Large theropod tracks (*Eubrontes giganteus*) tend to be oriented parallel, or nearly so, to the paleoshoreline, but the smaller brotozoids are oriented perpendicular to the shore (Getty et al., 2012) suggesting that the smaller theropods were going into and out of the water, plausibly to feed.

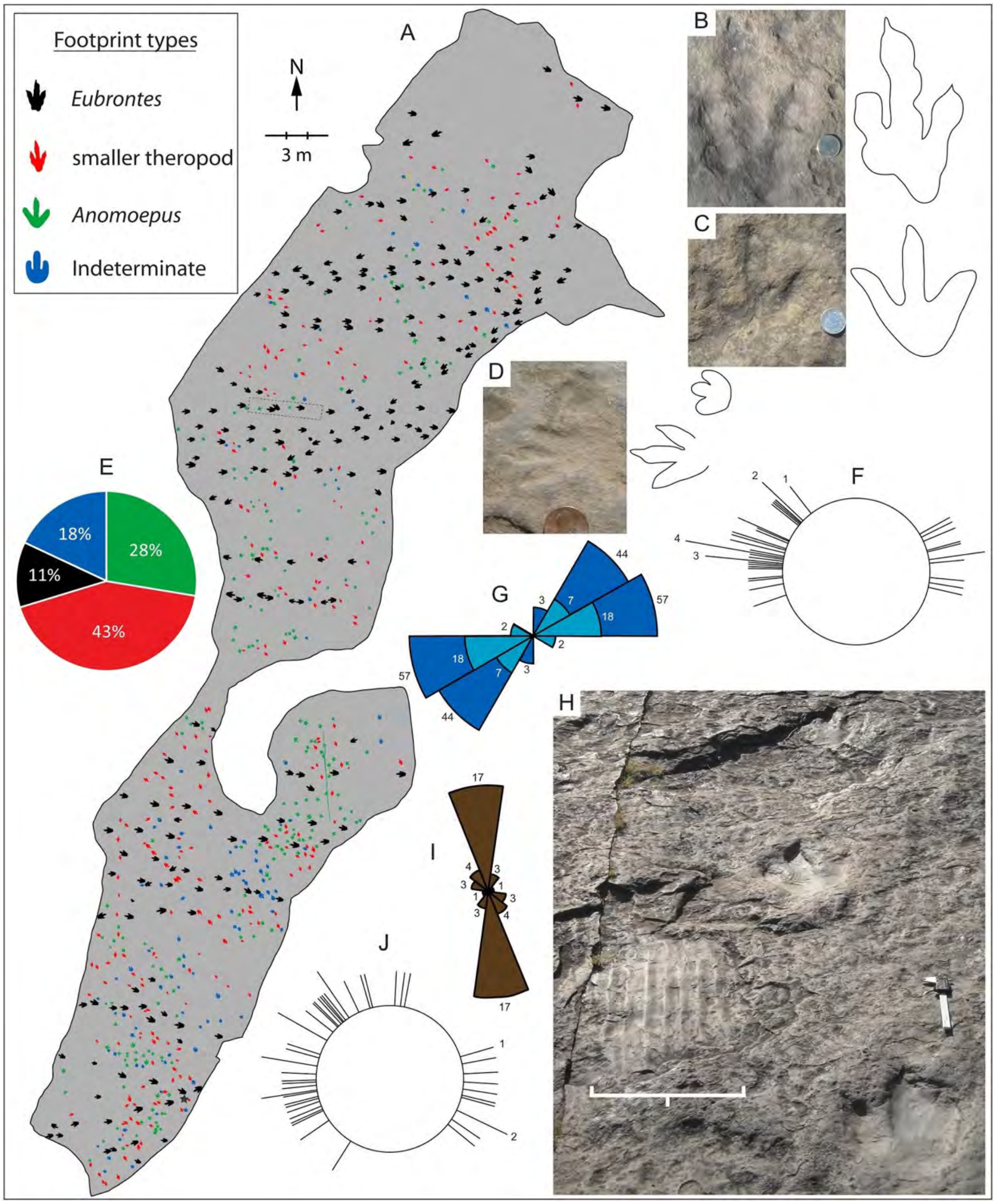

Figure 47. Tracks, structures, and orientations at Dinosaur Footprint Reservation [from Getty et al. (2012)]. A, map of the main surface, showing all 805 dinosaur tracks located. B, small brontozoid *Anchisauripus* isp. (theropod track). C, *Anomoepus scambus* (early diverging ornithischian track). D, *Batrachopus* isp. (basal crocodylomorph hand and foot tracks). E, relative proportions of the different trackway types. F, rose diagram of *E. giganteus* orientations. G, rose diagram of oscillation ripple crest orientations from above (light blue) and below (dark blue) the main track bed. H, *E. giganteus* paralleling ripple mark crests (bracketed) on underlying layer. I, Rose diagram of fossilized wood fragment orientations from 69 m above the main track bed. J: Rose diagram of *E. giganteus* on beds 69 m above the main track bed. Nickel for scale in B and C; penny for scale in D.

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Outcrops higher in the section along the river's edge have both red and gray strata exhibiting abundant smaller brontozoids and many oscillatory ripples surfaces. In gray beds there is abundant plant debris (Smith et al., 1996) with preferred orientations consistent with the ripples (Figure 47).

Overall, an important point, wonderfully displayed at Dinosaur Footprints, is that like so many track sites in the Hartford and Deerfield Basins, track-bearing layers are often on tabular, relatively thin-bedded oscillatory siltstones and sandstones with few to no desiccation cracks. As discussed by McDonald et al. (2025), Olsen and McDonald (2025), and at Stop 6, many detailed features of the track-bearing surfaces and the tracks themselves indicate a major role for microbial mats in modulating the preservation of the track, and the degree to which the track has fidelity to the trackmakers structure.

Return to vehicles.

Miles	Cumulative Miles	
0.0	44.49	Head northeast on Northampton St toward Cedar Hill Rd
3.6	48.09	Continue onto Mt Tom Rd/North St
1.3	49.39	Turn left to merge onto I-91 N toward Greenfield/Brattleboro
2.1	51.49	Take exit 25 for State Rte 9 toward Hadley/Amherst
0.2	51.69	At the traffic circle, take the 1st exit onto MA-9 E/Bridge St; Continue to follow to continuation onto College St
6.3	57.99	Turn left onto Dickinson St then immediate right into the Dickinson Lot and park, 90 Dickinson St, Amherst, MA 01002

Walk 0.2 mi south-southwest to Beneski Museum, Stop 6.

Stop 6: Beneski Museum of Amherst College, Edward Hitchcock Ichnology Cabinet; mostly Hettangian from Hartford and Deerfield Basins.
Parking at 42.373589°, -72.512996° (42°22'24.9"N 72°30'46.8"W) (GPS: 90 Dickinson Street, Amherst, Massachusetts).
Museum at 42.371952°, -72.514322° (42°22'19.0"N 72°30'51.6"W) (GPS: 11 Barrett Hill Drive, Amherst, Massachusetts).

Main Points:

1) Largest collection of footprints
2) Tracks illustrative of Early Jurassic continental animal diversity within two nillion years of the ETE
3) Tracks provide clear evidence of features shared between non-avian dinosaus and birds and cluses to the survival and success of dinosaurs through the ETE.

This stop is intended to be a deep dive into the famed Hitchcock Ichnology Collection, the largest museum collection of dinosaur footprints in the world, and how the footprint assemblages relate to the ETE, dinosaurian survival, and ecological expansion. The footprint slabs themselves also give us information about the environments in which they were produced and preserved and especially about the role of microbial mats. Most of the footprints in the Hitchcock collection are located in the “Hitchcock Ichnology Collection” and to a lesser extent in the “Dinosaur Hall”. The former is arranged as a series of galleries surrounded by walls, all of which have slabs on exhibit (Figure 48). We will examine a number of key specimens that illustrate the ichnological record of the major groups of tetrapods present located at specific stations along a path that begins in the Dinosaur Hall and weaves through the galleries of the Hitchcock

Ichnology Collection.

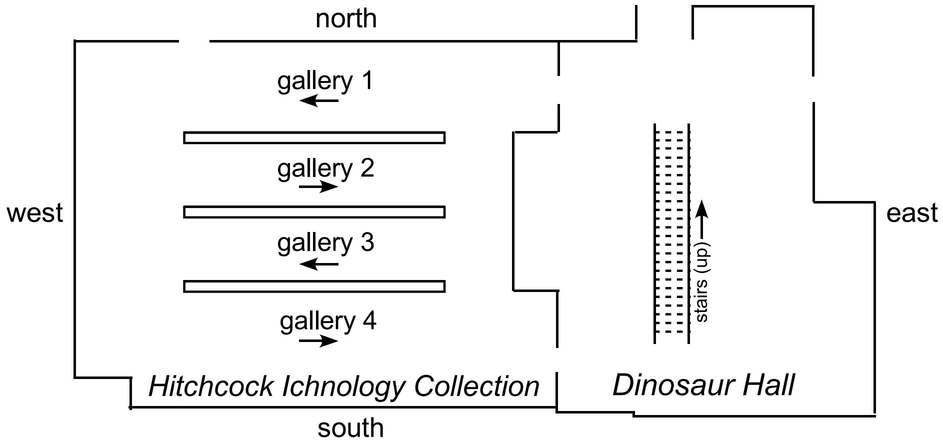

Figure 48. Map of the Dinosaur Hall and Hitchcock Ichnology Collection. Arrows below the gallery names show the direction of travel, beginning in the Dinosaur Hall and passing though the north door into the Ichnology Collection.

Station 1; *Eubrontes giganteus* and The Collection (Cart). Nearly all of the specimens were amassed from 1935 to 1854 by Edward Hitchcock (1793-1864), professor (1825-1845; 1854-1864) and president of Amherst College (1845-1854), and State Geologist of Massachusetts (1830-1844). But he did not discover them.

Dexter Marsh (1806-1853) was a laborer, quarrier, and stonemason born in Montague, Massachusetts who made the first documented discovery of dinosaur footprints. Although countless people and communities around the world noticed the fossilized footprints of animals, and in many cases built them into stories in their cosmologies [e.g., Ellenberger et al. (2005), Lockley et al. (2006), Mayor and Sarjeant (2001), Xing et al. (2011)], it was tracks quarried by Marsh that led to the first scientific descriptions of dinosaur footprints. Apparently, Marsh had quarried flagstones from his quarry in southwest Montague in the Mount Toby Formation[2] and was in the process of laying the flagstones when he noticed distinct traces (Marsh, 1848) which he brought to the attention of James Deane a local medical doctor who purchased two slabs in 1835, part and counterpart which are on exhibit on the NW rack of gallery 2 as ACM ICH 18/1 and 18/2 (although there is dispute about who first recognized the importance of Marsh's finds) (Herbert and Doyle, 2012). Oddly, the quarry from which these tracks come from has, to this day, not been exactly located, although based on Hitchcock's (1858) ichnogeological map, and March's own descriptions (Marsh, 1848), it has to be on the northwest side of Taylor Hill in Montague.

Deane brought the tracks to the attention of Hitchcock, eventually convincing him of their organic origin, (Deane, 1844a, b; Hitchcock, 1844). Thereafter, Hitchcock began his systematic study of these traces beginning in 1836 with the description of *Ornithichnites giganteus*, the first of what we now recognize as dinosaur footprints [although first publications of tetrapod tracks were in 1828 and 1831 (Pemberton et al., 1996)]. It was named five years before the term Dinosauria was coined by Owen and six years before Owen published that name (Owen, 1842). The holotype, ACM ICH 15/3 is preserved as a natural cast, is normally housed in the type room, but is out on a tray for our viewing. The taxonomic history of this specimen, summarized here, is given in Olsen et al. (1998). Like everyone who's opinion was recorded at the time, Hitchcock believed that this track was made by a bird. This concept was supported by Cuvier's principle of the "correlation parts" which states that the functional integration of animal

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[2] We use Mount Toby Formation (Emerson, 1891, 1898b, 1917) for all of the sedimentary strata above the Deerfield Basalt because it has clear priory over Turners Falls Formation (Willard, 1951) with both sharing the same kinds of cyclical sequences and fossils, differing only in grain size. Robinson and Luttrell (1985) already annexed into the Mount Toby Formation the upper half of the section along the Connecticuut River of cyclicial mostly fine-grained strata, and calling the entire sequence Mount Toby Formation would be consitant with this.

organs meant that the form of any single part implies the structure of all others, making anatomy predictive and systematic (Cuvier, 1798) and later supported by Owen (1843) who concluded that Hitchcock's tracks were made by birds of the same "low grade of organization" as his newly discovered moas. This specimen appeared in William Buckland's *Bridgewater Treatise VI* in 1836 and in Hitchcock's 1841, 1848, and 1858 works (Figure 49). It, along with the other tracks Hitchcock described, caused a sensation on both sides of the Atlantic and he was criticized due to the tracks' implications for biblical interpretation, although embraced by followers of "Natural Theology" such as Buckland.

Hitchcock (1836) stated that he found this specimen in a quarry on the East side of Mount Tom along the Connecticut River after seeing flagstones from that quarry in Northampton bearing tracks. This locality is almost certainly "Dinosaur Footprints" in Holyoke (Stop 5) where we saw similar tracks. According to Hitchcock (1865), it was both the first specimen of the ichnospecies found and also the "original type of the ichnospecies." Thus, ACM ICH 15/3 must be the holotype (single specimen upon which a species is based) of *Ornithichnites giganteus* by original designation. Its status as holotype has been affirmed by Baird (1957) and Olsen et al. (1998).

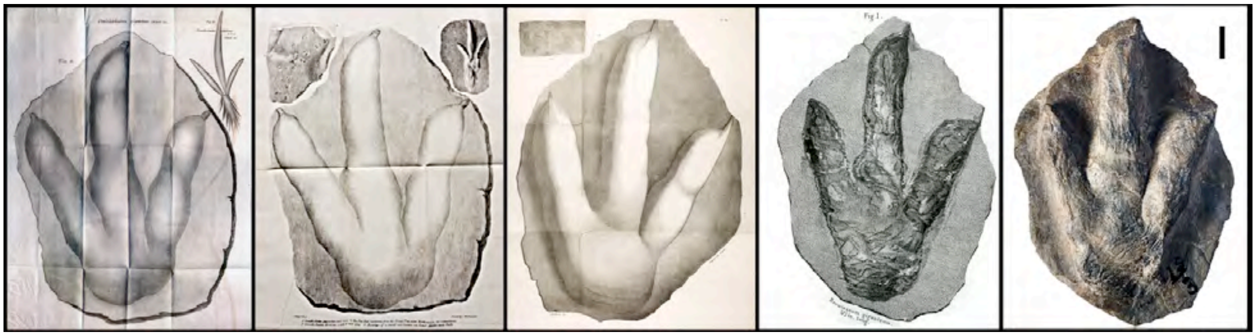

Figure 49. ACM ICH 15/3, the type specimen of *Eubrontes giganteus*. As is the case for most of these classic specimens, *Eubrontes giganteus* has been though a tortuous series of names, involving petitions to international nomenclature committees, and rulings many of which are not good in light of modern thought. These are from left to right: *Ornithichnites giganteus* Hitchcock (1836); *Ornithichnites giganteus* [from Buckland (1836)]; *Ornithoidichnites giganteus* (Hitchcock, 1841) and then *Eubrontes giganteus* (Hitchcock, 1845); *Brontozoum giganteum* (Hitchcock, 1847); *Eubrontes giganteus* (Hay, 1902) [image from Olsen et al. (1998) — scale is 5 cm].

ACM ICH 15/3 was clearly designated the type specimen for *Eubrontes giganteus* in 1836, but Charles H. Hitchcock, in his father's posthumous "Supplement to the Ichnology of New England" (1865), substituted ACM ICH 45/8 as the type specimen. This change was based on his perception that 45/8 fit his father's concept of the ichnospecies more closely, especially due to its broader toes, even though this track was collected nearly three decades after the species was named (Hitchcock, 1865, p. 23). Despite this chronological discrepancy, ACM ICH 45/8 continued to be cited as the type specimen in subsequent works, such as (Lull, 1953), until this was corrected by Olsen et al. (1998). The ongoing confusion nearly resulted in a significant loss: when the Geological Society of America's Boulder headquarters was constructed in 1972, ACM ICH 15/3 was sent on "permanent loan" from the Pratt Museum (predecessor to the Beneski) and embedded in a wall. The specimen was not returned to Amherst until its return in 1997 thanks to the efforts of the late Edward Belt.

After 1836, Hitchcock acquired more and more track material, purchasing footprints through the years from Marsh and other collectors most notably Roswell Field. In 1855 the Appleton Cabinet was constructed to house the burgeoning natural history collections (Figure 50). Then in 1951, the collection was moved to the Pratt Gymnasium, becoming the Pratt Museum. The track collection was in the basement of the Pratt, the former pool and was dubbed the "tombstone room" by Donald Baird (pers. comm.). The lighting was so flat many tracks were essentially invisible. Eventually it was moved into the new Beneski Museum where it currently resides.

