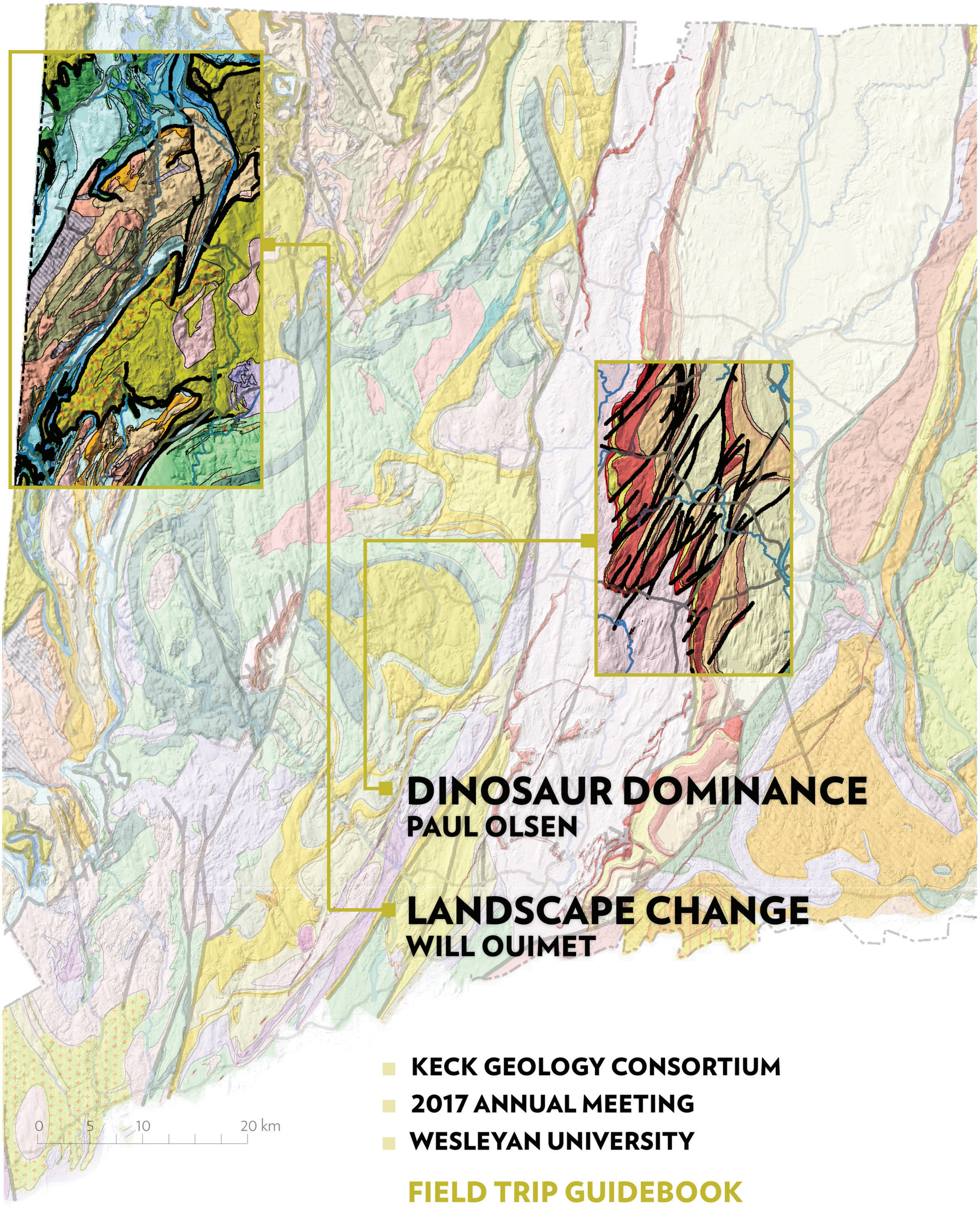

# DINOSAUR DOMINANCE

PAUL OLSEN

# LANDSCAPE CHANGE

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KECK GEOLOGY CONSORTIUM
2017 ANNUAL MEETING
WESLEYAN UNIVERSITY

## FIELD TRIP GUIDEBOOK

# ORIGINS OF DINOSAUR DOMINANCE IN THE CONNECTICUT VALLEY RIFT BASIN

A Field Trip Sponsored by the Keck Foundation

Paul E. Olsen
2017

# ORIGINS OF DINOSAUR DOMINANCE IN THE CONNECTICUT VALLEY RIFT BASIN

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&
Hosted by Wesleyan University

Paul E. Olsen

Lamont-Doherty Earth Observatory of Columbia University
Palisades, NY 10968

polsen@ldeo.columbia.edu

2017

Cover image, *Coelophysis and trithelodont* by Larry Felder, from the book *In the Presence of Dinosaurs*, by John Colagrande and Larry Felder, copyright 2000, TIME/LIFE Books, used with permission of the artist. Fire is from advancing CAMP lava flows.

## ABSTRACT

The Connecticut Valley Rift Basin is one of the best places in the world to see the record of the environmental and biological events that resulted from a mass extinction 202 million years ago that led to 136 million years of dinosaur ecological dominance. The extinction was tied to extremely high $CO_2$ and sulfur aerosols spewed out some of the largest volcanic eruptions in Earth history. We will examine excellent exposures of lavas from the eruptions that caused the extinction and interbedded and overlying lake and lake margin sediments that reveal the exaggerated climate swings that preserved diverse fish species and extraordinarily abundant dinosaur footprints from the recovery from the mass-extinction and consequent dinosaurian dominance.

## CONTEXT

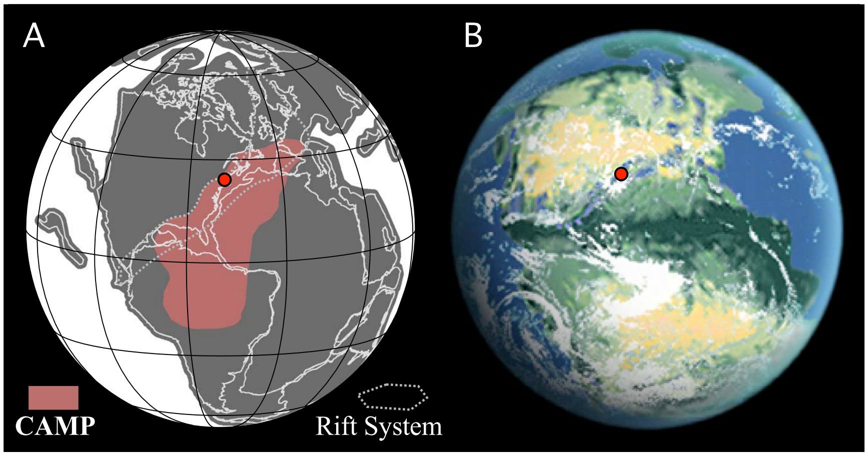


**Figure 1:** Earth at 202 Ma (red dot locates Connecticut Valley Rift Basin); A, outlines of the present continents, the CAMP, and rift system; B, interpretive image showing wet (green) and dry (yellow) areas.

This field trip is designed around a series of four vignettes, our field trip stops (Figs. 1-3), based on localities near Wesleyan University. While it is quite normal to discount one's surroundings as mundane, deep scientific exploration of virtually anything can reveal deep insights that transcend the provincial and parochial. That is the case with the geology of the Connecticut Valley Rift Basin in which Middletown, CT is located (Figs. 2-3). Formed during Triassic-Jurassic the sedimentary and igneous rocks of the basin preserved a record of events occurring during the rise to ecological dominance of dinosaurs, with implications for topics as diverse as mass extinction and solar system dynamics.

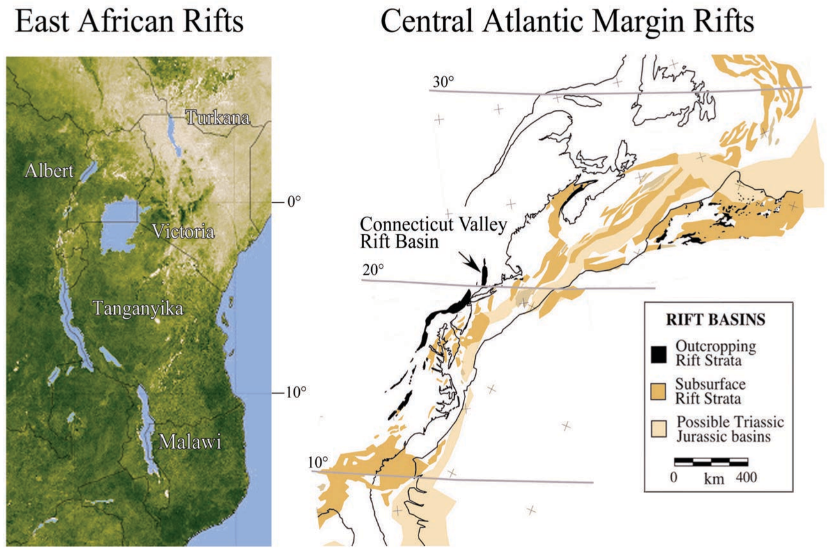


**Figure 2:** Present East African rift system compared to that of Eastern North American and African parts of the Early Mesozoic rift system.

### *The Great Triassic-Jurassic Rift System*

After more than 100 million years of continental assembly, the resulting supercontinent of Pangea (Fig. 1), was beginning a long period of pulling apart forming many rift valleys, each being a down-dropped segment of the Earth's crust formed where the crust is being stretched. En mass, these rift

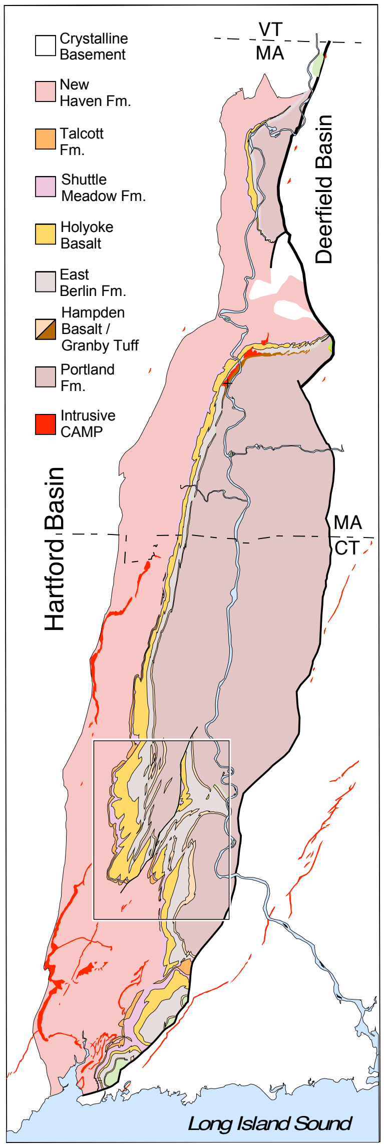


**Figure 3:** Geologic map of the Connecticut Valley Basin. See Figs. 3 -6 for key to units.

valleys comprised rift systems that can occupy thousands of kilometers. The initial stages of Pangean disassembly were underway during the early part the Age of Dinosaurs, the Triassic Period (253-202 million years ago), and what would become North America was beginning to pull away from the southern continents and Eurasia. This early continental rifting produced the World's largest rift system as innumerable faults and their attending rift valleys accommodated the stretching, extending over ten thousand kilometres, bisecting Pangea from the present Arctic Ocean through the Gulf of Mexico to the present Pacific Ocean. One of these rift valleys is preserved today as the Connecticut Rift [Valley] Basin, close to the center of the entire rift system (Figs. 1 and 2).

The Connecticut Valley Rift Basin subsided and accumulated sediments from the surrounding highlands at least from the Late Triassic around 215 to 195 million years ago in the Early Jurassic. During this time the crust in the rift valley slowly dropped asymmetrically like a gigantic westerly-hinged trap door opening along its east side along its west-dipping eastern border fault (Figs. 3-6), while all the time sediment was pouring in form the surrounding highlands keeping the valley floor nearly flat. During this time more than 6 km of sedimentary and volcanic rocks were deposited in the basin and these are divided into eight formations in the large southern sub-basin of the Connecticut Valley Rift Basin, called the Hartford Basin (Fig. 3). These are, from the bottom up; the New Haven Formation, an overwhelmingly red and tan fluvial unit with some minor lacustrine and eolian strata near the top (**Stop 1**); the Talcott Formation, a basaltic lava flow formation that often exhibits pillows, breccias, and coarse pyroclastics (**Stop 1**); the Shuttle Meadow Formation, a red, gray, and black cyclical lacustrine sequence with an unusual abundance of lacustrine limestone; the Holyoke Basalt (**Stop 1**), the thickest and most widespread basaltic lava flow formation in the basin; the East Berlin Formation, a red, gray, and black lacustrine sequence, famous for the very abundant dinosaur footprints (**Stops 2 & 3**); the Hampden Basalt (**Stop 2**), the uppermost basalt flow formation that is replaced in the north by the Granby Tuff, a formation of

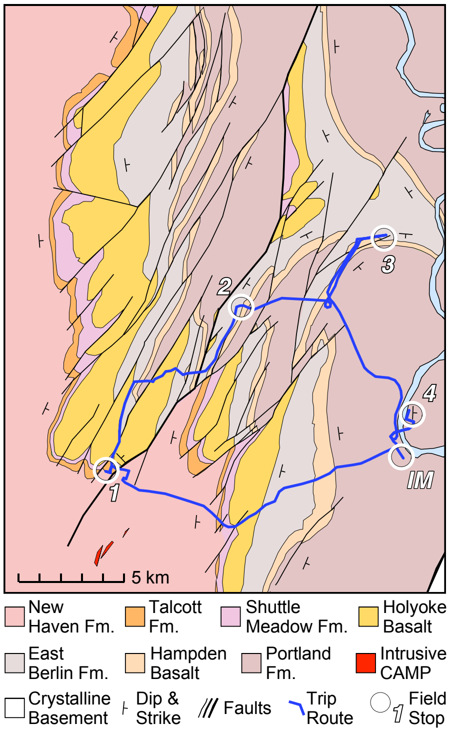


**Figure 4:** Geologic map of field trip area. Location is inset in Fig. 2.

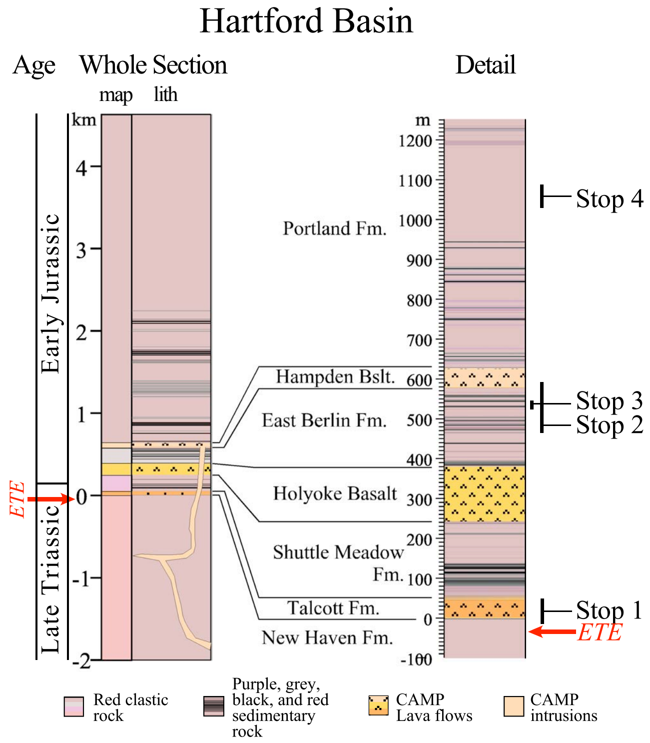


**Figure 5:** The Hartford Subbasin part of the Connecticut Valley Rift Basin showing basic units and field stops.

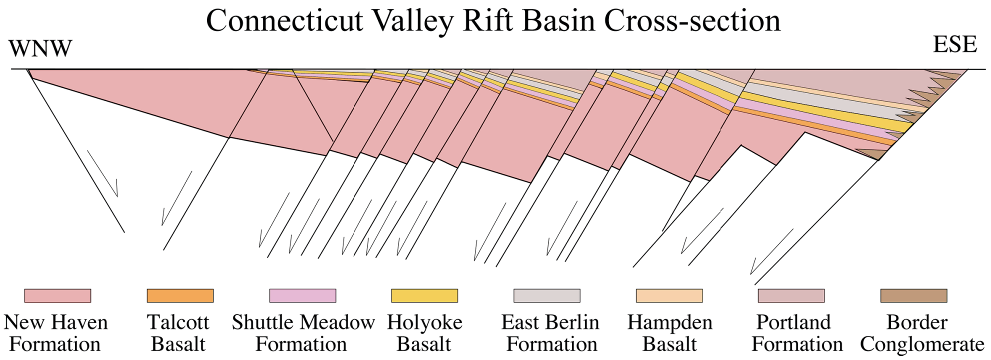
pyroclastics; and the Portland Formation that is the thickest formation in the basin with a lower red, gray, and black largely lacustrine portion (**Stop 4**) and an upper entirely red fluvial portion. The subsidence of the basin ceased at about the time rifting culminated between North America and Africa with the formation of the first ocean crust between the two continents and the birth of the Atlantic Ocean, although the exact timing of the latter remains murky. Since that time, the rift basin fill has been uplifting and eroding, supplying sediments to the continental shelf. But as a consequence of the 30 million years of tilting, the exhumed strata we see at the surface still largely tilt to the east.

