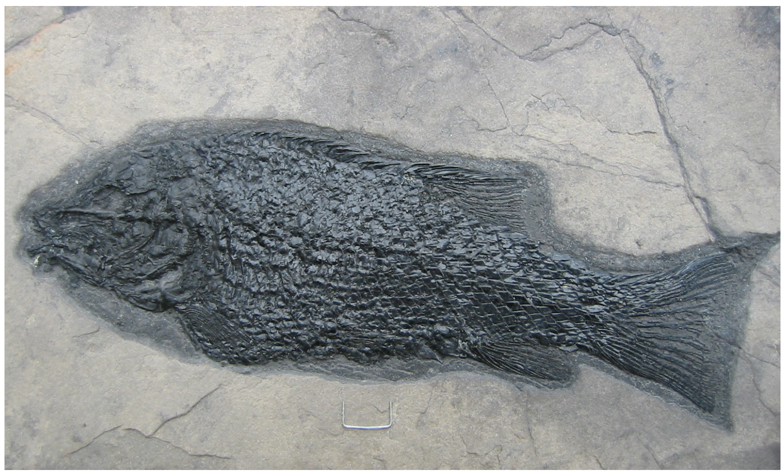
FOSSILS AND FACIES OF THE CONNECTICUT VALLEY LOWLAND: ECOSYSTEM STRUCTURE AND SEDIMENTARY DYNAMICS ALONG THE FOOTWALL MARGIN OF AN ACTIVE RIFT.

Peter M. LeTourneau[1,4], Nicholas G. McDonald[2], Paul E. Olsen[3,4,*],
Timothy C. Ku[5], and Patrick R. Getty[6]
[1] Iona College, Environmental Science Program, Dept. of Biology (*letour@ldeo.columbia.edu*)
[2]Triassic-Jurassic Working Group, LDEO-Columbia University; Olde Geologist Books, Pawcatuck, CT (*oldegeologist@gmail.com*)
[3]Columbia University, Dept. of Earth and Environmental Sciences (*polsen@ldeo.columbia.edu*)
[4]Lamont-Doherty Earth Observatory, Columbia University
[5]Wesleyan University, Dept. of Earth and Environmental Sciences, (*tcku@wesleyan.edu*)
[6]Center for Integrative Geosciences, University of Connecticut, Storrs (*patrick.getty@uconn.edu*)



Semionotus sp., North Guilford, Connecticut. N.G. McDonald Collection.

I. Introduction

For nearly 200 years the early Mesozoic rocks and fossils of the Connecticut Valley Lowland have provided a fertile field of study. Noted for its abundant dinosaur and reptile tracks, the Connecticut Valley has also produced a rich array of fossil fishes, invertebrates, plants, scarce, but important, reptile bones, and abundant trace fossils. As a result, a detailed picture of the ecosystem dynamics of the active rift in the Early Jurassic has emerged, particularly for lake, shoreline, and floodplain environments.

With minor exceptions, all of the important fossil localities are located within a few kilometers of the eastern fault margin of the rift basin. There, the complex interplay of cyclical climatic change and rapid tectonic subsidence produced a thick succession of sedimentary deposits representing a wide range of fluvial, lacustrine, eolian, and alluvial fan depositional environments. High sedimentation rates, coupled with the interfingering of diverse terrestrial facies created ideal conditions for preservation of body fossils, tracks, and trails.

Building stones, including the renowned Connecticut Valley brownstones and Longmeadow (Mass.) redstones, deposited in eolian and fluvial environments, were widely quarried in the late 19th and early 20th centuries. With fresh surfaces being exposed on a nearly daily basis, trace fossils, including dinosaur and reptile footprints, and plant remains were frequently discovered by quarrymen. In the 20th century, numerous road cuts and foundation excavations revealed significant fossil concentrations, including the

*This is a contribution to IGCP Project 623.

world-class trackways that are now the centerpiece of Dinosaur State Park in Rocky Hill, Connecticut. Many important fossil localities are found in natural outcrops along streams and rivers.

The purpose of this paper is to explore the evidence from sedimentary rocks and fossils to reconstruct the paleogeography, depositional environments, and ecosystem structure in the early Jurassic rocks (approx. 201 to 190 my) along the footwall margin of the Connecticut Valley, which encompasses the Hartford and Deerfield Basins. Although we will only visit a limited number of readily accessible exposures, specimens and examples from important sites will be presented and discussed at certain field stops. To preserve the scientific and historical integrity of noteworthy fossil localities, only those sites found within public parks and preserves, where, it is important to note, collecting is prohibited, will be specifically identified. The information provided in this guide does not constitute permission for access to field sites; the authors obtained specific permission for access only on the date of the NEIGC authorized trip.

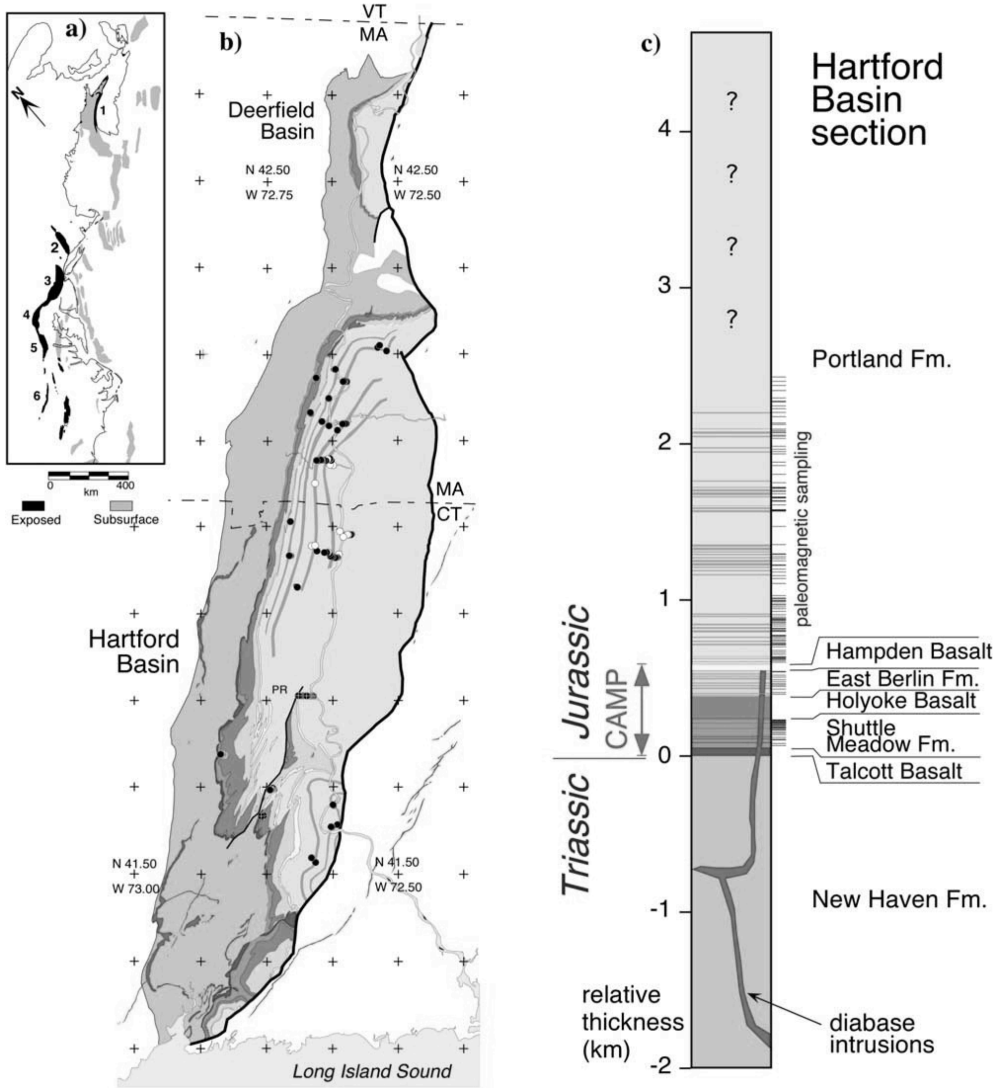


Figure 1. Geologic map and stratigraphic section of the Connecticut Valley Lowland (Hartford and Deerfield Basins). *Inset:* (a) Location of Triassic-Jurassic rifts in eastern North America. Source: Kent and Olsen (2008).

II. The Hartford Basin

Paleogeography and Facies. The Hartford Basin, comprising the southern two-thirds of the Connecticut Valley Lowland, is part an extensive series of early Mesozoic age rifts formed during the breakup of Pangea (Fig. 1a). Ranging in age from Late Triassic (Norian) through Early Jurassic (Sinemurian, and possibly younger), rocks of the Hartford Basin are organized as formations within the Newark Supergroup (e.g. Olsen, 1988; Kent and Olsen, 2008). The small northern extension of the Hartford Basin is called the Deerfield Basin.

The paleogeography of the Late Triassic stratigraphic section of the Hartford Basin is not well known, but clast size distributions, geophysical data, and comparison to the Taylorsville-Richmond Basins in Virginia, reveal that small, sub-regional half-grabens occupied the area that would become the regional-scale Hartford Basin by Early Jurassic time (LeTourneau, 2003). Evidence for "mini" half-grabens includes boulder conglomerates in East Meriden, Connecticut that coincide with an abrupt "step" in the basement rocks, as determined by gravity surveys (Chang, 1968) and seismic refraction interpretations (Wenk, 1984). The presence of sub-regional half-grabens complicates correlation of the New Haven Formation strata and the distribution of the Talcott Basalt in southern Connecticut.

In the early Jurassic, the Hartford Basin was an asymmetrical half-graben with a master border fault on the east side of the rift. The border fault consisted of several discrete segments that coalesced as subsidence continued. Relay ramps formed between fault segments in Durham, Glastonbury, and Manchester, Connecticut. There, large alluvial wedges prograded into the rift lakes from southeast to northwest to form broad littoral shoals, such as those at, and near, Dinosaur State Park.

Studies of the Jurassic strata of the Hartford Basin by LeTourneau (1985a, 1985b), LeTourneau and McDonald (1985) and McDonald and LeTourneau (1988, 1990) used facies analysis, paleocurrents, sediment provenance, lithosome geometry, and basalt flow directions (Ellefsen and Rydel, 1985) to model the paleogeography of the footwall and hanging wall margins of the rift. The eastern footwall margin is dominated by short-radius alluvial fans that interfinger with lacustrine black shale beds and fluvial deposits. The western hanging wall side of the basin is characterized by lake beds that thin and onlap the basalts toward the west. Fluvial-deltaic wedges in the western zone prograded toward the east, as demonstrated by stratal geometry and sedimentary structures indicating paleocurrent flow to the east.

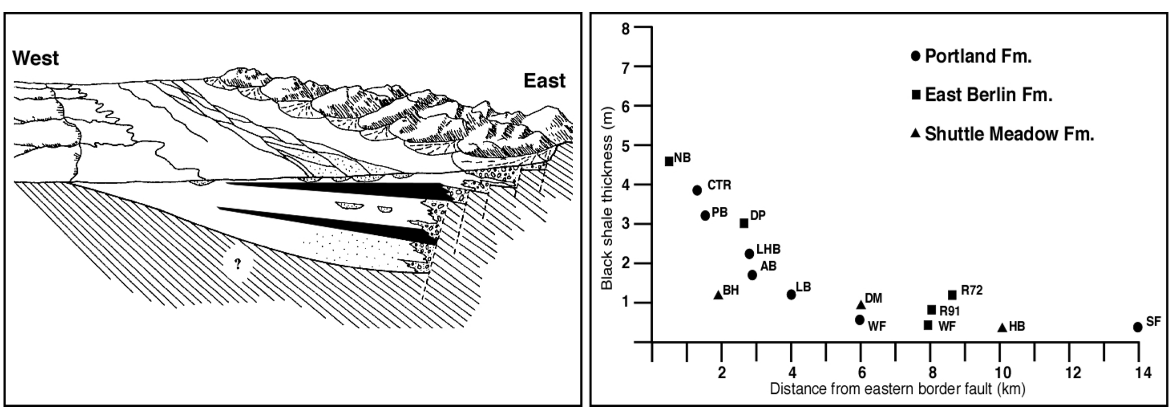


Figure 2. *Left:* Paleogeography of the Hartford Basin; asymmetrical subsidence controls facies distribution (Horne et al., 1993). *Right:* Thickness of laminated black shale relative to distance from the eastern margin of the basin (LeTourneau 1985a, 1985b).

The syndepositional structural configuration of the Hartford Basin exerted strong control on the distribution of depositional environments, mainly by the creation of tectonic slopes. Asymmetrical subsidence localized the deepest portions of the depositional basin adjacent to the fault-bounded eastern margin. Very latest Triassic (late Rhaetian) and Early Jurassic age (Hettangian) lacustrine black shale units invariably thicken toward the basin margin where they intercalate with coarse littoral and alluvial fan deposits. Footwall uplift resulted in short, steep drainages, which shed sediment onto small basin-margin alluvial fans. The presence of a few larger alluvial fan complexes may be a result of the capture of established antecedent drainages, or their location at breached footwall drainages at overlapping segments of basin margin normal faults.

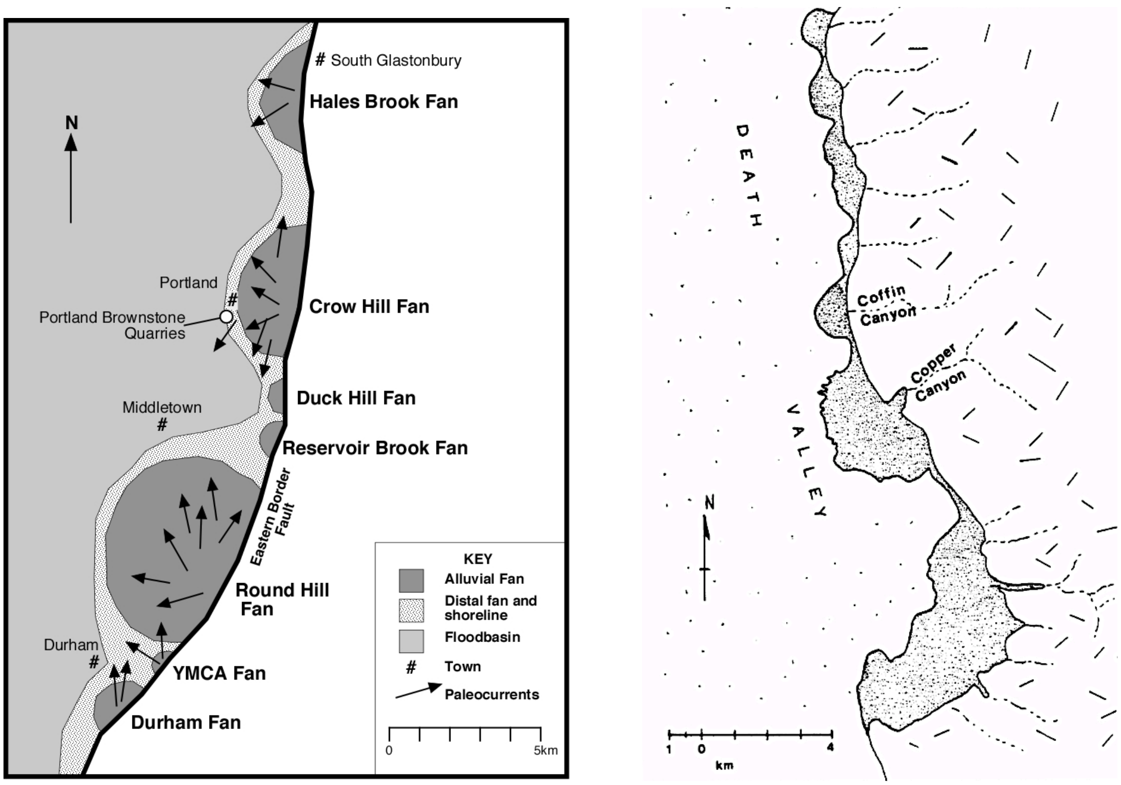


Figure 3. *Left:* Alluvial fan complexes along the footwall margin near Middletown, Connecticut. *Right:* Comparison of modern alluvial fan complexes, Death Valley, California.

On the hanging wall, or hinged western margin of the basin, larger watersheds contributed substantial sediment to the subsiding basin. Sediment derived from axial regions was also a major source of basin fill. Paleogeographic analysis indicates that broad areas of the western portion of the basin sloped east toward the off-axis depocenter. An idealized lacustrine interval (Fig. 4) has shallow-water deltaic and nearshore carbonate-rich deposits on the hinged margin and thick, deep-water dark shale intercalated with littoral sand and alluvial fan conglomerate on the footwall side (McDonald and LeTourneau, 1988).

This paleogeographic model for the Hartford Basin is supported by studies of modern rifts in Death Valley and East Africa, and structural models based on modern and ancient rifts which suggest that extended terranes share a similar tectonic framework. Asymmetric half-graben are the most common product of rift basin development. Due to differential isostatic loading, the footwall of the master border fault system undergoes profound uplift during extension, resulting in small, steep catchments on the faulted margin. The basin depocenter is skewed toward the faulted margin, and the hinged or platform margin also slopes eastward. Most basin-filling sediment is derived from hanging wall and axial sediment sources; footwall sources are only of local importance. Post-rift tectonism, including normal faulting and a late episode of compression, or basin inversion, created a series of tilted intra-basin blocks and broad folds that form the *ridge-and-valley* topography, which characterizes the geography of the Connecticut Valley today.

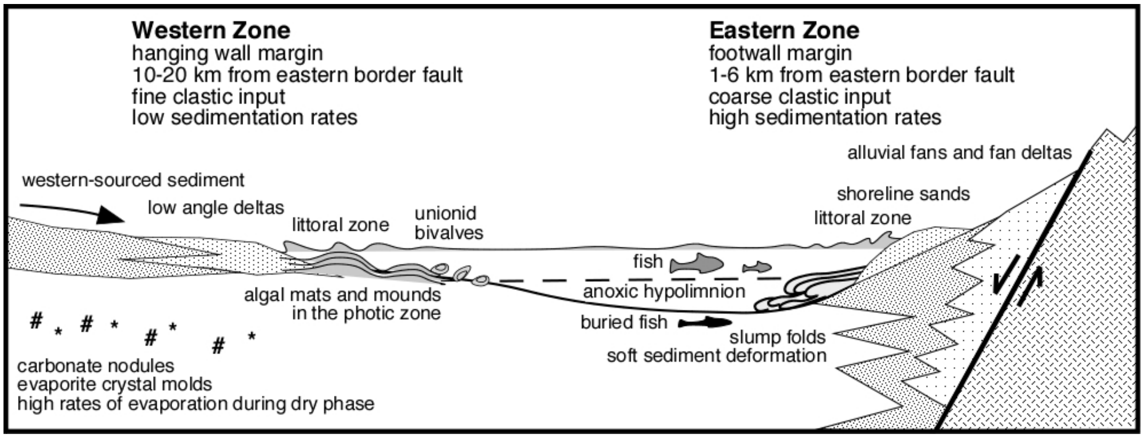


Figure 4. Depositional model for the Hartford Basin during a humid climate phase in the Early Jurassic.

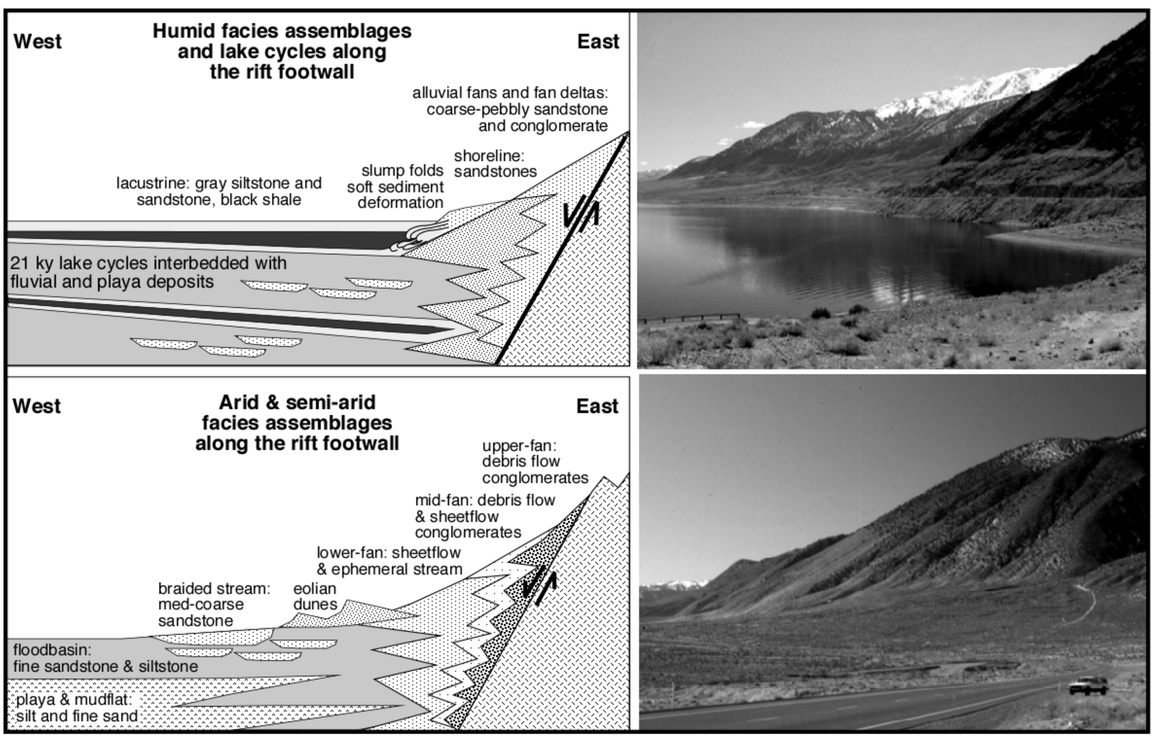


Figure 5. Facies models from the Early Jurassic Hartford Basin compared with modern analogues.
Top: "Wet" phase with perennial lakes overlapping alluvial fan conglomerates at Walker Lake, Nevada. Comparison is for illustration only; currently the entire Basin and Range Province is in an arid phase. During the Pleistocene pluvial period, perennial lakes up to 300 ft. deep filled these valleys. Stranded shorelines in foreground and right side of picture of Walker Lake demonstrate that water levels are continuing to drop from high levels approximately 12,000 years ago.
***Bottom*:** "Dry" phase with alluvial fans prograding onto basin floor playas at Death Valley, California; thin eolian dune fields and eolian sandsheets are superimposed on the lower fans.