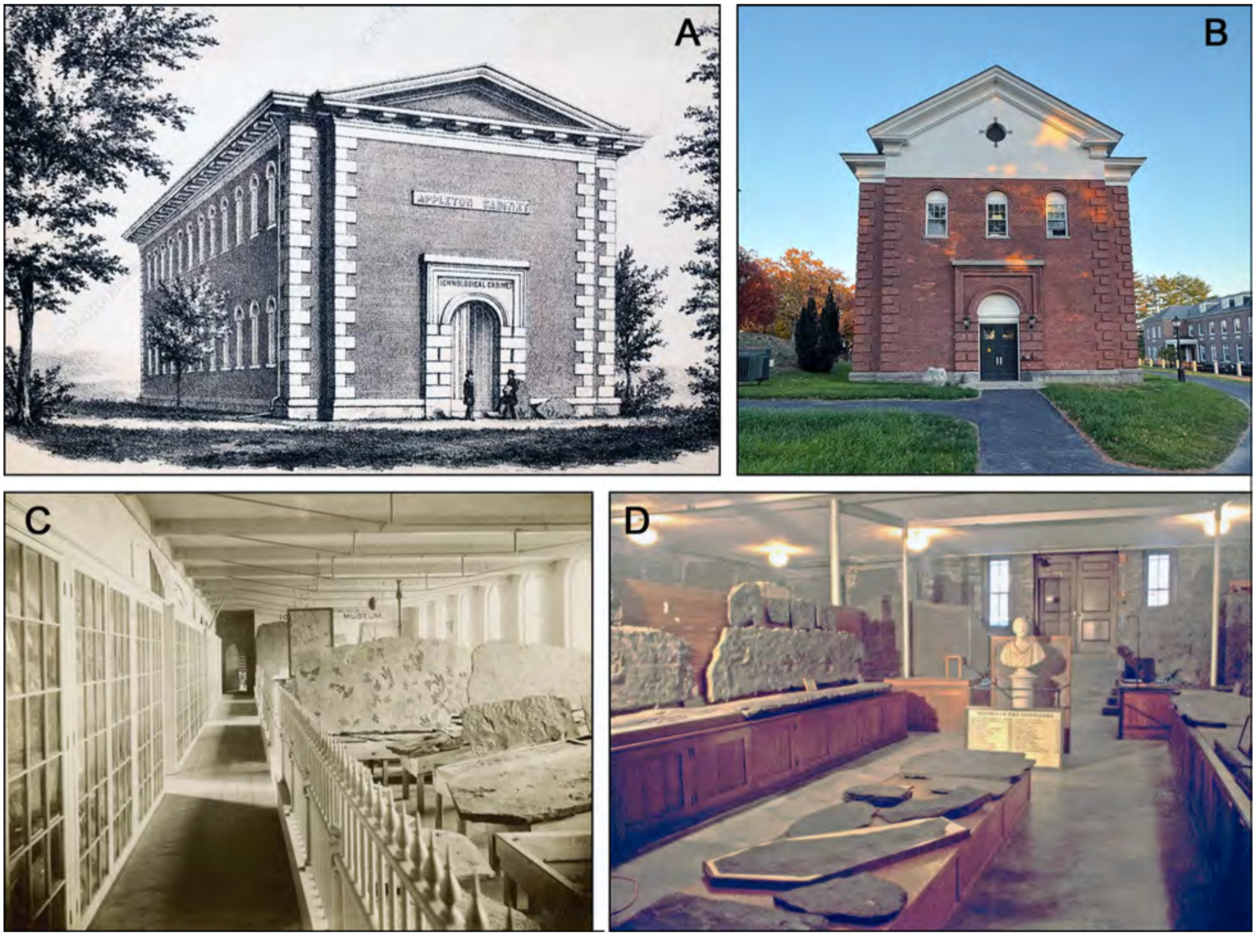

Figure 50. 1855 to 2025, 170 years of the Hitchcock Ichnology collection. A, Appleton Cabinet, built 1855 (from Hitchcock, 1858). B, Appleton Hall on October 22, 2024 (during PEO's sabbatical) which was first used for lecture halls and offices and is now a freshman dormitory. C, Appleton Cabinet, Ichnology collection in (courtesy of Archives & Special Collection at Amherst College, prior to 1858); femur, tibia and metatarsals of a Moa can be seen suspended on the middle-upper right. In the original Appleton Cabinet of 1855 (C), specimens were numbered according to their location Hence, slab 1/1 was on Wall 1, and 15/3 was on Table 15. All relationship to the original locations has been lost, but the number scheme is still useful. D, the ichnology collection in 1995 (former Pratt Gymnasium swimming pool), now the Charles Pratt Dormitory.

As has long been noted (Lull, 1953; Olsen, 1980; Olsen et al., 1992; Olsen et al., 1998) *Grallator*, *Anchisauripus*, and *Eubrontes* form a continuum with small tracks having a relatively longer digit III, and larger forms having a shorter digit III (Figure 55). This suggests they might be grouped into a single ichnogenus, because none are objectively diagnosable from the others, even in material with spectacular fidelity to the trackmaker with skin imprints. Regrettably, the name *Brontozoum* was regarded as invalid by Hay (1902) and suppressed by Baird (1957) in favor of *Eubrontes*. No one seems to want to call the generally diminutive *Grallator* a *Eubrontes* or *vice versa*, and thus, Rainforth's (Rainforth, 2004, 2005b, a) term brontozoid is very useful for all these forms.

Edward Hitchcock believed from the beginning to the end that most tracks he had collected were made by birds that lived in an ancient Earth. However, mounting evidence from the tracks themselves was making his belief complicated. In fact in 1860, four years before Hitchcock's death the same professional collector Roswell Field selling so many tracks to Amherst concluded that all of the tracks were made by quadrupeds capable of bipedal motion (Field, 1860; Herbert et al., 2013). A few years after that and

Hitchcock's passing, that both Thomas Henry Huxley and Edward Drinker Cope stated that the Connecticut Valley were made by dinosaurs (Cope, 1867; Huxley, 1868; Cope, 1870).

Looking again at ACM ICH 15/3, how do we know what kind of dinosaur it is? How do we get from this evidence of the tracks to understanding what these mean for the ancient biodiversity of the dinosaur world?

In extant cursorial birds, the articulations between phalanges in the pes are protected by cushioning pads, important in the push-off phase (Figure 51). Such pads are termed arthral. In perching birds, as on our own hands, pads tend to be between the articulations, mesarthral, because, they would interfere with flexion of the digits and the joints are well protected by because the pads come together. Non-avian cursorial dinosaur feet would be expected to have pads arranged like cursorial birds and arthral in position. Thus, the pads could be used as landmarks indicating where the joints were and allow a hypothesis of reconstruction of the bones from the track, using the arthral method. Historically, Lull (1915) and Abel (1912) argued that dinosaur tracks exhibited the mesarthral condition in which the pads lie between the joints, as is the case with our hands. However, Heilmann (1926) in his influential treatise "The Origin of Birds", showed that the soft tissue of birds' feet, the podotheca, has pads that commonly underlie the joints.

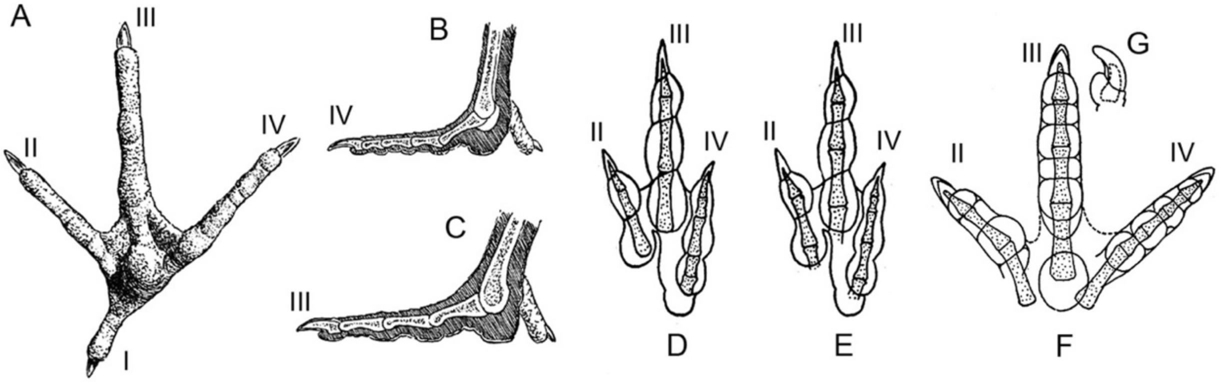

Figure 51. Arthral method of reconstructing skeletal anatomy from tracks. Pad vs. articulations (joint) positions in Galliformes (chickens, turkeys, etc.) and interpretations of their relationships in *Grallator cursorius,* all arranged to appear as a right pes: A-C from Heilmann (1926); D-G from Peabody (1948). A, sole of left foot (podotheca) of a chicken (*Gallus gallus*) – swellings are the pads and underlie the joints (arthral position); B, longitudinal section of digit IV of a chicken – note pads under joints of phalanges (arthral position); longitudinal section of digit III of a chicken – note pads under joints of phalanges (arthral position) (compare to Figure 13). D, Connecticut Valley theropod track, right pes impression of *Grallator cursorius* [from Lull (1904a)] with joints reconstructed in mesarthral (between the joints) position. E, same with joints reconstructed in arthral (beneath the joints) position. F, right pes of a turkey (*Meleagris gallopavo*) showing pads in arthral position. From (Getty and Thomas, 2017).

Hitchcock advanced both positions [summarized by Rainforth (2003)]. But since Heilman's time, the arthral hypothesis for reptile footprint pads has been supported (Peabody 1948; Baird 1957; Olsen in Getty and Thomas 2017; Olsen and McDonald, 2025). The simplest hypotheses relating pad position to function is that pads have an arthral position (for protection) in joints subjected to load-bearing or shock during extension (Farlow et al., 2018). However, in joints subject to flexion, the pads are mesarthral (for flexibility), as in grasping hands. Digits with short phalanges or those subject to little flexion are underlain by coalesced pads. Using the arthral method, the reconstructed pedal skeleton of *Eubrontes giganteus* is directly comparable to contemporary theropod dinosaurs (Figure 52). But, Early Jurassic theropod pedal anatomy is very conservative and identification of the trackmaker cannot be expected yield a more specific attribution.

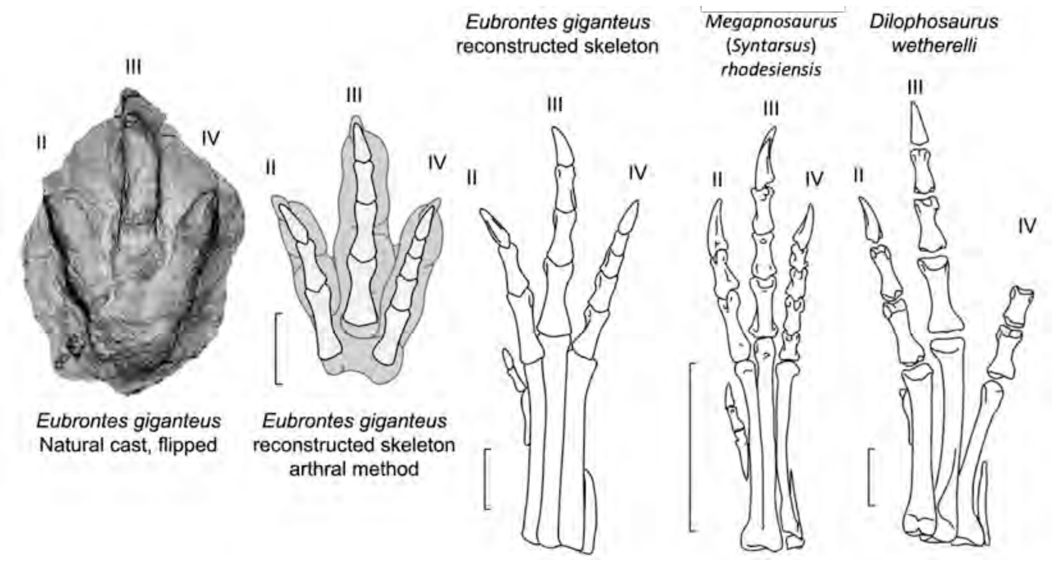

Figure 52. Osteological reconstruction and comparisons with osteological taxa of *Eubrontes giganteus*. From left to right: ACM ICH 15/3, the holotype; reconstructed osteology of the holotype using the arthral method; *Dilophosaurus wetherelli*, reconstructed right foot (flipped and corrected from photographs of UCMP V4214: http://www.ucmp.berkeley.edu/dilophosaur/closeup.html as well as based on the complete right hind limb TMM 43646; http://blogs.plos.org/paleocomm/2015/10/22/318/ as well as Wells, 1984); right Megapnosaurus (Syntarsus) rhodesiensis foot (flipped from image of left foot, from Raath, 1969). B: Dilophosaurus wetherelli, right foot (flipped from original left in Wells, 1984). Scale is 10 cm.

Using the arthral method we arrive at skeletal reconstruction suggesting the *Eubrontes giganteus* track maker was a theropod dinosaur very similar to *Dilophosaurus wetherelli* from the Early Jurassic Kayenta Formation of Arizona (Figure 53). The type material of this dinosaur was found in close proximity to hundreds of *Eubrontes giganteus* tracks. But not all researchers agree!

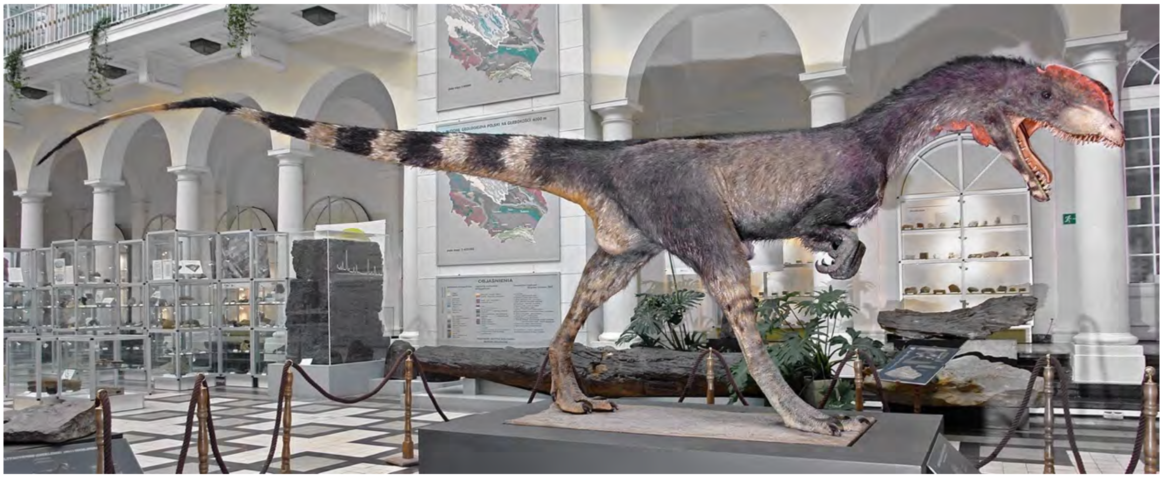

Figure 53. *Dilophosaurus* as reconstructed in the Geological Museum of the Polish Geological Institute, Warsaw. From (Courtesy Gerhard Gierlinski).

The arthral interpretation is the simplest hypothesis for reconstructing the bones in toes of animals in which the toes are on the ground and extend (bend backward using your fingers as models) during the propulsive phase. This means that the joints and the flexor ligaments are bearing the load of the foot as the toes extend with the weight rolling off the toes — hence it makes sense that the joints should be padded. That said, it is common for some pads to be conjoined in ground birds, and that seems to be an indication that part of the toe acted as a unit, often with shortened phalanges. That can be seen in digit III of the ostrich and the distal pads of digit IV in most non-avian dinosaur footprints.