From its inception to its demise, the Connecticut Rift Valley drifted north from about 12° to 21° North Latitude, along with the rest of central Pangea. Thus, this rift valley was in the tropics, drifting northward though its history from more typically humid to more arid climes. In contrast, rift valleys in higher Pangean latitudes, such as those in Greenland, drifted from more arid climates into more humid ones[1].

### *The Triassic-Jurassic Greenhouse World*

The Triassic and Early Jurassic had a very different global climate than today. There is no evidence of polar glacial ice, and foresets were present all the way to the Pangean North Pole and into the southern latitudes as far as land extended to more than ~70° S (Fig. 1). While there may have been other contributing factors, the leading hypothesis is that the Earth was in a "Greenhouse" state because of very high $CO_2$, compared to today. That very high $CO_2$, (~1000 to ~4000 ppm as opposed to the present's 400 ppm) was normal for this time period is indicated by geo-

**Figure 6:** Diagrammatic cross section of the central Hartford Subbasin of the Connecticut Valley Rift Basin.



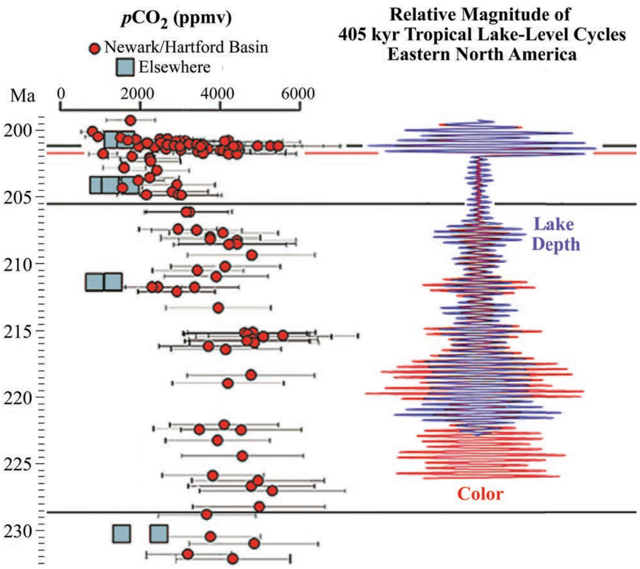


**Figure 7:** Soil carbonate proxy data for atmospheric $CO_2$ (left), compared to the relative magnitude of lake level variability envelope at the 405 kyr cycle scale from the Newark and Hartford basins (from ref. 4).

chemical and biological proxies (soil carbonate[2,3,4] and plant leaf stomata[5]) (Fig. 7). That does not mean there were not freezing temperatures in some areas. Evidence of freezing winter temperatures takes the form of what appears to be lake-ice-rafted debris in the high Pangean latitudes (~60°N) of at least present northwest China – but without evidence of glaciers or ice caps. The foresets of the high northern latitudes also had abundant deciduous relatively large-leafed conifers[6], consistent with a cool winter climate, but nowhere near as cold as today.

The humid tropical regions seem to have spanned about the same latitudes as today, as is also true for the arid belts (Fig. 9). Parenthetically, the common characterization of the Triassic being a time of great aridity is largely a function of the early and mid 20th century centers of Euro-American geological research accidently having been located in what were the semi-arid and arid belts of the Triassic where red beds were deposited, drifting to temperate regions later. Overall, because the polar regions today comprise the largest deserts in the world, given that they were covered by vegetation in the Triassic, everything else being equal, the Triassic would be seem to be more "humid" on average than today's climate, although it is worth keeping in mind that area of the Earth north of 60° or south of -60° constitute only 13% the total surface of the globe.

The Triassic-Early Jurassic climate pattern with freezing temperature at high latitudes, which were also heavily vegetated, is a pattern that is probably key to the evolution and ultimate ecological expansion of dinosaurs as explored below.

## *CAMP: Earth's Largest Volcanic Province*

For nearly all of its Triassic history, the rifting of most of central Pangea was singularly devoid of volcanism, with the exception of a small set of granitic intrusions in New Hampshire and Maine and another set of volcanic and igneous units in Italy. That quiet came to an abrupt and terrific end with the emplacement of the gigantic Central Atlantic Magmatic Province or CAMP. Remnants of intrusions and lavas of this mostly basaltic province are spread over a Pangean area of about 11 million square kilometres (Fig. 1), which for reference is about 1/3

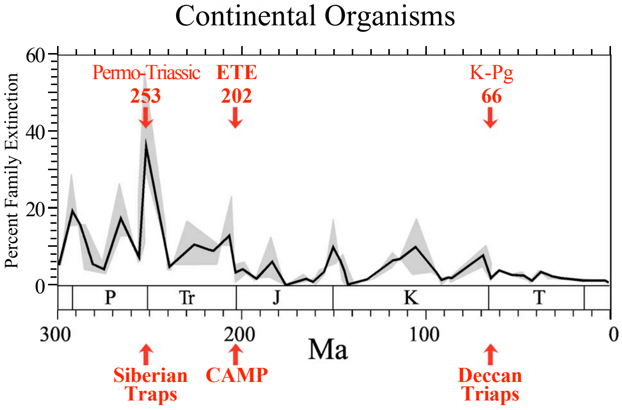


**Figure 8:** Extinction rate for continental organisms showing the positions of the 3 major mass extinctions and associated flood basalt provinces (Modified from ref. 7).

the area of the moon. CAMP rocks are found in northern France, Germany, the Iberian Peninsula, Morocco, most of the rest of the Maghreb, West Africa, Eastern and Southern North America, Guyana, Surinam, French Guiana, Brazil, and Bolivia. In places that are not as deeply eroded as exposed basins of Eastern North America, such as Morocco and on the continental shelves, flood basalt lavas of the CAMP are very widespread, while in exposed rocks of New England, the lavas are restricted to the preserved fill of the Connecticut Valley Rift Basin itself (**Stops 1 and 2**), where they comprise the Talcott Formation, the Holyoke Basalt, and the Hampden Basalt, although the intrusions that fed them extend far beyond. These flood basalt lavas are resistant to erosion and underlie landmarks familiar to Valley residents such as the Hanging Hills of Meriden (**Stop 1**), Lamentation, Totoket and Talcott mountains, and Mt. Tom and Mt. Holyoke. Parts of the plumbing that fed those lavas also make prominent hills, such as East Rock, West Rock, and Sleeping Giant.

The oldest CAMP intrusions and flood basalt flows date from about 202 million years ago, more than 30 million years after the rift system formed and at least 13 million years after the Connecticut Valley Rift Basin began accumulating sediment. The eruptions and intrusions seem to have ended very quickly as well, within 2 million years. This is very different than rifting areas today, such as in East Africa, where volcanism has been dribbling on for ~30 million years.

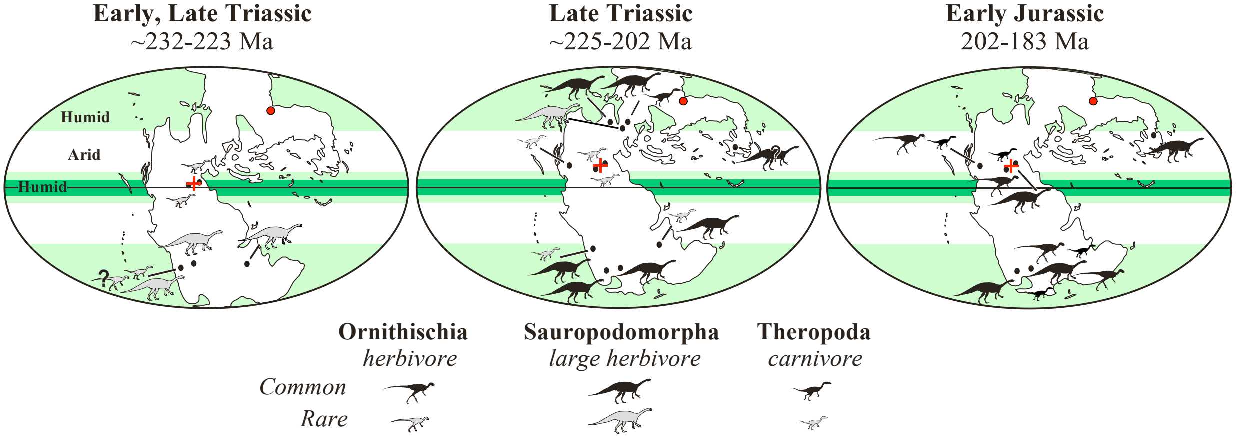


**Figure 9:** Early Late Triassic to earliest Jurassic (~232 – 200 Myr) Pangea showing the distribution of known dinosaurs (from ref. 8). Red cross is location of Connecticut Valley Rift Basin and red dot is position of Junggar Basin.

However, the abrupt, massive but short-lived CAMP, began at the onset of the end-Triassic mass extinction or ETE (Fig. 8) and is the most parsimonious explanation for that event. The ETE is one of the "Big-Five" mass extinctions of the last 600 million years and one of the three largest of the last 300 million years, including the famous Cretaceous-Tertiary (K-T, or more properly the K-Pg) mass extinction at 66 million years ago that witnessed the end of the non-avian dinosaurs and the end-Permian extinction that is known as the "Great-dying" (Fig. 8)[7]. These later two mass extinctions are also associated with flood basalts with a similar abrupt, massive but short-lived history, specifically the giant Siberian Traps overlapping the end-Permian event and the Deccan Traps overlapping with the K-Pg event. Of course the latter is famously even more precisely synchronous with a giant bolide impact at Chicxulub, and which more simply explains the observed pattern of K-Pg extinctions.

### *Protofeathers, the End-Triassic, and Jurassic rise of Dinosaurian Ecological Dominance*

The Triassic witnessed the evolutionary origin of all of the major groups of land vertebrates alive today, specifically modern amphibians, turtles, lizards, crocodilians, dinosaurs (alive today as birds), and mammals (more properly "protomammals"). But there were also "holdovers" from the Paleozoic such as giant temnospondyl "amphibians" and parareptiles. There were others that arose and went extinct in the Triassic, such as the great evolutionary radiation of the pseudosuchians, and a whole suite of diverse and bizarre, swimming, gliding, digging, and climbing forms, as well as a few groups that survived the Triassic but died out later in the Cretaceous or at the K-Pg boundary such as the flying-dinosaur-relatives the pterosaurs. A major evolutionary innovation within some of these groups (mammals, dinosaurs plus pterosaurs) was an insulatory integument (fur or protofeathers).

***Delayed Dinosaurian Dominance.*** Given the fact that dinosaurs arose in the Triassic and were around by 232 million years ago, it has come as a rather large surprise that they not only appear first at high (southern) latitudes, but all herbivorous forms stay restricted to the high latitudes of both hemispheres for the rest of the Triassic, until the ETE, 30 million years later[8] (Fig. 9). Where herbivorous dinosaurs are found in the Late Triassic in the higher latitudes, they are very abundant, often the most abundant of all land animals found. In contrast the Triassic tropical regions of Pangea have not produced a single bone or verifiable footprint of an herbivorous dinosaur, including areas famous for abundant skeletal remains such as the Chinle Formation of the Western United States. Instead, the tropics were dominated by large pseudosuchian reptiles, that included the lineage that gave rise to modern crocodilians, but far more diverse. Included are the crocodile-like phytosaurs (independently evolved), herbivorous forms some of which were dramatically convergent on dinosaurs, giant carnivorous top-predators, and a myriad of small forms. Some small dinosaur relatives are present, that did include some relatively common herbivorous as well as carnivorous forms, but the only true dinosaurs present were relatively small carnivorous forms that with the exception of one or two localities are very rare. This surprising bi-polar distribution of Triassic dinosaurs, coupled with the new climatic information about the cool high latitudes provides clues to both survival of dinosaurs through the ETE as well as their spectacular Jurassic ecological ascent.

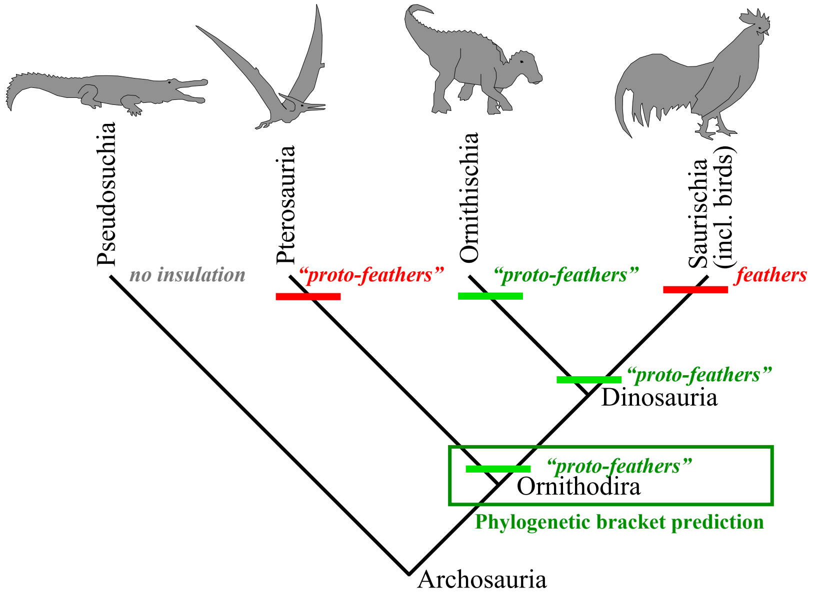


**Figure 10:** Phylogenetic relationships of major groups within the Archosauria showing the predictions of the phylogenetic bracket for insulation by feathers and "proto-feathers". Observations made before 1996 are shown in red. Green are predictions of the phylogenetic bracket approach corroborated by discoveries after 1999. This assumes that the "proto-feathers" (pycnofibers[15]) of pterosaurs are homologous with feathers in birds. This is contentious but consistent with recent discoveries.