Syndepositional tectonics and periodic climate variability exerted primary control on sedimentation. Alternating "wet" and "dry" paleoclimate conditions resulted from periodic changes in the shape of Earth's orbit, axial precession, and amount of axial tilt (Olsen, 1986). Termed "Milankovitch cycles", orbital variations overprinted the tectonic framework creating a predictable pattern of alternating arid and humid facies (e.g. Olsen, 1986; Olsen et al., 2005; Kent and Olsen, 2008). During humid intervals, perennial rivers, streams, and lakes occupied much of the Hartford Basin; during arid periods, intermittent streams, playas, and eolian dunes and sandsheets prevailed. Tectonic subsidence preferentially skewed the depocenter towards the eastern margin, resulting in the interfingering of alluvial fan, fluvial, and lacustrine sediments.

In the Early Jurassic, three great outpourings of basaltic lava produced flows up to 300 ft. (~100 m) deep. With low viscosity, high iron and magnesium content, and tendency to flow from long fissures rather than centralized craters, the Connecticut Valley flood basalts were emplaced rapidly over wide areas. The highly fluid lava filled the rift valley floor with broad 'lava lakes' that cooled to form the traprock ridges of the Connecticut Valley. These flows are preserved today as the Talcott, Holyoke-Deerfield, and Hampden Basalts. Extruded within a relatively short period of about 600 ky, (Olsen et al., 2003; Kent and Olsen, 2008; Blackburn et al., 2013) these flows, and related flows and dikes found along the Pangean rift margin are evidence of a massive igneous province that ranks among the largest volcanic events in Earth history.

III. Paleontology, Paleoecology, and Taphonomy

Fossils from the early Mesozoic sedimentary rocks of the Connecticut Valley Lowland (Hartford and Deerfield Basins of the Newark Supergroup) first began to attract scientific attention at the beginning of the nineteenth century, and by 1860, the region had received widespread notoriety for its fossil specimens, particularly reptile footprints and fishes. In recent decades, a resurgence of interest in local paleontology has fueled the reopening of classic sites and led to the discovery of numerous productive new localities.

The fossiliferous strata of the Connecticut Valley can now be termed a "Lagerstätte" by virtue of the concentration and exceptional preservation of its remains. During humid intervals in the earliest Jurassic, Connecticut and Massachusetts contained luxuriant forests of conifers, cycadeoids, horsetails and ferns, which were host to a diverse fauna of small to medium-sized dinosaurs (both herbivorous and carnivorous forms), lizard-like and crocodile-like reptiles. Numerous species of fishes inhabited the perennial lakes in the region. The abundance and variety of higher-order consumers (reptiles and fishes) confirms the existence of large populations of invertebrates, including bivalve mollusks, conchostracans, ostracodes and insects. Primary consumers in both terrestrial and aquatic habitats relied on autotrophic bacteria, algae and macroscopic plants as food. Recent discoveries of invertebrates at many localities have enhanced the understanding of paleoecology, enabling for the first time, reconstruction of detailed Early Jurassic food chains in the region.

Due to highly oxidizing depositional environments and a lack of ambient conditions for preservation, fossils are exceedingly scarce in most of the coarse-grained alluvial and fluvial "red beds" which constitute the Triassic New Haven Formation at the base of the Hartford Basin section; fossils are likewise rare in similar lithologies in the upper Portland Formation, the youngest unit in the basin.

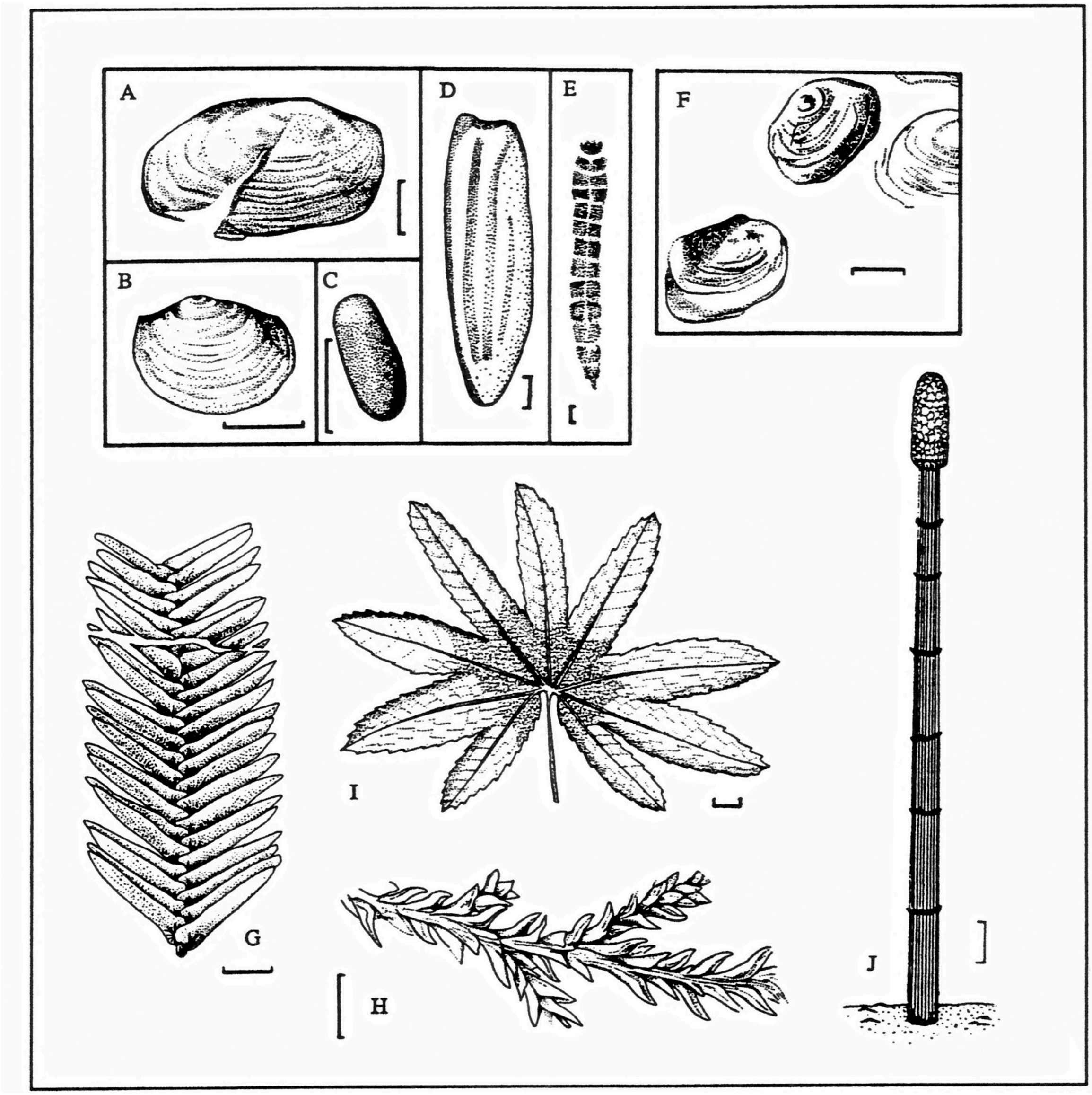


Figure 6. Invertebrates and plants from Early Jurassic lacustrine-deltaic deposits in the Hartford Basin. A) Unionid clam. B) Clam shrimp *Cyzicus sp*. C) Darwinulid ostracode. D) Beetle elytron (wing cover). E) Larval insect. F) Clam shrimps *Cornia sp*. G) Cycadeoid *Otozamites*. H) Conifer *Pagiophyllum*. I) Fern *Clathropteris*. J) Reconstruction of horsetail *Equisetites*. Scales: A, G-J, 1cm; B-F 1mm. Localities: A-D, Suffield, Conn.; E, Cromwell, Conn.; F, North Branford, Conn.; G. Durham, Conn.; H. South Hadley, Mass. Sources: A-H, Olsen, 1988; I-J, Ash, 1986. From McDonald (1992).

In the earliest Jurassic, a marked increase in lithospheric extension led to greater subsidence along the eastern boundary of the basin, periodically tapping underlying magma sources, and producing an asymmetric, internally drained half graben with regional paleoslopes to the east. Tectonic events, coupled with Milankovitch orbital cyclicity and a strongly monsoonal climate created lakes of varying size, depth and duration on the lowland floor. In central and southern Connecticut, symmetrical cycles of gray mudstone-black shale-gray mudstone are conspicuous and laterally persistent in the Shuttle Meadow, East Berlin and lower Portland Formations. These cycles record the history of perennial stratified lakes and typically thicken toward the eastern margin (Fig. 2). The larger, deeper lakes were comparable to those that now delineate the rift zones of East Africa or once occupied Death Valley. Lithology and sedimentary structures attest that lakes expanded and contracted seasonally as well as responding to longer-term orbital forcing. The preservation of fine laminations in some black shale units reflects reducing conditions and the absence of bioturbation, indicating that the deepest portions of many lakes were stagnant and anoxic: ideal environments for the preservation of fossils.

With the notable exception of a few reptilian skeletal remains preserved in alluvial or fluvial red beds, most early Mesozoic fossils from the Connecticut Valley Lowland are found in sediments deposited in or around perennial or ephemeral lakes in the earliest Jurassic. Not surprisingly, the majority of highly productive lake-bottom or lake-margin fossil sites are close to the down-faulted eastern border of the basin, where lakes were deepest and high sedimentation rates prevailed.

Fossil Fishes. In one of the earliest mentions of fossil fishes from North America, specimens from Westfield, Connecticut, near Middletown, were noted by Benjamin Silliman, Sr. in 1816, in the first edition of Cleaveland's *Mineralogy* (McDonald, 1996). Louis Agassiz included figures and diagnoses of Connecticut Valley fishes in his monumental treatise *Poissons Fossiles* (1833-1843), and later, local forms were described and classified by W.C. and J.H. Redfield (1837-1856) and J.S. Newberry (1888). Though he produced few publications, the most inveterate collector at the turn of the twentieth century was S. Ward Loper, Curator of the Natural History Museum at Wesleyan. Over four decades, Loper supplied many specimens to Newberry, O.C. Marsh, and to major museums. In an important 1891 paper with William Morris Davis, Loper recognized the lateral continuity of fossiliferous units (cycles) in the Shuttle Meadow and East Berlin Formations, naming and pinpointing productive localities. Following in Loper's footsteps, in recent years, McDonald, Olsen, LeTourneau, Phillip Huber, Bruce Cornet and others have added literally tens of thousands of Jurassic fossil fishes to collections at Wesleyan, Yale, the American Museum of Natural History, and the Paleontological Research Institution.

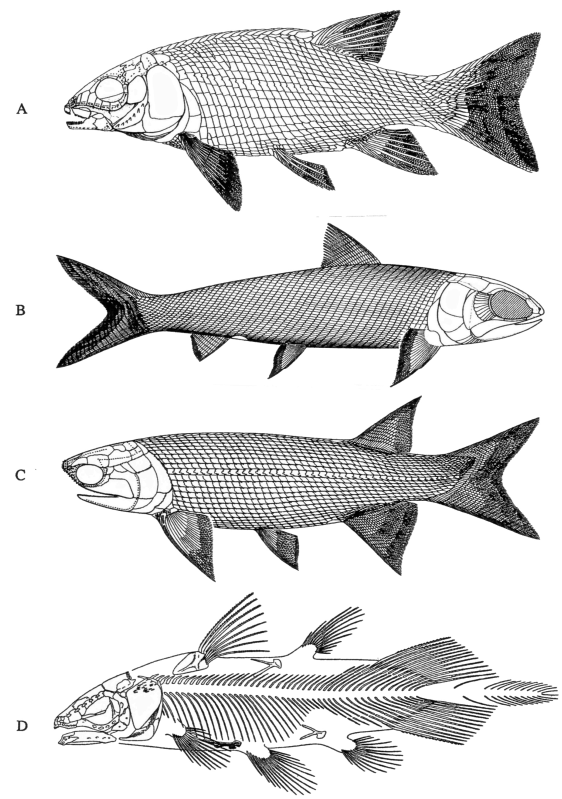


Figure 7. Newark Supergroup fishes. A: *Semionotus sp.* B: *Ptycholepis marshi.* C: *Redfieldius gracilis.* D: *Diplurus newarki.* Figure adapted from McDonald (1992).

Four genera of fossil fishes are currently recognized from the Early Jurassic rocks of the Connecticut Valley (McDonald, 1992, 2010). *Semionotus* is the most common genus and semionotids have been recovered from all the known fossil fish sites in the Valley. Semionotids display an astounding plethora of body forms and shapes, from slender types to deep-bodied, hunchbacked varieties and everything in between. More than three-dozen species have been described from local rocks and similar-age strata in New Jersey (McCune, 1987). *Semionotus* was a sturdy, heavily built fish; some species attained lengths of 40 cm. It had a short mouth armed with peg-like or conical teeth suitable for crushing conchostracans and other crustaceans, aquatic insects and small mollusks. Most semionotids likely inhabited near-shore environments where such food was plentiful. Coprolitic masses consisting of fragmented conchostracans are common at East Berlin Fm. fossil sites and probably derive from *Semionotus*.

Redfieldius and the scarce *Ptycholepis* were streamlined fishes averaging 16-20 cm in length. Both genera had elongated jaws lined with tiny teeth and large, subterminal mouths. *Redfieldius* was likely a bottom feeder on soft-bodied invertebrates and detritus; the torpedo-shaped *Ptycholepis*, whose mouth could be opened widely, presumably was a fast swimmer and an active predator (McDonald, 2010).

The coelacanth *Diplurus longicaudatus* is the largest but least common of the Connecticut Valley fishes. At maximum length approaching one meter, *Diplurus* was an apex predator in Early Jurassic lake ecosystems, with a diet consisting of other fishes. Its massive, gaping mouth allowed it to gulp its victims whole, grinding them up using its bony palate and throat plates. Among the most common fossils at Valley fish localities are round, ovoid or tapering, black, phosphate-rich organic masses up to 16 cm in length; these are very likely coprolites produced by *Diplurus*. Some of these coprolites contain fish bones and scales, and most specimens of *D. longicaudatus* contain large coprolites in the gut region.

Taphonomy. Taphonomy is the aspect of paleontology that examines the post-mortem history of organisms from their death to when they are discovered as fossils. This may include predation, decay and decomposition, transport, burial and compaction, as well as numerous diagenetic processes that may alter the physical condition or chemistry of the remains.

Fossil fishes have been discovered in perennial lake strata at more than 30 sites in the Connecticut Valley, though the quality of their preservation varies markedly. There is a direct correlation between distance from the eastern margin of the Valley and quality of preservation (McDonald and LeTourneau, 1989). The best-preserved specimens come from localities adjacent to the margin, where lakes were deepest, where anoxic bottom waters retarded decomposition and where high rates of sedimentation rapidly buried fish carcasses.

At nearly all localities, fish specimens consist of markedly flattened, black carbonaceous skeletons; most individuals are preserved lying on their side. On well-preserved examples of *Semionotus*, *Redfieldius* and *Ptycholepis* typically only the scales, fins and skull bones are visible. Like the modern gar, these genera have thick bony scales coated with ganoin (a glossy, enamel-like, calcified tissue composed of apatite and protein) giving specimens a varnished appearance. *Diplurus*, the large coelacanth, has relatively thin scales; the internal elements of its skeleton are readily apparent.

The vast majority of fishes preserved in black, microlaminated shale is whole and intact, and evidence of post-mortem predation is exceedingly scarce. Given their thick, heavy scales and bones, dead fishes soon sank into anoxic bottom water where few decomposing organisms could survive. Near the basin margin, higher sedimentation rates rapidly buried fishes in oxygen-depleted black mud. Fishes that were not quickly entombed were slowly decomposed and mechanically disarticulated (see Fig. 8). Physical decomposition began at the delicate fin and tail extremities, as well as in the snout and gill regions. Continued decay loosened belly and dorsal ridge scales. A few specimens show “exploded” masses of bones and scales, typically in the belly and head regions, likely caused by “gas bursts” from the buildup of decomposition gases in the gut and cranial cavities. Sometimes only a solitary bone or a patch of disseminated scales is all that serves to identify a fish fossil.

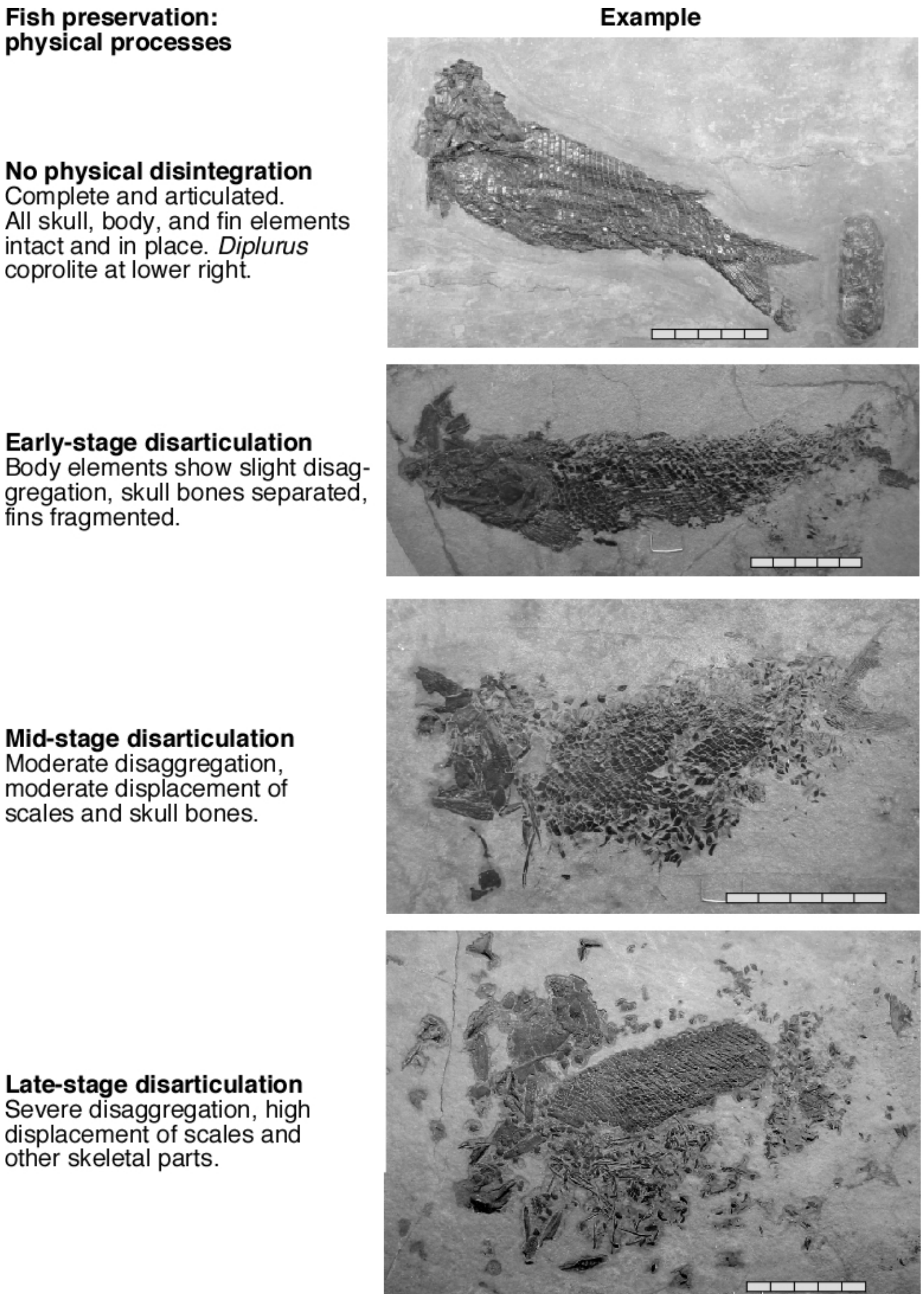


Figure 8. Physical disaggregation of fish remains. Specimens from the McDonald collection. Scale bar in cm.

Microbially-mediated biochemical decomposition and taphonomic phosphate loss also resulted in the dissolution of fishes (see Fig. 10), as documented in East Berlin Fm. lakes by McDonald and LeTourneau (1989). One lacustrine cycle in the middle East Berlin (informally the Westfield member) is highly fossiliferous and can be recognized at appropriate stratigraphic intervals over much of the Hartford Basin. At four localities this cycle is particularly well exposed. In North Branford, Connecticut, 0.7 km from the eastern boundary, the Westfield member fish beds are composed of 4.5 m of gray-black siltstone and microlaminated, calcareous black shale. *Semionotus* and *Redfieldius* from this site are complete and fully articulated, and occur in laterally compressed masses (up to 5 mm thick) with very robust scales and skull bones.