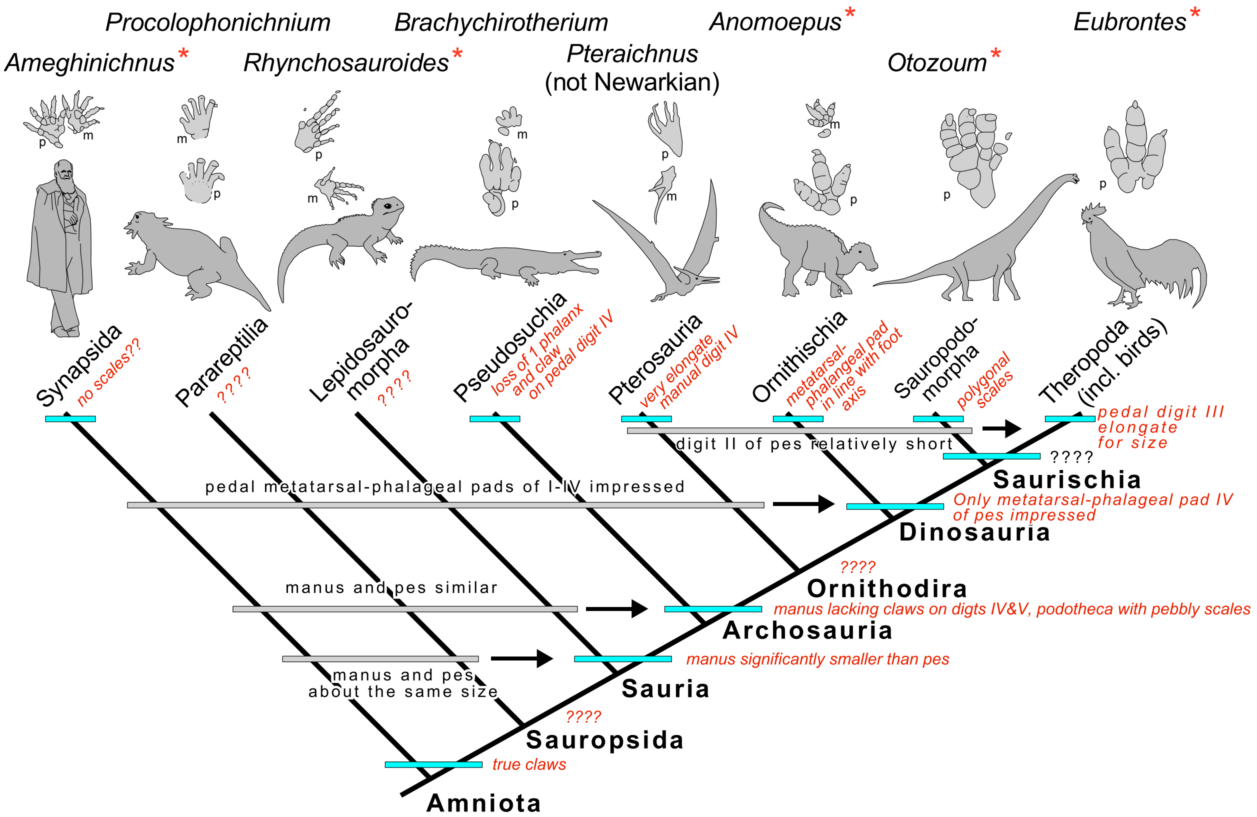

Figure 54. Ichnocladogram of the Amniota (tetrapods that have an amnion like us) with hypothesized ichnocladistic track apomorphies (in red italics – teal bars), primitive states for the same characters (along gray bars). There are some nodes (branching points) for which no track apomorphies are known. Red asterisks denote track taxa in the Connecticut Valley and have representatives in the Beneski. *Brachychirotherium* is shown as being produced by a member of the Pseudosuchia, but the latter group also contains the Crocodyliformes, protosuchian and sphenosucian members of which produced *Batrachopus*. Modified from Olsen and McDonald (2025).

Ichnocladistics

Although it is true that the arthral method does produce a satisfyingly similar reconstruction comparing well to large Early Jurassic theropods, it relies on general similarity. General similarity is problematic because it does not rule out all the many other kinds of functionally tridactyl archosaurs such as silesaurs or even some pseudosuchians such as poposaurs (Farlow et al., 2014). The same kind of problem besets all phylogenetic reconstruction. Rather, we use an apomorphy-based methodology to hypothesize the identity of trackmakers that made specific traces (Olsen, 1995; Olsen et al., 1998; Carrano and Wilson, 2001; Olsen and McDonald, 2025), (Figure 54). This approach has been called a synapomorphy-based method by Carrano and Wilson (2001), which we generalize to ichnocladistics. Employing this approach, we find characters of footprints that we assume faithfully reflect the trackmaker's morphological features. A track reflects only a small part of an animal’s anatomy; this approach parallels the apomorphy-based identification of fragmentary skeletal material (Nesbitt et al., 2007; Nesbitt and Sues, 2020). In keeping with our apomorphy-based approach, we do not discuss successions of tracks as lineages or argue that ichnotaxa can evolve or be ancestral to one another e.g., (Haubold and Klein, 2000)].

In ichnocladistics, the focus is on features on the track that reflect the anatomy of the trackmaker that evolved in the last common ancestor of specific groups descended from that common ancestor — i.e., clades. An example of a tentative cladogram of such features is diagramed in Figure 54. Keeping in mind ichnocladistics, *Grallator*, *Anchisauripus,* and *Eubrontes* have a suite of characters that distinguish them from other Newark Supergroup forms. These are: 1) pedal digit III is elongated compared to II and IV, relative to the size of the track, being most pronounced in smaller forms; 2) digital divarication tends to be low relative to the size of the track; 3) the metatarsal-phalangeal pad of digit IV tends to be more deeply impressed, that of digit II is less so; 4) distal digital pads are well defined, except for the most distal pads on digit IV; and 5) claws are large compared to other ichnotaxa. 6) quadrupedal trackways or pronated manus impressions are entirely absent and a manus when present consists of knuckle impressions only. Finding skeletal correlates to features 2-4 are challenging and will require a level of focused attention to autopod skeletal anatomy and function that has yet to be employed.

Using the arthral and ichnocladistic methods also forces us to confront what the features unite a track with a specific trackmaker and how those features might also allow us to recognize limits of our ability to do so. Considering the biologically important features of the track as they pertain to anatomy also show us that the basic kinds of animals we can recognize from the tracks are far less than the number of nominal track species. From 71 track genera and 185 track species the number boils down to 6 to 8 ichnogenera, with the number of ichnospecies being very uncertain (Figure 55), an indication that tropical tetrapod communities was massively diminished after the ETE. We will see all of the ichnogenera at this stop.

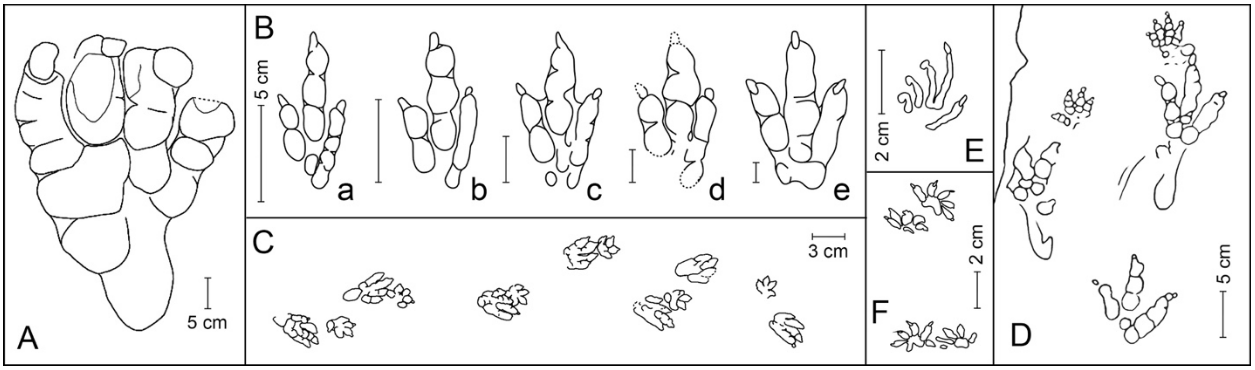

Figure 55. Footprints of the Connecticut Valley reduced to the valid forms that relate to biological taxa, all of which are represented in the Hitchcock collection, all drawn as impressions. A. *Otozoum moodii*, (ACM ICH 4/1a), a herbivorous basal sauropodomorph, e.g., "prosauropod", left pes. B, Brontozoid tracks made by carnivorous theropod dinosaurs , right pedes; a, *Grallator parallelus* (ACM ICH 4/1a) ; b, *Grallator* sp. (ACM ICH 3/2); c, *Anchisauripus sillimani* (ACM ICH 4/6); d, *Anchisauripus tuberosus* (ACM ICH 39/1); e, *Eubrontes giganteus* (ACM ICH 15/3) (Scale is 5 cm for all). C, *Batrachopus deweyii* (ACM ICH 26/6) made by a crocodyliform; D, *Anomoepus intermedius* (=*A. scambus*) (ACM ICH 48/1) made by a small ornithischian dinosaur; E, *Rhynchosauroides* isp., (ACM ICH UC 112) made by a lizard-like forms, right pes; F, *Ameghinichnus* isp. made by a "proto-mammal" or mammal. From Getty et al. (2017).

Influence of Microbial Mats on Anatomical Fidelity of Tracks

Most Connecticut Valley tracks are in shallow lake strata in which wind waves have spread out silt and sand into thin sheets exhibiting oscillatory ripple marks. Sometimes these ripples are very obvious, as when their crests are close together, and sometimes they are hard to see, especially when the crests are far apart and the ripples very flat as at Stop 3. There is often a thin clay layer separating sheets of these oscillatory ripples siltstones and sandstones and this makes it possible to split the rock into relatively thin sheets making it easy to find many footprints. McDonald et al. (2025) and McDonald et al. (2025) have stressed the importance of microbial mats in Connecticut Valley track and trace producing environments [see also Drzewiecki and Hyatt (2025)].

Examine the slab (ACM ICH 45/1) on the west wall, with parallel and overlapping *Eubrontes giganteus* tracks (and other smaller brontozoid). These are the tracks that Lull (1904a, 1915, 1953) based his iconic drawing of the ichnospecies. No locality data is listed for the specimen by Hitchcock (1865). Look carefully and you can see very flat, oscillatory ripples with crests spread nearly 10 cm apart running from upper left to lower right. This means the water depth was from 20 to 80 cm deep at the time the ripples formed [based on an unchecked AI assessment drawn from Stachurska and Staroszczyk (2016) among other sources].

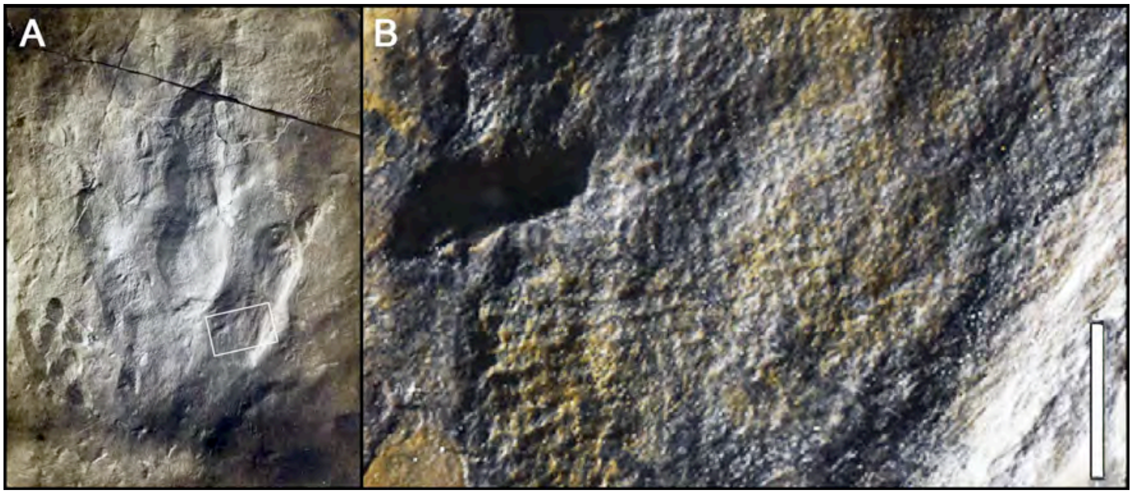

Figure 56. Holotype of *Anchisauripus minusculus* (ACM 56/1) showing details of the pedal squamation. **A**, salt print (photograph) from Deane (1861); white box shows position of B. **B**, reticulae (reticulate scales) on the podotheca of *Anchisauripus minusculus* in A on the proximal phalangeal pad of digit II [from Hendrickx et al. (2022)].

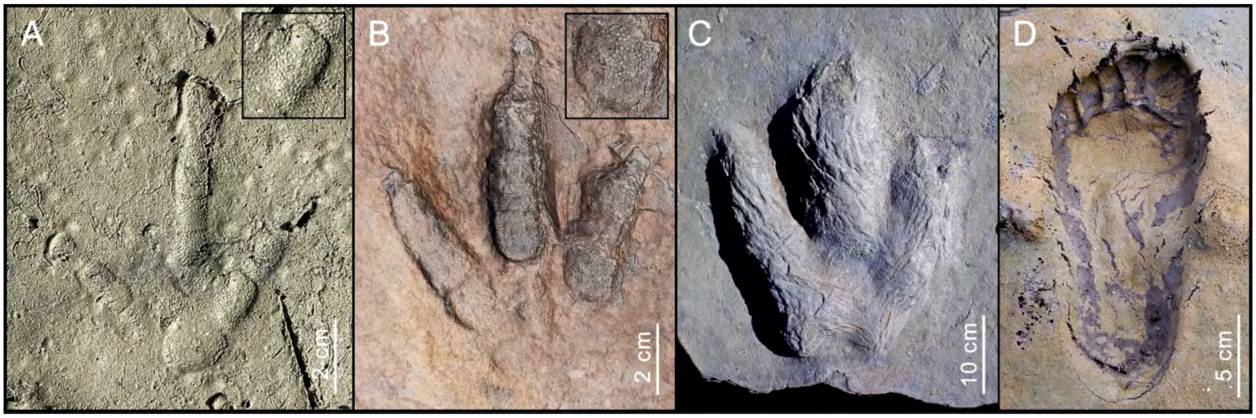

Figure 57. Effects of microbial mat thickness on footprint detail [from Olsen and McDonald (2025)]. Further detail in Figure 58. A, modern, thin (<1mm) mat with a right pes imprint of a wild turkey (*Meleagris gallopavo*) (flipped and hallux (digit 1) mostly omitted), from an ephemeral puddle in the H&K Birdsboro Quarry, Birdsboro, PA; inset shows detail of reticulae (scales). B, inferred thin mat with *Anomoepus scambus* (ICH AC 48/1) photogrammetric model of right pes impression (flipped); inset shows detail of scales [by Bennett Slibeck, from Olsen et al. (2024h)]. C, inferred thick microbial mat, natural cast of *Eubrontes giganteus* right pes impression (dinosaur State Park, CT) showing crinkly, extensional faults and cracks in the footprint. D, modern, thick microbial mat (>3mm) with human right pes impression (flipped), showing extensional structures. [from Marty et al. (2009)].

Compare ACM ICH 15/3, the type of *Eubrontes giganteus* with ACM ICH 56/1 (on cart), the type of *Anchisauripus minusculus* (now regarded as a synonym of *Eubrontes giganteus*). One (ACM ICH 15/3) has a crinkled surface, the other (ACM ICH 56/1) has detailed pebbly (reticulate) skin impressions Figure 56. We would argue this is a consequence of a thicker mat being present during the impression of ACM ICH 15/3 and a thinner mat was present during the impression of ACM ICH 56/1. Compare with Figures 57 and 58 which compares tracks on thin and thick mats.

Footprints made in very fresh mud, as in after a flood, is sticky and tends to produce tracks with very little fidelity to the anatomy of the track maker. Microbial mats and their mucilaginous excretions help prevent mud from sticking to feet and also stabilize and protects the track surface. However, depending on the thickness of the mat, it can either preserve beautiful detail, or obscure it. Even deep tracks on a surface with a thin microbial mat can register great detail and modern examples attest (Figure 58).

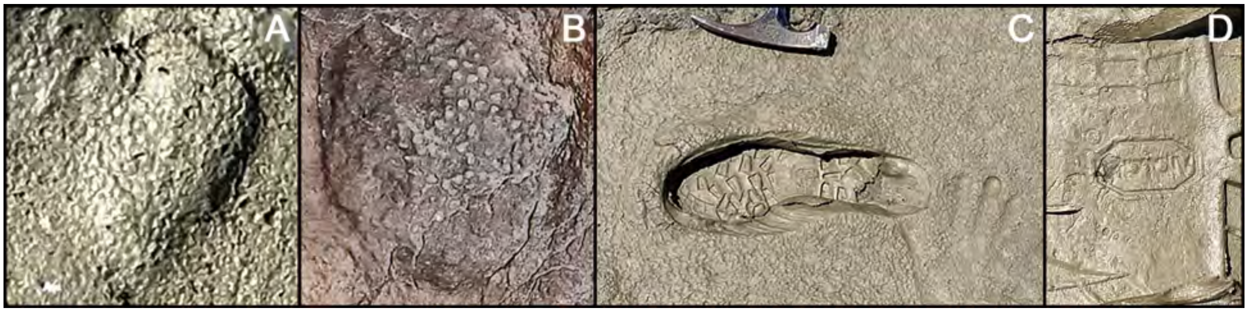

Figure 58. Details of footprints from thin microbial mat binding of sediment surfaces. **A** and **B**, from insets in Figure 57A and 57B (above). **C**, pedal and manual impressions of PEO in from an ephemeral puddle Silver Hill Quarry, Bowmansville, PA (hammer head is 19 cm long). Note how deep the pes impression is, yet there is no adhesion to shoe and fine details of the sole are rendered.