***Protofeathers***. After John Ostrom's 1970s revival of Thomas Henry Huxley's late 1860's argument that birds are the direct descendants of dinosaurs, providing Darwin with the first clear "missing link" predicted by "*The Origin of Species by means of Natural Selection*", several young firebrands, including Robert T. Bakker proposed that dinosaurs were metabolically more like birds or mammals than like crocodiles or lizards. Bakker[9] and Greg Paul[10] implicitly revived another late 19th century idea[11] and suggested that feathers may have evolved not for flight but rather for insulation and were already present in non-avian dinosaurs, notably the carnivorous theropods, like *Velociraptor*. By 1986[9] they were drawing them feathered. This concept was not popular with ornithologists[12,13]! What should have been a massive boost to the idea was the earlier (1971)[14] discovery in Kazakhstan lake sediments of a Jurassic pterosaur covered in filaments, clearly a form of insulation. Because pterosaurs are close relatives of dinosaurs, but not dinosaurs themselves, the simplest hypothesis possible is that these insulatory filaments were a kind of "protofeather" and that the common ancestor of pterosaurs[15] and dinosaurs and all of its descendants would have had protofeathers (Fig. 10, cover). Of course in large forms they could have been lost or reduced, not being needed for insulation because of "thermal inertia[16]", just like asian elephant adults are nearly hairless but their babies are quite hirsute. Instead, until recently, most of the community poo-pooed the idea, preferring instead to get wrapped up in progressively more contorted arguments to keep the feathers of birds unique. However, discoveries in lake sediments in China and Siberia of Jurassic and Cretaceous age, rather like those at **Stop 2**, have demonstrated without any doubt that filamentous integuments, that is "protofeathers" were widespread not only in theropod dinosaurs[17], including large ones[18], but also in small plant-eating ornithischian dinosaurs[19]. Further, these fossils also show that these protofeathers evolved in animals that were never capable of any sort of flight[17] and that filamentous protofeathers were only later co-opted by natural selection for flight. This argument ends up being critical to the origin of dinosaurs, the distribution of Triassic dinosaurs, and the survival of dinosaurs through the ETE and their ecological ascent.

***Dinosaurs are Fundamentally Cool-Climate-Adapted.*** Compared to most of the low latitudes, the vegetated high latitudes plausibly provided a predictable and large food source for herbivores. However, the new Chinese data of lake-ice-rafted debris, suggest that these regions were not just cool but had freezing winter temperatures. There is absolutely no evidence that the uninsulated herbivorous, or for that matter carnivorous pseudosuchians, so diverse and abundant in the tropics, could survive in such a climate. However, insulated dinosaurs with high metabolisms and their immediate relatives could survive. The dinosaurian herbivores common to the higher latitudes are the so-called "prosauropods", or more correctly basal sauropodomorphs, such as *Plateosaurus* that were the largest herbivores of their time. None have actually been found as yet with protofeathers, and none have been found in lake deposits likely to preserve them. However, the simplest hypothesis is that they had protofeathers, as did their ancestors (Fig. 10). None have yet been found in association with evidence for seasonal ice in the coal-bearing areas either, such as northwestern China, largely for lack of looking. However that gives us an opportunity to make a specific prediction and that is that they will be found in these coal-bearing high-latitude strata, and when they are, the terrestrial assemblages will lack pseudosuchians.

But why did the low latitudes lack herbivorous dinosaurs for 30 million years after they evolved? A reasonable explanation is that the very high $CO_2$ of most of the Late Triassic (Fig. 7) exaggerated tropical climatic extremes, as is suggested by models of the effects of current rising

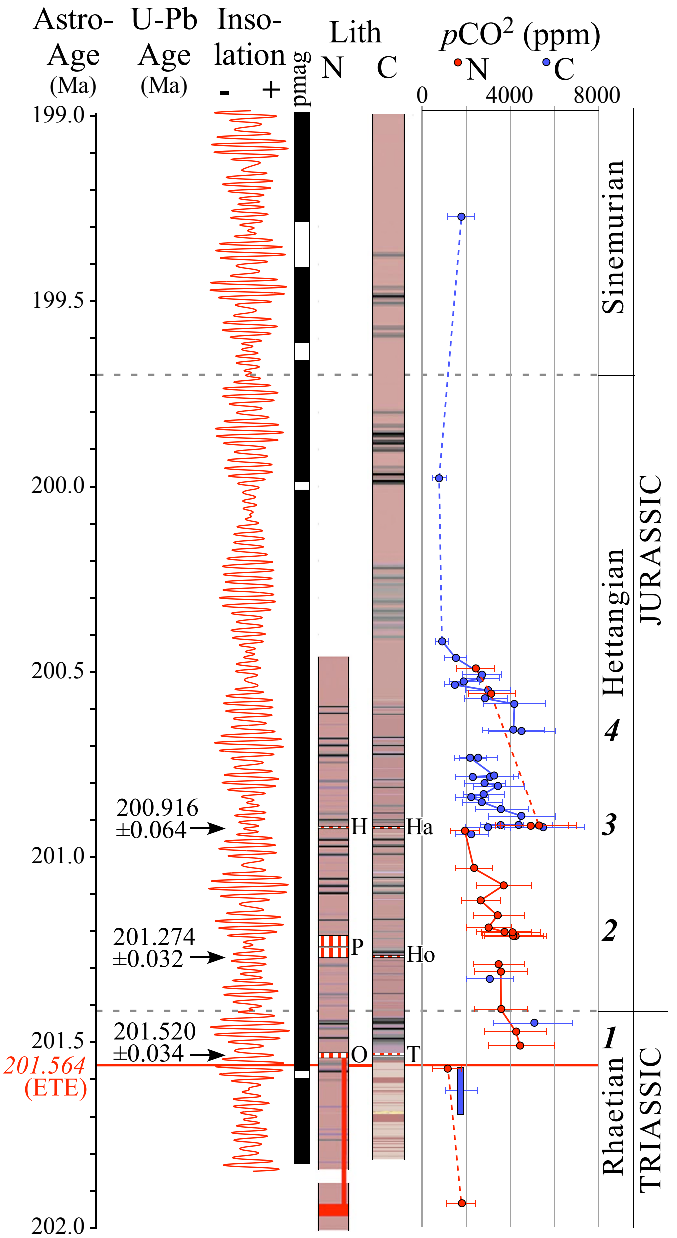


**Figure 11:** Consilience between astrochronological (insolation) and radioisotopic (U-Pb) time calibration of the syn- and post-CAMP lacustrine strata in the Newark (N) and Connecticut Valley (C) rift basins and the $CO_2$ changes associated with the lava flows in the same sequences. Colors are representative of the strata except for the lava flows (red vertical hachures) and intrusions (red). Lava flow formations are: H, Hook Mt. Basalt; Ha, Hamden Basalt; Ho, Holyoke Basalt; O, Orange Mt. Basalt; P, Preakness Basalt; T, Talcott Formation. *1*, *2*, *3*, *4*, are $CO_2$ pulses.

anthropogenic $CO_2$[20]. The seasonal and longer term climatic cycles would be exaggerated, and along with higher temperatures, there would plausibly be a high frequency of fire and plant resources would be unpredictable, Evidence for this is provided by stable carbon isotopic, spore and pollen evidence, and fossil charcoal[21]. There is strong evidence for the correlation between high atmospheric $CO_2$ and exaggerated climate extremes in the Triassic-Jurassic lake sediments of the giant Pangean Rift system, most notably from here in the Connecticut Valley Rift Basin (**Stops 2 and 4**) and the Newark Rift Basin, the next major basin to the south (Figs. 2, 11). The lower metabolic requirements of the herbivorous pseudosuchians suited them well for unpredictable resources, and that may have made dinosaurian herbivory non-competitive in the tropics, until pseudosuchians were nearly wiped out during the ETE.

The conclusion from this is that the common ancestor of dinosaurs and their close relatives the pterosaurs, was insulated, had high metabolic requirements, and was fundamentally adapted to cooler, high latitude climatic regimes, not the hot tropics.

***The ETE***. Eruption of the CAMP lavas and emplacement of associated intrusions would be expected to have pumped enormous amounts of $CO_2$ (and possibly methane) and sulphur aerosols into the atmosphere, with dramatically contrasting environmental effects [22]. Rising $CO_2$ would produce global warming that would last for tens to hundreds of thousands of years, as well as transient, if extreme, ocean acidification (if the rates of eruption were high enough). In contrast, the sulphur aerosols would cause global dimming and lead to volcanic winters[23] that would fade quickly – 3 to 5 years – after each eruption ceased. The pattern of extinctions of marine invertebrates is consistent with ocean acidification from the abrupt absorption of $CO_2$ but the patterns of both animal and plant extinctions are more consistent with extreme volcanic winters, as opposed to the direct effects of global warming.

$CO_2$ proxy data from soil carbonates from the Connecticut Valley (**Stops 2 and 4**) and Newark rift basins in sediments around the CAMP flood basalt lavas (Figs. 7, 11), as well as from leaf stomata from north of the CAMP area, show that $CO_2$ doubled to tripled in three to four pulses of CAMP eruptions taking hundreds of thousands of years to drop down to background levels after each pulse. The $CO_2$ levels in the 2000 to 6000 ppm after each pulse of CAMP eruption were not that different than the background levels of most of the Late Triassic, but $CO_2$ had been dropping for 5 million years before the CAMP, and then rose precipitously. Plausibly each doubling may have taken only hundreds of years, rather like what is happening now.

Each $CO_2$ doubling would be predicted to increase temperatures globally by an average of about 3° per doubling assuming the consensus climate sensitivity estimated by the Intergovernmental Panel on Climate Change (IPPC). This sensitivity is theoretically independent of the starting value, but its value is nearly entirely model dependent and not well tested by data for present $CO_2$ concentrations, not to mention starting at 2000 ppm or so. The actual temperature changes could be larger or smaller or could depend on unknown feedbacks that could themselves vary with initial concentrations. Nonetheless, its hard to see how an increase in the 3° range could be important except in marginal areas and especially hard to see how it could effect land communities already adapted to heat and extremes. This is notably true when migration into higher latitudes or up mountains were ecological options, especially when such high $CO_2$ values persisted for 10s of millions of years during most of the Late Triassic (Fig. 11) and the same organisms were thriving.

On the other hand, the sulphur aerosol-driven volcanic winters that may have been severe enough to freeze the tropics, even for a few days, could have had the effect of wiping out all large non-insulated land animals, especially large pseudosuchians and a large variety of warm-adapted plants. In contrast to the options available from a warming, victims of tropical cold have nowhere to go – everywhere else is worse. In contrast, insulated dinosaurs and pterosaurs were already “pre-adapted” to volcanic winters as were the plants in high latitudes. It is noteworthy that the high latitude floral changes were minor compared to what happened in the tropics and some groups such as the deciduous conifers went though the ETE without any change[6].

Thus, the pattern of extinction on land seems more in line with volcanic winters than global warming. While there is no proxy at this time for sulphur aerosols in sediments, the volcanic winter hypothesis does make the prediction that there should be evidence for freezing in the Pangean tropics. This evidence could be in the form of ice-rafted debris in lake strata, or impressions of ice crystals in the kinds of sedimentary strata that would otherwise have footprints. It is worth remembering, however, that the amount of time represented by the volcanic winters may be very short, and that the strata had to have been deposited during a time when major CAMP eruptions were happening somewhere else – in other words the evidence won’t be recorded in the lava layers themselves. In the Hartford Sub-basin of the Connecticut Valley Rift there are at least five sedimentary intervals in which to look[24]: 1) the ETE interval itself in sedimentary strata below the Talcott Basalt Formation; 2) the lower Shuttle Meadow Formation; 3) the middle Shuttle Meadow Formation; 4) the lower East Berlin Formation; and 5) the lower Park River Member of the Portland Formation. Finding such evidence will be tricky, not only because evidence is likely to occupy vanishingly small proportion of the thickness of the strata, but also because there are other mechanisms to raft in coarse debris into a lake than ice, notably root balls of trees, bushes and other plants, or floating algal (cyanobacterial) mats all of which are already known from Connecticut Valley lake strata. Even evaporate crystal impressions might be confused with those of ice.

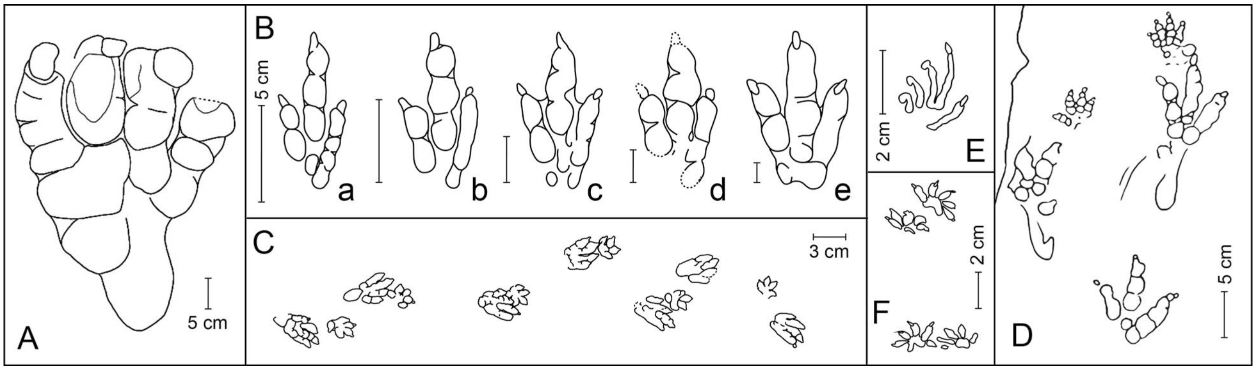


**Figure 12.** Post ETE footprints of the Connecticut Valley. A. *Otozoum moodii* a herbivorous "prosauropod". B, Brontozoid tracks made by carnivorous theropod dinosaurs; a, *Grallator parallelus*; b, *Grallator paralleus*; c, *Anchisauripus sillimani*; d, *Anchisauripus tuberosus*; e, *Eubrontes giganteus* (Scale is 5 cm for all). C, *Batrachopus deweyii* made by a crocodyioform; D, *Anomoepus intermedius* (=*A. scambus*) made by a small ornithischian dinosaur; E, *Rhynchosauroides* sp., made by a lizard-like forms; F, *Ameghinichnus* sp. made by a "proto-mammal" or mammal. These are drawings of actual specimens, all from ref. 25.

***Survivors***. Most groups that made it through the ETE, are still extant now. These include the dinosaurs (as birds), crocodilians, turtles, lizards and their relatives the sphenodontians, modern amphibians, and mammals. Also surviving were pterosaurs, some protomammals (such as the tritylodonts and trithelodonts), one other non-crocodilian lineage of pseudosuchians (sphenosuchians), and a very few archaic "amphibians". The only non-insulated forms surviving from Triassic continental communities were either forms small enough to burrow or forms that could hibernate in lakes. This pattern is again consistent with survival from volcanic winters. Strikingly, the latitudinal segregation of herbivorous dinosaurs ends at the ETE and subsequent latest Triassic and Early Jurassic assemblages became remarkably uniform globally and dinosaur size, especially among theropods increased dramatically, marking global ecological ascent of the dinosaurs.

However, compared to the Triassic, the post-ETE assemblages were of remarkably low diversity. This is especially notable in the footprint record in the Connecticut Valley Basin (Fig. 12) (**Stops 3 and 4**). This footprint record is overwhelmingly dominated by small to large carnivorous theropod dinosaur forms - the brontozoids, including *Grallator*, *Anchisauripus*, and the Connecticut State fossil, *Eubrontes*[25]. Also fairly abundant were tracks of small protosuchian crocodyliforms (*Batrachopus*), much less common footprints of herbivorous small ornithischian dinosaurs (*Anomoepus*), some medium sized to fairly large herbivorous "prosauropod dinosaurs" (*Otozoum*), and exceptionally rare lizard- and mammal-like forms (*Rhynchosauroides* and *Ameghinichnus*, respectively. This low diversity at high taxonomic levels might mask much higher species-level diversity that we have as yet no clear way to gauge. What is known is that these post-ETE assemblages are much lower in diversity at high taxonomic levels that those that existed before the mass-extinction.

The apparent striking numerical dominance of carnivores that seems to be a violation of the basic trophic or Eltonian ecological pyramid may be real. The base of the food chain may have been largely aquatic as we will discuss at **Stop 3 and 4**, and the carnivorous dinosaurs may have primarily subsisted on fish and other carnivores that ate fish[26]. Track assemblages from younger Middle and Late Jurassic deposits have much more abundant herbivores suggesting the recovery to a more "normal" looking terrestrial community with more herbivores than carnivores.