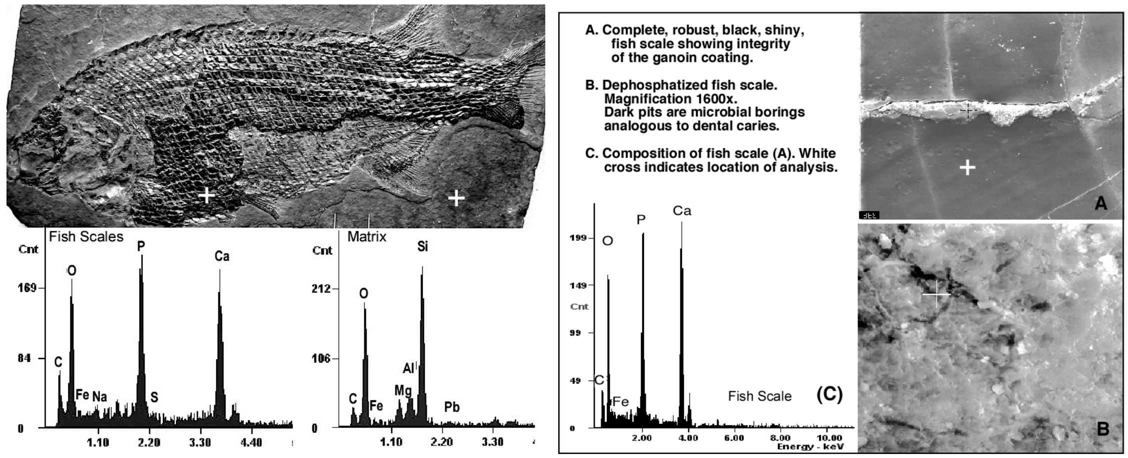


Figure 9. *Left:* Chemical analyses of fish scales and matrix; white crosses indicate sampling locations. *Right:* Chemical analyses of fish scales and electron microscopy (x1600) showing microbial borings; white cross indicates sampling target. Data: P.M. LeTourneau, EDAX analyses performed at Wesleyan University, 2009.

The mineral content of fish bones and scales is primarily hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$, which is sparingly soluble in lake water. However, fish bones are rapidly decomposed by the acidic end products of microbial (algal and bacterial) metabolism (Nriagu, 1983). In anoxic lacustrine environments, microbial dephosphatization is the primary cause of bone destruction; under oxic conditions, microbial action, coupled with mechanical abrasion and the activity of scavengers rapidly destroys fish remains.

At Loper's "Stevens" locality, just south of Durham, Connecticut, the Westfield member is exposed 2.3 km from the eastern edge of the basin. Here, approximately 1.5 m of micaeous, silty gray shale and very calcareous, microlaminated black shale comprise the fossil-bearing unit. The fishes from Stevens are complete, but typical specimens are only 1-2 mm thick and their skull bones in particular exhibit very apparent loss of volume. The skulls of *Semionotus* and *Redfieldius* from Stevens are black, but the scales and fins of fishes from the more calcareous layers are covered with a blue-white coating of calcite (once thought to be vivianite), which makes the specimens very conspicuous on the gray-black rock (see Fig. 10). Some fishes from the less calcareous upper beds have pyrite coatings on their scales and fins.

Eight kilometers from the basin margin at Westfield, Connecticut, near Middletown, a stream exposure of the Westfield member reveals 0.8 m of fossiliferous strata. The calcareous, microlaminated black shale here has been correlated layer-for-layer with beds at Stevens (Olsen, 1988). Fishes are typically complete, but even the best specimens are less than 1 mm thick and exhibit profound volume loss. Scales and fins are readily visible, but only vague, dark outlines of the skulls can be observed. Some specimens show blue-white calcite coatings on the scales. Skull and shoulder girdle bones are most susceptible to dissolution; many otherwise complete and fully articulated individuals possess only traces of skull elements. *Diplurus* coprolites from Westfield also show dissolution; the black coprolites sometimes are surrounded by light-colored "halos" of leached substances.

A fourth excellent exposure of the Westfield member is found in road cuts completed in 1987 in East Berlin, Connecticut, 12 km west of the basin margin. The dark shale-mudstone unit here is 0.7 m thick, but fishes are restricted to a 20 cm zone of calcareous, microlaminated black shale in the center of the lake cycle. As at other localities, specimens are whole and articulated, but here they are preserved only as indistinct, "headless" organic films.

Fish Preservation: biochemical processes, distance from footwall margin, and depositional environment

Example

No dephosphatization
Complete and articulated. All skull, body, and fin elements robust. No carbonate coatings.

<1.5 km

Deep lake interbedded with alluvial fan and fan delta, high sedimentation rates.

Partial dephosphatization
Articulated, skull bones thinned or partially absent. Scales and fin elements present, but reduced in volume. Exhibits blue-white carbonate coatings from dephosphatization.

2 -5 km

Deep lake, anoxic benthic zone

Nearly complete dephosphatization
Articulated. All body elements reduced to blue-white carbonate film from dephosphatization.

5 - 10 km

Deep lake, anoxic benthic zone, slow sedimentation rates.

Complete dephosphatization
Articulated. All bones, scales, and fins absent. No carbonate coatings. Dephosphatization halo present.

~ 10+ km

Deep lake, anoxic benthic zone, slow sedimentation rates.

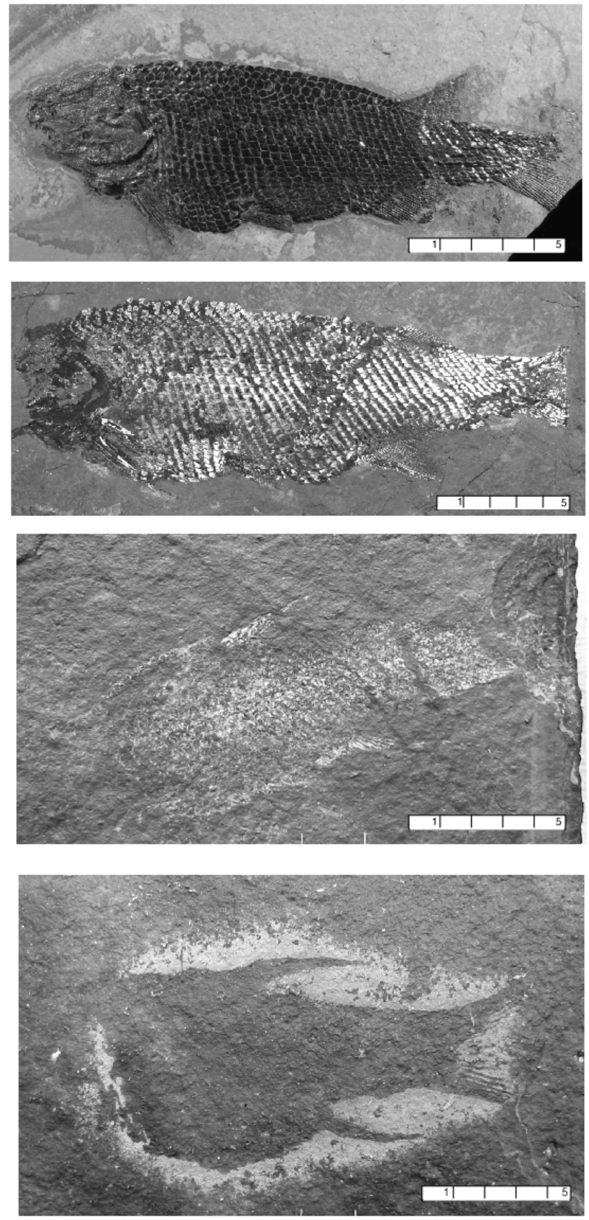


Figure 10. Dephosphatization of fossil fishes as a function of burial rates and paleogeography. Specimens from the McDonald Collection. Scale bar in cm.

Congruent with the geometry of other Hartford Basin perennial lakes, due to asymmetric subsidence of the basin floor, large East Berlin lakes attained maximum depths adjacent to the eastern fault boundary and shoaled gradually toward the west (LeTourneau and McDonald, 1985; McDonald and LeTourneau, 1988). Along the eastern margin, just offshore from alluvial fans and fan deltas, relatively high rates of sedimentation in anoxic bottom waters limited the dissolution of fish remains at the sediment-water interface, preserving the robust nature of bones, fins and scales. Subsequent compaction may have reduced pore-water volume, and hence, post-burial microbial dephosphatization.

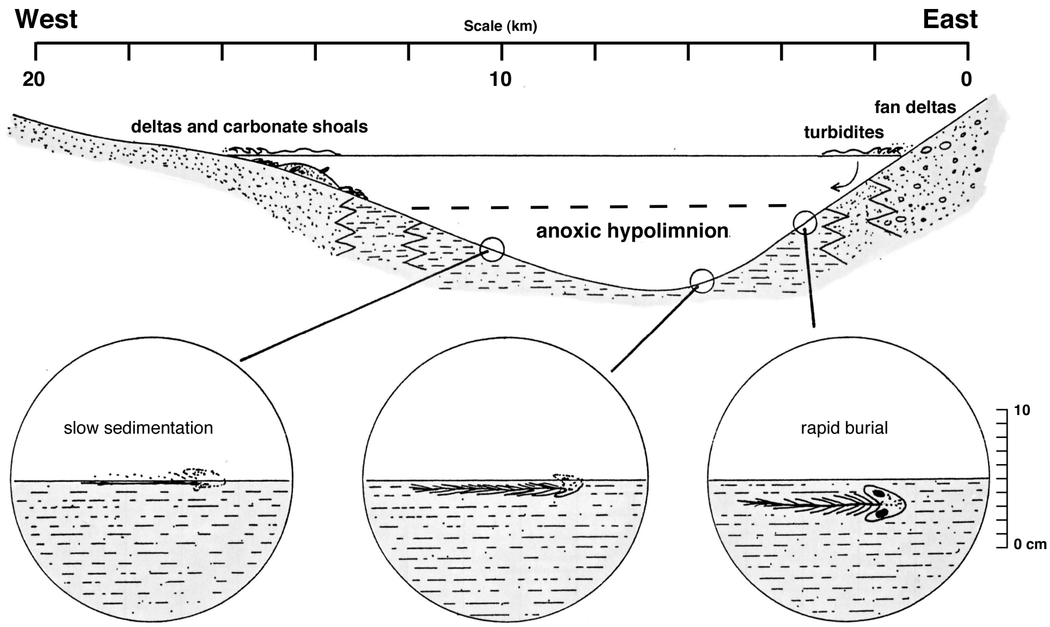


Figure 11. Taphonomic-depositional model of fossil fish preservation (McDonald and LeTourneau, 1989).

During lake high stands, the central portions of Hartford Basin lakes, as represented by the Westfield and East Berlin localities, were distant from sediment sources, and moderate to slow rates of fine clastic deposition prevailed. Fish carcasses may have lain for lengthy periods in anoxic waters on the lake bottom or within the upper few centimeters of sediment, and thus were subjected to prolonged microbial colonization and degradation. Bone-rich skull and shoulder girdle elements were readily dephosphatized; ganoin-covered, proteinaceous scales and fins were preferentially preserved.

The "Bluff Head" locality in the Shuttle Meadow Fm. in North Guilford, Connecticut, lies less than 2 km from the eastern basin margin. It was only partly quarried by Loper, but more extensive excavations by McDonald, Cornet, McCune, Huber and others have revealed it to be the premier site in the Valley in terms of density of fossils and quality of preservation. Taphonomic features of this locality include several "fish-kill horizons" - zones in which hundreds of fish are found on single bedding planes. Mass mortality of fish populations, also seen at other localities, was very likely caused by the shrinking of lakes during the monsoonal dry season and the entrapment of large numbers of fishes in near-shore waters.

Additional Geochemical Studies. Pyrite concentrations and sulfur isotopic compositions ($d^{34}S_{py}$) of fossil-fish-bearing laminated shales from the Westfield member reflect markedly varied depositional or diagenetic environments across the basin. At the four above-mentioned locations of the Westfield member (North Branford, Stevens, Westfield, and East Berlin), $d^{34}S_{py}$ values positively correlate with pyrite sulfur concentrations. Sites associated with deeper water, North Branford and Stevens, have more positive $d^{34}S_{py}$ values compared to the East Berlin location, which is interpreted as a shallower environment (Leonard, 2013). These relationships are consistent with a more closed sulfate-sulfide system in deeper water sites where pyrite formation greatly reduced the available sulfate pool resulting in higher $d^{34}S_{py}$ values and higher pyrite concentrations relative to the shallower water sites. The higher $d^{34}S_{py}$ values at the deeper water locations could be attributed to an increasingly stratified anoxic water column, or more extensive bacterial sulfate reduction in the sediment porewaters related to early diagenesis.

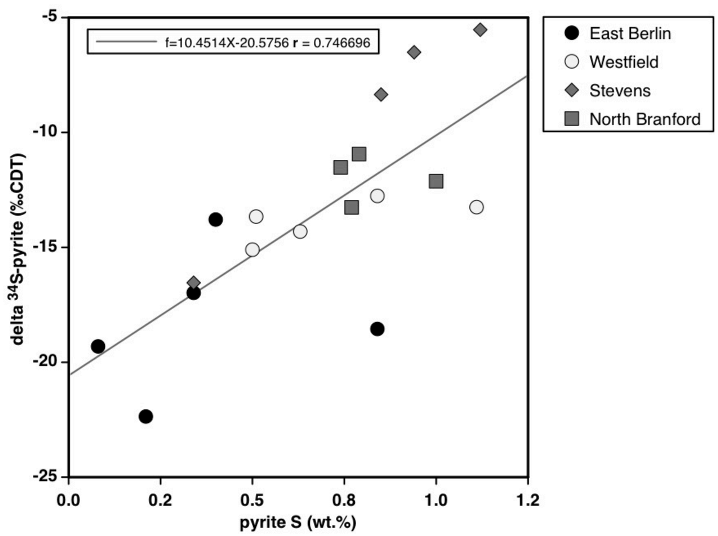


Figure 12. Pyrite sulfur isotopic compositions vs. pyrite sulfur concentrations in the Westfield member of the East Berlin Formation. Average sulfur isotopic compositions from the deeper sites (North Branford = -12.0‰, n=4; Stevens= -9.2‰, n=4) are more positive than shallower sites (Westfield = -13.8‰, n=5; East Berlin = -18.2‰, n=5) (Data from Leonard, 2013).

Soft fish parts containing organic P and hard fish parts largely composed of hydroxyapatite (HAp) undergo diagenesis simultaneously with the organic P being released into solution and metastable HAp being degraded on a timescale of days to months depending on water redox conditions (Nriagu, 1983; Posner et al., 1984). Both hard and soft parts of Jurassic fishes and coprolites are preserved as Ca-P mineral phases in the North Branford, Stevens, and Westfield locations of the Westfield member, while fishes in the East Berlin location exist as only outlines, carbonates, or thin apatite phases (McDonald and LeTourneau, 1989; Leonard, 2013).

Semionotus and *Redfieldius* have ganoid scales similar to modern gars. Ganoid scales consist of an anisotropic, highly mineralized outer ganoin (G) layer composed of ~95% HAp and <5% organics and a brownish, bony lamellar (BL) layer with variable HAp and relatively high organic content (Yang et al., 2013). X-ray diffraction, polarized light microscopy, SEM-EDS, and microprobe analyses of polished thin sections and powders demonstrate that the fossils from the Westfield member occur in a range of preservation mineralogies (Leonard, 2013; Ku, unpublished data).

In general, biogenic HAp will eventually be transformed into or be replaced by the more stable crystalline fluoroapatite (FAp) phase during diagenesis by gradual gain and loss of the carbonate ion in exchange with phosphate and fluorine anions (Manheim and Gulbrandensen, 1979). This process may include a range of intermediate phases including carbonate hydroxyapatite (CHAp) and carbonate fluoroapatite (CFAp). Well-preserved ganoid scales from the North Branford location are shown in Figure 13, with obvious ganoin and bony lamellar structures (upper left image).

Many North Branford fishes show the ganoin and bony lamellar structures being converted into fluoroapatite through a dark, organic-rich transition phase found between the FAp and HAp phases (Fig. 13, samples NB6 and NB15). The FAp phase is anisotropic and consists of nearly 100% total oxide concentrations as measured by microprobe, which compares well with accepted pure FAp mineral standards. The organic-rich transition phase has much lower Ca, P, and F concentrations and is nearly opaque in thin section. Coprolites often contain a mixture of apatite phases, though amorphous, organic-rich phases are more common. Ongoing mineralogical and chemical analyses will identify the various pathways of fossil fish preservation and further constrain the diagenetic conditions and depositional environments required to preserve these fossils.

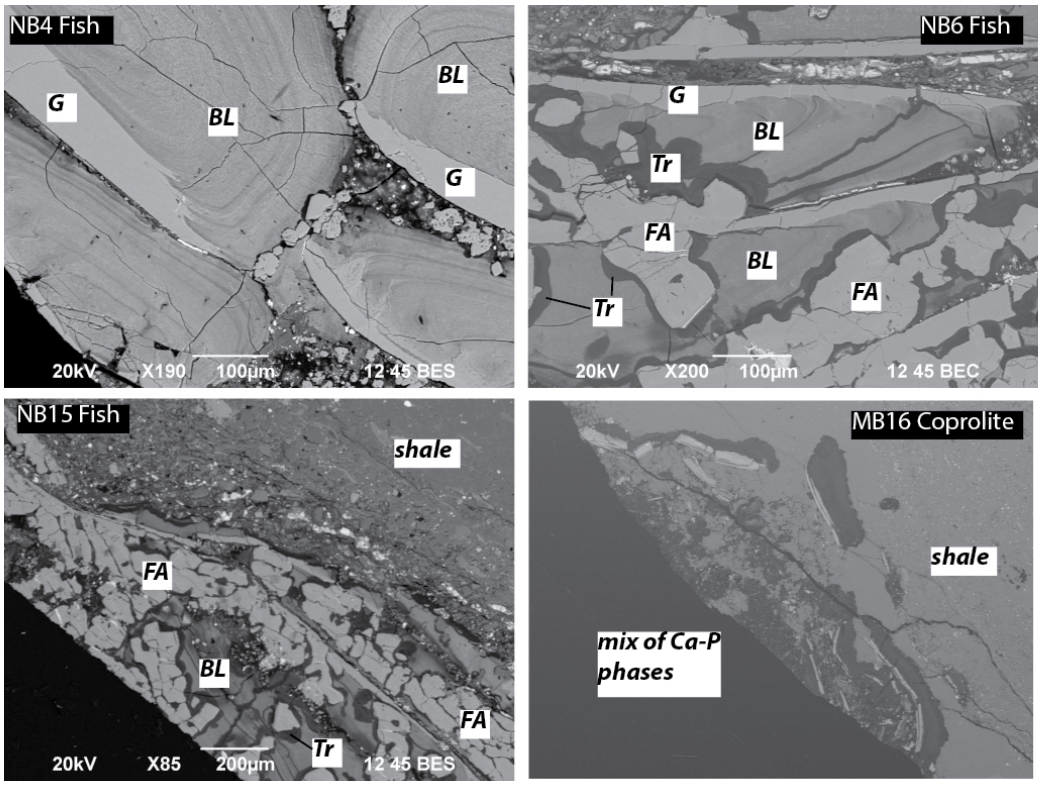


Figure 13. Scanning electron microscope images of fossil fish scales and coprolites. Sample NB4 (upper left) contains well-preserved scales with ganoin (G) and bony lamellar (BL) components. The mineralogy and structure of the scales appear relatively unaltered. Sample NB6 (upper right) demonstrates that the ganoin and bony lamellar sections alter to crystalline fluoroapatite (FA), most likely through an organic-rich transition (Tr) phase commonly found surrounding the authigenic fluoroapatite. Sample NB15 (lower left) is an example of a fish scale almost completely transformed into fluoroapatite with only traces of the ganoin or bony lamellar structures remaining. Sample MB16 (lower right) is an example of a coprolite, which contains a mixture of ganoin, bony lamellar, organic-rich transition phases, and fluoroapatite. Coprolites often contain several other Ca-P phases.

Dinosaurs, lakes and fishes. The existence of seasonally expanding/contracting perennial lakes may readily explain three perplexing questions regarding Connecticut Valley dinosaurs. Why are dinosaur tracks in such great abundance on single bedding planes, such as at Dinosaur State Park in Rocky Hill, Connecticut or the Mount Tom site in Holyoke, Massachusetts? Why are local tracks predominantly those of carnivorous theropod dinosaurs? What prey could support large numbers of carnivorous dinosaurs?