Station 2: *Otozoum*; Dinosaur Hall SE and gallery 1 north wall. *Otozoum moodii* is one of the most impressive and enigmatic eastern North American footprints (Figure 59). Described and named by Edward Hitchcock (1847), it is a large, nearly exclusively bipedal trace that is regionally rare, but locally fairly common in sandstone facies. It is known definitively only from post ETE strata, including the Portland Formation. Rainforth (2003) provided the most comprehensive treatment of *Otozoum*, including an analysis of possible trackmakers.

Otozoum specimens, all from lower Portland Formation at the Moody homestead, in South Hadley, MA, are on display in Dinosaur Hall as well in the ichnological collection room. One series of *Otozoum* trackways, preserved as natural casts, are hung on the north wall of Gallery 1. ACM ICH 4/1a consists of four successive footprints, collected by Pliny Moody in 1847, and given to Hitchcock for his collection (Hitchcock, 1865). The tracks are the holotype of *Otozoum moodii* Hitchcock (1847). They have been arranged with additional trackways, possibly of the same individual, but not demonstrably connected towards the west side of the north wall. *Otozoum* is distinguished from other large Connecticut Valley ichnotaxa by having four digits. Three point forward (digits IV, III, and II) and one (digit I) points sideways. The number of pads decreases going from outer to inner toes. There is a large posterior pad that connects digits IV and III, and a rear pad that is interpreted as underlying digit V.

Otozoum is a key element of post ETE track diversity in tropical regions because it indicates the presence of early diverging sauropodomorphs ("prosauropods") in the absence of skeletal evidence. Rainforth's (2003) outline drawing of the *Otozoum* foot allows the development of a hypothesis about the osteology of the trackmaker (Figure 59) aligning with it having been made by a prosauropod. Assuming an arthral model to reconstruct the skeleton results in foot that is similar in proportion and formula to a primitive archosaur, except for the very reduced digit V. Such skeletal structure is seen in pseudosuchians, which is what misled Olsen (1988b) and Olsen et al. (1989) to interpret Otozoum as a "sphenosuchid crocodylomorph". However, this is clearly wrong because crocodylomorph feet have lost a phalanx in digit IV, a possible apomorphy of a major clade within the Pseudosuchia or even Crocodylomorpha. Based on the number of pads, this specialized loss does not occur in *Otozoum*. The reconstructed foot is also very similar to that of early diverging basal grade non-sauropod sauropodomorphs, i.e., “prosauropods”, such as *Plateosaurus* and *Anchisaurus*, the latter of which is known from the Portland Formation and on display at the Yale Peabody Museum. Skeletal remains of “prosauropods” and definitive *Otozoum* are also known from the McCoy Brook Formation of the Fundy Basin (Sues and Olsen, 2015)(Sues and Olsen, 2015), and the Navajo Sandstone of the Glen Canyon Group (Lockley et al., 1999; Rainforth, 2003; Sertich and Loewen, 2010) in the Colorado Plateau region.

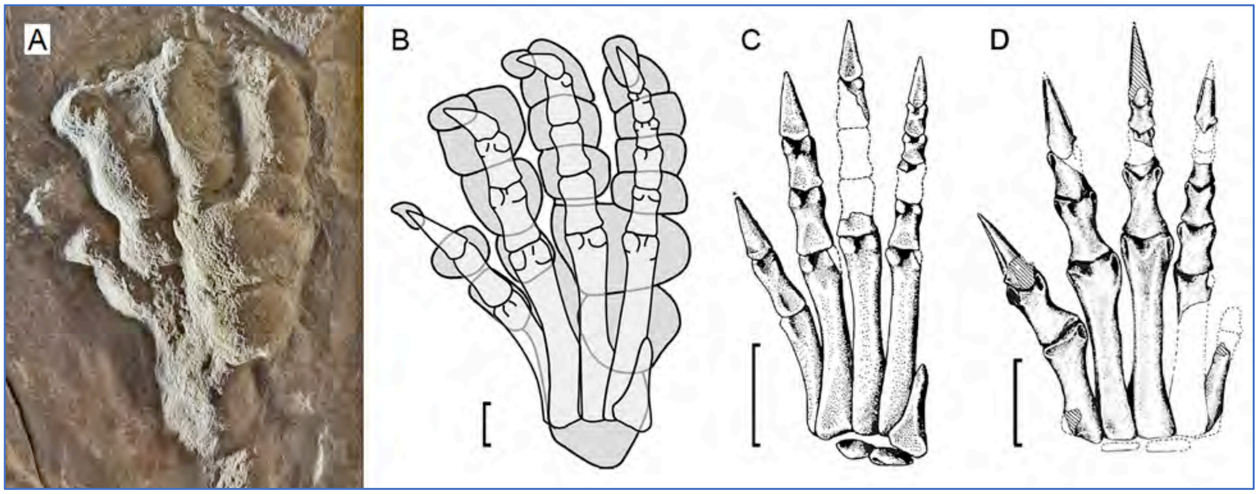

Figure 59. Comparison of the reconstructed left pedal skeleton, in bottom view, of *Otozoum moodii* with “prosauropod” feet. A, flipped photo of ACM ICH 4/1a, showing faint but distinct polygonal squamation. B, outline of *Otozoum* (from Rainforth, 2003) with superimposed reconstructed skeleton using the arthral model – note similarity to actual prosauropod skeletons (B-D). C, flipped, plantar view of right *Anchisaurus polyzelus* foot [from Galton (1976)] on display at the Peabody Museum Great Hall. D, flipped dorsal view of right pes of larger *Anchisaurus polyzelus* [*Ammosaurus major*; from Galton (1976).]

There are manus impression on only one known *Otozoum* specimen in the world, ACM ICH 5/14, which is not on display. Rainforth (2003) shows that, four digits are present and that the manus print morphology is most consistent with a “prosauropod” hand, impressing digits II-V and holding the digit I off the ground. As she pointed out, theropods are ruled out as making the hand imprints because they would make either tri- or didactyl imprints and in tracks they impress only knuckles (see Station 10). We argue that Jurassic basal ornithischians are ruled out because they would have a pentadactyl hand imprint. The evidence again leaves only “prosauropods” as trackmakers when only known Early Jurassic skeletal forms are considered.

In summary, the primitive retention of a full complement of phalanges in pedal digit IV, the apparent raised and non-impressed digit I of the hand, the large size of the tracks, and proportional similarity to Early Jurassic sauropodomorphs such as *Anchisaurus*, makes the hypothesis that *Otozoum* was made by a “prosauropod” the most parsimonious hypothesis, given what we know of available Early Jurassic osteological taxa. However, the information in the pes provides evidence only in terms of general similarity, and the interpretation of the manus impression requires assumption about function to be used ichnocladistally.

Pedal scaly skin (squamation) impressions provides stronger ichnocladistic evidence that the attribution of *Otozoum* to the sauropodomorpha is correct (Figure 60). Ichnocladistic reasoning suggests that because the character of small pebbly scales on the podotheca (fleshy part of a foot, as on a bird) appears at the Archosauria node (see Figure 54) and remain present in the Theropoda as well as the Ornithischia, Pterosauria and most Pseudosuchia, the presence of the very different relatively much larger, flattened, and polygonal scales *Otozoum* and sauropods (Paik et al., 2017; Pittman et al., 2022) is a plausible apomorphy placing *Otozoum* within the Sauropodmorpha, to the exclusion of other groups. The skin apomorphy is stronger evidence than general similarity of the pes or the supposed apomorphic manus interpretation.

Return to 4/1a and the *Otozoum* trackway. Close examination shows hints of polygonal scales on the sole of the pedes like those in Figure 60. How do these compare to the scales on ACM ICH 56/1, the type of *Anchisauripus* minusculus (on the same cart as ACM ICH 15/3, E. giganteus), taking into account the sizes of the parts of the digits that can be directly compared? *Anchisauripus minusculus* has been synonymized with *E. giganteus* by Weems (2003), a determination we agree with.

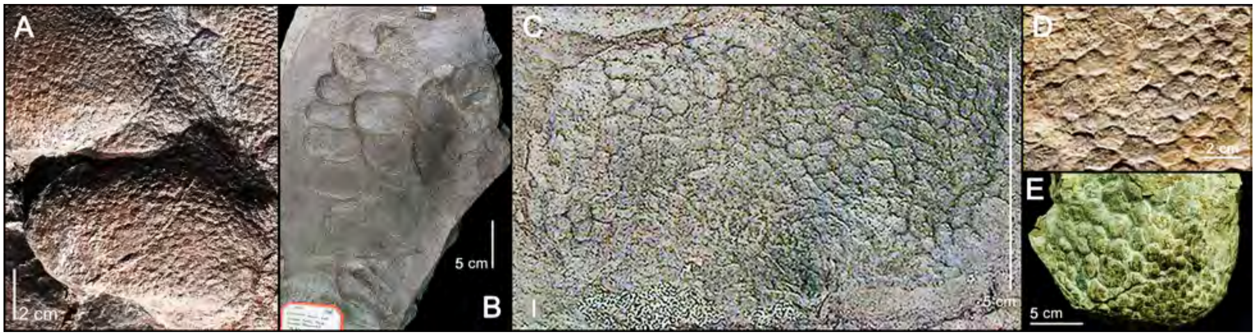

Figure 60. Comparison of pedal squamation of *Otozoum* and neosauropods. A, part of conjoined metatarsal-phalangeal pad conjoined metatarsal-phalangeal pad of digits III-IV and pad underlying digit V of natural cast of left pes, Portland Brownstone Quarries, Portland, Connecticut, Hettangian, Portland Formation, Hartford Basin (WUM 680 at Dinosaur State Park, Rocky Hill, Connecticut). B, partial left pes impression, Montague or Gill, Massachusetts, Mount Toby Formation, Deerfield Basin, Hettangian, Deerfield Basin (YPM VP 003411). C, detail of conjoined metatarsal-phalangeal pad of digits III-IV of B, showing unusually clear pedal squamation. D, squamation from an Early Cretaceous sauropod footprint [from Paik et al. (2017)]. E, forelimb squamation, *Haestasaurus becklesii* an Early Cretaceous neosauropod [from Pittman et al. (2022)]. Note the compelling similarity to the scale pattern of *Otozoum* indicating a shared apomorphy.

Head west, turn left and U-turn into Gallery 2 heading east.
Proceed east to wall on right.

Station 3: Dinosaurs in motion — penetrative tracks. Gallery 2 South and cart. The two, part and counterpart slabs, ACM ICH 18/1 and 18/2, are the paving pieces quarried by Dexter Marsh, passed on to James Deane and eventually to Hitchcock, starting the scientific study of dinosaur footprints. Besides their historical interest, these are examples of what are now called penetrative footprints (Gatesy et al., 1999; Gatesy and Falkingham, 2020). Unlike the tracks made upon a microbially-bound, cohesive mud, penetrative tracks are those in which the autopod penetrates through layers of sediment deforming them both as the pes or manus is implanted and again when it is withdrawn. This means the track records the movement of the foot or hand and is not a just an impression of the anatomy. What we lose in anatomical information we gain in functional information. The tracks record of living, moving dinosaurs.

Penetrative track are not undertracks, which are the bent sedimentary layers below the implantation surface with track shape transmitted downward, or overtracks which are layers conforming somewhat to a tracks shape. The foot was never in contact (disregarding the microbial community) with the sediment surface in those two cases. But in penetrative tracks the foot was in contact with the sediment all the way down and backup through the sediment.

You can see that ACM ICH 18/1 and 18/2 are penetrative footprints by peeking around in back of the slabs. You can also see grain lineations on the slabs, showing that the visible surfaces were not the sediment surface at the time the tracks were made. The digits tracks have a distinctive "V' shape in cross section, which develops because of the lateral collapse of the down- (or up-) warped) sediment into the void of where the manus or pes was (Figure 61). Because of the V-shape penetrative tracks often look like narrow-toed footprints and in fact Hitchcock (1836) thought they were the tracks of narrow termed birds, giving the category name of Leptodactyli (thin-toed), as opposed to Pachydactyli (thick-toed) bird track such as *Eubrontes*. But thin-toed appearance does not reflect trackmaker anatomy, as much as sediment behavior around a dynamically moving body. The plethora of ichnotaxa names applied to penetrative tracks does not reflect much about animal taxonomic diversity.

Look at ACM ICH 31/51, 31/57, 31/58, 31/59 (on cart). How do these "penetrative tracks" differ from the tracks we have seen so far? Also examine the "Track Book" (ACM ICH 27/4: north east corner). Compare also with Dexter Marsh's tracks ACM ICH 18/1 and 18/2. What do we learn that is different from non-penetrative tracks?

Numerical modeling of penetrative tracks promises a way of recovering the actual motions of dinosaurs from penetrative tracks (Figure 61C) (Novotny et al., 2019; Falkingham et al., 2020; Gatesy and Falkingham, 2020; Falkingham, 2025)(Novotny et al., 2019: https://youtu.be/F_-bQxTq1Mk). Penetrative footprints, often astoundingly common in ripple-cross-laminated units, seem to be much less common in pre-CAMP units than in syn-CAMP units. Perhaps this is related to much higher average accumulation rates, and presumed growth of accommodation space in these very latest Triassic and Early Jurassic strata, resulting in greater amounts of water-saturated sediment (McDonald et al., 2025). Their abundance means there is great potential for accurate, inverse modeling of dinosaur locomotion.

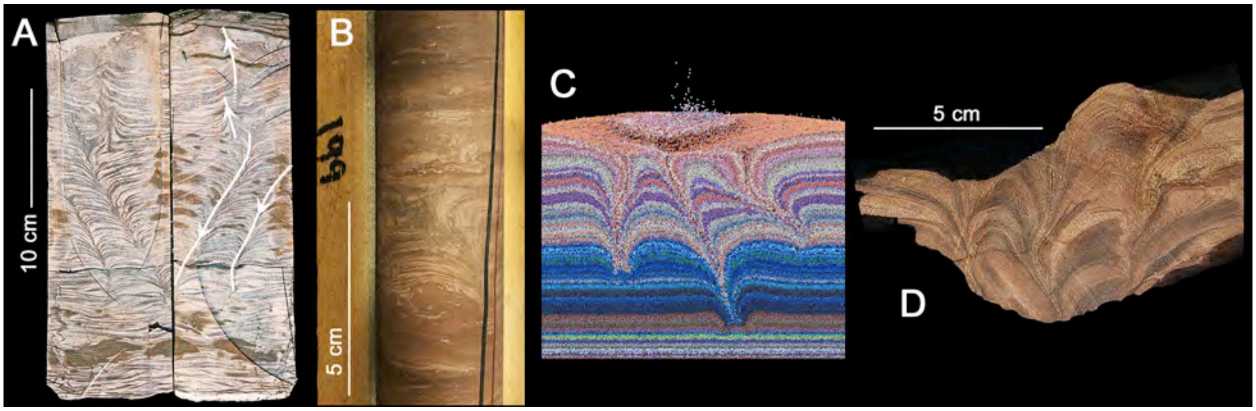

Figure 61. Penetrative tracks in cross section. **A**, split core of lower Portland Formation, Park River core, FD-12T, 44 ft. **B**, core of the lower East Berlin Formation, MDC 227A, 199.5 ft. **C**, transverse sectioned view of digitally simulated penetrative track volume [from Falkingham et al. (2020)]. D, cross section penetrative track upper Towaco Formation, Walter Kidde Dinosaur Park, Riker Hill Quarry.

Station 4: *Cynodontipus* is a burrow, Gallery 2 South and cart. On southern rack of gallery 2 are two part and counterpart slabs of red sandstone with red mudstone partings (BMNH UC 1-3), as well as some small slabs normally stored in cabinets that are out on a cart for viewing. The traces on the slabs are among the most peculiar in the Hitchcock collection, and they are conceptually new to North America. The slabs exhibit several *Batrachopus deweyii* trackways and a single medium-sized brontozoid, but most notable are a series of delicate, crescentic scratch-like traces that can be assigned to the ichnogenus *Cynodontipus* Ellenberger 1976 (Figure 62). *Cynodontipus polythrix*, meaning "dog-tooth-foot with many-hairs" was named by Ellenberger in 1976 based on two slabs of Middle and Late Triassic age from France and Germany, respectively, that he interpreted as footprints of a hairy cynodont synapsid. These slabs have natural casts of multiple crescentic clusters of fiber or scrape-like impressions that Ellenberger reasoned were traces of hairy toes. The French trace has been accepted as a footprint and as evidence of hairy synapsids in the Middle and Late Triassic [e.g., (Hunt et al., 1993; Lockley and Meyer, 2000; Kielan-Jaworowska et al., 2004; Silva et al., 2008; Klein and Lucas, 2021; Klein and Lucas, 2025)].