### *Cyclical Climate, a Time Scale, and the Chaotic Evolution of the Solar System.*

The lakes that deposited most of the sediments in the Connecticut Rift Basin rose and fell due to climate changes that were in synchrony with celestial mechanical cycles driven by the Moon and planets. These lake level cycles controlled the depositional environments in the basin and hence the distribution of different sediments appearing as a vertical patterning of sedimentary cycles and also controlled the distribution of fossil. The climate changes themselves, fluctuating form humid to hyper-arid, obviously had a major role in the kinds and distribution of organisms that lived in the region.

***Origin of the Cyclicity.*** The daily and seasonal cycles of environmental change, light vs. dark, summer vs. winter, are caused by the changes in the distribution and intensity of sunlight driven by the rotation of the Earth about its axis and combined effects of the tilt of the axis and the orbit of the Earth around the sun (Fig. 12), which play out differently depending largely, but not exclusively on latitude. On larger timescales, the orientation of the Earth's axis and the shape and orientation of the Earth's orbit also change, and this alters the daily and seasonal cycles as part of climate change. These changes in the orientation of the Earth's axis are largely driven by gravitational forces of the Moon and Sun on the equatorial bulge of the Earth and the changes in the Earth's orbit and are also driven by effects of all the other bodies in the Solar System. The rotation of all of those bodies around the Sun result in complex gravitational rhythms passed on as rhythms and resonances in the combined axial and orbital features of the Earth, which then affect climate.

The gravitational rhythms combine like many musical notes to produce a kind of celestial music to which the planets dance, and the result are not quite periodic, but rather are quasisperiodic changes in the distribution and intensity of sunlight per unit area, called insolation, that are also expressed variably with latitude. The complex insolation rhythms play out over tens of thousands of years to millions of years and are called Milankovitch cycles, after the Serbian meteorologist (Milutin Milankovic) who produced a quantitative explanation how these orbital changes could have paced the ice ages of the last two million years of Earth History. While these Milankovich cycles in insolation are quite subtle, especially compared with the daily and seasonal cycles, the Earth System apparently

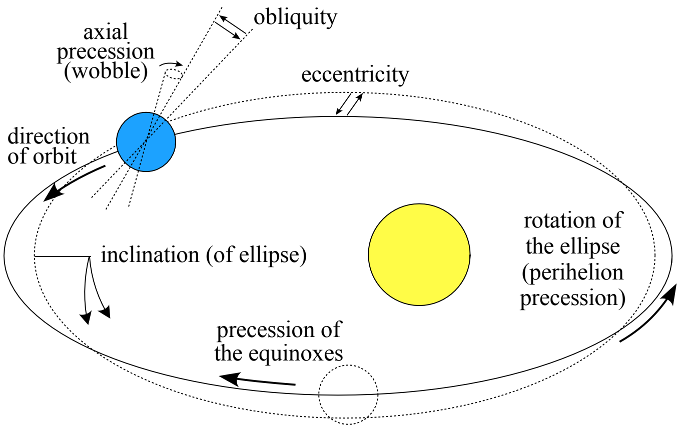


**Figure 13:** Basic geometric elements of variations in the Earth's orbit and the Earth's axis contributing to Milankovitch cycles. Modified from ref. 27.

non-linearly amplifies their effects to the point that they are major features of climate. These climate cycles unfold, of course, within the context of changing $CO_2$ boundary conditions that determine if climatic cycles are glacial ages, or wet-dry alternations.

While various astronomical theories of climate change appeared in the mid-19th century, nearly at the same time that it was realized there were repeated Ice Ages, and a quantitative theory linking celestial mechanics with the Ice Ages was developed by Milankovic in the 1920s, it was not until the 1976 paper of Hays, Imbrie, and Shackelton that it became widely accepted that the Ice Ages and climate changes of other times, were paced by changes in the Earth's orbit and axis. The key insights involved applying mathematical techniques of signal processing (Fourier time series analysis) to long sedimentary, deep-sea core records. It quickly became obvious that other aspects of the Earth's climate system were paced by Milankovitch cycles, including tropical wet-dry cycles.

As currently recognized, the most important Milankovitch cycles are quasiperiodic at periods of around 21, 41, 100, and 405 thousand years (kyr) and 1.2 and 2.4 million years (Myr). In fact, the cycles of 21, 41, 100 ky are actually averages of several cycles close to those averages. The 21, 100, and 405 kyr and 2.4 Myr cycles are related to a wobble of the Earth's axis (precession), modulated by the shape and orientation of the Earth's orbit (eccentricity), while the 41 kyr and 1.2 Myr cycles are related to the angle of the Earths axis relative to the plane of the Earth's orbit (obliquity), modulated by the rocking of the plane of the Earth's orbit (inclination). All of these cycles appear in Earth's climate record[27].

***Cycles in the Triassic and Jurassic.*** Unsurprisingly, perhaps, Milankovitch cycles also affected climate much further back in time than the last few million years including the Triassic and Jurassic in the Connecticut Valley Rift Basin. The repetitive sedimentary patterns, that are the lacustrine sedimentary cycles, are a major feature of the Shuttle Meadow, East Berlin, and lower Portland formations. Without large outcrops, exposures, or cores, however, these cycles can be hard to see, because the cycles are so thick (10 to 20 m) and the rock exposures tend to be so small. As with the sunlight changes that drove the environmental cycles, the rock cycles are not precisely repetitive, and instead there are cycles within cycles, within cycles and we will see these cycles at one of the largest exposures we will visit (**Stop 2**).

The mechanism thought to produce the environmental cyclicity seen in these lake sediments is thought to be relatively simple in outline and the same as that now governing the long-term behavior of climate in much of the tropics. The mechanism is that of the tropical, African Monsoon system, in which a zone of rain tracks the zone of maximum summer heating that in turn, tracks the dates that the sun is overhead. The magnitude of the rain varies with the magnitude of the insolation and therefore the lakes behave like rain gauges. The average state of the lakes in the Connecticut Valley Rift Basin was very shallow and often dry, so even though the insolation changes in Milankovitch cycles are sinusoidal, the Connecticut Valley Rift the obvious cyclicity reflects primarily the positive deviations from the mean – the lake can't get any shallower than dry.

What we see in the sedimentary sequence are cycles consisting of a shallower water lake deposit, deepening upward (transgressive), followed by a lake high-stand deposit formed when the lake was at its maximum depth (and insolation was at a maximum), followed by a shallowing water deposit (regressive), and then a generally thicker interval of very shallow water deposits (low stand) that in some cases have fossil soil sequences (paleosols). These are the primary cycles caused by the ~20 ky climatic precession cycles and they are modulated by eccentricity cycles with the effect of causing the expression of high-stand deposits to vary from black, to gray, to purple or even red, while the shallowest water sediments tend to be red all the time. This produces a bundling of cycles with black strata, separated from bundles of cycles without black strata. The very deepest of the lakes were so deep, perhaps hundreds of meters, that the lower part of the water column was devoid of oxygen and microlaminated mudstones were produced, often preserving complete fish. The shallowest water units, in contrast, tend to be more massive and have abundant desiccation cracks, root impressions and soil carbonate nodules, and reptile footprints. The cycles, thus, also determine the fossil content. The soil carbonate nodules provide a proxy in their carbon isotopic composition of atmospheric $CO_2$. Field **Stop 2** in the East Berlin Formation shows this cyclicity beautifully.

These cycles, because they are hypothesized to have tracked celestial mechanical cycles, allow the measurement of time in the sedimentary strata that have them. In the 1980s I used them to estimate the amount of time between CAMP flows and thus measure the duration of the part of the CAMP event preserved in the Connecticut Valley and the Newark rift basins coming up with a value of about 610 ky for the duration of all three lava flow formations. Only within the last few years have radiometric dating techniques, specifically U-Pb method become precise enough to test this hypothesis. In 2013[28], the flows were dated with a precession of 60 ky or less and showed that the predictions of the Milankovitch hypothesis for these lacustrine strata were correct. The modern geological time scale for the Late Triassic and early part of the Early Jurassic is based on these lake cycles, pinned in time by the radiometric dates from the CAMP lavas[29]. The dates for the various field stops on this trip are based on this astronomically calibrated time scale (Fig 8).

***Solar System Chaos***. Because the Solar System is a complex, moving array of bodies gravitationally interacting, it is a dynamical system, potentially subject to chaotic behaviour. Its long-term behaviour can only be described by numerical (as opposed to analytical) solutions, the validity of which is measured in 10s of millions of years. In fact, numerical solutions of the Solar System show chaotic behaviour over timescales greater than about 50 million years. The effects within the last few hundred million years are measurable only for the cycles with periods greater than the 405 kyr cycle. Those longer cycles act like interferometers varying in frequency by the differences of frequencies of the ~20 kyr precession and ~40 kyr obliquity cycles. This is predicted to show up in the very long eccentricity cycle that presently has a period of 2.4 Myr years and the inclination cycle of 1.2 Myr, when these cycles are examined over hundreds of millions of years. Those two cycles are manifestations of the interference of gravitational cycles caused by Earth and Mars, that themselves cannot be measured, but the periods of those cycles are predicted to vary in period by more than a million years over the last 200 million years - and that can be measured. Furthermore Earth and Mars are locked in a resonance that can theoretically flip the ratios of the eccentricity and inclination cycles from 2:1 to 1:1. In contrast the other cycles are predicted not to vary much at all, with the 405 ky cycle (due to Jupiter and Venus) being extremely stable, the ~100 kyr cycles varying practically immeasurably, and the present 41 Kyr and 21 Kyr cycles decreasing in period back in time due not to chaos, but instead to the recession of the moon, Thus, the Early Jurassic periods were closer to 39 kyr and 20 kyr respectively, because the moon was closer. For the Late Triassic and Early Jurassic the very long eccentricity cycle based on lake level cycles in the Newark and Connecticut Valley basins and deep-sea deposits in Japan is measured at between 1.6[30] and 1.8[31] Myr while the inclination cycle hints at being about 0.8 Myr[32] based on Chinese lake sequences, which is still a 2:1 ratio. These measured Late Triassic and Early Jurassic cycle periods as well as their phases strongly corroborate that the Solar System is chaotic, but they also do not match any of the current astronomical solutions for that chaos, which ultimately they must. The reason for these discrepancies could be as arcane as measurement error in the present positions masses and velocities of Solar System bodies or as potentially far reaching as an incomplete theory of gravity. Whatever their, origin the geological record can be the ultimate arbiter of the astronomical solutions.

Thus the sedimentary rhythms characteristic of the lacustrine sequences of the Connecticut Valley Rift Basin not only parse the kinds of fossils preserved, but they also provide a timescale for the sequence and give us a window into the behaviour of the Solar System.

## FIELD TRIP STOPS

### General Plan

The field stops are organised in stratigraphic order, from oldest to youngest, starting in the New Haven Formation and Talcott Basalt Formation, and ending in the Portland Formation and forming more or less a loop in geography (Figs. 4-5). Thus, they also proceed from the time of the ETE into the recovery of that mass extinction.

### Stop 1: Mega-Eruptions and Mass Extinction

Location: 41.552652, -72.816832 (back parking area of Meriden Target)
Units: New Haven Formation and Talcott Basalt Formation
Time: 201.564 Ma – latest Triassic (late Rhaetian), just after the ETE
Environments: Fluvial to shallow lacustrine and subaqueous flood basalt
Highlights: Oldest CAMP lavas in CT Valley Rift, ETE, pillow basalts, ashes

Leave vehicle and proceed to southwest corner of parking lot. Do not go up to the outcrop; we are here at the discretion of the owners. We will walk north along the west side of the parking lot to the northwest corner of the parking lot traversing parallel to the face of the exposure.

This spectacular exposure reveals nearly the entire thickness of the Talcott Basalt Formation resting on the uppermost few meters of the New Haven Formation (Figs.14 and 15). This is the oldest basalt Formation of the CAMP in the Connecticut Valley Rift Basin and lies close to and above the ETE.

***New Haven Formation, the ETE, and Hyaloclastite vs Ashes:*** At the base of the pillowed basalt sequence are red, well-bedded, laterally continuous, internally stratified sandstones and siltstones with graded beds comprised of small clasts of basalt and highly altered basalt (Figs. 14 and 15). These overlie “normal looking” New Haven Formation red beds. Beneath the pillow foresets and associated red beds there is well-bedded red sandstone and mudstone of the New Haven Formation. The basalt and what presumably was basaltic glass is generally altered to a yellow or tan material. All stages of alteration from unquestionable nearly unaltered basaltic material to the tan to yellow clasts seem to be visible. Based solely on macroscopic examination, the lowest beds of the New Haven Formation at this outcrop seem to lack basaltic material.

**Figure 14:** Pillowed basalt complex of the Talcott Formation. A, Pillow foreset onlapping red strata of the New Haven Formation, with graded beds of hyloclasite; white arrow shows upper surface of forest. B, Pillow basalt overlain by massive basalt of the feeder flow lobe (*fl*),

The basaltic material in the red beds has two simple possible origins. First, is that they could be beds of hyaloclastite shed from the advancing lava flows. Hyaloclastite is a hydrated igneous rock composed of angular, flat fragments 1 mm to a few cm across formed by granulation of the lava front due to quenching when lava flows into, or beneath water. They might be mobilized in the water by convection and steam and then settle out as graded beds. Arguing for this is the coarse-grained nature of some of the material and the fact that hyaloclastites are commonly associated with pillowed lavas, often under them. However, similar facies are not associated intimately within the pillow lavas themselves, suggestion that it was not an ongoing process during the entire time that the pillows were being extruded. Although locally deformed by the overlying pillow wedges, these volcanoclastic beds can be traced across this, admittedly limited, exposure of the New Haven Formation indicating that the volcanic material must have been transported a considerable distance to even out their thicknesses. Conversely, while similarly graded volcanoclastic beds have been observed in the uppermost New Haven[34], about 1 km east at Hubbard Park (41.556086°, -72.825998°), the cm-scale stratigraphy differs, indicating either differences in local depositional patterns, or slight differences in source position.

But, another possible origin is that they are ashes originating from the eruptive site itself as airborne pyroclastics – ash – that fell into the water and settled out. While some kinds of coarse ash can look exactly like this, the nearest known area of vents is 22 km away in East Haven, CT[33,34], although there could have been vents closer a minimum of 7 km away. In definitive pyroclastics proximal to the Talcott eruptions, there are abundant accretionary lapilli – basically volcanic hailstones formed by the addition of moist ash around a central nucleus as it is in motion in air. Accretionary lapilli have not been found at this site.

I tend to favor the hyaloclastite hypothesis, but that it mostly occurred early in the extrusion of the Talcott, perhaps just as the flows were entering the water for the first time. However, the distinction between the two explanations is important because they speak to the explosiveness of the eruptions, and that is related to their effectiveness at transporting materials into the stratosphere where they could have global, as opposed to relatively local effects.

**Figure 15:** Graded beds of ?hyaloclastite in uppermost New Haven Formation from Stop 1. Yellowish clasts are altered basalt.

A meaningful sidelight is that the red beds with the graded beds are lacustrine, because it is water in which pillow lavas form. There is little to suggest that these sediments formed in a lake except a lack of evidences of exposure to air such as desiccation cracks or roots – but they did.

Beneath the graded beds of hyaloclastite or ash are red sandstones and siltstones lacking igneous debris. At some level below, there is the horizon of the ETE. This has yet to be specifically identified but present evidence suggest that is should be within 10s of meters below the layers exposed. Several prominent discoveries of reptile skeletal remains have been made in stratigraphic levels below the presumed position of the ETE in the Meriden area (Fig. 16). These include the parareptile *Hypsognathus*[35], represented by a very handsome skull and partial skeleton, the skull of the pseudosuchian *Erpetosuchus*[36](known otherwise from Scotland), and a skull of a sphendontian[37]. The former two forms are unknown outside strata of Late Triassic age, while the latter are still extant as the Tuatara of New Zealand. These finds indicate that the age of most of the New Haven Formation is in fact Late Triassic and prelatest Rhaetian (the age of the ETE).