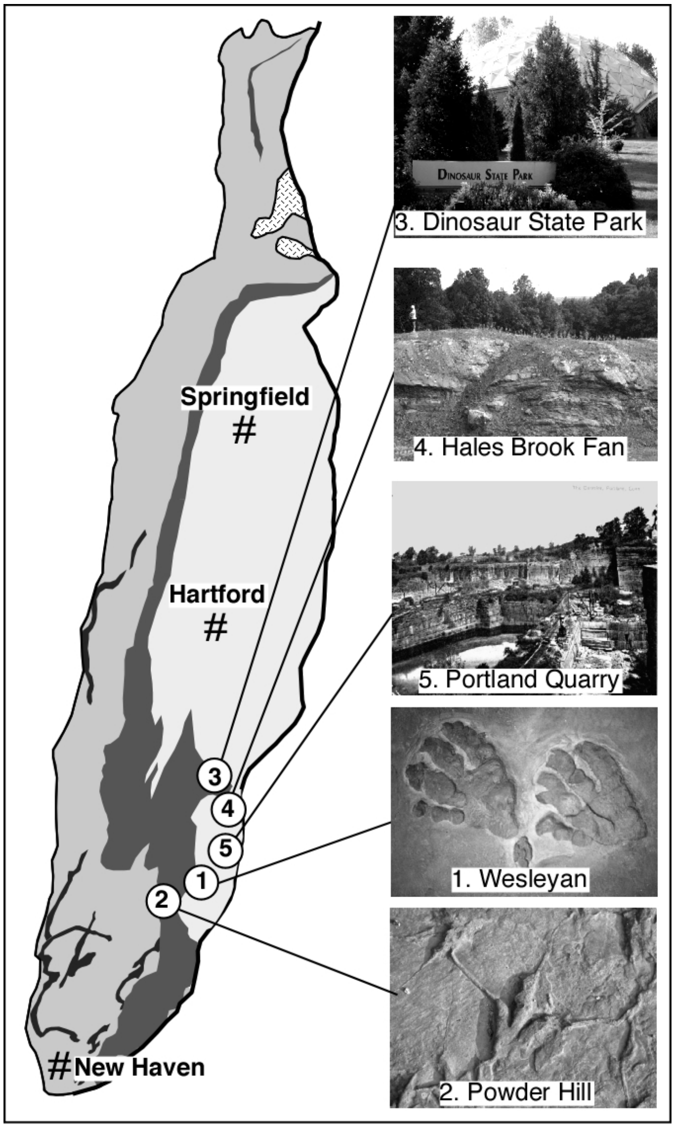
Many dinosaur tracks in the Connecticut Valley are preserved in lake shoreline sediments (Fig. 14). Trackway evidence indicates that individuals or small groups of dinosaurs frequented lake margins to obtain drinking water and to search for food. Surprisingly, no tracks of herbivores (notably prosauropod and ornithischian dinosaurs, common at the time) are represented among the 2000+ footprints uncovered at Dinosaur Park. During the monsoonal dry season, fishes stranded in shallow water were opportunistic prey for small theropods and larger carnivores such as *Dilophosaurus*, likely producer of the numerous *Eubrontes* tracks at Dinosaur Park and Mount Tom. Patrolling daily for food, theropod dinosaurs left myriad tracks in shoreline muds and sands. Baked hard by exposure to the sun as lakes shrank further, the footprints were covered and preserved by fresh sediment introduced during wet intervals. Dinosaur bones were seldom preserved in oxidizing shoreline environments. In the rainy season, when fishes were not so easy to catch, perhaps theropods sought out food in forested upland regions. Animals living in forested habitats also leave few preserved remains.

At 6 m in length, and nearly 2 m tall at the hip, the Early Jurassic *Dilophosaurus* was an imposing carnivore; clearly it ate anything that it desired! However, this theropod had an elongated head, flexible upper jaw, long, serrated teeth at the front of its mouth, and nostrils far back on the snout. Some researchers have suggested that these anatomical features were ideal for the capture of fishes. A food chain of algae, bacteria, and plants -> zooplankton -> conchostracans and other invertebrates -> *Semionotus* -> *Dilophosaurus* seems entirely reasonable.

Although the details of early Mesozoic terrestrial communities and ecosystems in the Connecticut Valley remain vague, evidence of thriving populations of plants, herbivores and carnivores is preserved in the rock record, and new discoveries steadily add to our understanding of the Jurassic world.

Figure 14. Early Jurassic lake shoreline scene featuring *Dilophosaurus,* the possible producer of *Eubrontes* tracks. Diorama and mural at Dinosaur State Park. Photo by Richard Bergen. From McDonald (2010).

IV. Field Trip.



List of Stops

Stop 1. Wesleyan University, Exley Science Center, Parking Lot D, Lawn Ave., Middletown, Conn.
41.552552, -72.657051

Stop 2. Powder Hill Dinosaur Park, 105-135 Powder Hill Road, Middlefield, Conn.
41.502533, -72.730589

Stop 3. Dinosaur State Park, 400 West St., Rocky Hill, Conn. BYO Picnic Lunch Stop.
41.651599, -72.655819

Travel to South Glastonbury via historic Rocky Hill Ferry
Ferry Landing, Route 160 to Meadow Road, Rocky Hill, Conn.
41.666385, -72.629895

Stop 4. Hales Brook Fan Delta, Old Maid's Lane, South Glastonbury, Conn.
41.632185, -72.617663

Stop 5. Portland Brownstone Quarries, Brownstone Ave., Portland, Conn.
41.574911, -72.645334

Stop 1. Wesleyan University, Exley Science Center, Middletown, Conn.
Lat. 41.552552, Long. -72.657051

Stop 1 features the Wesleyan dinosaur track collection and eolian building stones from sandstone quarries in Longmeadow, Massachusetts and Portland, Connecticut. Wesleyan University once held an economic interest in the Portland brownstone quarries. The extensive use of brown sandstone for campus buildings was not only fashionable but cost effective and practical as well. Noticing abundant marks and impressions on bedding planes, quarrymen and masons would set particularly interesting samples aside for Wesleyan geologists, or for use as decorative blocks. Superb dinosaur track specimens became part of the collection once housed in the Natural History Museum in Judd Hall, itself built of brownstone. When the "new" science center was completed in 1970, about a dozen blocks of sandstone displaying excellent footprints were mounted on the walls surrounding the central lecture hall. Today, the prints may be viewed in the Exley Science Center lobby and the Science Library. A light coating of varnish was applied to the tracks to enhance visibility.

The Wesleyan Dinosaur Track Collection. The Exley exhibit of tracks from the Connecticut Valley is dominated by specimens excavated from the Portland brownstone quarries, but full acquisition records are unavailable. The most common tracks are small brontozoid footprints that within the 20th century became called *Grallator* and *Anchisauripus*, and these, along with the larger *Eubrontes* (now the state fossil of Connecticut even though the holotype comes from Massachusetts), exemplify the nomenclatural chaos of Connecticut Valley tracks in general (Fig. 15) (see Olsen et al., 1998). There are also fine examples of the very rare sauropodomorph track *Otozoum* (Fig. 16). *Note:* For this paper, tracks in the Exley Science Center are referenced as follows: those on the north facing walls are designated with the suffix "[n]" (as in slab 4[n]); those on the south wall have suffix "[s]" (as in slab 4[s]).

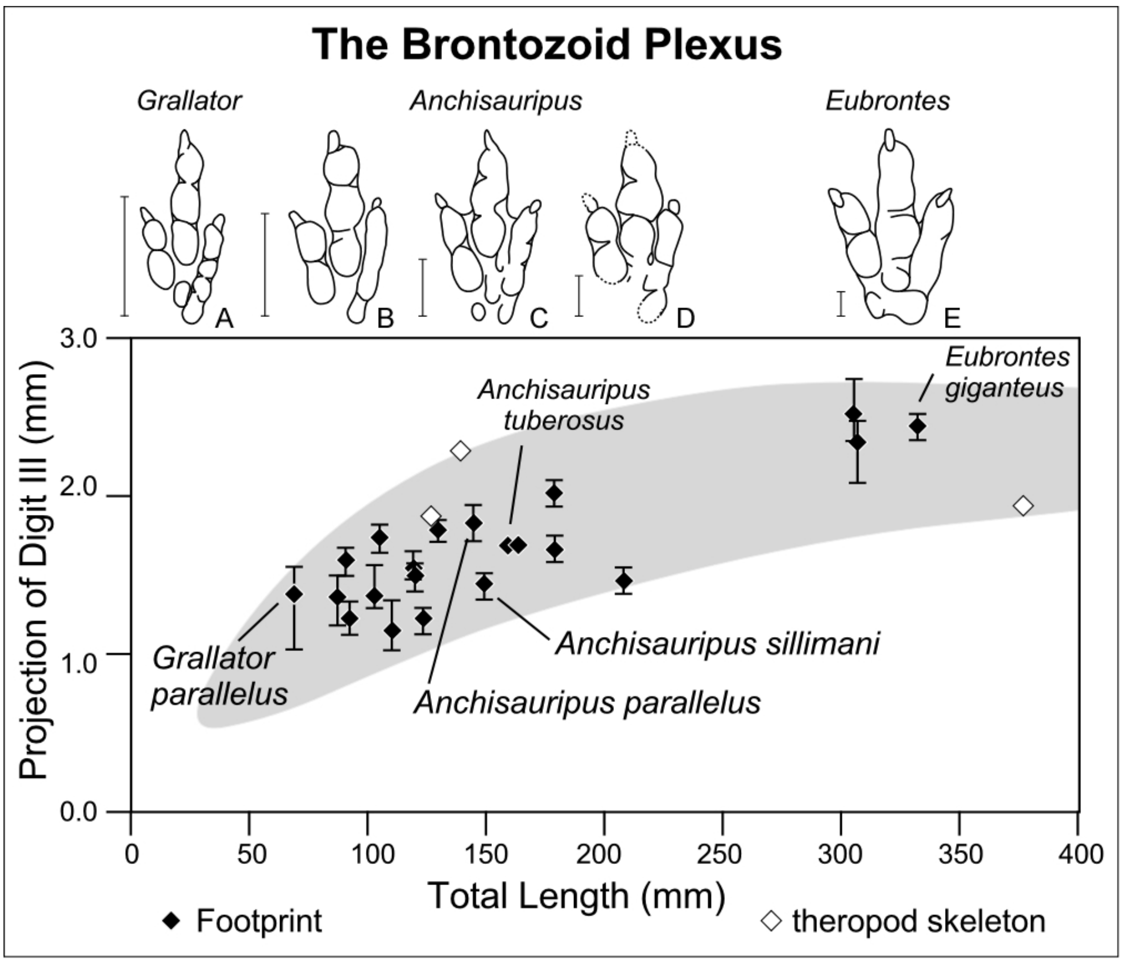


Figure 15. Changes in form with increasing size in brontozoid tracks makes objective identification and systematic classification difficult. Only holotype specimens are labeled: A) *Grallator parallelus*; B) *Anchisauripus parallelus*; C) *Anchisauripus sillimani*; D) *Anchisauripus tuberosus*; E) *Eubrontes giganteus*. Scale is 5 cm. Data from Olsen, et al. (1998).

Eubrontes giganteus (Figs. 15-E and 22) was the first dinosaur footprint to be named (Hitchcock, 1836), but that was not its original genus name. It was originally named *Ornithichnites giganteus* by Hitchcock, the genus name meaning "stony bird tracks". All of his bird-like tracks were intially included in this form-genus which he explicitly stated was not a biological genus. Hitchcock changed the name to *Ornithoidichnites* in 1841 to reflect the concept that they were "bird-like" tracks. Then in 1845, he decided he *could* name the animals themselves based on their traces, and renamed *Ornithoidichnites giganteus* as *Eubrontes giganteus*. To make matters worse, he never referred to *Eubrontes* again, substituting the name *Brontozoum* in 1847 and sticking to that name until his death. He also used *Brontozoum* for the majority of relatively narrow tracks later called *Anchisauripus* (Lull, 1904) and *Grallator* (Hitchcock, 1858). Hay (1902) recognized that the name *Eubrontes* had priority over *Brontozoum*, and regarded *Ornithichnites* and *Ornithoidichnites* as being invalid because they were *not* intended to be biological genera. Lull (1953) and most others have followed Hay's revision. Oddly, current zoological practice is exactly the opposite, and instead treats footprint names, i.e., ichnotaxa, as separate from biological (body) taxa. Thus, as argued by Rainforth (2005), it is quite clear that of all these names, *Ornithichnites* has priority and that Hitchcock intended for this name to apply to all of the tracks now commonly referred to as *Eubrontes*, *Anchisauripus*, and *Grallator*.

When faced with such a large number of specimens, it is very hard to distinguish these three ichnogenera from one another because they constitute a graded series in which shape changes with size (Fig. 15). These tracks, nonetheless, are easily distinguished from the other Connecticut Valley ichnogenera, *Anomoepus*, *Otozoum*, *Batrachopus*, *Rhynchosauroides*, and *Ameghinichnus*. Ichnologists do not yet know how to distinguish tracks formed at different stages in the growth of individual theropod dinosaurs. This is why the term brontozoid is used for this group of track forms. Ideally, it would be much clearer if *Ornithichnites* were resurrected, but because that name has been out of use for so long and *Eubrontes*, *Anchisauripus*, and *Grallator* are so entrenched, it seems quixotic to try to attempt this. Therefore, we continue to apply these three ichnogenera to the Connecticut Valley brontozoids.

Among the various slabs at Exley, several that are certainly from the Portland brownstone quarries look very much like a classic slab in the Hitchcock collection at Amherst's Beneski Museum. In particular, slab 4[n] bears a remarkable resemblance to BMNH 9-14, not just in its specific style of preservation, but also in having individual tracks that look virtually identical on the two slabs.

In regard to BMNH 9-14 (Fig. 16-A), Hitchcock (1858, p. 68-69) states:

> "*Not a few of them are seen … especially on Plate LX, fig. 1, which is from Middletown,* ***and is the gem of the Cabinet***" [our emphasis]. *The engraving is intended to be no more perfect than the specimen, which exhibits between fifty and sixty tracks with the phalangeal impressions und claws exceedingly distinct. They are in relief; and were it not for the mud veins, would show the foot of the animal as perfectly as if one lay petrified in each track, or rather projecting from the slab; for the tracks are in relief.*
>
> *This slab, of slightly reddish micaceous sandstone, has been used as a flagging stone in the streets of Middletown for sixty years. Fifteen or twenty years ago it was taken up, when the tracks were discovered on the under side, and it was secured by Dr. JOSEPH BARRETT, who thus early had become much interested in footmarks, and from him I purchased it for the Ichnological Cabinet. It was dug from the quarry about two miles west of the city, as Dr. BARRETT supposes, nearly eighty years ago; but at present that quarry exhibits no sign of any such tracks, and scarcely of any other*."

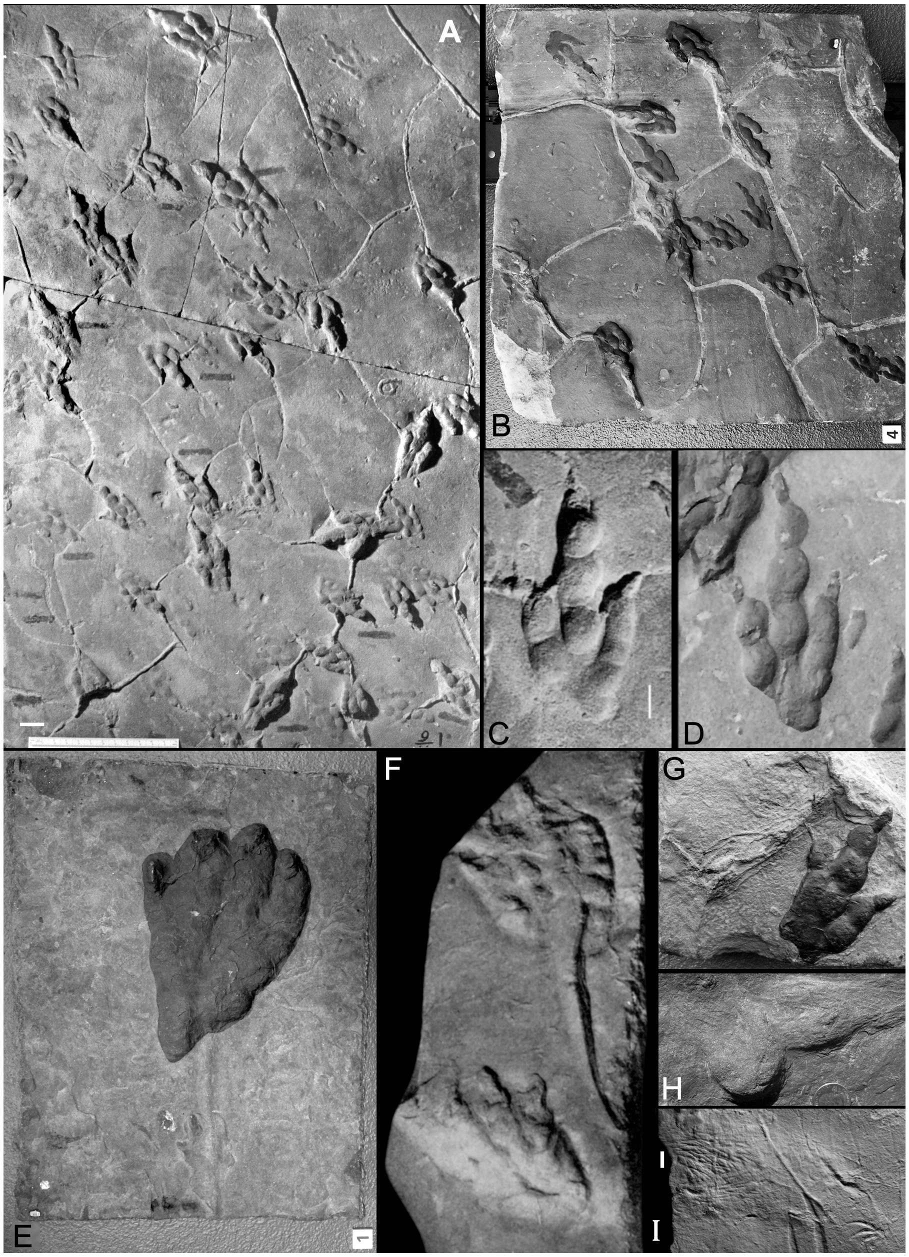


Figure 16. Exemplary tracks from the Exley Science Center and related specimens from the Beneski Museum, Amherst College.
A) Natural casts of brontozoid theropod tracks and mudcracks, once used as a sidewalk stone in Middletown, Conn. Beneski Museum (BMNH 9-14). Scale 5 cm.
B) Very similar smaller slab of brontozoid natural casts (4[n]) from the Portland quarries.
C) Single brontozoid track incorrectly designated the type of *Anchisauripus* (*Ornithichnites*) *sillimani* by Lull (1904), from BMNH 9-14 near middle of slab. Scale 2 cm.
D) Single track from slab 4[n] (at middle of B) that could have been made by the same individual as the track in C.
E) Slab 1[s](WU 183), natural cast of *Otozoum moodii*, made by a sauropodomorph and showing a tail trace. From the Portland quarries.
F) Natural cast of *Otozoum moodii*, WU 725, also from the Portland quarries, with a more prominent tail trace.
G) Natural cast of possible *Cynodontipus* burrow termination to left of a small brontozoid track (slab 7[n] = WU 185), from the Portland quarries (compare with H and I).
H) Natural cast of *Cynodontipus* burrow terminations, Meehan Quarry, Portland, Conn.
I) Impression of *Cynodontipus* burrow (left) and *Rhynchosauroides* sp. manus impression, Early Jurassic, Turners Falls Formation, Turners Falls, Massachussets (BMNH UC 112).

These two slabs convincingly represent the same horizon and bed. Especially prominent is the individual track that Lull (1904) used as the holotype of *Anchisauripus sillimani*. Amherst specimen BMNH 9-14 finds nearly an exact match on Wesleyan slab 4[n] (Fig. 16-B), and it is hard to believe they were not made by the same dinosaur. In addition, it is probable that the location as "…*two miles west of the city*…" is in error as that location is either in the Hampden Basalt or very close to the base of the Portland Formation, which has never to our knowledge produced a lithology anything like that of BMNH 9-14 or slab 4[n]. These two slabs are certainly from the Portland quarries. There are other similar slabs bearing small brontozoids, such as 5[n], 7[n], 9[n], and 10[n] that are also similar, but not as much as 4[n]. Joseph Barratt, whose name Hitchcock misspells above, died in 1882 and is buried in Indian Hill Cemetery about 500m from the Exley exhibit. His gravestone is comprised of a slab of red sandstone covered with brontozoid tracks (Guinness, 2003).

The Exley exhibit is especially noteworthy for the large proportion of the sauropodomorph track *Otozoum moodii* (Fig. 16-E, F). One slab in particular is mentioned from this collection by Hitchcock (1858, p. 125):

> "*Another fine slab from the same quarries belongs to the Wesleyan University at Middletown, and it is only on one part of this slab that I have ever seen the trace of a tail belonging to this animal. It is possible that the trail may not have been thus made; but such was not my conclusion when looking at it*."

There are two such traces in the collections at Wesleyan, both noted by Lull (1915). One, on exhibit here (WU 183 = 1[s]) (Fig. 16-E) is mentioned by Lull as the type of *Otozoum caudatum*, but he considered it a junior synonym of *O. moodii*. Slab WU 725, figured by Lull and located in the Joe Webb Peoples Museum at Wesleyan (Fig. 16-F) is a crisper specimen, with two tracks and an obvious tail-drag mark.

Several specimens of *Eubrontes* and other brontozoids on exhibit (e.g., 2[n]) are in a grayish lithology and certainly not from the Portland quarries. In fact, very few if any *Eubrontes* in this collection come from Portland. It is interesting to note that as a general pattern *Eubrontes* tends to be very rare in strata with *Otozoum*. For example, the type locality of *Otozoum* in the lower Portland Formation at South Hadley, Massachusetts has produced many *Otozoum*, and many small brontozoids, but no *Eubrontes*. Considering that *Otozoum* was made by a large sauropodomorph and *Eubrontes* was made by a large carnivore (the only one large enough to kill a healthy adult sauropodomorph) their near mutual exclusion may not be accidental.

Another slab of interest is 7[n] (WU 185) that has several good small brontozoids on it. In one corner, however, are marks (Fig. 16-G, H, I) that resemble the scratch marks on tetrapod burrows called *Cynodontipus*. For many years *Cynodontipus* was thought to be the footprint of a hairy non-mammaliform cynodont (Olsen et al., 2012). One example (Fig. 16-H) was found in the now closed Meehan Quarry, the most recent incarnation of the Portland brownstone quarries.

Eolian Features, Hall-Atwater Chemistry Building. The Hall-Atwater Chemistry building on the east side of the Exley complex was expanded in 1967, using light reddish-brown sandstone from quarries in an unusual facies of the Portland Formation in Longmeadow, Massachusetts. These quarries are located in the mid- to upper-stratigraphic levels of the Portland Formation, whereas, the Portland brownstone quarries occur in the lower part of the Formation. Once a serious competitor to the stone from Portland, the Longmeadow sandstone was of decidedly different character – more porous, better sorted, and overall more durable than the chocolate brown, often micaceous Portland rock. Like the Portland brownstone, the Longmeadow stone had also been widely used for gravestones and monuments since colonial times.