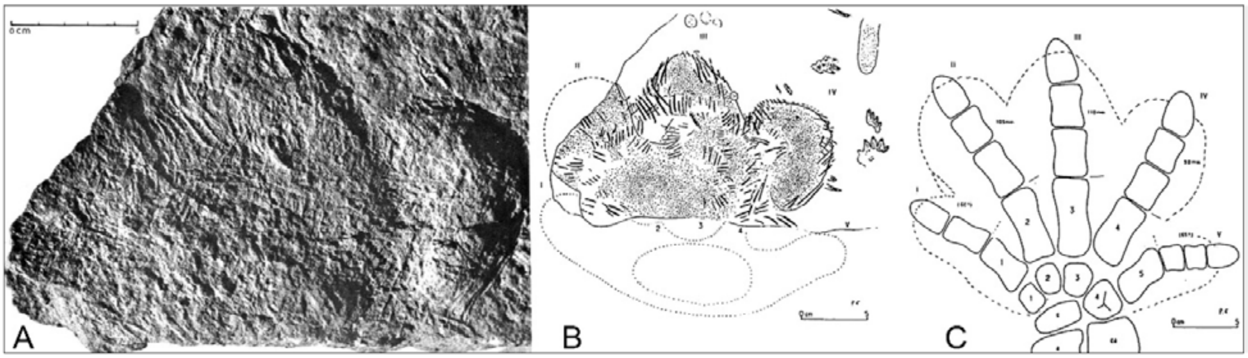

Figure 62. *Cynodontipus polythrix* from Ellenberger (1976). **A**, photograph of main slab from the Middle Triassic of Lodève, France. **B**, Interpretive drawing of A. **C**, Osteological reconstruction of right cynodont foot in the trace outline. Interpretations by Ellenberger. Scale is 5 cm.

However, analysis of more recently discovered material from the Late Triassic Fundy Basin of Nova Scotia, Canada (Figure 63), Late Triassic of the Newark Basin, and Middle and Late Triassic of Morocco, and Early Jurassic of the Deerfield Basin and Kayenta Formation show that *Cynodontipus* is, rather than a footprint, a vertebrate burrow that terminates at a resistant subsurface bed interface, (Olsen et al., 2012a; Sues and Olsen, 2015; Olsen et al., 2025). Because the impenetrable interface was often a clay bed that was subaerially exposed prior to burial, there are often true footprints on the same surface intersected by *Cynodontipus*. The simplest hypothesis of the trace maker of *Cynodontipus* is that it was a produced by burrowing tetrapod. The only apomorphy visible in the traces are the scratch marks that appear to have been made by claws, and those are a plausible synapomorphy of the Amniota (Figure 54) [e.g., Long et al. (2025)]. Some could be made by protosuchians crocodylomorphs such as *Stegomosuchus* from the Portland Formation (see cart), which may be preserved within a burrow, to lizards or stem mammals (Figure 65).

PEO first noticed these two large part and counterpart slabs bearing *Cynodontipus* in the Hitchcock collection in the 1980s., while they were stored in the Pratt Museum basement However, there was no catalogue number on the slabs and no known information in the Museum documents. At the time, PEO thought they might be feeding traces of the *Batrachopus* trackmaker, rather than a cynodont track, but no sensible geometric arrangement could be discerned. In 2004, however, a particularly informative specimen that revealed the true nature of *Cynodontipus* was found by J. H. Whiteside (NCSU) in the late Triassic Blomidon Formation (Sues and Olsen 2015) during a field trip led by PEO (Figure 63). The specimen could not be collected due to various factors, but slabs had multiple burrows resembling the systems reported by Voigt et al. (2011) from the Triassic of the Argana Basin in Morocco. The Blomidon Formation specimen also had clear *Cynodontipus*-type crescent-shaped scratch marks in positive hyporelief attached to the burrows, demonstrating their connection (Sues and Olsen, 2015).

Also in the 1980s, PEO identified small slabs with clear *Cynodontipus*, *Rhynchosauroides* sp., and *Batrachopus deweyii*, some of which (BMNH UC 122, BMNH UC 116) were once attached to the larger slabs (BMNH UC 1-3). At the time, no locality data was found with the specimens. When the specimens were moved to the Beneski Museum, however, former Collections Manager Kate Wellspring found labels affixed to the back of a specimen (BMNH 60/26) that provided unambiguous locality and collector information. The label has a Hitchcock-like fractional number (60/26), although there are no specimens with numerators above 59 in Hitchcock's (1865) supplement, suggesting that the specimens were added close to or after his death. A handwritten paper label indicates that the specimen was discovered in 1864 by C.U. Shepard, an Amherst College mineralogist, and that it comes from a quarry on the east side of the canal on Connecticut River directly at the canal [in northwest Montague, Massachusetts]. The other specimens probably came from the same locality based on similarity lithology and preservation style.

Shepard's collection was purchased by the College in 1877 (Wilson and Fiske, 1888). In 1913, B.K. Emerson catalogued Shepard's footprint specimens (Rainforth, 2003), presumably adding Hitchcock-type numbers.

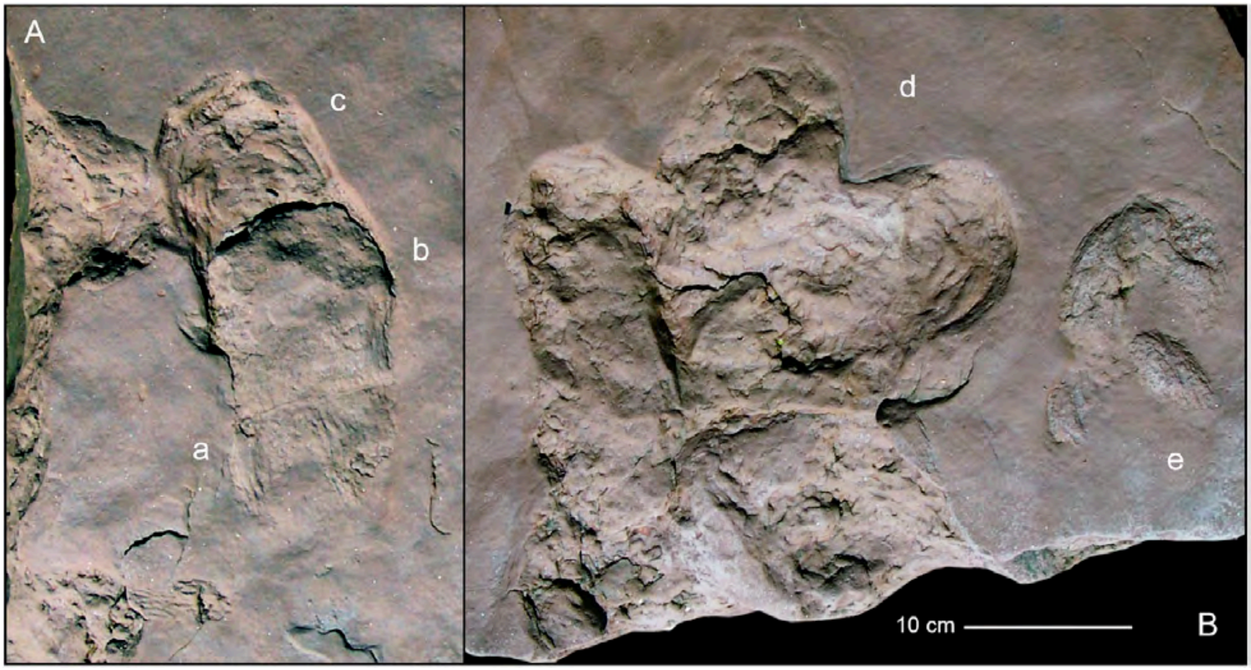

Figure 63. Slightly worn *Cynodontipus* burrow system from the Late Triassic Blomidon Formation of the Fundy Basin, Nova Scotia. **A**, Burrow fill: a, characteristic crescentic scratch marks of *Cynodontipus* where burrows intersected resistant bedding surface; b, 3-d burrow cast following bedding; c, upper surface of burrow visible where burrow fill has fallen out – note crescentic scratch marks on upper surface. **B**, same slab: d, lobed-appearing set of upper surfaces of burrows with crescentic scratches; e, two sets of *Cynodontipus* crescentic scratch marks. Scale for A and B is the same.

Based on the label, the *Cynodontipus*-bearing bed is in the early Hettangian (Blackburn et al., 2013) lower Mount Toby Formation of the Deerfield Basin, which correlates with the East Berlin Formation of the Hartford Basin and the Towaco Formation of the Newark Basin. The track assemblage is unique in the Connecticut Valley in having both *Cynodontipus* and *Rhynchosauroides*. PEO found a possible *Cynodontipus* in the upper Park River Member of the Hartford Basin's Portland Formation in 2012, and *Rhynchosauroides* is known from some specimens in the correlative Towaco Formation (Olsen, 1988b). That these specimens escaped mention is amazing, given that they were plausibly available to C. H. Hitchcock and Lull (1904a, 1915, 1953).

Very recently additional *Rhynchosauroides* and *Cynodontipus* have come to light from the Deerfield Basin. The *Rhynchosauroides* is in red siltstone and was found by Willis McCumber in riverbed rubble presumably downstream from its origin, the simplest hypothesis for which is that it comes from below the lowest well developed dark shale cycle of the Mount Toby Formation which is "lake bed 1" of (Wise, 1988). This is at least potentially consistent with the location given by Shepard for the *Rhynchosauroides* and *Cynodontipus* specimens. The new *Cynodontipus* consists of multiple overlapping traces in convex hyporelief found by Noah Charney (University of Maine, Orono) in red siltstone from the northwest face of Mount Toby at what must be a significantly higher level than the previous Deerfield Basin specimens. What these specimens suggest is that neither *Rhynchosauroides* and *Cynodontipus* are extremely rare and that at least *Cynodontipus* occurs in multiple intervals in the basin. Based on finds around the world *Cynodontipus* occurs in strata ranging in age possibly as old as Carboniferous through at least the Early Jurassic.

Station 5: Dino pedal pathology Gallery 2 North. Opposite *Cynodontipus* is an unnumbered slab with a brontozoid trackway comprised of two right footprints and a left. The two left footprints are deep, but lack a digit II and have peculiar posterior pads, whereas the left print has three digits and normal pads. This is a case where digit II was lacking, probably due to pathology, on the trackmaker's right foot. A similar example is seen on ACM ICH 23/2 (Station 11). Who hasn't seen an unfortunate gimpy city pigeon?

Go straight ahead towards east.

Station 6: Noah's Raven Gallery 2 East. The tracks on ACM ICH 16/2 have been described as the first footprints documented in eastern North America. Hitchcock (1836, p. 322) was aware of them, but he gave them only perfunctory mention (see section on Historical Context Appendix 1) until 1844 when he described his perspective on the dispute over who was first to understand the significance of the Connecticut Valley footmarks that developed between himself and James Deane. In this paper, he introduced the ACM ICH 16/2 specimen, apparently to diffuse the situation by documenting the discovery of tracks long before either he or Deane knew of them. Hitchcock states, "About the year 1802...Mr. Pliny Moody of South Hadley...then a boy, turned up with a plough upon his father's farm in that place, a stone, containing in relief five tracks of the *Ornithoidichnites fulicoides*…and it was put down as a door-step, because it contained tracks, and the neighbors used facetiously to remark to Mr. Moody, that he must have heavy poultry that could make such tracks on stone. After Mr. Moody (junior) had left home for school or college, Dr. Elihu Dwight of South Hadley purchased this stone, because it contained these tracks. It was retained by him nearly thirty years, when I purchased it for my cabinet, I think in 1839. Dr. Dwight used pleasantly to remark to his visitors, that these were probably the tracks of Noah's raven."

In 1858 and again in 1865, Hitchcock recounts that these were the first tracks to be found. He noted in 1858 added that they were then in his collection and assigned specimen number 16/2. In 1865, H. Hitchcock stated that ACM ICH 16/2 bears trackways that he called *Anomoepus minor* and *Ancyropus heteroclitus* (?). The nomenclatural history of ACM ICH 16/2 is very complicated, which is typical for Hitchcock's tracks. Olsen and Rainforth (2003) attempted to rectify this confusion and designated the specimen the lectotype of *Ornithoidichnites cuneatus* since it appears to be the only remaining specimen of three assigned to that species by Hitchcock 1841 (p. 488). However, the better of the two trackways on ACM ICH 16/2 is clearly *Anomoepus* a form that gave Hitchcock no end of trouble.

As we understand now, *Anomoepus* is a bipedal, functionally tridactyl footprint less than 20 cm long that has a metatarsal-phalangeal pad of digit IV almost directly or directly in line with the axis of digit III in walking tracks (Olsen and Rainforth, 2003). This latter feature, visible in 16/2, is unique among early Mesozoic tracks. Additionally, compared to brontozoids, Digit III is relatively short and the toes are widely splayed, which is also true of ACM ICH 16/2. Foot digit I (hallux) of Anomoepus is relatively long and often at least partially impressed, especially in sitting tracks. The latter is not evident, however, in ACM ICH 16/2. Of note, is that while the name *Ornithoidichnites cuneatus* has priority over *Anomoepus scambus*, *O. cuneatus* was never actually described and is therefore a *nomen nudum* (Olsen and Rainforth, 2003). Further, because name *Ornithoidichnites* had not been used since 1844, it should be considered a *nomen oblitum*. In any case, the type species of the latter is *Orinthichnites* (*Eubrontes*) *giganteus*. Thus, the approriate name for "Noah's Raven" is *A. scambus*.

Anomoepus is often found in a sitting posture with pentadactyl hand imprints, a fact that grieved Hitchcock because he desperately wanted the bird-like tracks to be of bird origin. It is clear, however, that *Anomoepus* was made by an ornithischian similar to *Lesothosaurus* or *Kunindadromeus* (see Station 12), below.

Turn right and U-Turn into Gallery 3, heading west.

Station 7: *Batrachopus deweyii* – crocodylomorph tracks, Gallery 3 North. ACM ICH 26/5 and 26/6, which are part and counterpart, exhibit fine examples of small quadruped tracks called *Batrachopus deweyii* (Figure 64). The trackway on ACM ICH 26/5 and 26/6 is unusual in recording one foot imprint with a pad for digit I. As reconstructed using the arthral hypothesis (Olsen and Padian, 1986), the trackmaker's osteology is indistinushable from that of protosuchians and modern crocodilians. The pad number in *Batrachopus* suggests that digit IV had only four phalanges (or of if five perhaps in cartilage and minute), which may be an apomorphy for a clade including at least the Crocodyliomorpha. However, Olsen and Padian erred in showing a claw on manual digit IV in *Batrachopus* and *Alligator*. Modern crocodilians do not have claws on manual digits IV or V although the naked toes can be very pointy. In addition, the pes of *Alligator* at least has a cartilaginous terminal phalanx on pedal digit IV (Müller and Alberch, 1990), which also lacks a claw, another potential apomorphy. There is variation in the cartilaginous terminal phalanges of digits IV and V on the manus and IV on the pes among various crocodilian species and even among individuals of the same species, however (Müller and Alberch, 1990; Gregorovičová et al., 2018).

Protosuchian, crocodyliform crocodyliomorphs are only one of three non-dinosaurian archosaur groups, including the sphenosuchian crocodyliomorphs and pterosaurs, to make it through the end-Triassic extinction. Protosuchian skeletal remains are the most common archosaurs found in post ETE strata in eastern North America, and include *Stegomosuchus longipes* from the upper Portland Formation of the Hartford Basin (Figure 65), *Protosuchus micmac* from the McCoy Brook Formation of the Fundy Basin (Sues and Olsen, 2015), and undescribed material found by PEO in the Feltville Formation of the Newark Basin. Lull (1904b), in fact attributed Batrachopus to *Stegomosuchus* although at that time the skeletal taxon was thought to be aetosaur, and feet of *Stegomosuchus* are poorly preserved. It is also possible that some *Batrachopus* were made by small sphenosuchian crocodylomorphs, as group that went extinct in the Cretaceous.

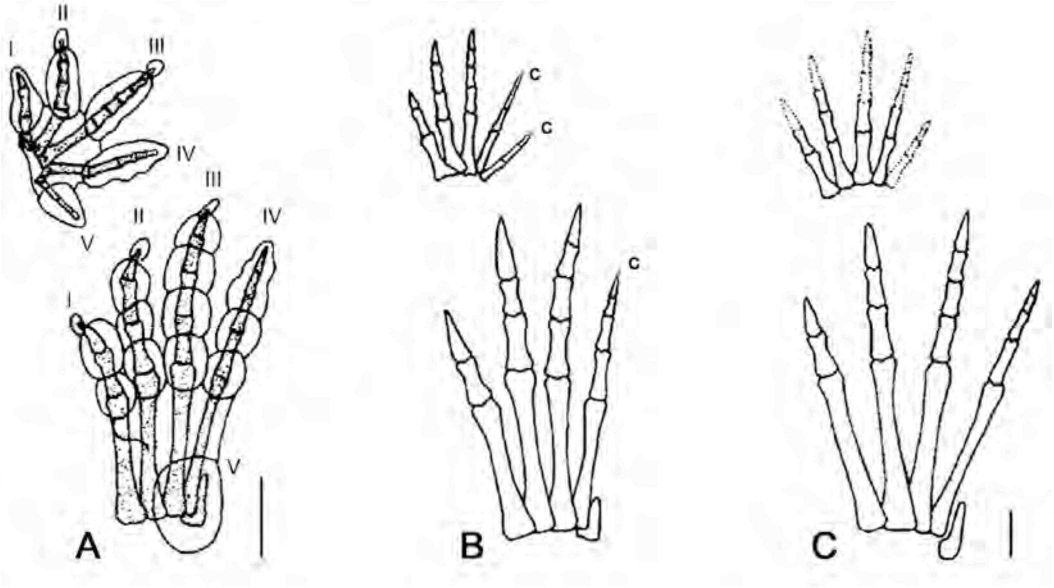

Figure 64. *Batrachopus deweyi* and comparison to crocodilians [slightly modified from Olsen and Padian (1986)]. **A**, Composite of right manus-pes set of ACM ICH 26/5 with reconstructed skeleton. **B**, *Alligator* sp. hand and foot [from Romer (1956)] corrected with information from Müller and Alberch (1990) and Gregorovičová et al. (2018) showing cartilaginous unguals (lacking claws), "c" in grey. **C**, *Protosuchus richardsoni* manus and pes [from (Colbert and Mook, 1951)]. All drawn as right manus-pes sets. Scale is 1 cm.