***Advance of the lava flows.*** Pillow basalts make up the most abundant kind of igneous rock on the Earth's surface because it forms at spreading ridges at mid-ocean plate boundaries, and comprises the upper part of 'Layer 2' of normal oceanic crust. Pillow basalts are also abundant around oceanic hot-spot volcanoes, such as those that formed the Hawaiian Islands. However, in both of these cases, the pillow basalts form very close to the vents sourcing the flows and fundamentally form flowing down hill. Therefore, our understand may be not completely applicable to the CAMP flows into the rift basins, because they generally formed lava lakes in which the advancing flow can actually flow up hill just like the waters edge flows up the shoreline as a lake fills. This exposure presents a rare opportunity to examine features that help understand the dynamic behavior of this kind of pillowed flow.

The Talcott Formation comprises a complicated system of interbedded and intermixed flows, pillows complexes, breccias, and py-

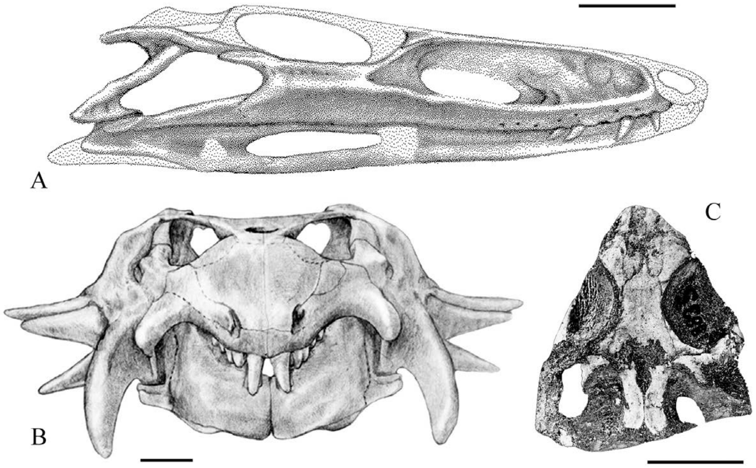


**Figure 16:** Triassic Reptilian skeletal remains from the New Haven Formation of the Meriden area (scale bar is 1 cm): A, *Erpetosuchus* from Cheshire; B, *Hypsognathus fenneri* from Meriden; C sphenodontian from Meriden (from ref. 37).

roclastics variably distributed in geography and vertically at any one site. The pillow complexes are present over most of the outcrop area. Pillows form by extrusion underwater from an aperture in the solidified crust of a much large flow lobe. The outside of a pillow chills very rapidly and then can itself rupture and extrude another pillow. Fundamentally, pillows form because the rapidity of cooling greatly limits their size, especially their diameter. Their along-flow length is also limited by the fast cooling, and hence it is impossible for pillows to extend far from a flow lobe. Therefore, there must have been streams of large lobes extending at least tens of kilometers, maybe hundreds, from the vents. Many lobes must have overrun earlier lobes and pillow complexes progressively from the vents outward and these may have been out of the water even as older lobes further out in the basin continued to exude pillows submerged. Insulation by burial by other parts of the flow complex may have allowed lobes to remain molten for protracted periods of time allowing them to extend for much greater distances then if they were surrounded by water.

Visible at these exposures are northeast tapering wedges comprising foresets of pillowed basalt onlapping each other in the lower 10 m of the flow complex (Fig. 14). These are easily traced by following red sandstone and siltstone beds that extend upward from the underlying New Haven Formation into the basalt. Locally pillows have foundered into the underlying sediment. Higher up in the Talcott Formation, amongst the wedges of basalt pillows, are larger bodies of massive basalt without pillows some of which are over 6 m thick and scores of meters long (Fig. 14B). These are almost certainly examples of flow lobes that were the sources of the pillowed wedges. The direction of the local foresets need not bear any specific relationship to the overall direction of progradation of the flow complex, because the foresets could have come breaches on any side of the flow lobes.

The uppermost Talcott here is highly vesicular, not pillowed and appears to have been deposited subaerially. With water displaced from this spot by underlying flows this may still be part of the same eruption as the underlying unit, despite being a separate cooling unit.

Assuming that the various pillow wedges and flow lobes represent one major eruptive event constrains the accumulation rate and water depth of the uppermost New Haven Formation. The couple or so meters of basalt-bearing sedimentary strata obviously took no more time to accumulate than the flow complex took to advance over the site, which was probably on the scale of days. The lake into which the lava poured had to be at least the depth of the high points of the individual wedges of pillowed basalt (i.e., 5 m or so), but probably not the depth of the entire Talcott Basalt because lava displaces water.

At a smaller scale, the typical geometries of basalt pillows are obvious here with concave upper surfaces and variously shaped bottom surface that conform to the underlying geometry. The glassy rinds of the pillows were altered by heated lake water and then deeper burial processes resulting clay formation and the release of materials reprecipitated as various mineral including zeolites that formed crystals in voids within the basalts complexes. These are much sought after by mineral collectors and their removal has resulted the big voids you see here and there along the face. The alteration of the glassy pillow rinds at this particular outcrop has been recently studied for insights into the study of volcanic rocks and lakes on Mars[38].

Looking closely at the rock face, you will see high angle cracks, irregular pockets, and flow-parallel contacts with red mudstone and basalt breccia fill, along with adjacent reddened basalt surfaces. Such red zones are often assumed to be fossil soils between flows, where they parallel flow contacts, injections from below, or violent mixtures of lava interacting with underlying sediment (pepparites) when they have other geometric relationships. If they were fossil soils they would indicate significant passage of time between flows, as is visible at the north end of the exposure. These red zones are actually infiltrated material coming down from above after the flows cooled. While none have been found here, these infiltrations often have reptile bones in them, because the open spaces they fill were good places for animals to live or get trapped in. I have found bones in such infilling in lava flows in Nova Scotia and New Jersey[39]. It's a very important distinction because the more time there was between flows the more dilute the environmental impact was.

The simplest interpretation based on what is visible at this exposure is that the lava was prograding into a large lake as a series of lava streams during one eruptive event. At the advancing front of these lava streams the cooling crust constantly ruptured, sending basalt pillows tumbling down in front and on their sides making cones and wedges of pillows. Eruption of these wedges shed hyaloclastite into the turbulent water into muds far in advance of the pillow wedges. After the lava flow system cooled, the voids were filled from above. Although the Talcott Formation is a relatively small flow system compared to the entire CAMP it was a part of the largest phase comprised of many eruptions spread over four major tectonic plates during an early phases of the igneous province that is the leading contender to have caused the ETE.

**Figure 17:** Characteristic prisimatic fracture of the lower part of flow 2 of the Holyoke Basalt. Location is 42.007423°, -72.727982° in West Suffield, CT. The pattern is typical of the second flow almost everywhere, including the Meriden area. The origin of this fracture pattern is not understood but is clear distinct from cooling fractures.

**Lavas of the Holyoke Basalt:** The Talcott Basalt Formation is overlain by the lacustrine Shuttle Meadow Formation. That unit is well known for very well-preserved fossil fish found in carbonate-rich deep-water lake sediments. That formation is not exposed here, however, buried by talus and soil. It underlies the shelf in the landscape as you look up and west toward the hill. In that direction you can see cliffs of Holyoke Basalt, the thickest lava flow formation in the Connecticut Valley Rift Basin. The lower part of the second flow of the Holyoke visible here, has a very interesting and distinctive splintery fracture that along with several other unique features makes it possible to recognize this one flow from northern Massachusetts to central Virginia, a linear distance of over 700 km. Assuming just what is preserved, plus the intervening areas that have now eroded, yields a volume of over 2400 km$^3$ as a minimum estimate of this one eruptive event that probably lasted less than 100 years[40]. For comparison, the Laki eruption in Iceland of 1783 and 1784, which by some estimates killed indirectly by global dimming and consequent crop failures, famine, disease and war (including the French Revolution) more than 5 million people[41], was only 15 km$^3$

in total[42]. The Holyoke Basalt, although well constrained is only a small part of the CAMP.

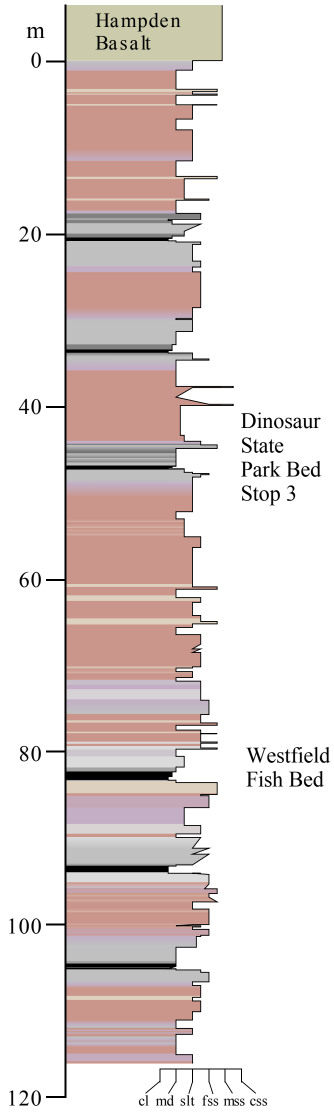


**Figure 18:** Upper East Berlin Formation and Hampden Basalt at Stop 2.

## Stop 2: Time Keeper of the Solar System and Pacemaker of Life

Location: 41.622162, -72.740125 (service lane on right side of entrance ramp for CT-9 south from CT-15, East Berlin Formation)

Units: East Berlin Formation and Hamden Basalt

Time: ~201.0 Ma – Early Jurassic (Early Hettangian)

Environments: Fluvial and shallow to deep lacustrine and flood basalt

Highlights: Milankovitch and lacustrine cycles, giant lakes, fossil fish and species flocks, fish taphonomy and sediment deformation

After parking, we will walk east on the south side of the road going up section along the outcrop until we reach the Hampden Basalt, taking care not to stray onto pavement. Once there we will look at the basalt and then walk down through the sedimentary section focusing on the highlights.

The highway cut at East Berlin at the intersection of US-15 and CT-9 and a similar cut at the intersection with I-91 reveal fault-repeated sections of the upper 2/3 of the East Berlin Formation. The lacustrine sedimentary cyclicity of this section was first recognized in the 1950s[43],[44] and commented on by many subsequent workers. I hypothesised that the East Berlin cyclicity was paced by Milankovitch cycles in 1986 and that has been highly corroborated by U-Pb radiometric dates in 2013[28]. In fact, this section is nearly a cartoon of Milankovitch cycles, albeit on a huge scale (Figs, 18-20), and its obviousness, itself calls for an explanation.

About 117 m of sedimentary section is exposed on the south side of the cut (Fig. 18). The most obvious cycles have a well-developed dark gray to black laminated deepest water interval exemplified by the cycle bearing the Westfield Fish Bed (Figs. 18 and 19). Similar meter-scale lithological cycles were described by Van Houten in the 1960s in the Triassic age Lockatong Formation of the Newark Rift Basin (NY, NJ, PA) and interpreted as lake level cycles paced by the precession cycle, and this was at a time that the Milankovitch theory of the Ice Ages was thought by many to be "disproven". I named this type of transgressive-regressive cycles after him. To facilitate description and discussion, I have described Van Houten Cycles as comprised of three divisions defined relative to each other: Division 1, lake transgression; Division 2, lake high stand; and Division 3, lake regression and low stand. Each division is recognised by suites of sedimentary feature indicative of the relative sense of water depth change, such as an upward decrease and disappearance of desiccation cracks in a Division 1; followed by finely laminated mudstone of Division 2. Division 3 will show the opposite sense of change with the reappearance of signs of shallow water such as desiccation cracks and roots. In the case of the cycle bearing the Westfield Fish Bed, these transitions and divisions are easy to recognize and they are accompanied by very obvious color changes. But in some other cycles the changes are more subtle and sometime with no color changes. It is important to realize that these cycles are defined by the *relative* sense of change not absolute kinds of sedimentary rock.

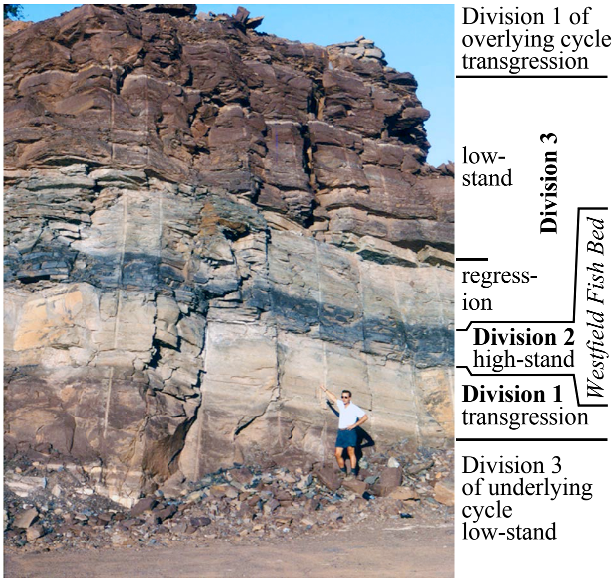


**Figure 19:** Cycle with he Westfield Fish Bed with Peter LeTourneau for scale in 1985.

***Hampden Basalt:*** We begin our traverse at the Hamden Basalt, which is representative of the youngest known CAMP flows known in eastern North America and Morocco, although there are hints of a younger eruption based on a fourth $CO_2$ pulse in the Portland Formation (Fig. 11). The basalt is typically massive but is vesicular at its base. Tilted pipe-stem vesicles are common at the lower contact and seem to indicate a northeasterly flow direction[45]. A known feeder for the Hampden basalt is the Black Rock diabase dike of Massachusetts. The visible thermal effects of the flows are minimal, restricted to the upper meter of the East Berlin. The Hampden Basalt is the thinnest of the extrusives in the Hartford basin, reaching a maximum thickness of 30 m, but interestingly is seemingly associated with one of the largest magnitude $CO_2$ pulses (Fig. 11). It is also one of the most widespread flows known in the CAMP, extending from the Connecticut Valley Rift to the Newark Rift and to Morocco where it is known as the "recurrent basalt formation". The age of the Hampden Basalt is 200.916±0.064 based on correlation to U-Pb - dated intrusions[28].