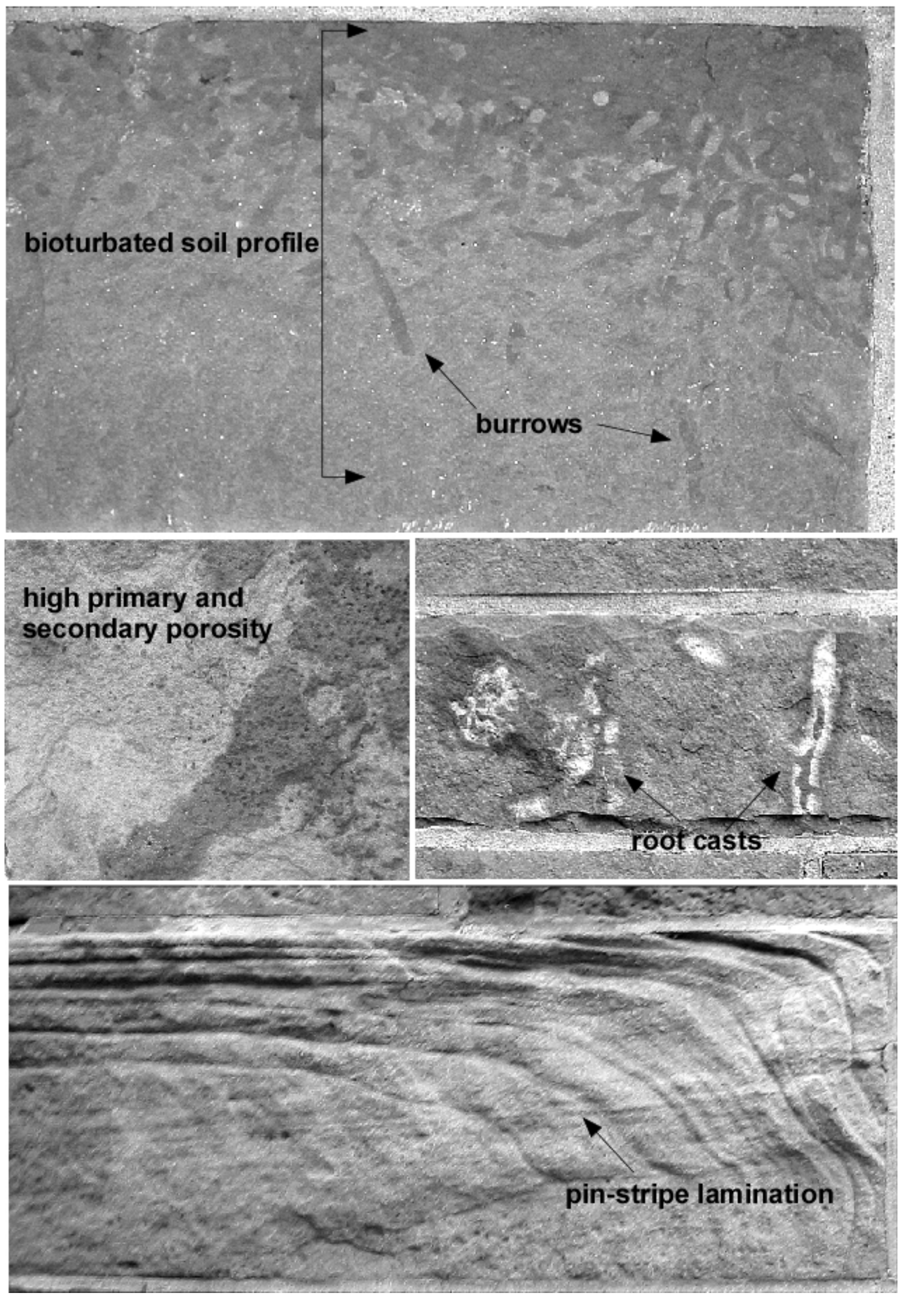


Figure 17. Longmeadow sandstone, Chemistry Building, Wesleyan University

Studies by LeTourneau and Huber (2006) determined that the Longmeadow sandstone was primarily deposited as eolian dunes and sand sheets during a dry climatic phase. The high porosity, good sorting, rounded and frosted grains, and diagnostic "pin-stripe" lamination demonstrate an eolian origin for much of the Longmeadow sandstone. Invertebrate burrows, root casts, and bioturbated soil profiles indicate that conditions alternated between arid and semi-arid; dry enough to promote eolian deposition, but with enough moisture to support sparse plants - similar to modern desert environments. The presence of root casts reveals the importance of vegetation in coppice dune initiation and stabilization. Similar features are also found in the Portland brownstone quarries.

Figure 18. Portland brownstone, Judd Hall, Wesleyan University. This building formerly housed Wesleyan's Natural History Museum and the Geology Department.

Many of the 19th century buildings along College Row are built of Portland brownstone from the quarries located across the Connecticut River from Middletown. Buildings with blocks lain with bedding in a horizontal position, such as those on Judd Hall, have weathered extremely well. In contrast, stones placed with bedding oriented vertically, such as the Chapel portico, have been severely impacted by water seepage and frost damage. During the peak years of production, high prices led to the widespread use of brownstone as veneers and "face-bedded" blocks that soon succumbed to weathering. As a result, brownstone gained an undeserved reputation as a poor-quality building stone (Guinness, 2003; LeTourneau, 2010).

Stop 2. Powder Hill Dinosaur Park, Powder Hill Road, Middlefield, Conn.
Lat. 441.502533, Long. -72.730589

Powder Hill Dinosaur Park has attracted tourists and scientists ever since dinosaur tracks were uncovered in a small rock quarry in the mid-1800s. Between 1848 and 1849, stone from the quarry was excavated and used to construct a dam across a stream known as the Beseck River. The resultant lake, called Beseck Lake, provided power to factories located nearby (Atkins, 1883). Dinosaur tracks were discovered in the rock being quarried (Warner and Fowler, Sr., 1966), and the engineer who designed the dam, A.M. Bailey, had slabs with the best tracks placed atop the dam so that they were visible to passersby (Thompson, 1996). Longwell and Dana (1932) referred to this site in their classic "*Walks and Rides in Central Connecticut and Massachusetts*" as the "Outdoor Exhibit of Dinosaur Tracks at Baileyville".

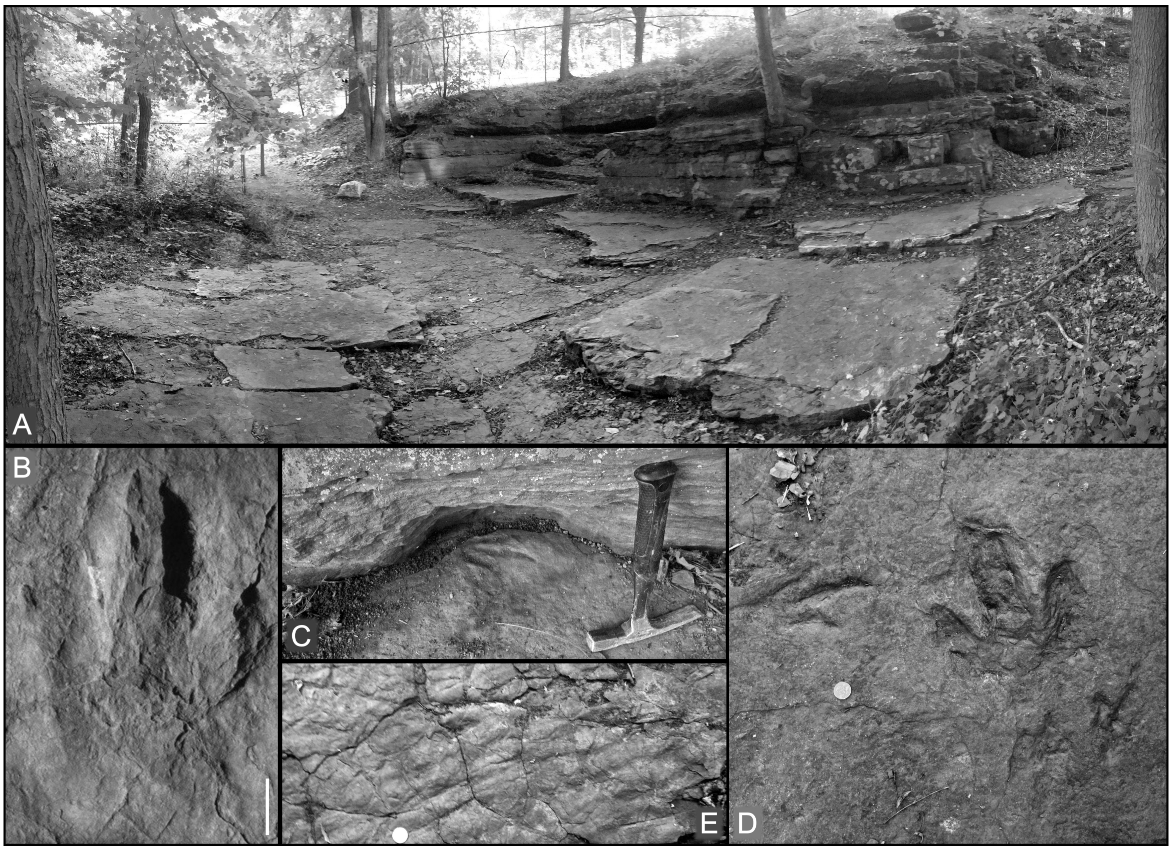


Figure 19. The Powder Hill Dinosaur Park: A) view of the quarry looking southeast on August 23, 2015 showing the general tabular form of the beds and the multiple track-bearing layers on the quarry floor; B) *Eubrontes* cf. *E. giganteus* undertrack from Getty et al. (2015), scale 5 cm; C) *Grallator* track excavated at base of thin-bedded sandy mudstones of shallow lacustrine origin; D) multiple sizes of brontozoid tracks showing how the larger forms are broader with less of a projecting middle digit, quarter for scale; E) oscillatory sandy mudstone desiccation cracks (enhanced by modern cracking).

Owned by the Coe family through the 19th century, the site became connected to Yale because Wesley R. Coe became a member of the faculty and Curator of Zoology at the Peabody Museum of Natural History, after earning his Ph.D. in zoology from Yale in 1895. As a result of the Coe-Yale connection, the portion of the quarry containing tracks was transferred to the University in 1929. For nearly half a century, Yale maintained the site for educational purposes, but eventually it was turned over to the Town of Middlefield who maintains the site as Powder Hill Dinosaur Park (Barclay, 1941).

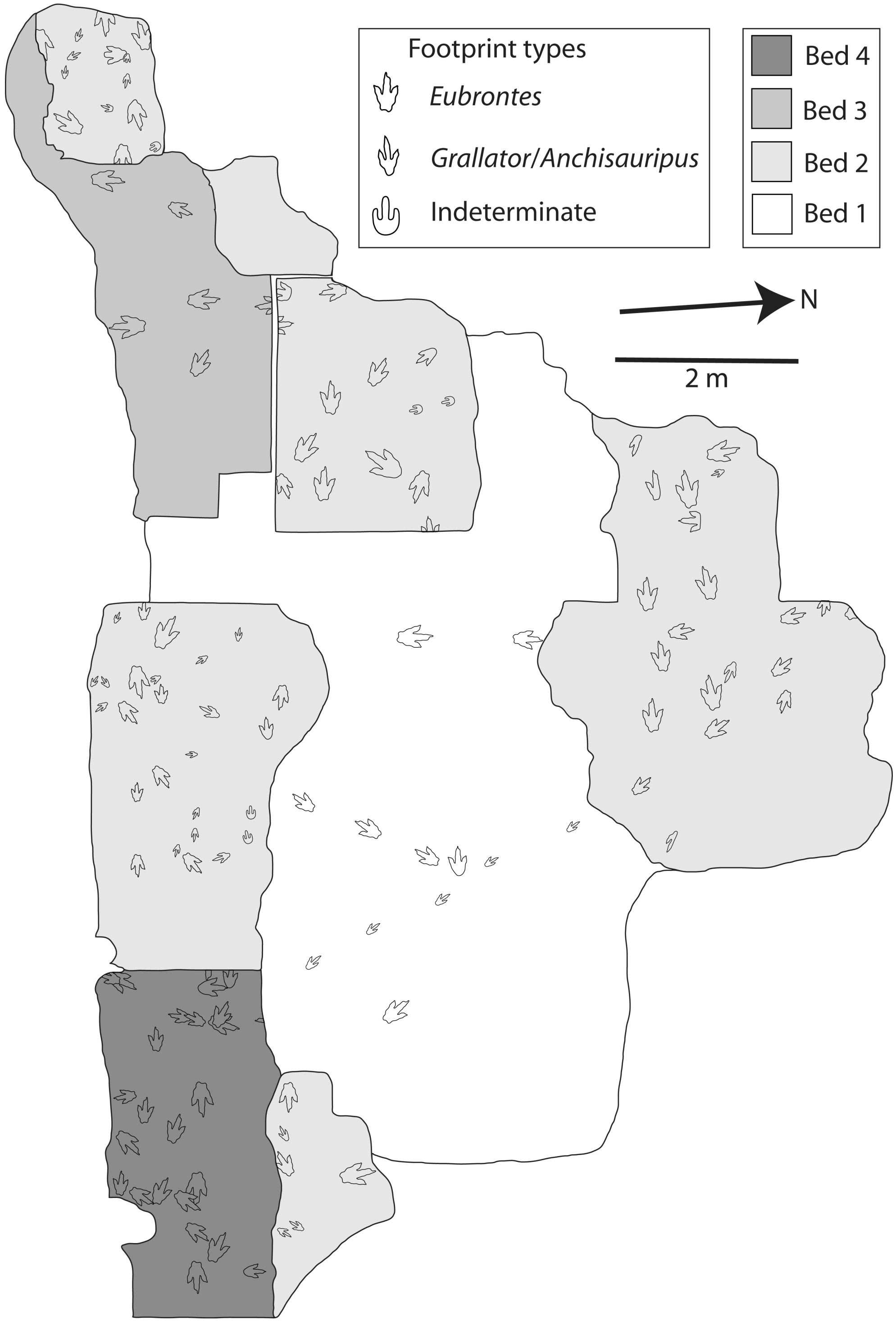


Figure 20. Map of dinosaur tracks, Powder Hill Dinosaur Park. Image after Getty et al. (2015).

The strata at Powder Hill Dinosaur Park belong to the Early Jurassic age East Berlin Formation. The layers exposed at this site mostly display drab reddish hues and were deposited in shallow lake, playa, and ephemeral stream environments. Sedimentary structures include oscillatory ripples, thin cross-bedding and planar laminations, sand-filled desiccation cracks, and soft-sediment deformation mainly formed by animal activity ("dinoturbation"). Scarce invertebrate burrows and crawling traces are present on some bedding surfaces and in cross-section. Bedding strikes N12°E and dips 20°E. Surfaces of at least four distinct layers display track impressions of three brontozoid ichnotaxa; *Eubrontes*, made by a large carnivorous theropod, and *Grallator* and *Anchisauripus* tracks made by smaller theropods. These are also a number of indeterminate underprints, impressions, or penetrative tracks made in water-saturated sediment.

Getty et al. (2015) identified more than 120 individual footprints that were made during four separate time intervals. *Eubrontes* trackways have no preferred orientations and provide no evidence of herding behavior. The alignment of some sets of tracks with wave ripples reveals shore-parallel movement of the trackmakers, consistent with hunting and scavenging along the lake margin (Getty et al., 2015). It is likely that some theropods fed on the abundant fish and small reptiles living in the littoral zone (McDonald, 2010). Orientation of wave-ripple crests indicates a local shoreline oriented roughly N-S, consistent with the axial orientation of Hartford Basin rift lakes proposed in the paleogeographic models of LeTourneau (1985a, 1985b), LeTourneau and McDonald (1985), and Horne et al. (1993).

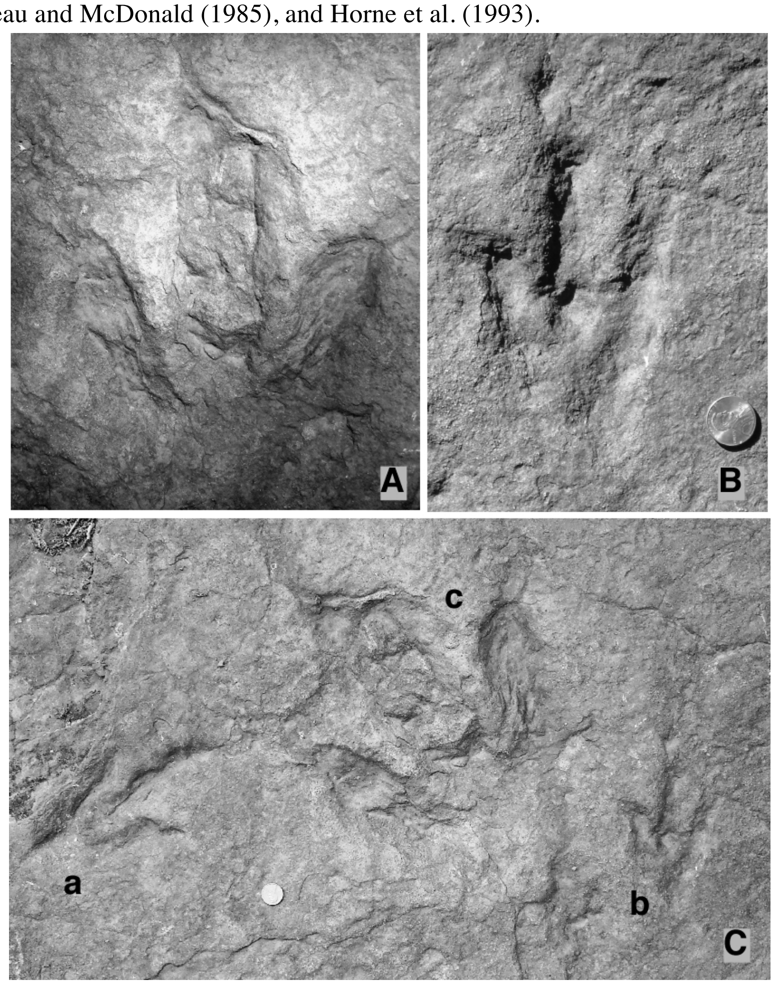


Figure 21. Typical dinosaur tracks at Powder Hill Dinosaur Park. **A)** *Eubrontes*, approx. 28 cm in length. **B)** *Grallator*, penny for scale. **C)** a-b. *Grallator*, c. *Eubrontes*, penny for scale. Photos: Patrick R. Getty.

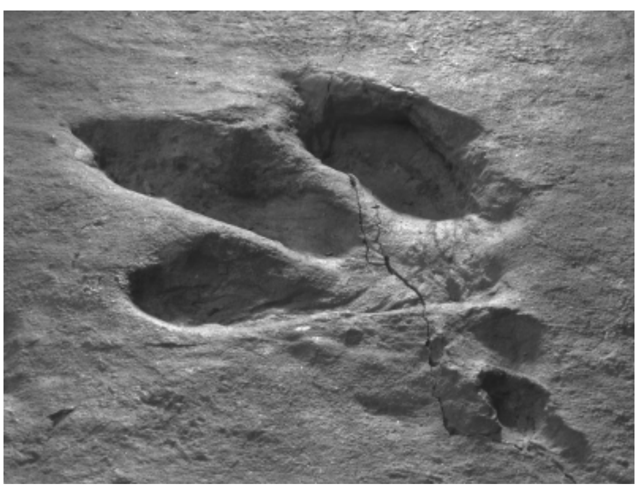
Stop 3. Dinosaur State Park, 400 West St., Rocky Hill, Connecticut. (BYO picnic lunch stop)
Lat. 41.651599, Long. -72.655819

The Dinosaur State Park trackways were discovered in 1966 during excavations for a state building. Recognizing that the abundant and well-preserved dinosaur tracks constituted a world-class find, Sidney S. Quarrier of the Connecticut Geological Survey, Joe Webb Peoples from Wesleyan, Yale's John Ostrom, and others, acted swiftly to preserve the site under State auspices (see McDonald, 2010). Today, Dinosaur State Park is one of the most visited Connecticut state parks and is an important locus of scientific research and environmental education. Due in large part to the Park's popularity and its wide recognition as a premier dinosaur track locale, the large theropod track *Eubrontes* was named the Connecticut state fossil.

Exposures here reveal nearly 2000 reptile tracks, most of which have been buried for preservation and future exhibition. The present geodesic building at the Park houses approximately 600 tracks. The tracks are found in lake shoreline gray sandstones, siltstones, and mudstones of the East Berlin Formation, about 20 m below the contact with the Hampden Basalt. Ripple marks, raindrop impressions, mudcracks, and the footprints themselves indicate shallow-water conditions and intermittent subaerial exposure. The track-bearing beds grade upward into gray mudstone and then tan sandstone and red mudstone.

The typical Connecticut Valley ichnogenera *Eubrontes*, *Anchisauripus*, *Grallator*, and *Batrachopus* have been identified at this locality (Ostrom and Quarrier, 1968). All but *Batrachopus* were made by small to large theropod (carnivorous) dinosaurs. *Batrachopus* was made by a small, fully terrestrial protosuchian crocodilian. *Eubrontes giganteus* tracks are the most common and are the only clear tracks visible *in situ* within the geodesic dome. *Eubrontes* trackways are oriented in all directions of the compass, trackways travel in fairly straight lines, and there is no obvious evidence of herding (Farlow and Galton, 2003). Based on what appear to be claw drags without any pad impressions, Coombs (1980) suggested some of the track makers were swimming, but Farlow and Galton (2003) argue that equivalent tracks were made by the *Eubrontes* trackmaker walking on a hard substrate.