Examine slabs 26/5 (gallery 4, north) of a trackway of *Batrachopus deweyii*. Ichnocladistics suggest that *Batrachopus* was made by small basal crocodylomorph pseudosuchians (Figure 24), either protosuchians of sphenosuchians or both. Neither protosuchians nor sphenosuchians comprise proper clades, but rather a grade that in the protosuchians include the ancestors of living crocodilians. In this interval of the Early Jurassic there is no evidence of large continental crocodilians and *Batrachopus* based om the anatomy of known protosuchians and sphenosuchians would have fully terrestrial. *Batrachopus* is small, as are *Rhychosauroides* and *Ameghinichnus*, and all larger forms were dinosaurs.

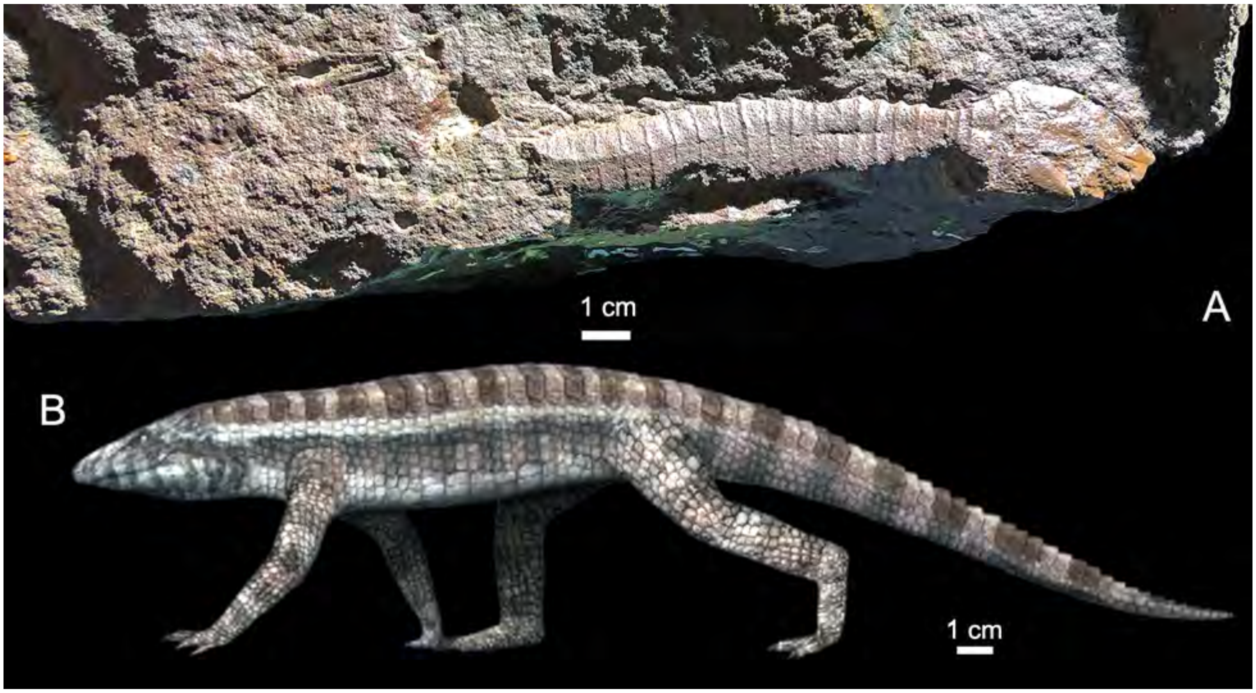

Figure 24. Protosuchian crocodylomorphs. A, the holotype of *Stegomosuchus longipes* from Longmeadow, MA, a plausible trackmaker of *Batrachopus*. B, reconstruction of *Protosuchus* (which may be a senior synonym of *Stegomosuchus*) by Gabriel Ugueto https://i.redd.it/pjs7vzfnx2s51.jpg. Are there traces of a burrow visible on the specimen (cart)?

Station 8: Tales of feathers I - *Gigantipus caudatus* Gallery 3 North. ACM ICH 9/10 is a large trackway of Hitchcock's ichnospecies *Gigantipus caudatus*, discovered by Roswell Field at the Lily Pond on his farm (Figure 66). It is from the middle Mount Toby Formation. This slab illustrates two important features relevant to theropod postures and gaits and presence or absence of feathers or protofeathers. Unlike *Eubrontes giganteus*, *Gigantipus caudatus* has a tail trace and has an imprint of digit I. As Weems (2003) argues, *Gigantipus caudatus* is most simply interpreted as a variant of *Eubrontes giganteus* that differs from typical examples because of differing behaviors that affected the degree to which the trackmakers were or were not walking fully on their toes. We would think the inclination of the body axis would also vary.

The tail drag is relevant to the identification of feathers or feather homologues in showing a series of small to large chevrons around a central groove, pointing in the direction of motion (Figure 66B). These are identical to the doubly ruffled grooves found in flysch (Craig and Walton, 1962) that are made as current-dragged tools crumple the surface of cohesive microbially-bound mud (Dzuynski and Walton, 1965). Such a tool mark appears feather-like although they are inorganic. Similar marks, present in ACM ICH 1/7 (Station 13), have been interpreted as theropod feather imprints.

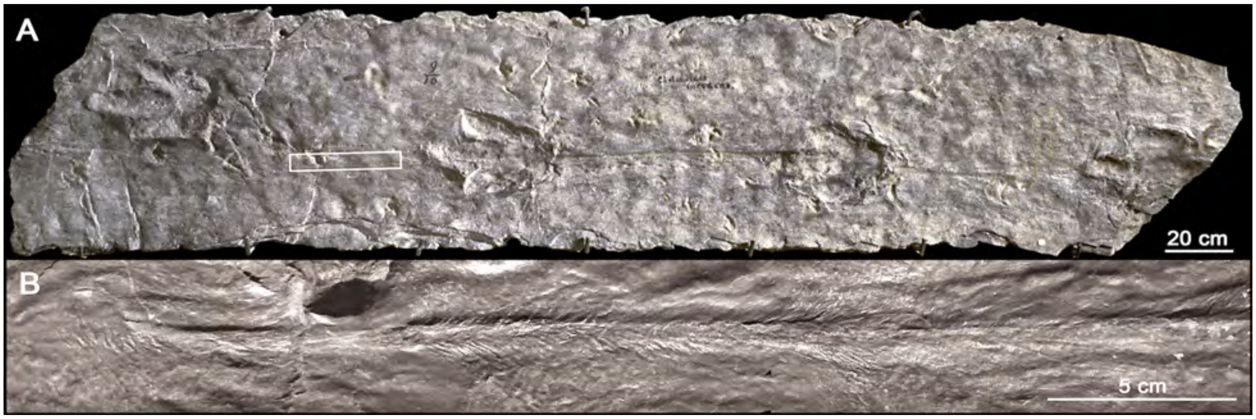

Figure 66. *Gigantipus caudatus* (ACM ICH 9/10). **A**, trackway overview. Note distinct hallux imprints and tail drag. **B**, Detail of white box in A showing tail trace with doubly ruffled grooves superficially resembling feathers, but indicative of cohesive, microbially bound mud.

Station 9: Tales of feathers II - *Ænigmichnus multiformis* Gallery 3 North and cart. *Ænigmichnus multiformis* (ACM ICH 51/15: counterpart on right [North] side of entrance to the Hitchcock collection) is a slab with many grooves and chevrons. These are clearly tool marks caused by sticks or other objects dragged along the bottom by currents. The doubly ruffled grooves of various scales again require a cohesive microbially-bound film. No one would interpret these as feathers.

On the cart is a very peculiar little specimen (Figure 67). When PEO first examined a decade or so ago, he thought it was a conifer frond, but then he noticed the pattern repeated. ACM ICH 63/07 was purchased from C. H. Hitchcock, Edwards son, labeled as an insect trace [according Emerson (1873?)]. Its sinuous shape, however, reveals it to be a fish trace comparable to (but fancier than) the trace fossil *Undichna*, known from the Connecticut Valley (Getty, 2018). Unfortunately, there is no locality information.

Station 10: "*Sauropus*": Theropod (*Anchiauripus*) sitting trace Gallery 3: South. ACM ICH 1/1 is very important because it reveals a potential apomorphy for bronozoids (and theropods) which is that the manus cannot pronate and when resting on the ground only the knuckles impress (Figure 68). ACM ICH 1/1 is a large slab covered with various sized brontozoid trackways. It was excavated from Roswell Field's Orchard, in Gill, Massachusetts and procured at Dexter Marsh's auction in Greenfield in 1853. One trackway is of an animal in a sitting position (Figure S1.10). This crouching trace, along with the similar ACM ICH 1/7, has produced much confusion. As with so many of the classic specimens, the taxonomy of this specimen is complicated and several very different ichnotaxa were conceptually conflated in the process [see Olsen and Rainforth (2003)]. In 1843, Edward Hitchcock established *Ornithichnites lyellii* for an isolated, medium-sized brontozoid track on ACM ICH 31/85, which came from the Mount Toby Formation of Turners Falls, Massachusetts. We would now call this track *Anchisauripus*. In succession, he renamed the track *Fulicopus lyellianus* (1845), *Aethyopus lyellianus* (1848), and *Amblonyx lyellianus* (1858). Hitchcock (1858) referred the trackways on ACM ICH 1/1 to *Amblonyx lyellianus* too. Both specimens were designated types of *Amblonyx lyellianus* by Hitchcock (1865). The crouching trace on ACM ICH 1/1 was, however, referred to the ichnogenus *Anomoepus,* giving it and another specimen (ACM ICH 1/7) the new specific name *Anomoepus major* (see below Station 13).

Hitchcock interpreted this trackway as if it were the standard *Anomoepus* sitting pose because he thought he could see two parallel hand-foot sets and two "heel" imprints posterior to the footprints, and because of the presence of a more posterior and central "ischial" imprint. This was important because he was clinging to near-correct idea that brontozoids were birds, but if this specimen had manus it must instead be a bird-like form, not a bird, such as he interpreted the trackmaker of *Anomoepus*. Lull (1904a) chose Hitchcock's *Fulicopus lyellinanus* as the appropriate name for the track and reconstructed the trackmaker as similar to a sitting "ornithopod" like *Hypsilophodon* (Figure 68D). Lull (1953) provided a new trackmaker reconstruction, again based on *Hypsilophodon*, which is of interest because it has a rather sheep-like face with cheeks.

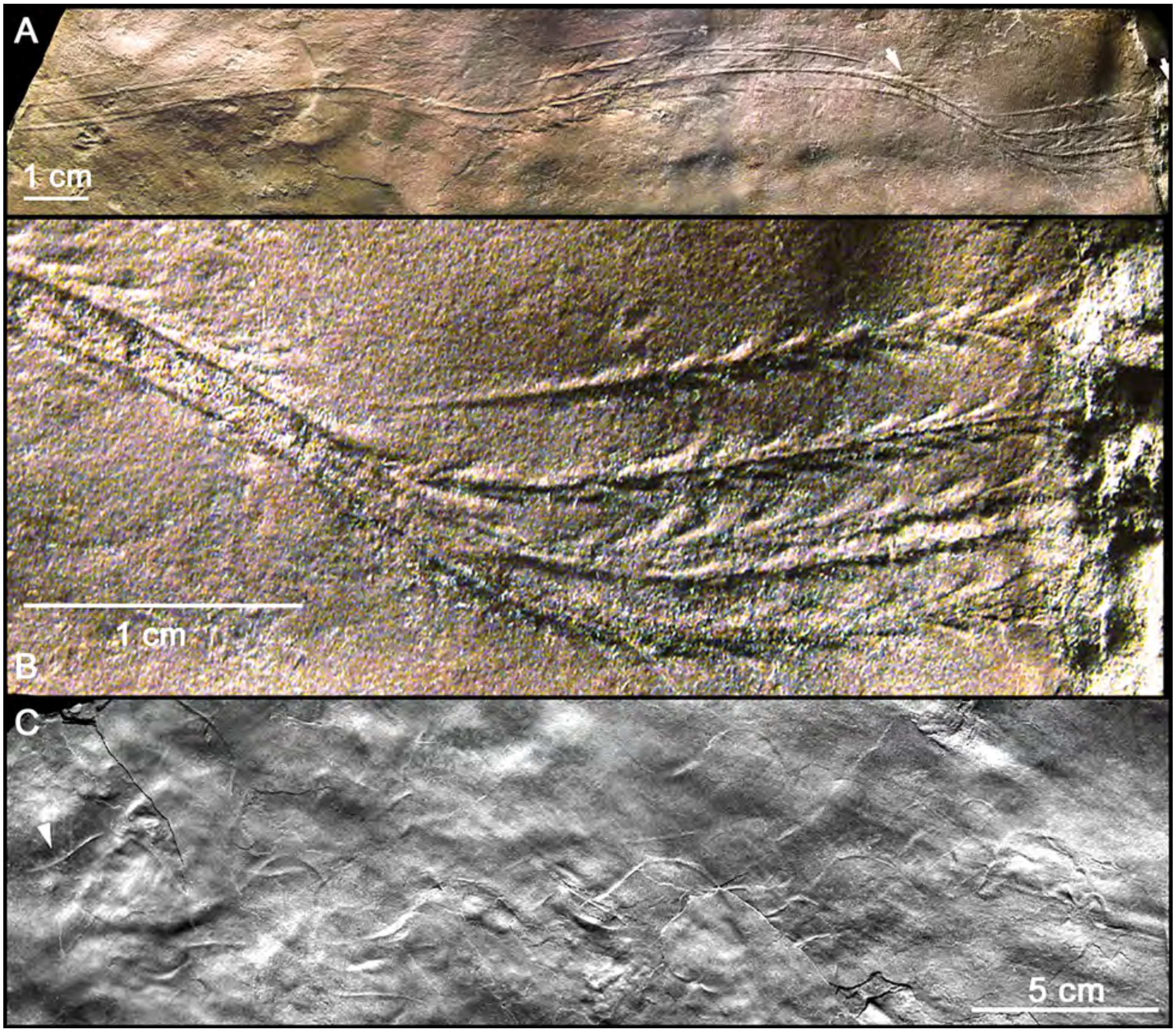

Figure 67. *Undichna*-like fish fin traces and *Undichna*. **A**, delicate sinuous trace with double chevrons indicating cohesive microbial bound mud scraped by the rays of a fish's fins, ACM ICH 63/07. **B**, detail at same, beginning at white arrow in A. **C**, *Undichna* cf. *britannica* SSM 2016/11-1 (Springfield Science Museum) from the East Berlin Formation, Gary Gaulin Track Site, Holyoke, Massachusetts; photo from Getty (2018).

ACM ICH 1/1 shows what are interpreted as a pair of manus imprints. This is a new interpretation that differs from that of Olsen and Baird (1986), in which PEO disparaged these marks (incorrectly) as similar to other imprints on the surface. Additionally, what Hitchcock (1858) figured as the left "heel" of A. major is in fact a metatarsus imprint superimposed on a complete left foot impression of the same trackway (Figure 68C). The two small imprints in front of the heel seem to be the only ones of the foot corresponding to that heel, as Hitchcock (1858) suggested. This is not unexpected in that birds, such as ratites, can often be seen sitting with metatarsi impressed but most or even all of one or both feet suspended above the ground (Figure 69). It is also possible for birds to rise from that position using only one foot and not impress the one that was suspended until the next step. The "ischial" imprint is faint and could conceivably be part of a foot imprint of a larger brontozoid on the same slab, but given its similarity to the genuine "ischial" imprint in (ACM ICH 1/7) it seems appropriate to retain it in its reconstruction (Figure 68C).