***Cyclicity and Comparison to the Present:*** Perhaps the most remarkable aspect of this outcrop is the very obvious cyclicity tied to Milankovitch climate change. Pacing of climate celestial mechanical variations was first clearly demonstrated in the Quaternary and amazingly we can make a close comparison between this sequence and the Pleistocene (Fig. 20). In particular, the pattern of Mediterranean sapropels as seen in cores and outcrops is very close to that seen here, despite the fact the Mediterranean is a sea and marine, these strata are continental, and the mechanism is very different. Sapropels are organic-rich muds or mudstones generally interpreted as being deposited below anoxic water. The hydrodynamic and climatic origin of these sapropels in the Mediterranean is debated, but there is agreement that their proximal cause is chemical and density stratification of water column that is close in time to intervals of *minimum* insolation overall intimes of highest precessional variability, that is, times of high orbital eccentricity (Fig. 20). Recent modelling suggests that the stratification was generated by a reduction in the supply of oxygenated bottom water, however, the precise mechanisms appear involve a complex interplay between regional and large-scale climatic patterns, such as warming, sea-level rise, insolation-driven enhanced African run-off, and ocean-biogeochemical mechanisms, such as enhanced late glacial nutrient content and major shifts in the pelagic ecosystem structure. Despite this apparent complexity, the sapropel pattern is remarkably simple and looks very

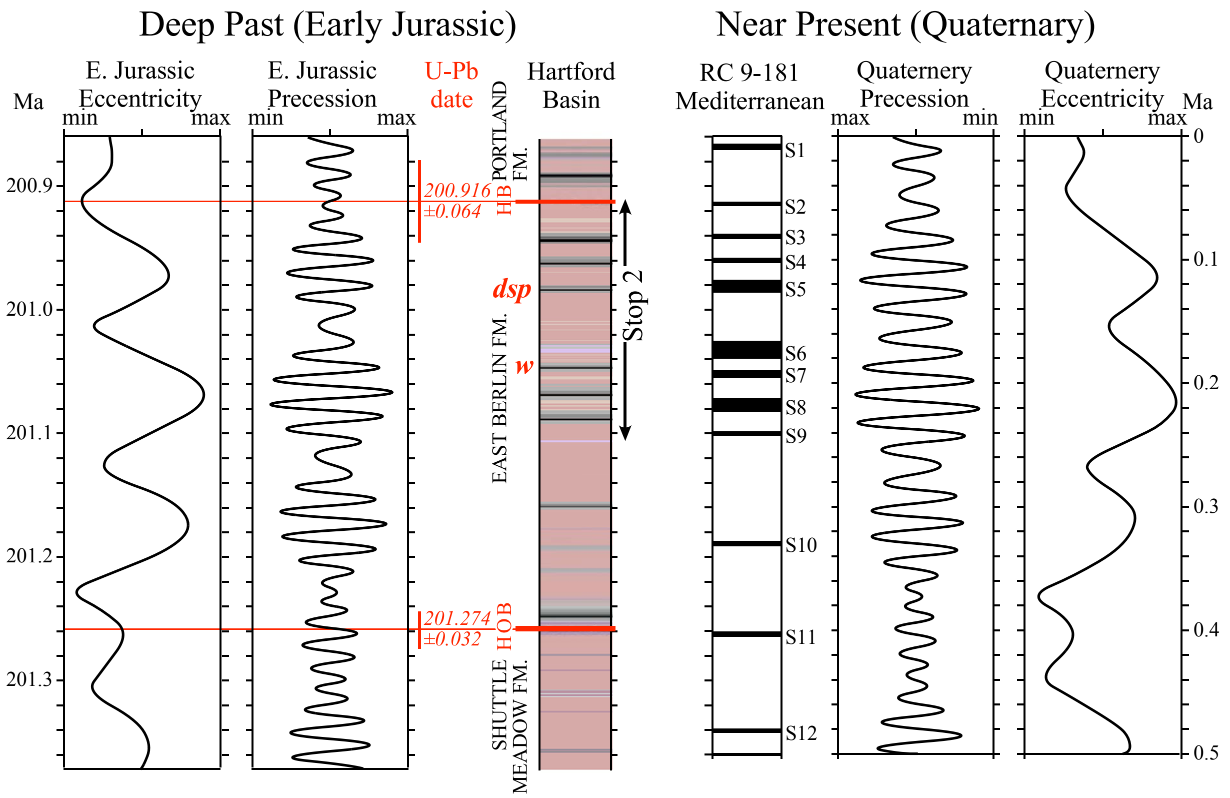


**Figure 20:** Comparison of the pattern of cyclicity between the East Berlin Formation and Mediterranean sapropels (from ref. 27). Note that the min-max axes are opposite for the Deep Past vs. Near Present.

much like this section. The conceptual model for the East Berlin or of the Eastern North American lacustrine cycles is exactly anti-phased at the precessional scale compared to the sapropels, but in-phase at the eccentricity scale in terms of insolation, with deeper lake occurring during times of maximum insolation.

***First 100 kyr Before the Hamden Basalt and the Dinosaur State Park Bed***: As we walk west and down-section, you will see red strata below the basalt and then there is an interval of no exposure. Looking across the highway, you can see there is an equivalent gap there as well. This gap is a glacially scoured valley that has followed the uppermost of the black shale-bearing cycles in the East Berlin. We know this because the upper 50 m of the formation is more completely exposed at the interchange for I-91 about 3.8 km east and that section has been used to fill in the gap in Figure 18[46]. The next cycle down also has a black shale, as does the one below that. The latter, the third black-shale-bearing cycle from the top, is the unit that is exposed at Dinosaur State Park (Stop 3) (Figs. 18 and 20), the main footprint layer that is the gray regressive part of Division 3 of this cycle. Together these three cycles along with the redbeds underlying the basalt comprises a most of a 100 ky short eccentricity cycle, with the last 20 ky or so of that larger cycle being in the basal Portland Formation overlying the Hampden Basalt (Fig. 20).

***Low Variability in a Short Eccentricity Cycle:*** Walking further to the west and down-section, we encounter a long section of red beds. There is a thin-bedded red interval with some interbedded tan sandstone beds at about at about 62 m in Figure 18. This is a very weakly developed division 2 deposited during a time of low precessional-scale variability corresponding to low eccentricity in a ~100 kyr cycle. At roughly 75 m in Figure 18, there is a purplish siltstone and sandstone, much more visible on the north side of the entrance ramp, that represents a slightly better developed Division 2 of a cycle, still with in the interval of low eccentricity.

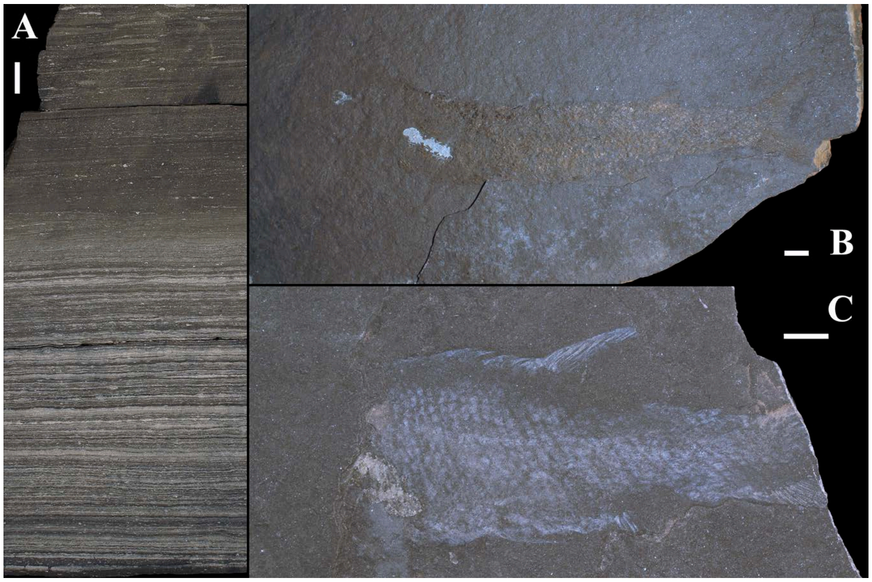


**Figure 21:** Westfield Fish Bed and dephosphatized fish. A, Microlaminated mudstone passing upward into sedimentary melange. B, Complete *Redfieldius* represented only by an organic film head is not visible. C, Complete *Semionotus* revealed by calcite film. In both AB and C head is not visible because of extreme dephosphatization. Scale is 1 cm.

***Westfield Fish Bed:*** At roughly 82 m below the Hampden Basalt is Division 2 of the cycle depicted in Figure 19. This Division 2 is the Westfield Fish Bed, This bed has a calcareous, organic-rich, microlaminated interval that has abundant, if oddly preserved, fish (Figs. 21 and 22) and bivalve crustaceans and also contains the Pompton Ash (Fig. 23).

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 paleonisciform, that has been found at another site) (Fig. 22). 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[47]. 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[48].

The fish here, as at most localities of the Westfield Fish Bed, are to varying degrees "dephosphatized" (Fig. 21); that is, the phosphate mineral matter of the bone has been mostly or completely dissolved early in diagenesis by microbially mediated post-burial processes[49]. This can lead to complete disappearance of the fish or just the faintest of "ghost fish" may remain. That this is not due to acidity is shown by the fact that calcitic fossils (such as charophytes) are well preserved and carbonates are more soluble than phosphates under acidic conditions alone. This dephosphatization is almost certainly a very much more wide spread phenomena than realized[50] and in fact may be the norm rather than the exception.

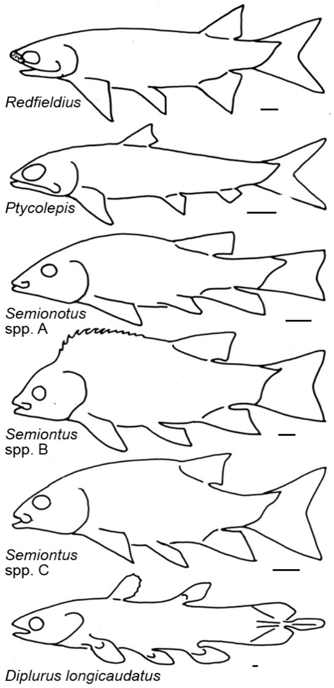


**Figure 22:** Fish taxa rom the Westfield Fish Bed.

Also present in the Westfield Fish Bed are *Bulblimnadia* sp. clam shrimp (spinocaudatan crustaceans), carbonate parts of charopyte green algae, and land plant fragments of various sizes.

***Giant Chemically Stratified Lakes:*** The Westfield Fish Bed is representative of a specific facies that normally preserves whole fish and sometimes terrestrial vertebrates and insects. The micro-laminated strata of this bed are comprised of carbonate rich and carbonate poor laminae forming couplets most simply interpreted as annual in origin – that is they are lacustrine varves. Today these kinds of sediments form in bodies of water that perennially have no oxygen at depth because the area of the water body is small compared to its depth and therefore the work of the wind does not mix the lake[51]. Individual couplets and patterns of couplets are tracable over extent of the Westfield Fish Bed. This indicates that wave base never intersected the bottom during deposition of the bed, which is consistent with the lake being perennial stratified. Given the minium length of the strata not exposed to wave base (~ >100 km) and a range of reasonable wind speeds, the Westfield Fish Bed was deposited in lake a minimum of about 50 m[51] with an anoxic hypolimnion. There is some evidence that the lake in which the Westfield Fish Bed was deposited extended into the Newark Basin. Similar strata are present in the Culpeper Rift Basin of Virginia as well. If the lake extended that far, it would be in excess of 700 km long. Making it larger than any present lake, save the Caspian and Black seas.

***The Pompton Ash and CAMP Mega-eruption:*** The lower 10 cm of the Westfield Fish Bed has a thin, graded basaltic crystal tuff called the Pompton Ash[52], named for an outcrop in Pompton, NJ in the correlative Towaco Formation, although this is its discovery locality. The graded, apparently andesitic ash consists of euhedral, non-rounded, plagioclase laths in clay or chalcedony matrix that was originally glass, fine-grained feathery feldspars, carbonate, and distinct sub-mm spherule-like volcanic grains at the base. Pyrite is abundant and can comprise more than 25% of the bed by weight[53], and consequently, the ash weathers to an expanded bright orange jarositic mush. The pyrite is most simply explained as having formed in the pore space of the ash after deposition, rather than part of the ash itself. At this outcrop, the surface of the ash is often orange, but if you break off a piece the inside is dark gray.

Thus far, the Pompton ash has been found at 10 localities, 7 (2 cores and 5 outcrops) in the Hartford Subbasin of the Connecticut Valley Rift Basin and 3 (2 cores and 1 outcrop) in the Newark Rift Basin, spread out over a distance of about 200 km. Several aspects of this ash are surprising. First, its thickness does not change over its 10 known sites and 200+

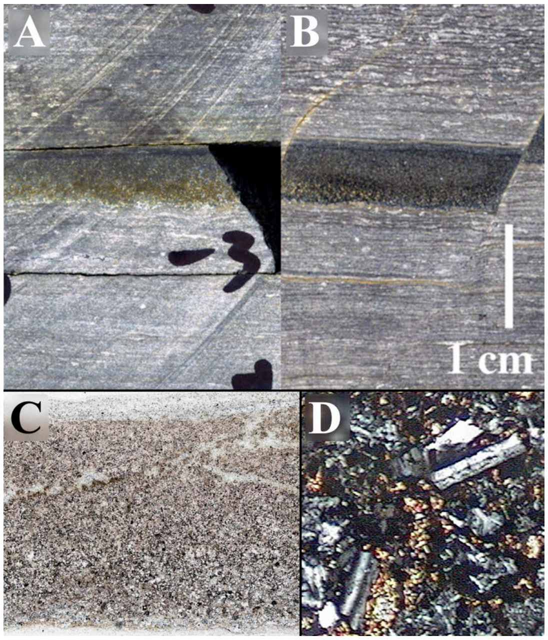


**Figure 23:** Pompton Ash: A, Army Corps of Engineers C-128 Core in the Towaco Formation, with the Pompton Tuff being the ~0.5 cm dark graded layer; B, East Berlin Fm. at Parmelee Brook about 130 km away in the Connecticut Valley Rift Basin; C, Thin section of the Pompton, Tuff at Stop 2, with thickness of layer at 6.8 mm and largest particles at base of layer are 0.15 mm; D, thin section with euhedral plagioclase laths 0.1 mm long with a high aspect ratio, showing no signs of rounding. Originally they were enclosed in glass that is now converted to a clay or chalcedony.

km extent, implying it is either the product of a huge, distant eruption, or a smaller eruption closer and positioned just-so. Second, there is a <1 mm ash a few cm higher that also does not change thickness. Third, while validating that ~30-year-old lake cycle correlations between basins are shown correct by the presence of these ashes, it is astounding that these ashes are enclosed by congruent patterns of microlaminae over the same distances. This implies either that the Newark and Hartford basins could have been connected in a single giant rift lake, as suggested above, or that seasonal to centennial climatic variations overrode all other sources of sediment variability, or both. It is noteworthy that no such correlation has been described for separate extant lakes. Fourth, as has been seen in some basaltic ashes, the Pompton Ash has a modest Ir anomaly, suggesting similar ashes might be the source of more cryptic Ir anomalies in other Triassic-Jurassic strata. Finally, fifth, not only can we evidently correlate strata among various Triassic-Jurassic basins at the 20 ky cycle level, for some intervals we can confidently also correlate at the seasonal scale.

The Pompton Ash is likely part of the CAMP as it is andesitic to basaltic in composition. It does not change thickness over a distance of 200 km suggesting that it is a distal product of a giant Yellowstone-scale mega eruption very far away, like south Florida a possible center of the CAMP plume. Despite the suggestion that this ash is the result of a mega-eruption it was but a puny part of the CAMP, one of the largest eruptive complexes on Earth.

***Melange:*** Overlying the microlaminated part Westfield Fish Bed is an odd unit consisting a mélange of small (usually <20 cm) quadrangular to rounded or folded clasts with truncated oblique-to-bedding laminae floating in a poorly-bedded matrix. In 1989, PEO half-jokingly termed the clasts “dead horses” (derived from "horse" for a fault-bounded sliver of rock and its flattened or prone position), hoping in vain to provoke interest. When noted at all, "dead horse" mélanges have been interpreted as depositional units such as turbidites, rip-up clasts indicating subaerial exposure, slumps, or seismites, but I argue that they are “early” shear and dewatering-related units that did not have a free surface at the time of deformation [54]. These are very common; in lacustrine sequences of the Triassic-Jurassic of the eastern US, nearly every sedimentary cycle with a dark gray to black mudstone has such a layer, amounting to hundreds of beds, including all of the black shales at this site. Similar beds are abundant in the Eocene Green River Formation and are found in many other organic-rich, laminated mudstone sequences.

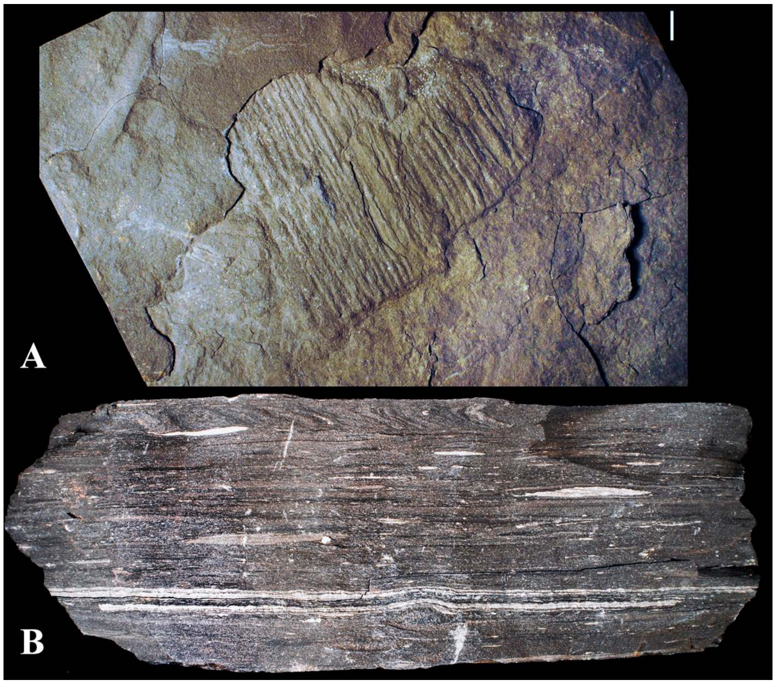


**Figure 24:** Early post-depositional bedding-plane-parallel melanges created by shear and liquefaction: A, plan view; B, cross-section.