Figure 22. *Eubrontes* track at Dinosaur State Park.
Length 40 cm. Photo by Richard Bergen. From McDonald (2010).



Eubrontes giganteus has the appropriate size and pedal morphology to be made by a dinosaur the size of the ceratosaurian theropod *Dilophosaurus*. Olsen et al. (2002) show that *Eubontes giganteus* appears within 10 ky after the Triassic-Jurassic boundary and that it represents the first evidence of truly large theropod dinosaurs following the boundary extinctions. The largest Triassic theropods *Gojirosaurus* and *Liliensternus* were less than 80% the size of the larger *Dilophosaurus*. The appearance of these larger Jurassic theropods could be due to either an abrupt evolutionary event or an immigration event. Although we cannot currently distinguish between these two possibilities, we favor the former in which the size increase is an evolutionary response to “ecological release” in which extinction of the Triassic top predators (rauisuchians and phytosaurs) allowed a very rapid size increase in Jurassic carnivores in the absence of competitors.

Figure 23. Wesleyan Professor Joe Webb Peoples pointing to the newly discovered trackways at the future Dinosaur State Park in 1966. Photo by John Howard. From Dinosaur State Park archives.

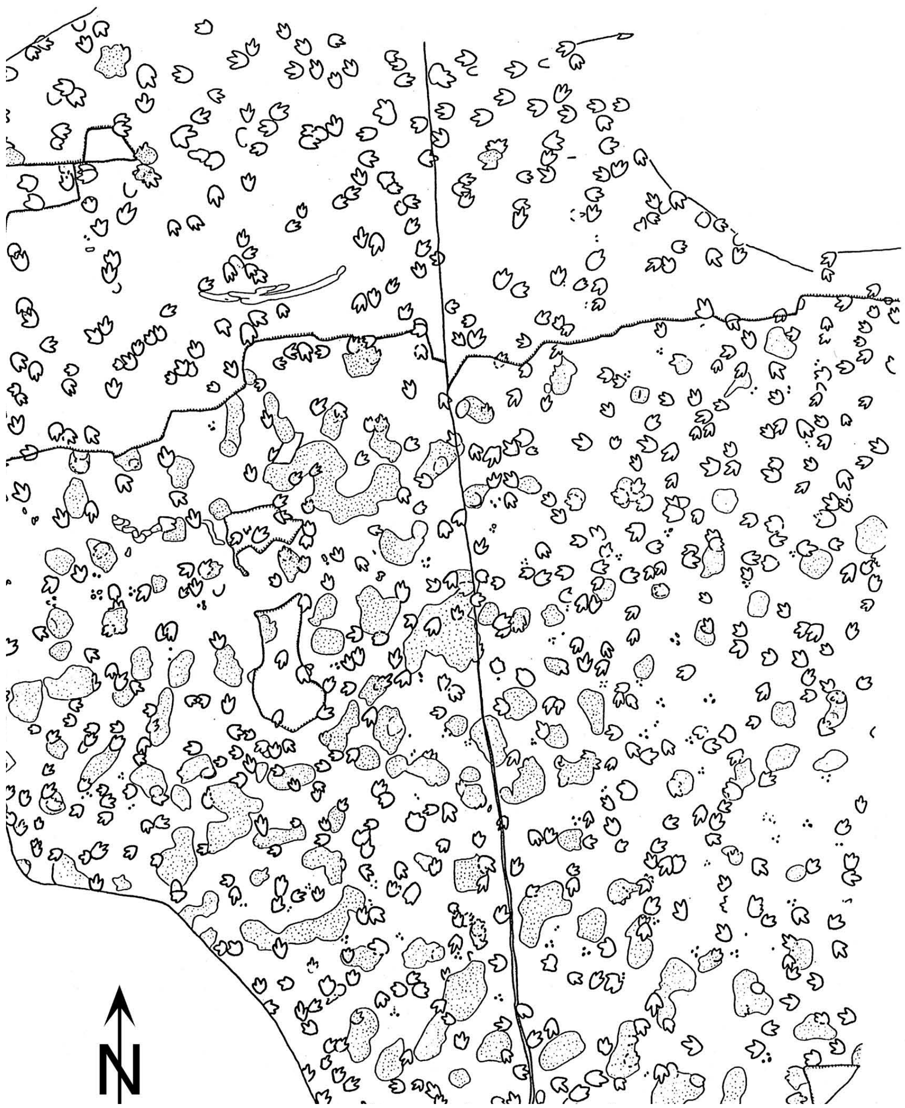


Figure 24. Dinosaur footprints on display *in situ* at Dinosaur State Park. Most footprints are 30-40 cm long. Stipple illustrates where overlying rock did not separate cleanly from the upper track-bearing layer, cross-hatched lines indicate boundary between the upper and the lower track-bearing layers (cross-hatches directed toward the lower layer). From Farlow and Galton (2003).

Paleobiology of the Late Triassic and Early Jurassic Connecticut Valley: An Extraordinary Time in Earth History. [*Note: see www.ldeo.columbia.edu/~polsen/nbcp/peo.cv2.html and online sources for the numerous references in this section*]**.**

The paleobiology of the Connecticut Valley is unusual in that the bulk of the fossils come from strata dating between the very end of the Triassic (late Rhaetian) and the beginning of the Early Jurassic (Hettangian and Sinemurian), a very peculiar time interval following the great end-Triassic extinction. The Triassic-Jurassic boundary was recently dated to 201.564±0.015 Ma (Blackburn et al., 2013). Furthermore, the late Rhaetian and Hettangian strata are interbedded with, and overlie, the flood basalt sheets that are such a conspicuous feature of Connecticut Valley geology and topography. Local basalts are part of the great Central Atlantic Magmatic Province (CAMP) that encompasses eastern North America, western Europe, northwestern Africa, and northeastern South America. Massive, widespread lava flows are implicated in the end-Triassic extinction, plausibly initiated by both elevated CO_2, causing tens of thousands of years of extreme warming (Schaller et al., 2011), and sulphur aerosols causing short (a few years), but intense and numerous episodes of extreme cold (Olsen, 1999; McHone, 2003; McHone and Puffer, 2003; Olsen et al., 2015). Thus, the fossils from Valley are not representative of “normal” Mesozoic ecosystems; they represent taxa that thrived under extremely stressful environmental conditions following one of the largest mass extinctions in the geologic record, and during one of the largest known eruptions of basalt lava.

The two most conspicuous indications of the peculiar nature of the assemblages, observable at our field stops are: 1) the extraordinarily low genus-level taxonomic diversity; and, 2) the fact that the terrestrial vertebrates apparently were not part of a normal ecological, or “Eltonian”, pyramid. Apparently, terrestrial carnivores vastly outnumbered herbivores, both in terms of numbers of individuals and in terms of biomass.

Amongst the thousands of fish specimens collected over two centuries, surprisingly only four fish genera (see Fig. 7) are currently recognized (McDonald, 2010; Whiteside et al., 2011). Within this apparent low generic diversity, however, hide "species flocks" of dozens to possibly hundreds of closely related species, especially in the nominal genus *Semionotus* (McCune et al., 1984; McCune, 1996; Whiteside et al, 2011). The low generic diversity may be a consequence of the end-Triassic extinction, which decimated fish populations in the watersheds, or it may be due to high temperatures and low O_2 concentrations in water bodies during the CAMP-related interval of high CO_2. The phenomena of "species flocks" are almost certainly a function of dramatic fluctuations in the size of the rift lakes. During wet periods, the lakes were hundreds of meters deep and covered enormous areas; extreme desiccation during dry intervals reduced the great lakes to salt flats and playas .

A long history of study, and vagaries in the processes of creating and preserving footprints, led to an unwieldy and inaccurate proliferation of names for dinosaur and reptile tracks in the Connecticut Valley. Edward Hitchcock and his son, Charles, alone described 94 ichnogenera and 216 ichnospecies (Rainforth, 2005). Furthermore, allometry – the change of shape with growth that occurs within the lifetime of an organism – added to the variety of track names (e.g., Olsen et al., 1998). Fortunately, however, most of the apparent diversity in trackmakers can be ascribed to the track-making process, and not true biological diversity.

There are perhaps four common, easily recognizable, and reliable ichnotaxonomic (track name) entities that have biological and ecological meaning:

- 1) the brontozoids (*sensu* Rainforth, 2005) made by carnivorous, large to small theropod dinosaurs (including *Eubrontes* - the name with clear priority – and its small, more slender probable subjective synonyms, *Anchisauripus* and *Grallator*);
- 2) *Anomoepus*, the tracks of small, herbivorous ornithischian dinosaurs;

- 3) *Otozoum*, produced by relatively large sauropodomorph ("prosauropod") dinosaurs; and
- 4) *Batrachopus*, made by small protosuchid and possibly sphenosuchian crocodilomorphs.

All of these listed forms have been subject to revisions in recent decades (Olsen, 1980; Olsen and Galton, 1984; Olsen and Padian, 1986; Olsen et al., 1998; Rainforth, 2003, 2005; Olsen and Rainforth, 2003).

In addition, there are two extremely rare but very distinctive ichnotaxa:

- *Ameghinichnus*, a non-mammaliform advanced cynodont possibly made by a very mammal-like trithelodont or tritylodont; and
- *Rhynchosauroides*, a lepidosauromorph track with a very primitive hand and foot structure, the maker of which in the Early Jurassic could have been sphenodontians, lizards, or choristodirans, all of which basically looked like modern lizards.

These two ichnogenera have been found at only one site apiece in the Connecticut Valley: *Ameghinichnus* is known only from the Shuttle Meadow Formation in Berlin, Connecticut (Olsen et al., 2005); *Rhynchosauroides* is known only from the lower Turners Falls Formation at Turners Falls in the Deerfield Basin (an as yet undescribed occurrence in the Beneski Museum collection found by C.U. Shepard in 1864 that somehow escaped detection by the Hitchcocks).

Skeletal representatives of the track ichnotaxa have been found in the Connecticut Valley or correlative strata in the Fundy Basin, in Nova Scotia:

- <u>theropod dinosaurs</u>, *Podokesaurus* (Talbott, 1911), bone casts (Colbert and Baird, 1958; Getty and Bush (2011), and isolated teeth (McDonald, 1992; Sues and Olsen, 2015);
- <u>ornithischian dinosaurs</u>, teeth and fragmentary bones – possibly the worlds oldest, (Sues and Olsen, 2015);
- <u>sauropodomorph skeletons and bones</u>, *Anchisaurus* (and its synonym *Ammosaurus*), unnamed taxon or taxa (Marsh, 1885 [but known from 1820]; Fedak, 2007; Yates 2010; Sues and Olsen, 2015);
- <u>protosuchid crocodylomorphs</u> - skeletons, skulls, and bones (Emerson and Loomis, 1904; Walker, 1968; Sues et al., 1996; Sues and Olsen, 2012);
- <u>lepidosauromorphs</u> - skulls, jaws, and skeletons of sphenodontians (Sues and Baird, 1993; Sues et al., 1994; Sues and Olsen, 2015); and
- <u>tritheodonts and tritylodonts</u> - mostly jaws and isolated bones (Olsen et al., 1987; Shubin et al., 1991; Sues and Olsen, 2015; Fedak et al., 2015).

These finds demonstrate that the footprint record of Late Triassic and Early Jurassic vertebrates in the Connecticut Valley and associated rift basins is consistent with the skeletal record.

However, as we see at Wesleyan, Powder Hill, Dinosaur State Park, and the Portland quarries, brontozoid footprints are orders of magnitude more common than the tracks of anything else. There is little doubt that Early Jurassic brontozoid footprints were made by various-sized theropod dinosaurs, which were unquestionably carnivorous. *Batrachopus* footprints are common, but they were also made by carnivorous forms. Does the overwhelming abundance of tracks of carnivorous forms reflect the ecological structure, and how could carnivores be more abundant than herbivores?

As expected in normal terrestrial ecosystems, in younger Jurassic and Cretaceous track assemblages, herbivorous dinosaur tracks are more abundant than carnivorous forms (Lockley and Hunt, 1999). Inasmuch as the assemblages at the field stops post-date one of the largest mass-extinctions of all time, the end-Triassic extinction, the terrestrial ecosystems were anything but normal. Milner and Kirkland (2007) have made a strong case that Early Jurassic brontozoid tracks from the Moenave Formation, Utah (an assemblage which looks remarkably like that from the Connecticut Valley) were made by dinosaurs that subsisted largely on fishes, as do many extant dinosaurs (birds). 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" pyramid of the Early Jurassic terrestrial realm had its base in the water. 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.

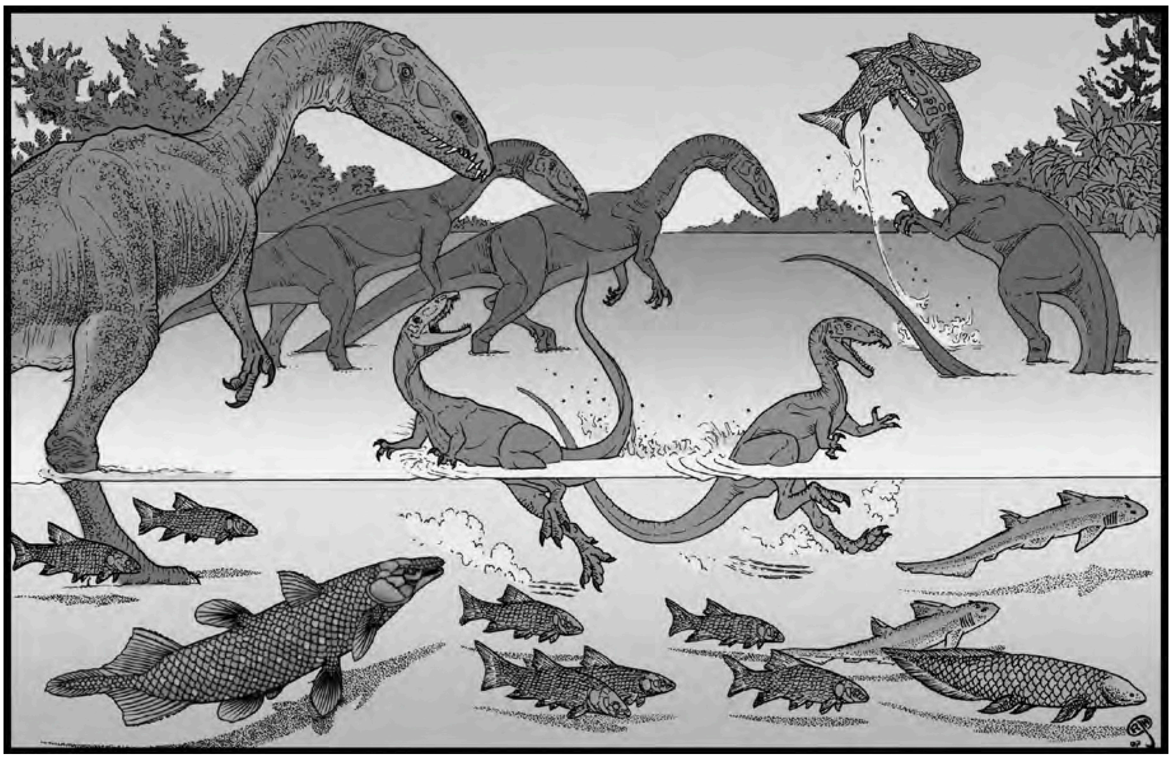


Figure 25. Reconstruction of theropod dinosaurs of various sizes fishing in a lake. While this construction is based on the Early Jurassic age Moenave Formation of Utah, it applies well to the Connecticut Valley, except that thus far there is no evidence of lungfish or sharks. Illustration by Russell Hawley (from Milner and Kirkland, 2007).

Travel to South Glastonbury via historic Rocky Hill Ferry.
Ferry Landing: Route 160 to Meadow Road, Rocky Hill, Conn. Lat. 41.666385, Long. -72.629895

Stop 4. Hale's Brook Fan-Delta, South Glastonbury, Conn. Lat. 41.632185, Long. -72.617663

In 1991, an illustrative exposure of very coarse alluvial fan conglomerate and microlaminated, fossiliferous black shale was uncovered in a sand and gravel quarry in South Glastonbury, Connecticut. This exposure is an unsurpassed example of fan-delta deposition at the faulted margin of the Hartford Basin.

In the context of previous studies of the alluvial fan deposits of the Portland Formation, this locality is considered the type fan-delta facies association in the Hartford Basin for the following reasons: 1) accessibility and lack of vegetative or soil cover; 2) great range of grain size, from clay to boulders over 2 m in length in close stratigraphic proximity; 3) evidence of rapid sub-aqueous fan deposition including turbidite beds and slump folds; 4) well-preserved fossils including fish, conchostracans, and plants; 5) a dramatic coarsening-up sequence; 6) one of few well-exposed fan-lake sequences found within 1 km of the eastern fault margin of the basin; and 7) unusual three-dimensional exposures showing bedding plane, along-strike and along-dip views of beds and sedimentary structures.

This site has much utility for educational purposes, demonstrating diverse geological principles including:

- *Sedimentology*: finely laminated lacustrine shale and siltstone, shallow water near-shore sandstone, sub-aqueous mass flow deposition (turbidites), slump folds and soft-sediment deformation, sub-aqueous and sub-aerial conglomerate; fan progradation, Walthers Law;
- *Structure*: post-depositional normal faults, effects of bed strength on fault plane attitude, bedding plane shear;
- *Paleontology*: modes of fossil fish preservation, paleoecology, lacustrine environments;
- *Glacial Geology*: glacial striations, effect of bedrock on ice flow; ice contact deposits.

The main outcrop is about 150 - 200 ft. long and consists of a north-facing vertical section of dark silty shale, sandstone and conglomerate and a broad, south-facing dip slope of boulder conglomerate. Bedding strikes N 70° W and dips about 25° SW. The eastern and western ends of the outcrop are terminated by normal faults striking roughly north-south. The entire outcrop shows evidence of glacial scour, with deep, sub-parallel grooves and scratches that envelop bedrock surfaces. The glacial striations also wrap around the eastern and western ends of the exposure, providing dramatic evidence that bedrock influenced the flow path at the base of the overlying ice sheet.

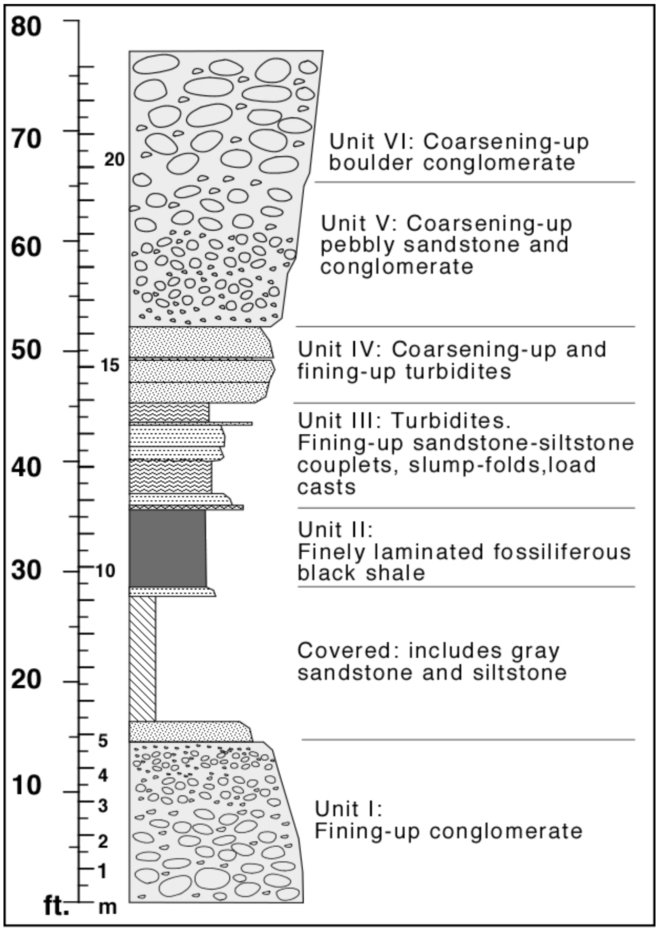
The beds coarsen dramatically upward and exhibit an extremely wide range of grain sizes and bedding styles, from thin-bedded, finely laminated dark shale to crudely stratified boulder conglomerate within a continuous vertical section. The depositional environments represented include deep-water lacustrine, shallow or littoral lacustrine, sub-aqueous fan-delta, and sub-aerial alluvial fan. The fan-delta sequence is divided for reference into six units (Fig. 26), from top to base:

<Top of section>

- Unit VI: Very coarse boulder conglomerate;
- Unit V: Coarse to pebbly sandstone with a sharp basal contact and gradational upper contact;
- Unit IV: Turbidite sandstone and siltstone beds;
- Unit III: Turbidite beds with slump folds, flame and load structures, fining-up couplets;
- Unit II: Finely laminated, fossiliferous black shale and gray siltstone interbeds;
- Covered interval: approx. 4.5 m;
- Unit I: Partially exposed pebble and cobble conglomerate.

<Base of section>

Figure 26. Hale's Brook fan-delta measured section.