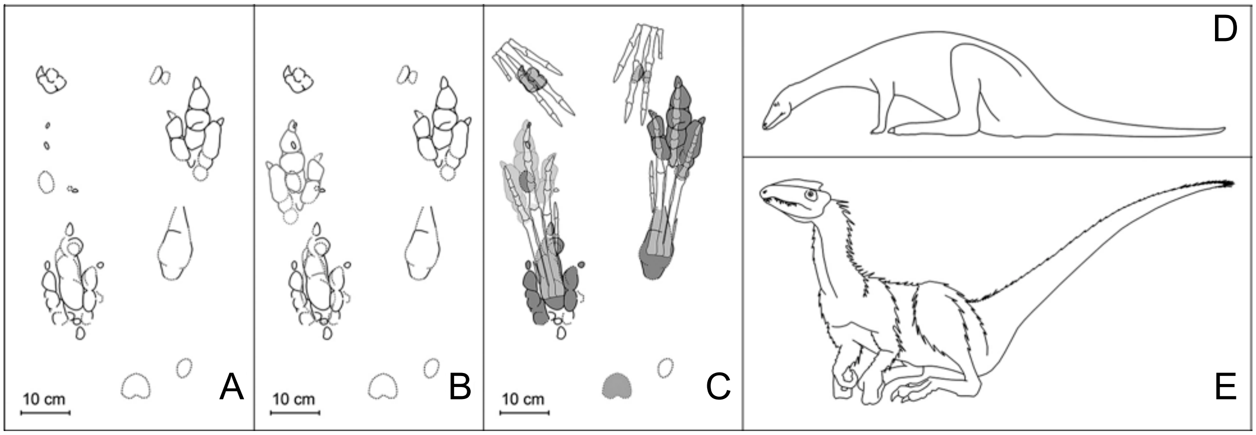

Figure 68. Sitting theropod trace ACM ICH ICH 1/1: **A**, outline drawing of visible; **B**, same as "A" but with right foot (with metatarsal imprint) flipped and superimposed on left imprint; **C**, skeletal reconstruction of hand and foot –hands would be flexed when resting with only proximal phalanges of digits II and II in contact with the ground. **D**, trackmaker imagined as a small ornithopod (Lull, 1904a), assuming a five-fingered hand; **E**, Trackmaker reconstructed as a theropod similar to *Megapnosaurus* (*Syntarsus*) *rhodesiensis* or *Coelophysis bauri*, with only the first two of knuckles of digits II and III on the ground.

Using the arthral hypothesis for joint reconstruction, the foot imprints of the sitting trackway on ACM ICH 1/1 fit the *Coelophysis* skeleton closely (Figure 68C). They therefore corroborate that these brontozoids are most parsimoniously interpreted as theropod tracks. The apparent hand imprints, however, pose a problem, as they did for Hitchcock. They seem very incomplete. However, as pointed out by Milner et al. (2009), however, for similar brontozoid tracks in the contemporaneous Moenave Formation of Utah, functional analyses of theropod forearms suggest that pronation of the hand was not possible (Carpenter, 2002; Senter and Robins, 2005). A simple interpretation is that the hand imprints were made by the dorsal surfaces of the subequal proximal phalanges of digits II and III (Figure 68C, E). Reconstructed this way (but shown not flexed for simplicity), the hand imprints fit the *Coelophysis* manus skeleton [from Barta et al. (2017)] perfectly. In a natural pose (Figure 68E), the hand would be flexed with the palms pointing backward and medially, with only the knuckles of digits II and III resting on the ground. This pose matches both the preserved traces and the functional interpretations of a theropod hand. The result (Figure 68E) is very close to the reconstruction by Milner et al. (2009). These are the most distinct theropod sitting traces known.

Turn left and head east into Gallery 4.

Station 11: Dinosaur displaying and pathology Gallery 4 North. Take a look at slab ACM ICH 23/2 (gallery 4, north) (Figure 70). This has, in addition to several *Anomoepus* and *Grallator* or *Anchisauripus* (who can tell!), there are some oddly symmetrical deep grooves named *Antipus bifidus* by Hitchcock (1865). Carefully look at the symmetry and see if you can figure out how they were made. Olsen in (Getty and Thomas, 2017) interpreted these marks as closed fists of an *Anomoepus* trackmaker making a scratch display in which the forelimbs were used to mark the sediment by moving the fore limbs powerfully and symmetrically in arcs away from the midline, in this case twice. Another specimen (23/3, not on display: Figure 70) has at least three swipes.

Figure 69. How ratites often sit: left, ostrich (https://www.dreamstime.com/royalty-free-stock-photo-ostrich-sitting-1-image7464555); right, rhea (https://animals.net/rhea/). Note how the posterior portions of the pes do not touch the ground.

Antipus bifidus is a very peculiar trace on slab (Figure 70) which is not at all the same kind of trace as *Antipus fexiloquus*, which is clearly a few small impressions of actual feet with toes, based on Hitchcock's (1858) figures. Hitchcock (1858 states, “The name is *Antipus binfidus*; the first part meaning that the feet point in opposite directions, the second part meaning that the feet have two branches.” He believed it was made by a giant lizard-like form with two giant toes on each foot that pointed outward. ACM ICH 23/2 is the holotype of the ichnospecies) and there is another somewhat similar specimen, ACM ICH 23/3, also from same source. Both slabs have associated *Anomoepus* and ACM ICH 23/3 has at least one sitting trace. ACM ICH 23/2 also has a trackway of brontozoid that is missing digit II on the right foot (small arrow on ACM ICH 23/2, Figure S1.11) – another pathology similar to what is seen at Station 5, Gallery 2 North.

The symmetry of the traces seems to be rather different than Hitchcock thought. First, each groove appears to be a separate structure that shallows along its axis, away from its center (a, a’; b, b’; c, c”, d, d’”: Figure S1.11). Second, the longer traces on either side seem to be symmetrical to each other (a, a’; d, d’), as do the shorter traces (b, b’; c, c’). Additionally, longitudinal grooves occur in each trace. The simplest interpretation of these marks is that each symmetrical pair was produced by smoothly pushing the mud by symmetrically arranged limbs, each of which ascribed an arc in a plane nearly perpendicular to the ground and the mid-line. The only body parts that could move like this would be the forearms and hands of a bipedal tetrapod whose body was perpendicular to the long axis of the traces, with the hands closed (there are no clear digit marks). The trackway that bisects the grooves on 23/2 is an *Anomoepus*, but there is no obvious bisecting trackway on 23/3. The *Anomoepus* trackmaker was a small ornithischian and, based on hand reconstructions (Olsen and Rainforth, 2003), could have made the grooves. Viewed in this way, *Antipus binfidus* is best interpreted as a scratch display in which the forelimbs were used to mark the sediment. Careful analysis of the range of motion in the basal ornithischian arms is needed, however, to test the plausibility of this hypothesis.

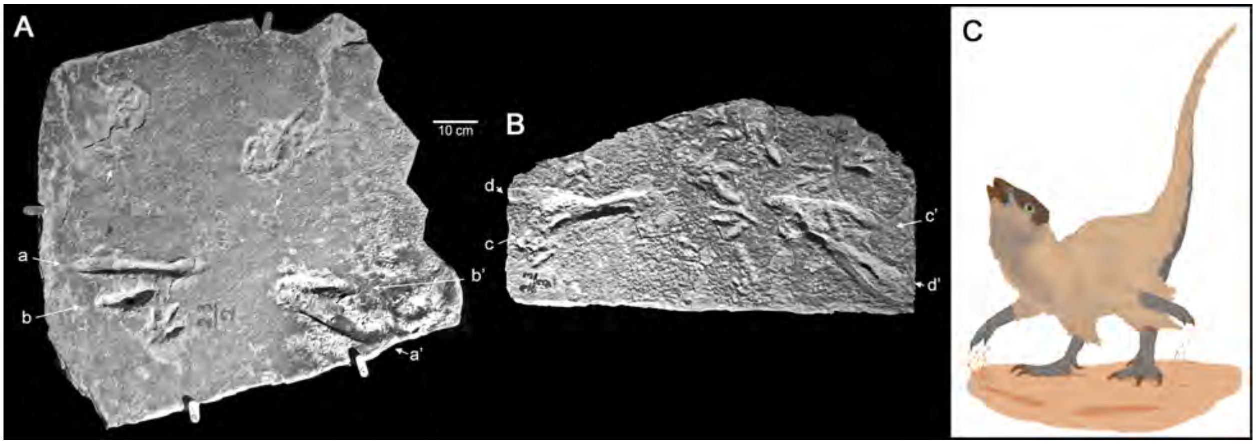

Figure 70. *Antipus bifidus* with many *Anomoepus,* including some sitting with manus. For explanation see text. **A**, ACM ICH 23/2 (holotype). **B**, ACM ICH 23/3. **C**, Reconstruction of *Anomoepus* trackmaker making *Antipus bifidus* by Matthew Inabinett, Amherst class of 2018.

Station 12: Tales of a feather V: Anomoepus Gallery 4 Southeast. In Hitchcock's (1865) Supplement to the Ichnology, he named and described *Anomoepus intermedius*, pointing out characters that relate to the problem of a bird origin for the tracks. It has bird-like hindlimbs and feet, but with a five-fingered hand and a long tail. *Anomoepus* combines very bird like hind limbs and feet with hands with five short fingers and a tail – a real problem if transformation of species, evolution, is not an option. Neither Darwin nor Huxley are mentioned in the 1865 volume, but it would be only three years until T. H. Huxley would make explicit the evolutionary link between dinosaurs and birds in his analysis of *Compsognathus* and *Archaeopteryx* (Huxley, 1868) and in fact allude to the Connecticut Valley tracks, pointing out how so many are indistinguishable from birds.

Carefully examine ACM ICH 48/1 (southeast corner on cabinets gallery 4). Look for evidence of details of integument and compare to Figure 71. One pes impression on this slab is illustrated in Figures 57B and 58B. The podotheca of the *Anomeopus*-maker was clearly very similar to that of living birds and would seem to have indistinguishable reticulate squamation. The reticulae are also very similar to that of non-avian theropods as seen in Figure 56 and described by (Hendrickx et al., 2022).

Slab 48/1 was described by Hitchcock (1865), with a figure depicting a cloth tracing of the tracks Figure 72). Hitchcock (1865) stated that ACM ICH 48/1 (Figure S1.12) has "…four trackways ...of *Anomoepus intermedius*, and four of *A. gracillimus*, probably the typical specimen of *A. intermedius*, showing impressions of all four feet and the tail." Lull (1904, 1915, 1953) and Olsen and Rainforth (2003) accept ACM ICH 48/1 as the holotype of the ichnospecies (the sitting trace), although the latter regard both A. *intermedius* and *A. gracillimus* as junior synonyms of *Anomoepus scambus*. Most of Hitchcock's 1858 comments about *Anomoepus* relate to this particular specimen, which is from the Mount Toby Formation at the former Bissell's Ferry.

These footprints must have deeply troubled the Reverend Edward Hitchcock who described the them in 1863, shortly before his death (Hitchcock, 1865). He had spent much of a lifetime arguing that the functionally three toed tracks, so abundant in the Early Mesozoic Connecticut Rift Valley, were those of antediluvian, giant, and not so giant birds (Hitchcock, 1836). But on this slab of tracks, the three toed hind tracks had five fingered fore tracks clearly im-pressed as the animal sat down. Sixteen years earlier, he named this kind of track Anomoepus, for Anomo-, "unlike, different,"-pus, "foot" (Hitchcock, 1847), in recognition of its seemingly incongruous hands and feet. Even more troubling on this newer slab was the clear trace of a tail (Hitchcock, 1863). That long tail trace really bothered him.

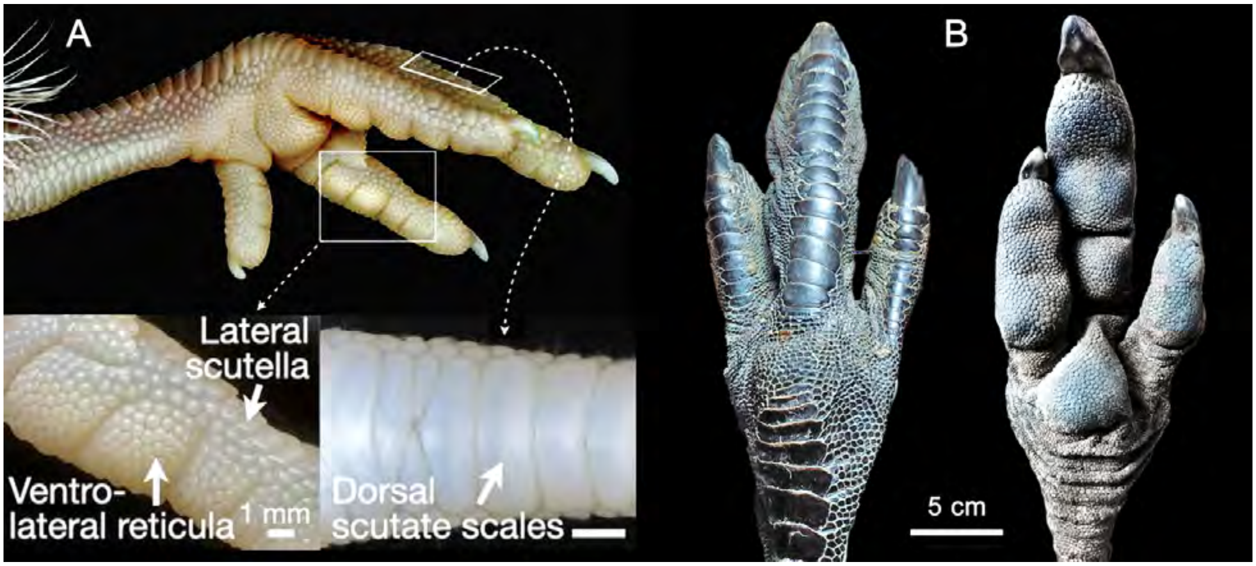

Figure 71. The bird (theropod dinosaur) podotheca, showing reticulae on sole and scutate scales on dorsal surface — compare to ACM ICH 48/1. A, juvenile domestic chicken (Cooper and Milinkovitch, 2023); B, emu left pes (https://www.mrjakeparker.com/blog/2022/1/2/emu-foot); right, right pes (https://x.com/Srutisss/status/1776794158398656701/photo/1).

Hitchcock thought when he named *Anomoepus*, it might be a batrachian (frog or toad) or an ornithoid (bird-like) marsupialoid, as kangaroos have what appear like three toes on the hind (two toes are co-joined) and five toes on the fore foot, as well a tail. For this slab, he took pains to describe the delicate "papillate" appearance of the impressions of the soles of the feet, the clear five-toed manus impressions of the sitting trackway, and the delicate tail trace associated with the latter.

Figure 72. Plate XV, Figure 1, in Hitchcock (1865). Note the tail trace on the right associated with the sitting track and the lack of any hint of the "less perfect" tail trace at the left end of the slab, mentioned in the description. This was made by feeling through the cloth laid upon the slab.

Hitchcock (1865) stated, "The tail of the *Anomoepus intermedius*, although rarely leaving an impression, did sometimes drag along and make a narrow continuous trail. This would indicate greater length, and perhaps tenuity. But how much of attenuation and elongation might be consistent with an ornithic type, we have no means of knowing. Professor Dana speaks of "a posterior elongation of the body as connected profoundly with inferiority of grade in the different types of animal life," and says that "…it is the very one of all abnormal features to be looked for in the early birds." Upon the whole, the singular markings of the tail upon stone, with the exception perhaps of *A. intermedius*, do really suggest a curious coincidence between the caudal extremity of this genus, and that of the *Archœopteryx*." Hitchcock (1858) makes special notice of the tail traces on ACM ICH 48/1 stating, "As confirmatory of these conclusions, it ought to be added that this animal had a tail; for just before it sat down on all fours, we find a distinct tail-trace on the stone, and a less perfect one near the right extremity of the longest row, which would not have been noticed, had not the revelations made by the first, awakened careful scrutiny."

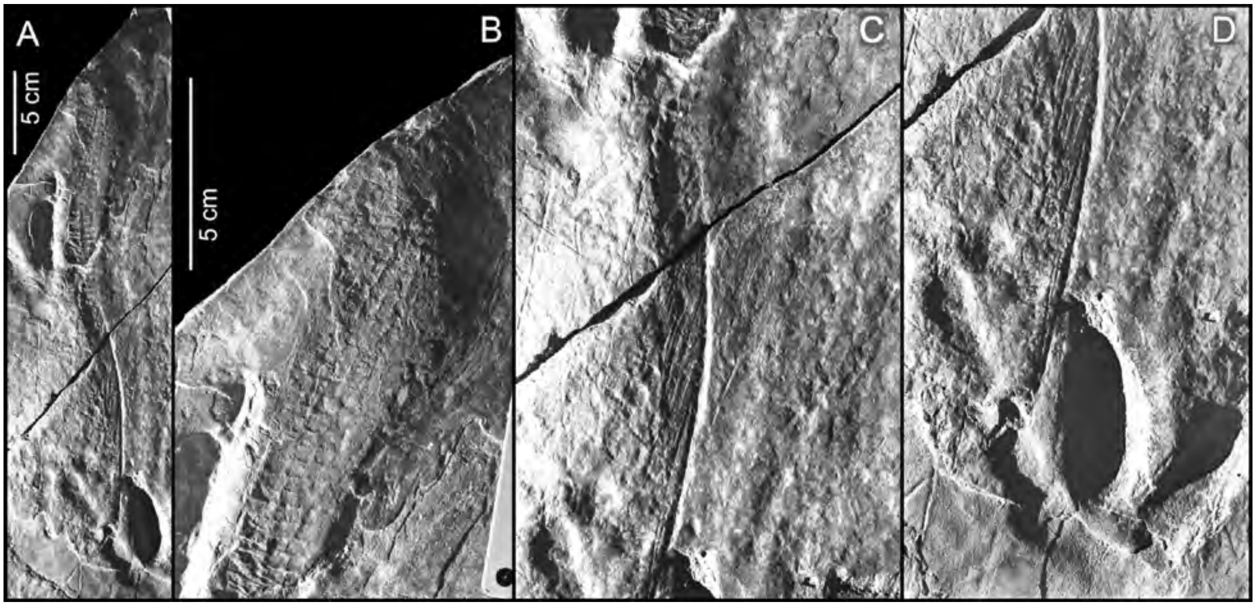

Figure 73. *Anomoepus scambus* (*intermedius*) with scale and ?proto-feathered tail imprint, slab ACM ICH 48/1. A: complete tail trace. B-D: progressively more posterior details. Compare with Figures 74, 75, 76.