Assuming these mélanges are depositional leads to very serious mistakes in environmental interpretation. Moreover, because they formed post-depositionally, between pre-existing beds, and their formation was controlled by a combination of specific rheology at unknown depths and pressures (with or without specific triggers) each bed cannot be treated as resulting from a specific event, and a stratigraphy of sequential beds cannot be interpreted as a history of events.

It is a serious mistake to interpret every layer one sees as a historical event – sometimes the main feature of a sedimentary unit are postdepositional and the appearances are a result of their rheology under stress not their sedimentology.

***The rest of the section:*** Continue walking to the west and examine two more Van Houten cycles, each with a black shale-bearing division 2. The middle cycle has a bedding plane fault that has chewed up most of the laminated portion of Division 2. The lowest cycle has a division 2 with numerous crystals of magnesite (magnesium carbonate). The significance of these crystals is not clear and it is possible that they represent a relatively local diagenetic effect. Most of the division 2 does not appear to be well laminated, however the base is and those laminae are traceable at least 5 km to the southwest.

### Stop 3: The Inverted Pyramid – Dinosaur State Park

Location: 41.651887, -72.656877 (Display Building of Dinosaur State Park, Rocky Hill, CT)
Unit: East Berlin Formation
Time: ~200.99 Ma – Early Jurassic (Early Hettangian)
Environments: Shallow lake over deep lake
Highlights: Hundreds of dinosaur footprints, few herbivores

Leave the vehicle and proceed to the Dinosaur State Park (DSP) interpretive center (IC).

The spectacular trackways at DSP were uncovered in 1966 during the excavations for a state building (Figs. 25 and 26). Sidney S. Quarrier of the Connecticut Geological Survey, Joe Webb Peoples from Wesleyan, and John H. Ostrom of Yale, among others, recognized the importance of the finds and acted to protect the site and worked to have the site preserved as an in situ display in a state park[55]. Subsequently, a large track-bearing surface was preserved beneath the DSP IC where they are visible today, while the larger original discovery surface was reburied for possible future exhibit. DSP is today one of the most popular parks in Connecticut attracting some 50,000 visitors a year, and *Eubrontes giganteus*, by far the most abundant track at the site, is now the Connecticut state fossil.

Since its discovery, the largely gray strata comprising the footprint-bearing interval in DSP has been recognized as being located in the upper

**Figure 25:** Natural Cast in sandstone of a typical *Eubrontes giganteus* from Dinosaur State Park. Quarter is 24.26 mm in diameter.

**Figure 26:** Original excavation of *Eubrontes giganteus* trackways at DSP in 1966.

East Berlin Formation as is clear from physical proximity of the overlying Hampden Basalt. Short rock cores[56] taken at the site early in its history show that the footprint layers lie closely above a well-developed black shale, indicating that the tracks occur in the over-all regressive phase of the orbitally-paced lake laminated mudstone. Based on the recent quadrangle mapping in this area[57], given a dip of 11° and a map distance of 220 m from the track bed to the mapped base of the Hampden Basalt, the track sequence should lie about 42 m below the basalt which shows that the track bed in is third black-shale-bearing cycle below the basalt (Figs. 18 and 20).

What appears to be the same black mudstone underlying the track beds at the park was encountered in an excavation along West Street just west of the service entrance for the park. N.G. McDonald found several mostly dephosphatized *Semionotus* (Fig. 27) and many clam shrimp similar to those in the Westfield Fish Bed in the rubble heaps. These make a nice addition to the park's fossil assemblages.

**Figure 27.** Largely dephosphatized *Semionotus* from the laminated mudstone below the track beds at DSP found at excavation along West Street.Scle is 1 cm. N.G. McDonald collection.

***Inverted ecological pyramid:*** As seen at the DSP post-ETE track assemblages are overwhelmingly dominated by the tracks of carnivores. The DSP track level is at about 201.0 Ma in the Early Hettangian of the Early Jurassic, only half a million years after the end-Triassic-extinction. As noted in the introduction, this reflects a post-mass extinction tetrapod community that was water-based with the theropods subsisting largely on fish and other carnivores.

*Eubrontes* was made by a theropod dinosaur. Reconstruction of the osteology of the foot using the "arthral" method, in which pads are assumed to underlay the joints, results in a skeleton that is

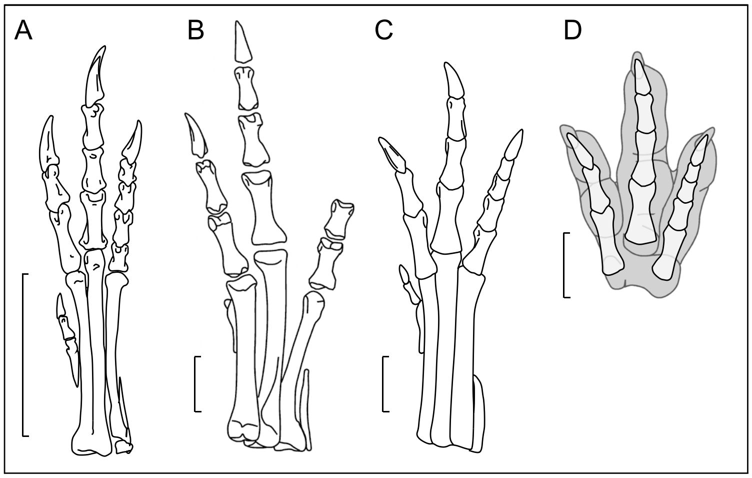


**Figure 28:** Osteological reconstruction and comparisons with osteological taxa of the holotype of *Eubrontes giganteus* at the Beneski Museum AC 15/3: A, right pes of *Megapnosaurus* (*Syntarsus*) *rhodesiensis* ; B, *Dilophosaurus wetherelli*, right pes; C, *Dilophosaurus wetherelli*, reconstructed right pes; D, arthral model reconstruction of the holotype *Eubrontes giganteus*, AC 15/3; Scale is 10 cm.

very similar to the Early Jurassic theropod *Dilophosaurus* from the Kayenta Formation of Arizona (Fig. 28)[58]. A full size model of this dinosaur is on display at DSP in a diorama next to the tracks. This model was made before it was known that non-avian dinosaurs were feathered. A more recent model (Fig. 29)[59,60] shows *Dilophosaurus* covered with "protofeathers" consistent with the phylogenetic bracket analysis looking very similar to the Early Cretaceous tyrannosaur *Yutyrannus* preserved with protofeathers[61].

The vast majority of tracks found in the post-ETE latest Triassic and Early Jurassic strata in Eastern North America were made by theropods the tracks of which are collectively called brontozoids. Some herbivore tracks are present such as *Anomoepus* and *Otozoum*, but they are rare. In contrast middle and Late Jurassic and Cretaceous track assemblages are comprised of track assemblages in which herbivorous dinosaur tracks are more abundant than carnivorous forms[62]. Inasmuch as the assemblages at our field stops post-date one of the largest mass-extinctions of

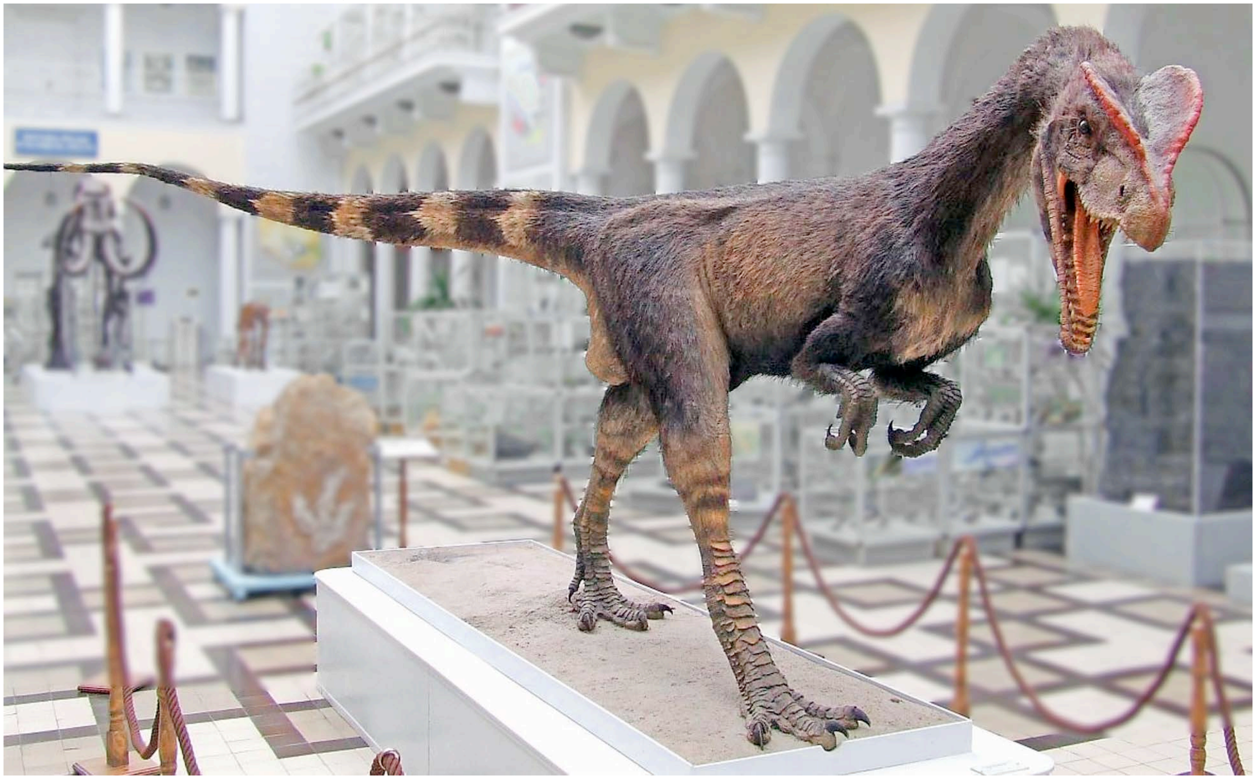


**Figure 29:** *Dilophosaurus* as reconstructed in the Geological Museum of the Polish Geological Institute, Warsaw.

all time, the end-Triassic extinction, the terrestrial ecosystems were anything but normal. A strong case has been made that Early Jurassic brontozoid tracks from the Moenave Formation, Utah (an assemblage that looks remarkably like that from the Connecticut Valley) were made by theropod dinosaurs that subsisted largely on fishes[63], as do many extant dinosaurs (birds). This is supported by the presence of the teeth of *Dilophosaurus* and isolated teeth found with the Moenave tracks that are similar to those of known theropod piscivores such as the spinosaurids, with which they also share snout adaptations with[63]. Similar, though smaller, teeth have been found in lacustrine strata in the Connecticut Valley Rift Basin[64] (Fig. 30). With a water-based economy, theropods could be proportionally much more abundant than if they subsisted on herbivorous dinosaurs alone. Additionally, the end-Triassic extinction wiped out all the tropical semiaquatic carnivores, such as phytosaurs and large labyrinthodont amphibians, so theropods had few competitors. The crocodylomorphs were comparatively small (~1 m) and were more likely prey than competition. Thus, the “Eltonian” or ecological pyramid[65] of the Early Jurassic terrestrial realm had its base in the water and that is why it appears to be upside down. Similar water-based terrestrial communities must have existed when tetrapods first moved onto land. It would not be until the late Early Jurassic and Middle Jurassic that herbivores became more common than carnivores, and the typical terrestrial trophic pyramid was re-established.


**Figure 30:** Theropod dinosaur tooth from the Shuttle Meadow Formation. N.G McDonald collection.

Recent work at DSP has concentrated at digitally rendering the trackways in 3 dimensions so that they can be quantitatively analysed in more objective manner using morphometric methodologies[58]. This includes digitally remapping the exposed track bed as well as the ability to 3d print specimens at any size.

Note that the DSP IC has many other kinds of tracks from other localities (such as *Otozoum* from our Stop 4), as well as well fish and plants on display that should be examined. One of these is a recently discovered trackway of the mammal-like ichnotaxon *Ameghinichnus* (Fig. 31), also known from the Newark Basin[66]. Close mammal relatives and early mammals have very conservative foot structure and there are a number of Early Jurassic forms that could have made these tracks. Actual known mammaliforms from the Early Jurassic are too small to have made these footprints, but tritelodonts (pictured on cover) and tritylodonts were the right size and are known from skeletal remains from the Fundy Rift Basin[67].

**Stop 4: Drylands and Recovery**

Location: 41.578562, -72.642671 (Portland Brownstone Quarries, Portland, CT)

Unit: Portland Formation


**Figure 31:** *Ameghinichnus* from the middle Shuttle Meadow formation of Berlin, CT. Scale is 1 cm.

Time: ~200.5 Ma – Early Jurassic (Middle Hettangian)
Environments: Fluvial, ephemeral lake, eolian
Highlights: Drylands, dinosaur and other footprints, recovery from ETE, brownstone

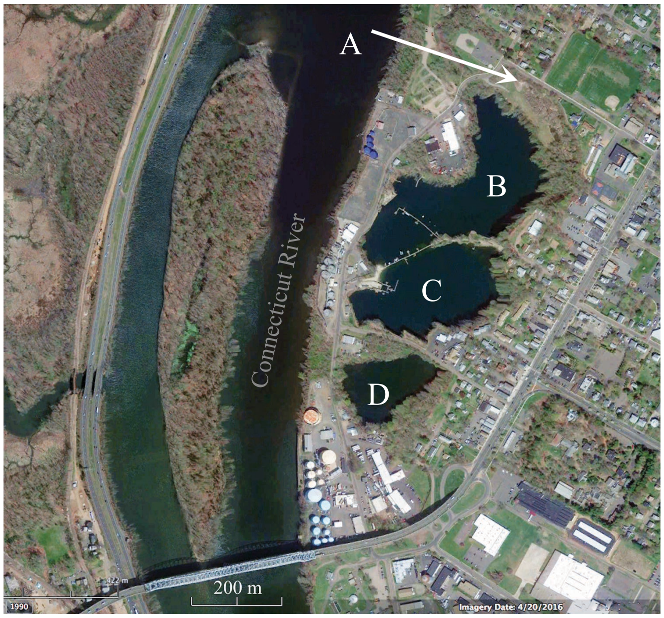


**Figure 32:** Google Earth view of the Portland Brownstone Quarries, Portland, CT: A Meehan Quarry; B Middlesex Quarry; C, Brainerd Quarry; D, Shaler and Hall Quarries.

The Portland Brownstone Quarries (largely the Middlesex, Brainerd, and Shaller and Hall quarries) were THE major producer of highly desirable brown sandstone during the latter half of the 19th century (Fig, 32)[68]. Not only were many of the famous "brownstones" of New York and other East Coast cities built from stone from these quarries, but stone was also shipped half way around to San Francisco via Cape Horn (no Panama Canal) to build the James C. Flood Mansion on Nob Hill in 1885. Brownstone lost favour in the early 20th century and the quarries were flooded in 1936 and 1938 bringing large scale quarrying to a permanent halt. However a small quarrying operation started in 1994 and lasted to 2012, operated by the Connecticut Brownstone Co. (G. Michael Meehan). This more recent quarrying afforded a close look at the sedimentology of the section (Fig. 33).

The sandstone was deposited in largely fluvial and some eolian and very minor lacustrine (playa) environments in the upper part of the Park River Member of the Portland Formation. This part of the Park River Member was deposited during an interval of very low precessional variability during the phase of a 405 ky with the lowest eccentricity. Well-developed lacustrine cycles occur up section in Portland (South Hadley Falls Member) and down section in Middletown in the lower part of the Park River Member. Eolian sandstone are present and at times the landscape must have been more or less a desert.