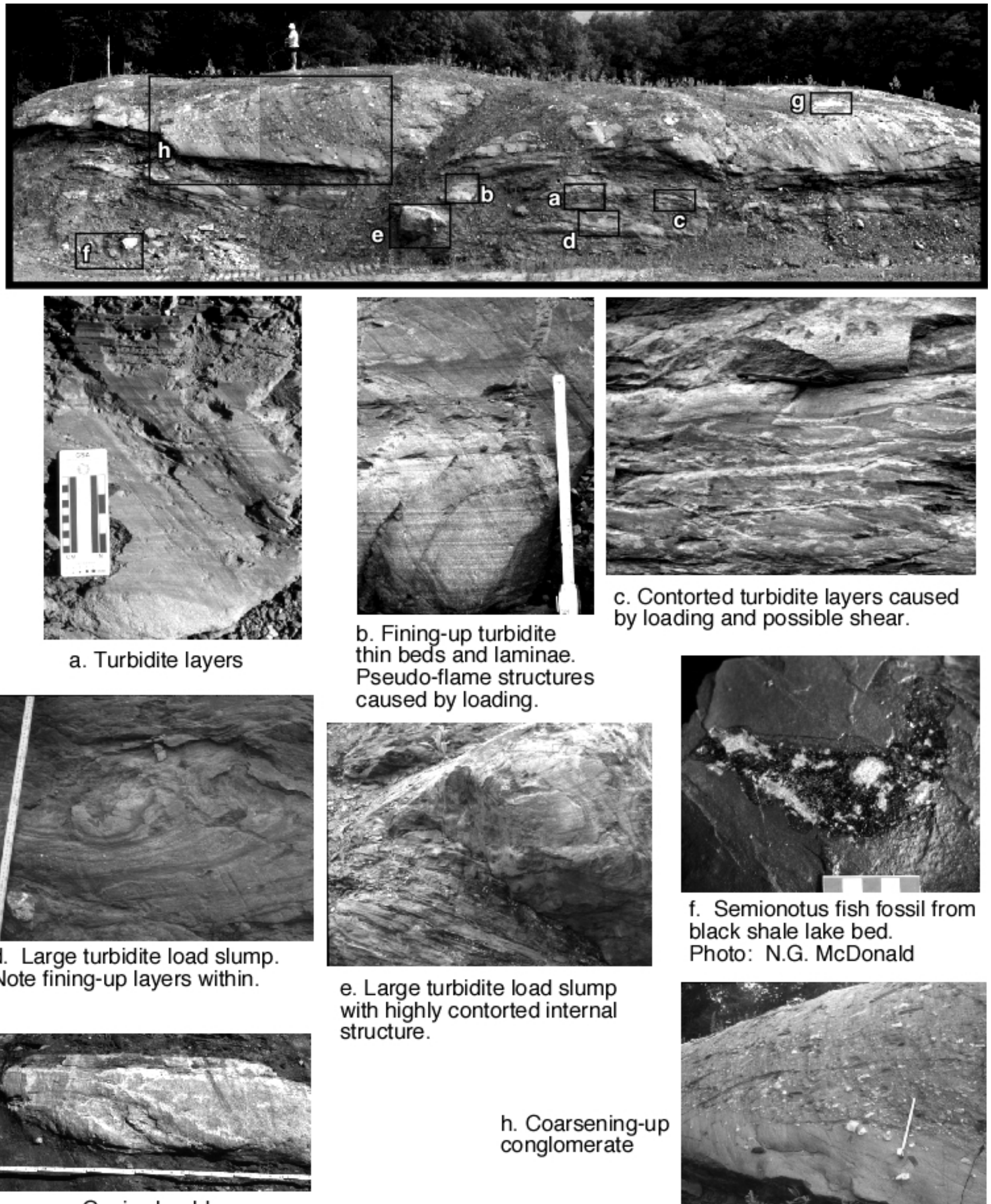


Unit I. The base of the outcrop consists of poorly sorted, poorly-stratified conglomerate with a few thin silty sandstone beds or partings. Although the exposure of this bed is poor, a fining-up trend can be observed in the size of the major conglomerate clasts. Clast composition is polymict, and derived from varied low- to high-grade metamorphic rocks and plutonic igneous rocks. Clasts are sub-rounded to sub-angular; no preferred orientation can be observed. Unit I is interpreted as an alluvial fan deposit based on comparison with other well-known ancient and modern examples.

Unit II. The base of Unit II is partially covered. The upper 0.75 m consists of microlaminated, thin-bedded, black fossiliferous shale and interbeds of gray siltstone. Bedding contacts are sharp and planar. Laminations consist of clastic and carbonate couplets (varves). No evidence of subaerial exposure such as mud cracks, root traces, or invertebrate burrows is present. Fish fossils are typically whole and articulated, but are in some cases disrupted by normal faults and bedding plane faults of small displacement. Unit II is interpreted as a perennial, stratified lake deposit. Fossils from Unit II include the holostean *Semionotus*, conchostracans, and plants. The excellent preservation of bone in the fishes is typical of specimens found within 0.5 to 2 km of the eastern basin margin.

Unit III. Unit III consists of interbedded gray mudstone, thin, normal-graded sandstone to siltstone beds, and light gray to brown, medium to coarse sandstone with subordinate granule lenses and small pebble layers and lenses. The gray mudstone is thin-bedded with planar horizontal lamination, and minor pinch and swell lamination. The mudstone beds include rusty-weathering ferroan dolomite-rich beds and nodules. Thin normal-graded sandstone-siltstone beds occur in repetitive bed sets throughout Unit III. Thick slump folds and soft sediment deformation are noteworthy in this unit.

A recumbent fold in the central portion of the exposure is about 1 m thick and 1.5 m wide with a rounded lower boundary and a shallow, convex-upward upper surface. Normal-graded couplets of fine and coarse sand occur within the slump, and are crenulated and of different attitude than those on the outermost portion of the slump. This indicates that internal deformation was independent of the shear forces that shaped the outer boundaries (Fig. XX-e). About 3 m to the west of the largest slump fold is another smaller slump about 0.5 m thick by 1.2 m wide (Fig. XX-d). This fold also has complex internal deformation and recumbent, multiply folded layers. The slumps appear to be part of a formerly continuous coarse sandstone wedge that tapers toward the west, away from the basin margin.



a. Turbidite layers

b. Fining-up turbidite thin beds and laminae. Pseudo-flame structures caused by loading.

c. Contorted turbidite layers caused by loading and possible shear.

d. Large turbidite load slump. Note fining-up layers within.

e. Large turbidite load slump with highly contorted internal structure.

f. Semionotus fish fossil from black shale lake bed. Photo: N.G. McDonald

g. Gneiss boulder

h. Coarsening-up conglomerate

Figure 27. Fan-delta features.

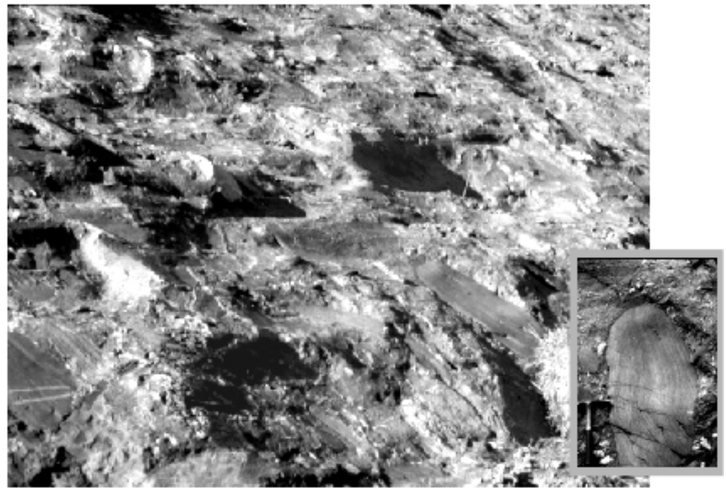
Beds overlying the folded horizon are thin-bedded and laminated gray mudstones and normal-graded sandstone-siltstone couplets. In the upper few centimeters of the mudstone beds a complexly deformed 2-4 cm medium sand bed forms a "train" of recumbent and overturned folds (Fig. 27-c). We interpret that the folded sand layer is a result of bed-shearing forces during the mass-flow emplacement of the overlying thick sand wedge that forms the base of Unit IV. Unit III is the product of mass-flow, turbidite-dominated sedimentation in a pro-delta environment.

Unit IV. Unit IV is similar to the underlying Unit III but is coarser-grained and less dominated by the large folds that characterize Unit III. The base of Unit IV is formed by a massive coarse to granule sandstone bed with a wedge-like shape that progressively thins from 40 cm in the eastern portion of the outcrop to 20 cm in the western portion. The lower surface of the sand bed is generally sharp and planar, although some soft sediment load structures are present. The upper surface is hummocky to irregular and is "on-lapped" by normal-graded sandstone beds in the western portion of the outcrop. Internally, the sand bed is massive to laminated with no cross-stratification. The normal-graded sandstone beds that overlie the massive sandstone wedge are about 20 to 30 cm thick and consist of 3 to10 cm normal-graded couplets. The apparent "on-lap" of these beds on the massive sandstone beds is caused by the westward thickening of the normal-graded beds. Unit IV also represents a prograding, turbidite-dominated, fan-delta sequence.

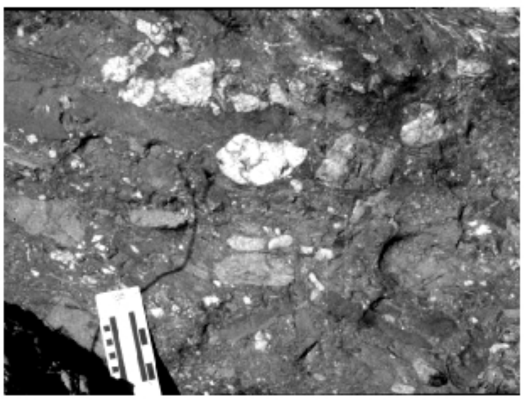
Unit V. Unit V displays an abrupt grain-size transition from the underlying turbidite sandstone. Very coarse sand and fine gravel predominate in the lower part of the unit, and pebbles and cobbles appear in higher abundance toward the top of the unit. A few scattered pebbles and cobbles “float” within the matrix throughout the unit. Characteristic fluvial sedimentary structures are missing from Unit V, including cross-bedding and lag gravels. Typical deltaic features, such as climbing-ripple cross-laminae, load casts, or sorted layers and lenses are also absent. Furthermore, there are no sub-aerial alluvial fan features such as fining-up layers capped by silt drapes, or debris flows. Based on the sedimentary evidence we conclude that the coarse-grained Unit V was deposited beneath lake waters, which is unusual in the Harford Basin.

Unit VI. Unit VI is a spectacular, coarsening-up cobble and boulder conglomerate, perhaps the best of its kind in the Connecticut Valley. The conglomerate can be observed in three dimensions, including breathtaking bedding plane views on the south side of the outcrop. The largest clasts, ranging up to 2 meters in length, occupy the highest stratigraphic levels in the outcrop. The polymict conglomerate includes both low- and high-grade metamorphic rocks derived from the Paleozoic eastern highlands; phyllite, gneiss, and quartzite are all common, and several basalt clasts are present. Stratification within Unit VI is obscure. In many places, grain size segregation suggestive of bedding are observed, but, except in a few locations, cross-bedding is faint or absent. As in Unit V, evidence of sub-aerial alluvial fan deposition, including, but not limited to, well-defined channels, silt drapes, or debris flow lobes, is absent. This unit was deposited at and below the lake margin where rapid sub-aqueous sedimentation resulted in poorly sorted and poorly segregated, amalgamated conglomerate with faint bedding.

a. Unit VI: polymictic conglomerate containing high- and low-grade metamorphic clasts

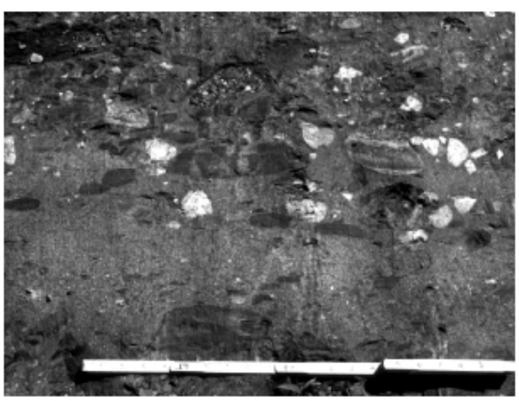


b. Unit VI: view of upper bedding plane, south side of outcrop. Arrow marks 2m phyllite.

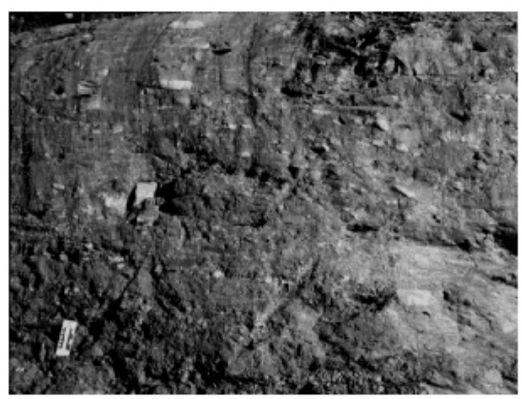


c. Detail of coarse conglomerate Unit VI. View parallel to bedding.

f. Unit VI: basalt boulder



g. View parallel to bedding.



h. View of east side of outcrop showing internal structures of Unit VI.

Figure 28. Fan-delta deposits: grain size, clast composition, and bedding in Unit VI.

Stop 5. Portland Brownstone Quarries, Brownstone Avenue, Portland, Connecticut.
Lat. 41.574911, Long. -72.645334

No building material is more closely associated with American cities than brownstone. The word conjures up images of row houses, elegant town-homes, ornate decorative carvings and monuments. Brownstone was a highly fashionable and desired building material during the late 1800's and early 1900's. The golden age of urban development coincided with the peak desire for the warm brown stone, and as a result, brownstone buildings are common in cities along the eastern seaboard. A comprehensive discussion by Guinness (2003) provides the definitive history of the brownstone quarries.

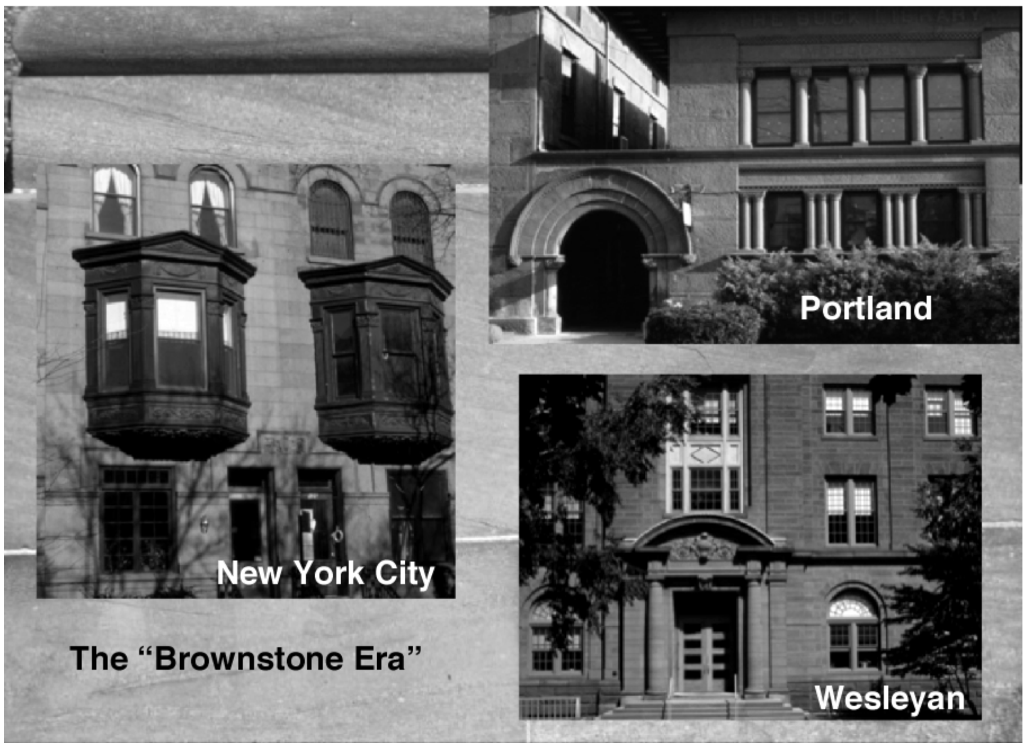


Figure 29. Examples of late 19th century buildings constructed of Portland brownstone.

Stone was extracted from the quarries beginning in the 1700s. The cut and seasoned stone was hauled by horse cart and later by steam-powered cable winches to barges docked on the riverbank. The barges then transported the stone to cities all over the east coast, especially New York City. At the peak of its popularity, Portland brownstone was even shipped to Denver and San Francisco (Guinness, 2003).

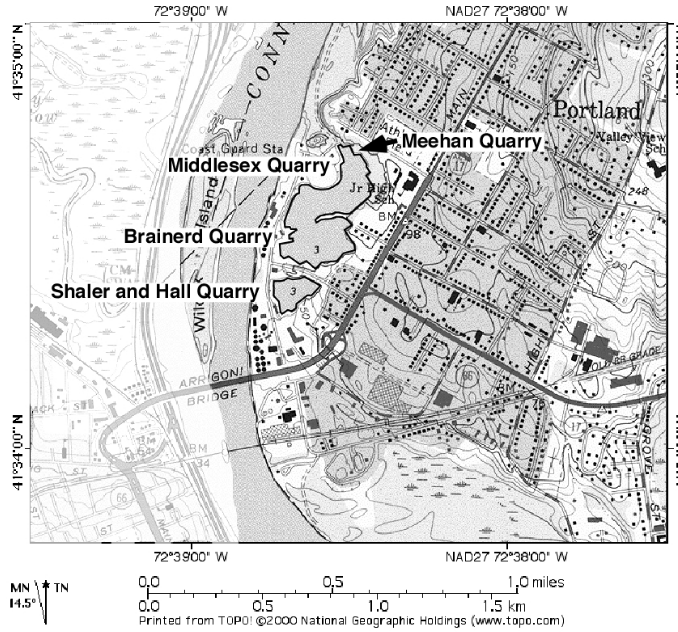
In Portland, the chance occurrence of fine eolian ("wind-blown") sandstone deposits was responsible for the growth of a regional industry and a national trend in architectural fashion. Red-bed quarries existed elsewhere in the Connecticut Valley, and in the rift valleys of eastern Virginia, northeastern Pennsylvania, and New Jersey, but none rival the fine quality and color of the stone found in Portland, Connecticut.

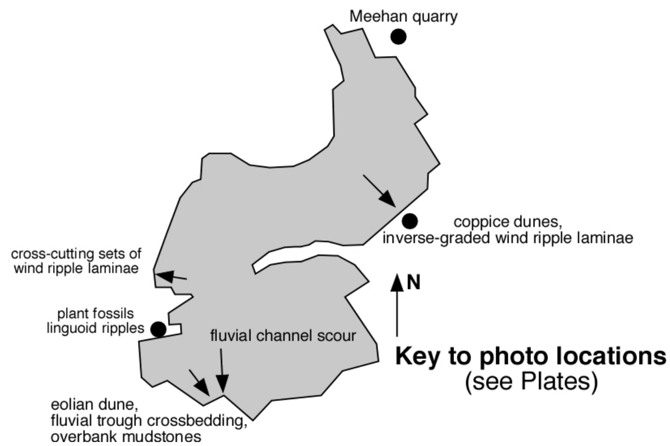
The Portland brownstone quarry sections, and nearby exposures, are good examples of the diversity of sedimentary environments at the rift margin. Boulder conglomerates, organic-rich laminated black shale, fluvial sandstone and siltstone, and eolian sandstones are all found within 1 km of the eastern border fault, which roughly parallels Connecticut Rt. 17.

The Portland quarries are part of the Crow Hill Fan complex, a well-defined wedge of alluvial fan, fluvial, and eolian beds, with its depocenter near the high school on the top of Crow Hill, in Portland (see Fig. 3). The boulder conglomerate near the golf course along Route 17 is the eastern edge of the fan complex. The thinning and fining southern flank of the fan complex is exposed in the vicinity of the miniature golf course along the north side of Route 66. On the north side of the fan complex (in the vicinity of Petzold's Marina on the Connecticut River), a long stratigraphic section consists of interbedded alluvial fan and deep water lacustrine deposits.

Today, the only remains of the former quarry operations are two large, water-filled pits. The main (northern) pit, where we will focus, includes the Middlesex quarry on the north side of the promontory and the Brainerd quarry on the south side. South of Silver Street, which bisects the quarries, are the Shaler and Hall workings. The quarry sandstone, comprised mainly of quartz and feldspar clasts with calcite and hematite cement, is known to builders and architects as "Portland Brownstone".

Figure 30. Location of the Portland brownstone quarries.

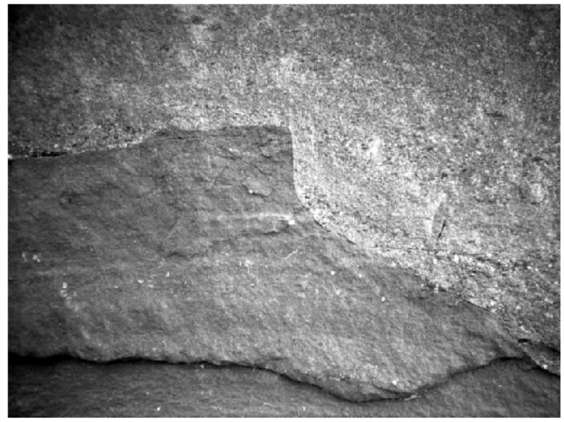




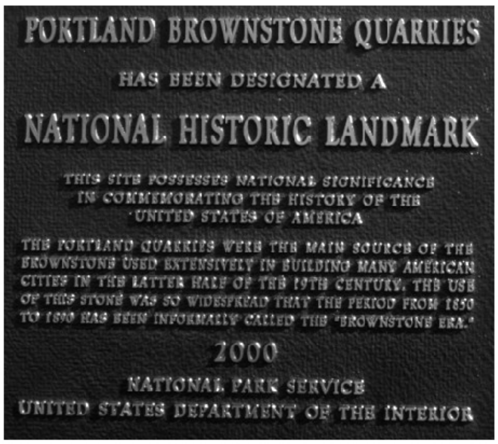
Krynine (1950) designated the type section for the Portland Formation (formerly known as the Portland Arkose) at the quarries even though the rocks there are atypical of the formation. LeTourneau (1985, 2010) described the paleogeographic distribution of alluvial fan and eolian complexes located along the rift margin in central Connecticut.