It is this "less perfect" tail trace that is revealing and unique, yet curious in that it was not figured in 1865. He made no mention of the most clear and startling feature of the latter in that it is in fact remarkably detailed with clear impressions of rectangular scute-like (scutellate) scales proximally and filaments or bristles, distally (Figure 73). These features went unmentioned for the subsequent 133 years until noticed in 1998 by Emma Rainforth and myself when shining an oblique light on the slab in the "Tombstone room" of the Pratt. How peculiar that neither Hitchcock nor his son (C.H.) mentioned these detailed imprints on the tail trace, especially since they are so relevant to the questions consuming the former. Perhaps the shallowness of the traces or dim light prevented the Hitchcocks from seeing them, although they did notice the fine "pappilate" scale pattern on the pads. This combination of features suggests that feather homologs and similar scutate scales were present in the earliest definitive ornithischians, dating from ~30-40 million years before the age of known body fossils with similar structures (Zheng et al., 2009; Godefroit et al., 2014; Cincotta et al., 2019; Godefroit et al., 2020).

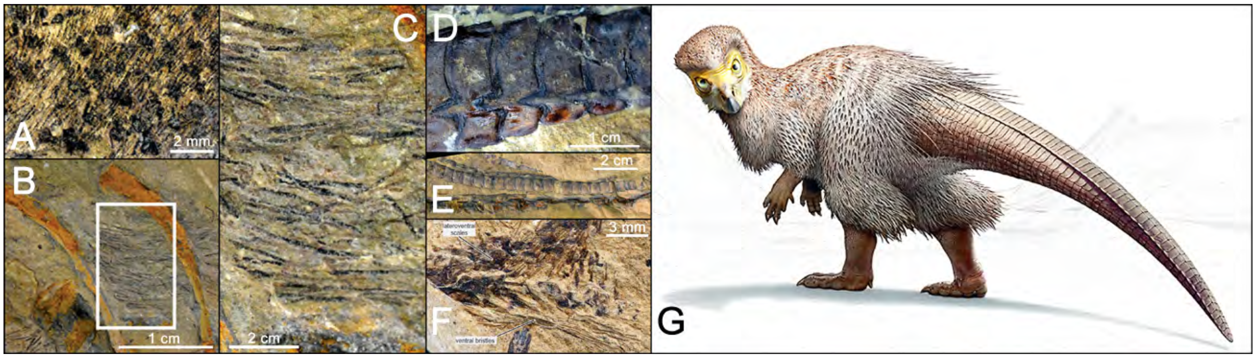

Figure 74. The feathered basal ornithischian *Kulindadromeus zabaikalicus* from the Middle Jurassic (~173 Ma) age. A, "bristle scales" on flank. B, simple filaments on torso. C, enlargement of "B". D, left dorsal row of large, retangular scutellate tail scales. E, distal tail vertebrae (below) and displaced rectangular, dorsal scales (above). F,

lateroventral scutellate scales and ventral bristle-like structures on the tail. G, reconstruction of *Kulindadromeus* by Bob Nicholls. A-F are from Godefroit et al. (2014, 2020) and G is from Benton (2021).

It is striking that a combination of filaments (on the body) and rectangular scales on the tail is known from the Late Jurassic ornithischian *Kulindadromeus zabaikalicus*, (Godefroit et al., 2020), from the Kulinda locality in Siberia (Figure 74). Another Jurassic ornithischian with filament-covered integument is the heterodontosaurid *Tianyulong confuciusi* from the Late Jurassic Daohugou assemblage of China (Zheng et al., 2009) (Figure 75). The later filaments are preserved on the dorsal tail and some are also preserved on the rest of the body. The ventral side of the tail does not seem to preserve integument at all, although that is plausibly preservational. A seemingly complete *Tianyulong* has been recently reported (Figure 75B, C). The specimen has not been scientifically examined, but should it prove be as it appears, this early diverging ornithischian has filaments distally along its tail ending in a tuft. In addition, *Psittacosaurus* from the Early Cretaceous has bristle-like fibers on an otherwise scaled tail (Mayr et al., 2002; Bell et al., 2022), although no enlarged rectangular scales anywhere are present. Some later ceratopsians do have ventral scutellate scale, however, for example *Triceratops* (Figure 76).

Long assumed to be a character defining birds, the revitalization of Huxley's theory that birds evolved from dinosaurs, along with arguments for dinosaurian endothermy from John Ostrom and Robert Bakker (Ostrom, 1969; Bakker, 1971) and others, led support to the idea that feathers initially evolved for insulation, as opposed to flight (Gregory, 1916; Ostrom, 1973; McGowan, 1979). The 1996 description of the proto-feathered theropod, *Sinosauropteryx*, unequivocally demonstrated that feathers evolved first for insulation and later coopted for feathers. This has been backed up by many additional feathered dinosaur finds. In fact, because pterosaurs have filamentous insulation [first described in 1831(!) (Goldfuß, 1831) and (Jäger et al., 2018)] indistinguishable from that in *Sinosauropteryx* and many other non-avian dinosaurs, the simplest hypothesis is that the common ancestor of dinosaurs and pterosaurs and all of its descendants would have had feather or their derivatives.

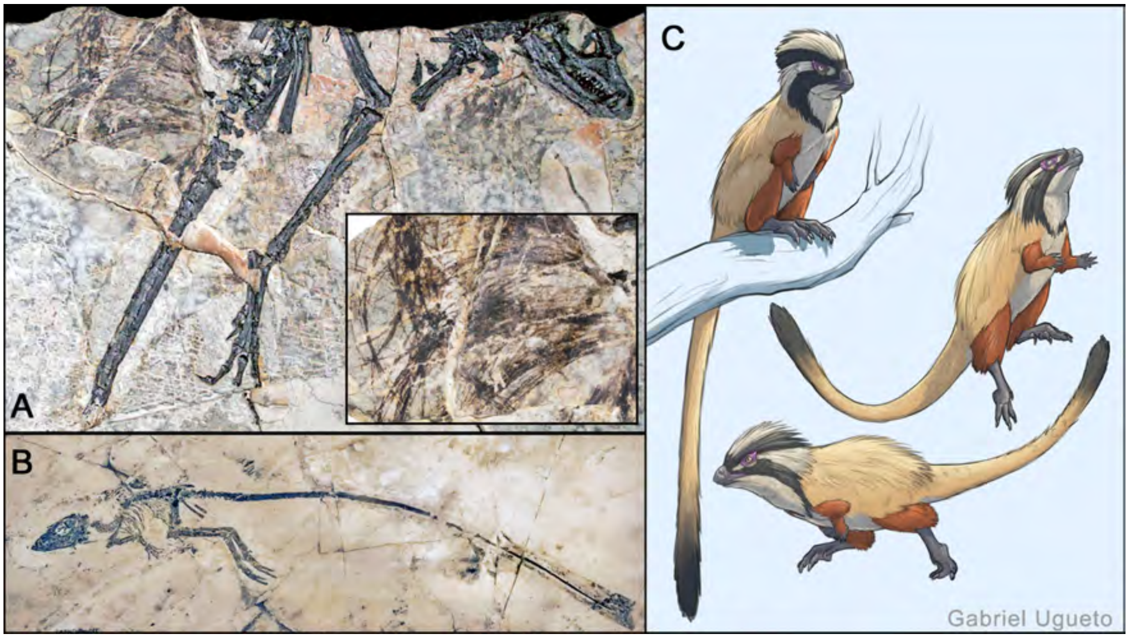

Figure 75. The early diverging, heterodontosaurid ornithischian, *Tianyulong confuciusi* (early Cretaceous) showing covering of filaments and tuft of filaments on tail. A, reconstruction from https://www.facebook.com/photo.php?fbid=740598771400926&id=100063524283004&set=a.12860369260040. B, holotype specimen showing filaments over body, some very long (inset), from Zheng et al. (2009). C, undescribed specimen at the

Beijing National Natural History Museum (https://www.reddit.com/r/Naturewasmetal/comments/qx9aiu/undescribed_complete_specimen_of_tianyulong/).

The ACM ICH 48/1 *Anomoepus* is now the only example of an ornithischian, other than *Kulindadromeus*, known to have rectangular scales on the tail. All other ornithischian scale patterns are either arranged as polygons, rosettes, rounded papillae, or tubercles (Mayr et al., 2002; Bell et al., 2022). Christiansen and Tschopp, 2010). What is very clear at this point is that there is a very large range of epidermal structures in the Ornithischia, and given the filaments present in *Kulindadromeus*, in Tianyulong, and the quill-like structures in *Psittacosaurus*, such filamentous integument along scales on parts of the body are most simply hypothesized to be primitive for the Ornithischia. This is consistent with a cladistic phylogenetic bracket approach (Figure 77), given the presence of a filamentous integument in pterosaurs (Sharov, 1971) and feathers, filamentous integument, and scales in saurischians (including birds). That a filamentous and insulating integument was a character at the base of the Ornithodira (Avimetatarsalia) should have been fairly obvious since the middle 1980s at least.

Figure 76. Examples of scale pattern types in *Triceratops* from the specimens at the Black Hills Institute (South Dakota) (from https://x.com/knight_Steve_/status/1650259639156740097/photo/2): **A**, ventral neck area; **B**, dorso-lateral thigh area; **C**, dorso-lateral hip area. Scale is cm. Compare A with Figure 73B. Perturbances on large scales on B and C may have supported quills or filaments similar to the bristle scales in Figure 74A of *Kulindadromeus*.

We can use this kind of phylogenetic bracket interpretation (Figure 77) to argue that all of the dinosaurs that were trackmakers of Connecticut Valley forms would have been feathered to some extent (see also Figure 12), including *Otozoum*. Younger Mesozoic, very large animals, such as sauropods and hadrosaurs, had very reduced feathers, much as in present-day, low latitude, nearly naked elephants and rhinoceroses. But, we know that closely related, recently extinct, high latitude woolly mammoths and rhinoceroses were shaggy! In fact, even though the relatively abundant skin traces known from sauropods and hadrosaurs indicate their bodies were mostly not insulated, some, maybe all, retained some structures, so called feature scales, made of filaments analogous the hairs bound together comprising a rhinoceros's horns (Czerkas, 1992; Hieronymus et al., 2006; Bell, 2014). We have no physical evidence of the integument of arctic hadrosaurs and other dinosaurs, but insulation by protofeathers seems very plausible (Druckenmiller et al., 2021).

Station 13: Tales of a feather VI: Another sitting theropod – Gallery 4 Southwest. Examine slab 1/7 (wall, southwest corner). This is very famous specimen that records a sitting *Anchisauripus* trace similar to slab 1/1 (Station 10, gallery 3, south). The metatarsi are impressed as well as what has been interpreted as an ischial impression. Close examination reveals many fine details associated with the trace, many looking like short filaments. In fact, these were intepreted as protofeather impressions along the belly by Gierlinski (1996), Gierliński (1998), and Kundrát (2004). However, these are more parsimoniously interpreted as ruffled grooves caused by the dragging of the mud, bound by microbial mats, as the foot was implanted. This was basically the interpretation by Deane (1861) who said of this specimen,

> "The momentum or propulsion of the animal was such as to drive it far forward after its posterior feet had touched the earth. The right foot grazed the ground to a considerable extent ere it assumed a state of rest. The first contact of the toes with the ground occurs at [at a] furrow or trail produced by these slipping members, and … similar grooves were caused by the nails of the lateral toes."

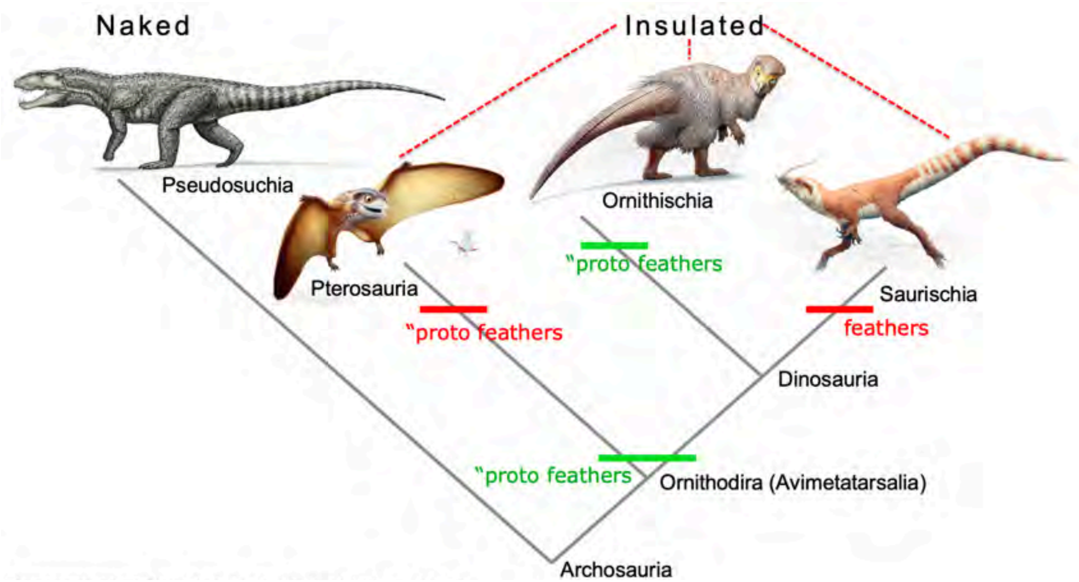

Figure 77: Phylogenetic bracket interpretation of the known distribution of protofeather insulation. The implication is that protofeathers should be present in the common ancestor of pterosaurs and birds and all of its descendants. From left to right, animals depicted are *Postosuchus* (Late Triassic), *Anurgnathus* (Late Jurassic), *Kulindadromeus* (Middle-Late Jurassic), *Sinosauropteryx* (Early Cretaceous). Reconstructions by Bob Nichols [from] and Jeffery Martz [in Weinbaum (2013)].

The traces thought to be furry protofeather integument are ruffled groves that recorded the motion of the feet as the dinosaur sat down on a cohesive, microbially bound surface. As we have seen, similar ruffled grooves can be seen on many specimens cause by many things dragging in the microbially bound mud, perhaps most notably on the tail drag of *Gigantipus caudatus* (9/10, gallery 3 north). However, the theropod that made this sitting trace most plausibly had a furry, feathery insulating cover nonetheless!

Stop 6 — Beneski Conclusions

The Beneski Museum track collection shows us the survivors of the ETE, one of the "big five" largest mass extinctions of the last half billion years (Raup and Sepkoski, 1982; Sepkoski, 1986). All of the Connecticut Valley tracks come from strata that postdate the ETE – but only by a maximum of about 2 million years (Kent and Olsen, 2008; Olsen et al., 2021) and continental communities had not had all that much time for evolutionary change.

The selective pattern of extinction and survival as well as the track evidence we see in the Beneski tell us a lot about the cause of the extinctions on land. The two most dramatic features of the ETE on land are: 1) all large non-insulated animals went extinct while insulated animals of all sizes thrived; and 2) herbivorous dinosaurs spread from higher latitudes into the Pangean tropics, and ornithischians appear for the first time (perhaps having evolved in the unsampled polar regions). Both of these features are consistent with cold from CAMP sulfur aerosol volcanic winters being the driving force for extinction on land as opposed to global warming from CAMP CO_2 (which may have had a much larger effect in the oceans due to acidification). Dinosaurs thrived because they were already living in cold polar areas with wintertime freezing before the ETE, as well warmer low latitudes because they were insulated, as we have seen (Olsen et al., 2022b)

Thus, what triggered the true Age of Dinosaurs, post-ETE, were the bird-like adaptations to cold of dinosaurs, as opposed them being primarily adapted for tropical warmth. These cold-adaptations were inherited by the survivors of the End-Cretaceous driven mass extinctions when an impact winter was the killer. As birds, these dinosaurs still populate some of the most inhospitable places on Earth with a species diversity about double that of mammals.

Life goes on during the end Triassic mass extinction event (ETE). A CAMP lava flow advances during a volcanic winter snowstorm in an eastern North American rift basin as a feathered theropod dinosaur and *Grallator* trackmaker runs off with its furry mammal prey which would have made *Ameghinichnus* tracks. Modified, with permission, from (Colagrande and Felder, 2000).

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