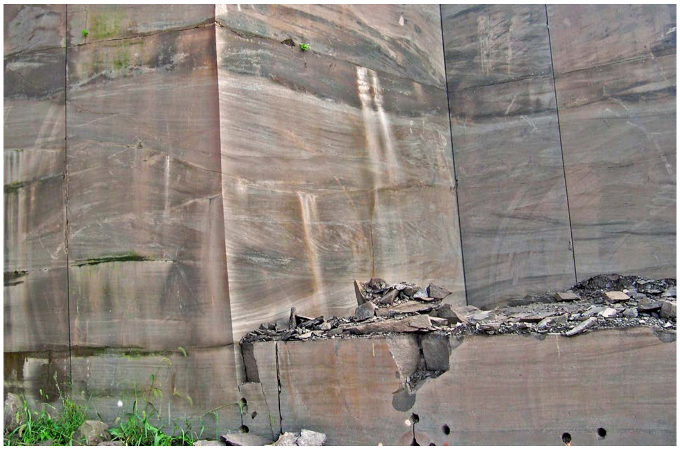


**Figure 33:** Cross bedding in sandstone in the Meehan Quarry in 2012.

During quarrying operations many footprints and other trace fossils were found, largely recovered as natural casts on soft red playa and overbank mudstones. Many exceptional fossils were found and made their way to various museums on the East Coast, most notably at Amherst College (now the Beneski Museum), the Boston Museum of Science, and Yale University.

As was the case for the East Berlin Formation the track assemblage is still dominated by brontozoids, although large forms are very rare (Fig. 34 and 35). However, the "prosauropod" track *Otozoum* is relatively common, and the ornithischian dinosaur track *Anomoepus* occurs in forms that are larger than any seen in older units (Fig. 34). Brontozoids have been placed in a bewildering array of track taxa. On the whole, small tracks tend to have relatively long middle digits and narrow feet, while larger forms tend to have relatively shorter middle digits and squatter feet. This change in shape with size could be growth or the different shapes could represent different biological species. Regardless there is a continuum of shape that makes it very difficult to identify track species.

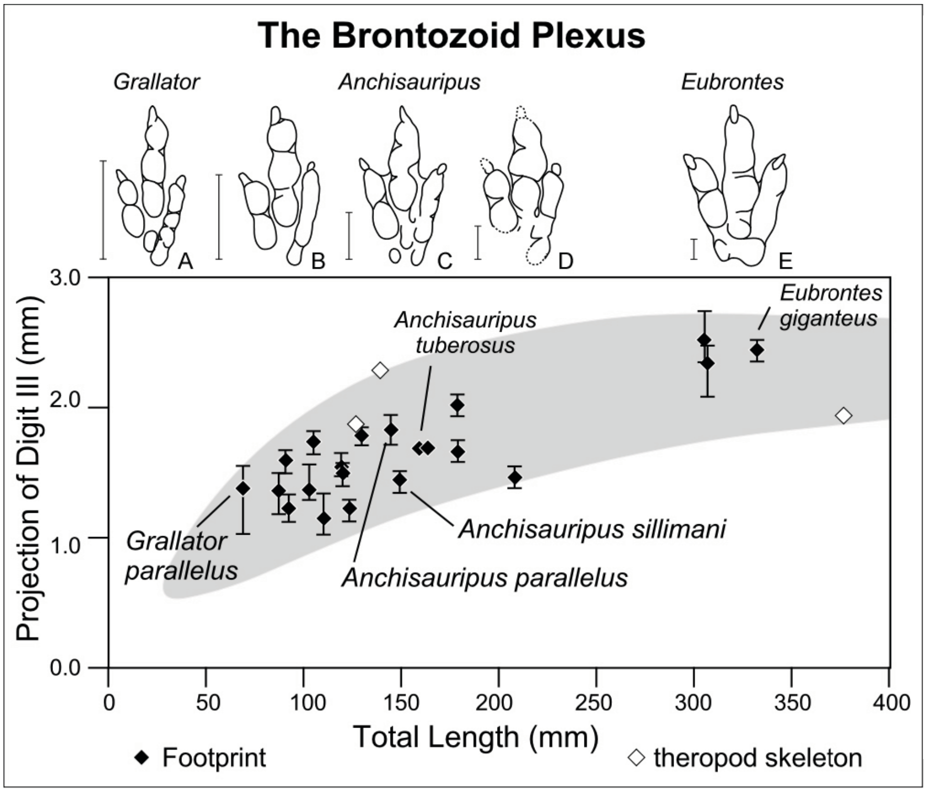


**Figure 34:** More or less continuous change in form with increasing size in brontozoid tracks makes objective identification and systematic classification of brontozoid tracks difficult and arbitrary. In this graph, only holotype specimens are labeled: A) *Grallator parallelus*; B) *Anchisauripus parallelus*; C) *Anchisauripus sillimani*; D) *Anchisauripus tuberosus*; E) *Eubrontes giganteus*. This range of form can be seen in the brontozoid from the Portland Quarries.

Tetrapod, burrows are present, indicating that the sediment was at least at times well drained (Fig. 36). Small forms appear to be assignable to *Cynodontipus* that was previously thought to be a footprint of a hairy cynodont[58]. A much larger burrow form is present, however, as well. The presence of claw marks on the burrow show that in both cases amniote tetrapods, as opposed to an amphibian, made the burrows. The largest form (Fig. 35) was large enough to have been made by a dinosaur. Some ornithischian dinosaurs, such as the median Cretaceous *Oryctodromeus*, that would have left tracks similar to *Anomoepus*, have been found as skeletons with in burrows[69], so it is not impossible that a small dinosaur could have been made this large burrow.

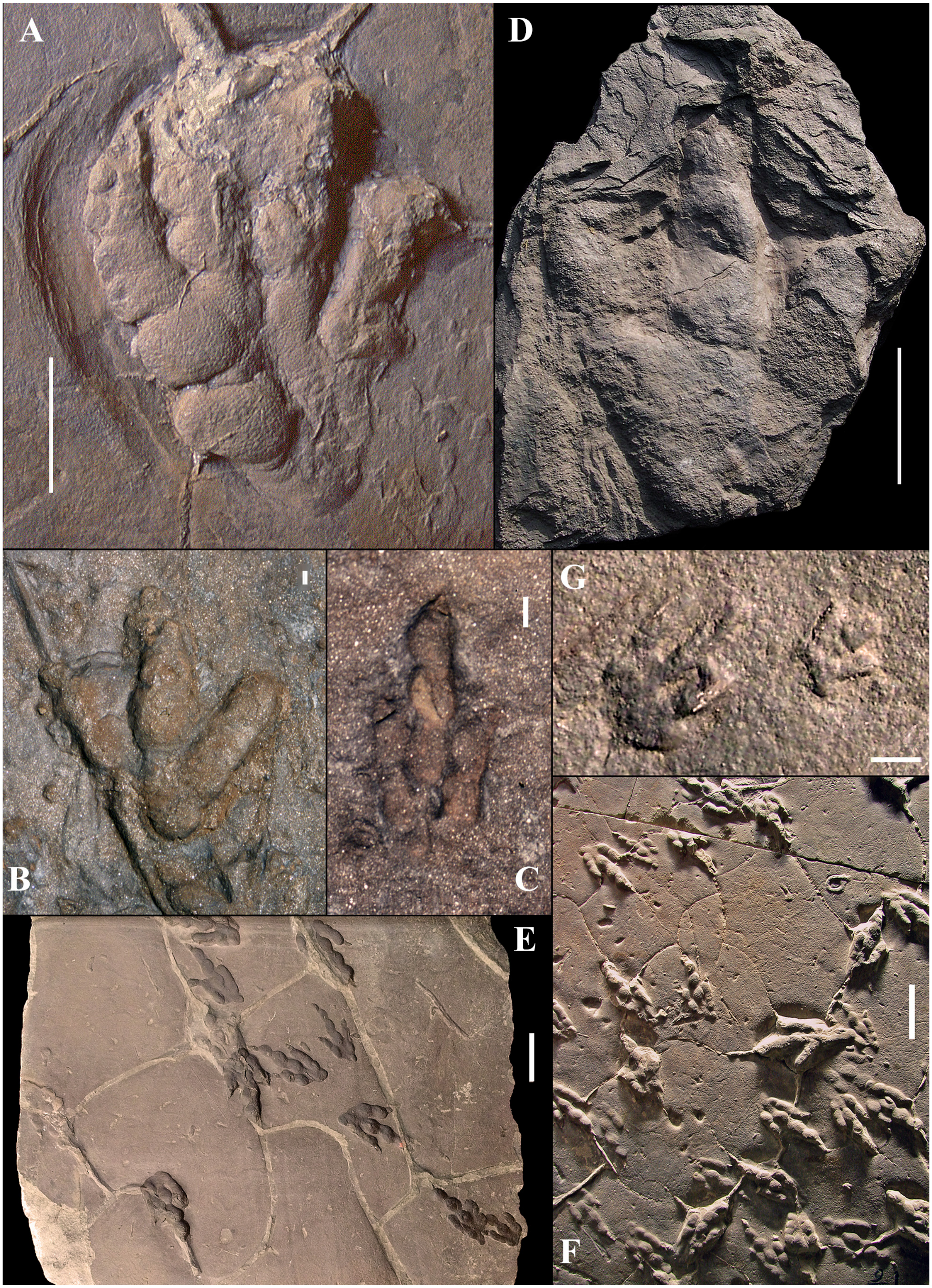

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**Figure 35:** (previous page) Footprints forms from the Portland Brownstone Quarries (Stop 4): A, the "prosauropod" dinosaur track *Otozoom moodii*, note scale impressions (DSP specimen); B, the ornithischian dinosaur track *Anomoepus scambus* (DSP specimen); C, small theropod dinosaur (brontozoid) track usually assigned the *Grallator* (DSP specimen);; D, large brontozoid track, *Eubronte*s cf. *giganteus* (Meehan Quarry specimen); E, slab of small-medium brontozoid (theropod) tracks usually assigned to *Grallator* and *Anchisauripus* (Wesleyan University specimen); F, very similar slab of small-medium brontozoid (theropod) tracks usually assigned to *Grallator* and *Anchisauripu* (Beneski Museum slab); G, crocodylomorph, probably protosuchid manus pes set (slab built into quarry structure). Scale for A, D, E, F is 10 cm; for B, C, G scale is 1 cm.

Natural casts of dinosaur bones have been found in the Portland Brownstone quarries (Fig. 36). These are theropods and could represent a coelophysid-grade form. Formerly these were assumed to be natural casts of impressions of the bones[70], but recently they have been interpreted as sand pseudomorphs after bones[71]. As pseudomorphs, the bones would have been buried and then dissolved away leaving cavities that filled with sand. Actual bones have yet to be found in these exposures. However, younger strata of the Portland Formation have produced partial skeletons of the protosuchid crocodylomorph *Stegomosuchus*, multiple specimens of the "prosauropod" dinosaur *Anchisaurus*, and the small theropod dinosaur *Podokosaurus*, [72]all of which are plausible track makers, for the footprint forms at this stop.

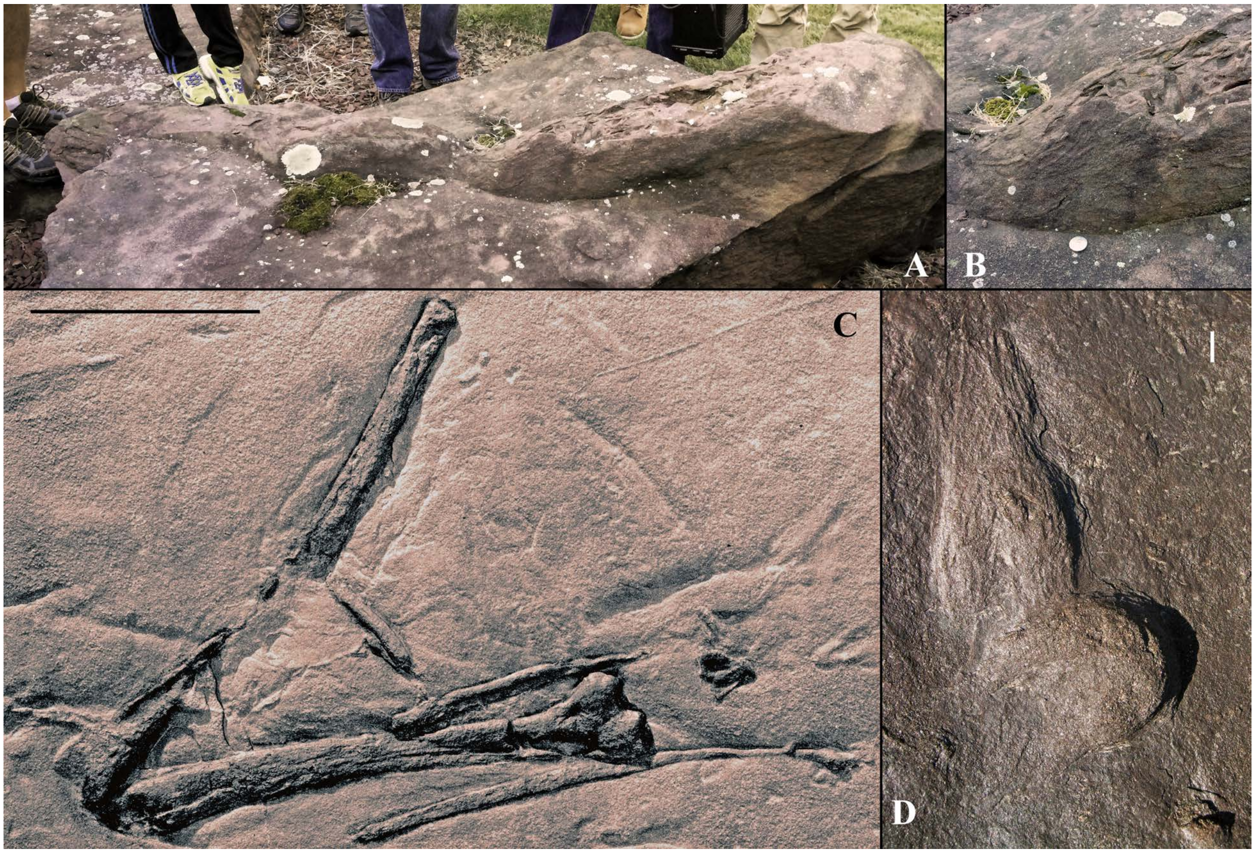

**Figure 36:** Burrow and bones from the Portland Brownstone Quarries: A, unique large burrow (WU 185), outside at Wesleyan University; B, detail of same showing scratch marks made from inside the burrow; C, bone casts or pseudomorphs of a coelophysid-grade theropod (Boston Museumof Science MOS 2001.248) (scale is 10 cm); D, *Cynodontipus* – a small tetrapod burrow that has intersected a hard substrate (Meehan Quarry) (scale is 1 cm).

Based on the soil carbonate proxy (Fig. 11), $CO_2$ consentrations were dropping during the deposition of the upper Park River Member. It had been more than a million years since the ETE and the communities that were recovering had survived through not only at least four episodes of global warming, but also perhaps more importantly many intense volcanic winters. Herbivores seem to be on the increase in abundance and size, and recovery in evolutionary time was well underway. The large forms that persisted through the ETE were all members of clades that were insulated, and all the small forms could apparently burrow. The dinosaurian survivors evolved into diverse small as well as truly gigantic forms that were ecological dominants on land for the next ~136 million years. The large dinosaurs were wiped out at the end of the Cretaceous, probably because of food-chain collapse, but small ones still persist; they are still insulated and they are still more diverse in species than mammals by a factor of two – the birds.

## Acknowledgements

My thanks to Nick McDonald and Peter LeTourneau who generously shared their knowledge and materials. Thanks also to Sean Kinney who's comments and edits greatly improved the. Thanks finally to the land owners and agencies who allow us to visit the field stops. This is a contribution to IGCP 632. I also thank the Special Basic Research Program of Ministry of Science and Technology of China (2015FY310100) and the Bureau of Geological Survey of China and National Committee of Stratigraphy of China (DD20160120-04), for support in work in the Junggar Basin, China.

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