The strata in the brownstone quarry were mainly deposited in stream or river environments, including sand and gravel channels, gravel bars, and overbank sand and silt, but beds of eolian sandstone form a significant part of the stratigraphic section (LeTourneau, 2002; LeTourneau and Huber, 2006; LeTourneau, 2010). The eolian beds include thin sand sheets, low angle dunes, and linear "coppice" dunes that were anchored by plants. Eolian sedimentation at Portland was promoted by a favorable paleolatitudinal position (20° N), deposition within a dry climatic interval, and proximity to fan-related sources of sand. Because of their homogenous texture, absence of mica partings, and rich color, the eolian beds were ideal for building stone. The alternation of fluvial sandstones and mudstones with eolian sandstones reflects cyclical climatic controls on rift sedimentation.

a. Channel scour. Base contains channel-lag gravel.



b. Detail of channel scour showing gravel lag



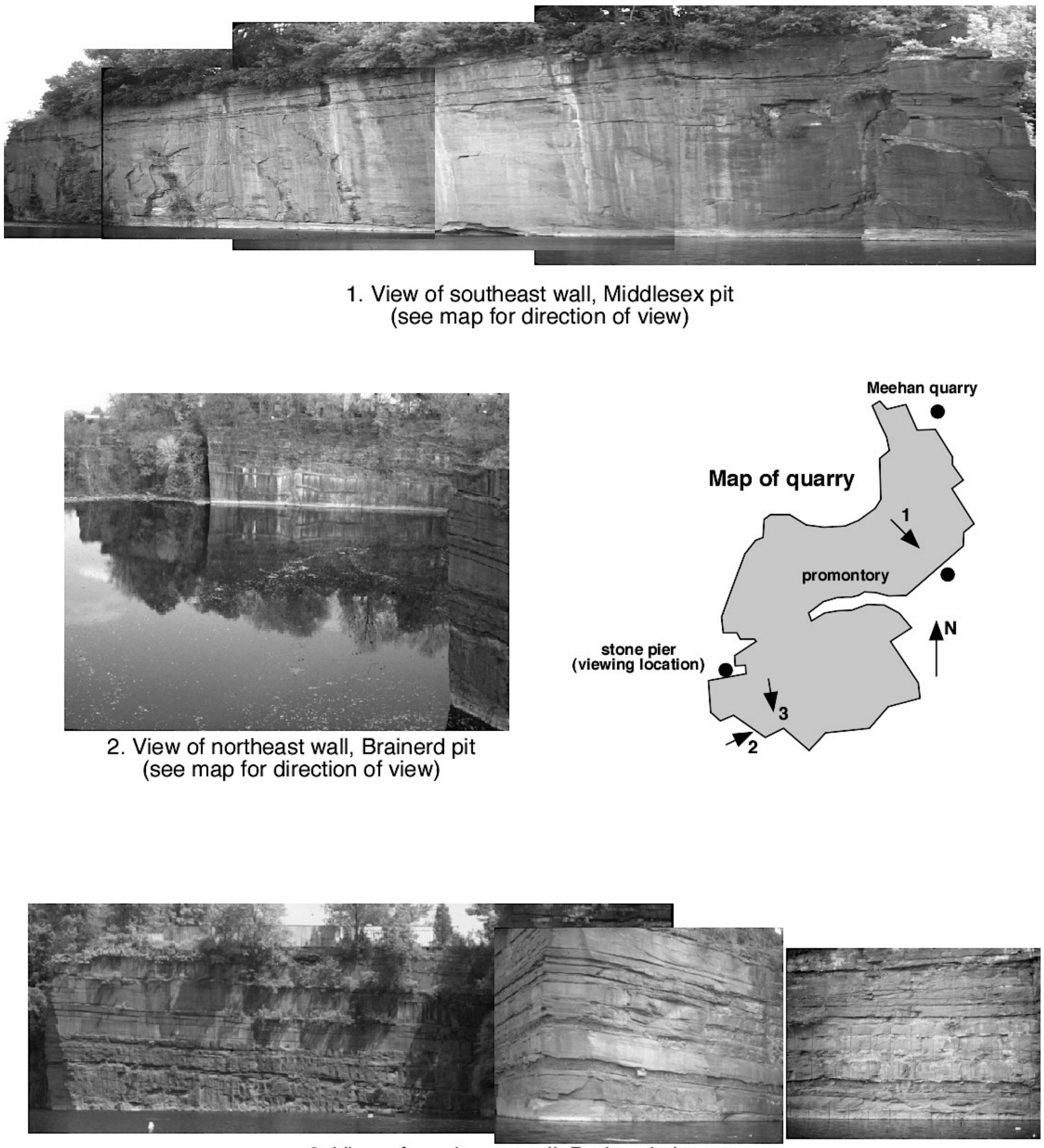
c . National Historic Landmark sign
Portland Brownstone Quarries

d. Postcard view of the Portland brownstone quarry, early 20th century

e. Active Meehan quarry located at northwest corner of Middlesex (main) pit

f. Quarryman Michael Meehan (left) discusses the finer points of brownstone with paleontologist Nick McDonald

Figure 31. Portland brownstone quarries.



1. View of southeast wall, Middlesex pit
(see map for direction of view)

2. View of northeast wall, Brainerd pit
(see map for direction of view)

3. View of southwest wall, Brainerd pit
(see map for direction of view)

Figure 32. Quarry wall exposures of fluvial-eolian beds, Portland, Connecticut.

A view to the north and east, in the Middlesex pit, shows the dramatically different character of the down-section rocks, in particular the massive sandstone forming a large wall on the eastern side. Intercalated fine-grained rocks are nearly absent in this part of the quarry. A close-up view of the large east wall of the Middlesex pit reveals an abundance of inverse-graded, low-angle, planar stratification indicative of migrating wind ripples (pin-stripe lamination). LeTourneau (2002) and LeTourneau and Huber (2006) identified several large-scale, convex-up dune forms as “coppice dunes”, formed around clumps of plants. Evidence for the coppice dune origin of these features includes complex internal stratification with root traces and inverse-graded wind ripples. A modern model for the Portland brownstone eolian deposits is the Stovepipe Wells dune field in Death Valley, California.

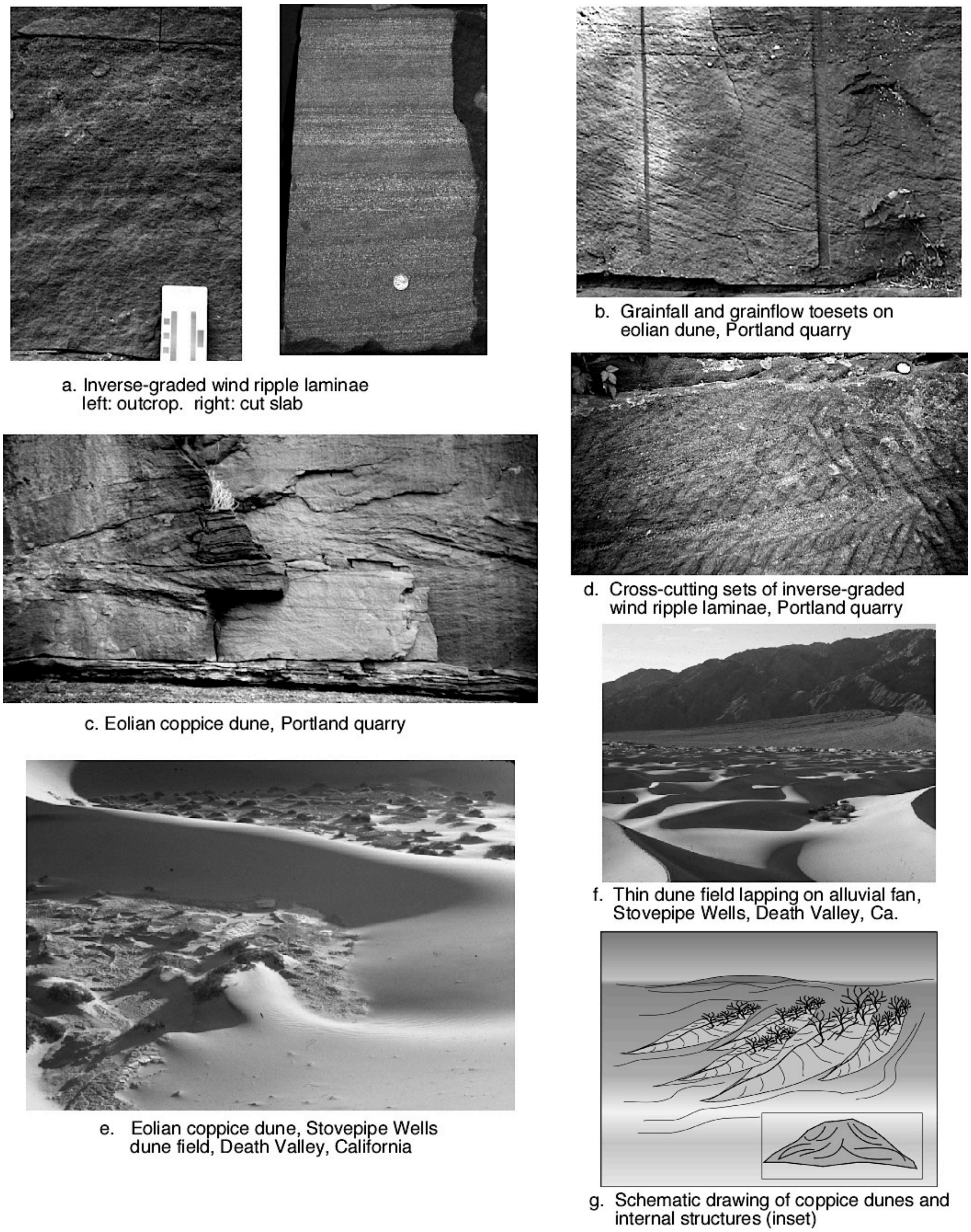
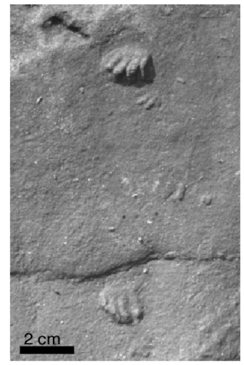


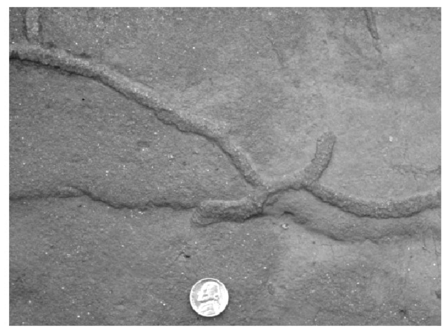
Figure 33. Eolian features of the Portland brownstone quarries and comparison to modern dunes, Death Valley, California.

a. Otozoum and Grallator tracks
Wesleyan University Collection

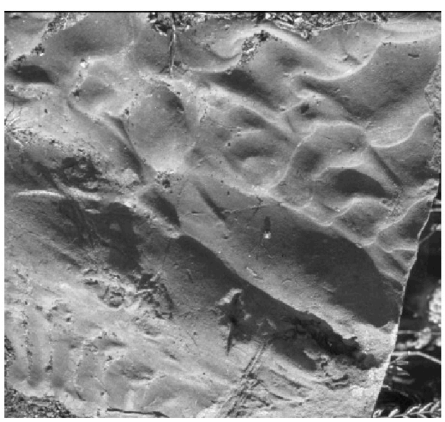


b. Batrachopus manus and pes impressions

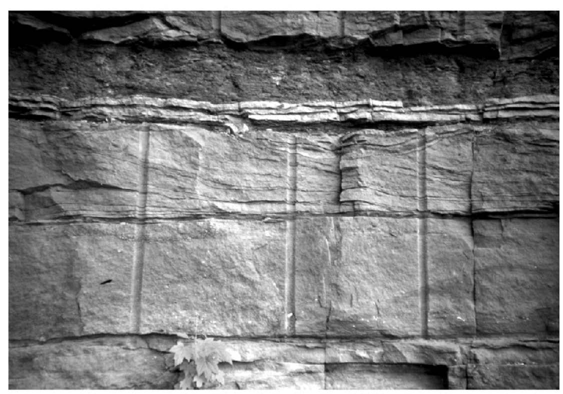
c. Plant stem impressions



d. Meniscate backfilled “Scoyenia” burrows



e. Linguoid ripples in fluvial sandstone



f. Trough cross-bedded fluvial sandstone
and overbank mudstone

Figure 34. Fossils and fluvial features, Portland brownstone quarries.

Fossils are relatively common in the Portland quarries, but they occur as traces, molds, and casts rather than mineralized body fossil remains. Dinosaur tracks include *Eubrontes* and *Grallator*, the three-toed prints of carnivorous theropods, and *Otozoum*, massive prosauropod tracks. Excellent examples of these footmarks from the Portland quarries are on display at Wesleyan University and Dinosaur State Park. Small, terrestrial crocodiles created quadrupedal tracks known as *Batrachopus*. Burrowing invertebrates also left their marks in the wet sediment. Backfilled burrows called *Scoyenia* are attributed to crayfish or other decapod crustaceans. Plant fossils include layers of macerated debris and impressions of branches and trunks.

IV. References

Ash, S.R., 1986. The Early Mesozoic land flora of the northern hemisphere. *In:* T.W. Broadhead, (ed.), Land Plants: Notes for a Short Course. University of Tenn., Dept. of Geol. Sci., Studies in Geology, no. 15, p. 143-161.

Atkins, T., 1883. History of Middlefield and Long Hill. Hartford, Case, Lockwood, and Brainerd, 196 p.

Barclay, E.E., 1941. Outdoors. The Hartford Courant, July 20, p. D2. Available from: The Hartford Courant Archives (1764–1986); http://pqasb.pqarchiver.com/courant/advancedsearch.html

Blackburn, T.J., Olsen, P.E., Bowring, S.A., McLean, N.M., Kent, D.V., Puffer, J., McHone, G., Rasbury, E.T., and Et-Touhami, M., 2013. Zircon U-Pb geochronology links the end-Triassic extinction with the Central Atlantic Magmatic Province. Science, v. 340, p. 941–945.

Chang, C.C., 1968. A gravity study of the Triassic valley in southern Connecticut. M.A. Thesis, Wesleyan University, Middletown, Conn., 108 p.

Coombs, W.P., Jr., 1980. Swimming ability of carnivorous dinosaurs. Science, v. 207, p. 1198-1200.

Davis, W.M. and Loper, S.W., 1891. Two belts of fossiliferous black shale in the Triassic formation of Connecticut. Geological Society of America Bulletin, v. 2, p. 415-430.

Ellefsen, K.J. and Rydel, P.L., 1985. Flow directions of the Hampden basalt in the Hartford Basin, Connecticut and Massachusetts. Northeastern Geology, v. 7, p. 33-36.

Farlow, F.O. and Galton, P. M., 2003. Dinosaur trackways of Dinosaur State Park, Rocky Hill, Connecticut. *In:* P.M. LeTourneau and P.E. Olsen, (eds.), The Great Rift Valleys of Pangea in Eastern North America, Volume II, p. 248-263. New York, Columbia University Press.

Getty, P.R., and Bush, A.M., 2011. Sand pseudomorphs of dinosaur bones: Implications for (non-) preservation of tetrapod skeletal material in the Hartford Basin, USA. Palaeogeog., Palaeoclim., Palaeoecol., v. 302, no.1, p. 407–414.

Getty, P.R., Hardy, L., and Bush, A.M., 2015. Was the *Eubrontes* Track Maker Gregarious? Testing the Herding Hypothesis at Powder Hill Dinosaur Park, Middlefield, Connecticut. Peabody Museum of Natural History Bull., v. 56, no.1, p. 95–106.

Guinness, A.C., 2003. Heart of Stone: the Brownstone Industry of Portland, Connecticut. *In:* P.M. LeTourneau and P.E. Olsen, (eds.), The Great Rift Valleys of Pangea in Eastern North America, Volume II, p. 224-246. New York, Columbia University Press.

Hay, O.P., 1902. Bibliography and catalogue of the fossil Vertebrata of North America. U.S. Geological Survey Bull., no. 179, 868p.

Hitchcock, E., 1836. Ornithichnology - Description of the foot marks of birds, (Ornithichnites) on New Red Sandstone in Massachusetts. American Journal of Science, series 1, v. 29, p. 307-340.

Hitchcock, E., 1858. Ichnology of New England. A report on the sandstone of the Connecticut Valley, especially its fossil footmarks. Boston, Commonwealth of Massachusetts, 220 p.

Horne, G.S., McDonald, N.G., LeTourneau, P.M. and deBoer, J.Z., 1993. Paleoenvironmental traverse across the early Mesozoic Hartford Rift Basin, Connecticut. *In*: J.T. Cheney and J.C. Hepburn, (eds.), Field trip guidebook for the northeastern United States: Geological Society of America Annual Meeting, Boston, Massachusetts, Oct. 25-28, 1993, vol. 2, chapter P, p. 1-26.

Kent, D.V. and Olsen, P.E., 2008. Early Jurassic magnetostratigraphy and paleolatitudes from the Hartford continental rift basin (eastern North America): Testing for polarity bias and abrupt polar wander in association with the central Atlantic magmatic province. Jour. Geophys. Res., v. 113, B6, p. 1978-2012.

Krynine, P.D., 1950. Petrology, stratigraphy, and the origin of the Triassic sedimentary rocks of Connecticut. Connecticut Geological and Natural History Survey Bull., no. 73, 247 p.

Leonard, E., 2013. The taphonomy and depositional environment of Jurassic lacustrine fish deposits, Westfield bed, East Berlin Formation, Hartford Basin. B.A. Honors Thesis, Department of Earth & Environmental Science, Wesleyan University, Middletown, Conn., 124 p.

LeTourneau, P.M., 1985a. The sedimentology and stratigraphy of the Lower Jurassic Portland Formation, central Connecticut. M.A. Thesis, Department of Earth & Environmental Science, Wesleyan University, Middletown, Conn. 247 p.

LeTourneau, P.M., 1985b. Alluvial fan development in the Lower Jurassic Portland Formation, central Connecticut - Implications for tectonics and climate. *In:* G.R. Robinson and A.J. Froelich, (eds.), Proceedings of the Second U.S. Geological Survey workshop on the Early Mesozoic basins of the eastern United States. U.S. Geological Survey Circular 946, p. 17-26.

LeTourneau, P.M., 2002. Eolian sandstones from the Pomperaug and Hartford rifts, Connecticut: Indicators of Early Jurassic paleoclimate gradients? Geological Society of America, Abstracts with Programs, v. 34, no. 2.

LeTourneau, P.M., 2003. Tectonic and climatic controls on the stratigraphic architecture of the Late Triassic Taylorsville Basin, Virginia and Maryland, USA. *In:* P.M. LeTourneau and P.E. Olsen, (eds.), The Great Rift Valleys of Pangea in Eastern North America, Volume II, p. 12-58. New York, Columbia University Press.

LeTourneau, P.M., 2008. Traprock Ridgelands: The environmental geography of endangered landscapes of the Connecticut Valley. *In:* M.V. Baalen, (ed.), Guidebook for field trips in Massachusetts and adjacent Connecticut and New York. New England Intercollegiate Geological Conference, 100th Annual Meeting, Trip C3.

LeTourneau, P.M., 2010. The stone that shaped America in the 19th Century: The geology and history of the Portland brownstone quarries. Geological Society of Connecticut Field Guide No. 1, Chapter III, p. 17-30.

LeTourneau, P.M. and Huber, P., 2006. Early Jurassic eolian dune field, Pomperaug basin, Connecticut and related synrift deposits: stratigraphic framework and paleoclimatic context. Sedimentary Geology, v. 187, p. 63-81.

LeTourneau, P.M. and McDonald, N.G., 1985. The sedimentology, stratigraphy and paleontology of the lower Jurassic Portland Formation, Hartford Basin, central Connecticut. *In*: R.J. Tracey, (ed.), New England Intercollegiate Geological Conference, 77th Annual Meeting. State Geological and Natural History Survey of Connecticut Guidebook No. 6, p. 353-392.

LeTourneau, P.M. and Olsen, P.E., (eds.), 2003a. The Great Rift Valleys of Pangea in North America, Volume I: Tectonics, Structure, and Volcanism of Supercontinent Breakup. New York, Columbia University Press.
ISBN 0-231-11162-2

LeTourneau, P.M. and Olsen, P.E., (eds.), 2003b. The Great Rift Valleys of Pangea in North America, Volume II: Sedimentology, Stratigraphy, and Paleontology. New York, Columbia University Press.
ISBN 0-231-12676-X

LeTourneau, P.M. and Thomas, M.A., (eds.), 2010. Traprock, tracks and brownstone: the geology, paleontology, and history of world-class sites in the Connecticut Valley. Geological Society of Connecticut Field Guide No. 1, 43 p.

Longwell, C.R. and Dana, E.S., 1932. Walks and rides in central Connecticut and Massachusetts. New Haven, Conn., 229 p.

Lull, R.S., 1904. Fossil footprints of the Jura-Trias of North America. Memoirs of the Boston Society of Natural History, v. 5, p. 461-557.

Lull, R.S., 1915. Triassic life of the Connecticut Valley. Connecticut State Geological and Natural History Survey Bulletin, no. 24, 285 p.

Lull, R.S. 1953. Triassic life of the Connecticut Valley. (Revised.) Connecticut State Geological and Natural History Survey Bulletin, no. 81, 336 p.

Manheim, F.T. and Gulbrandensen, R.A., 1979. Marine Phosphates. Reviews in Mineralogy, v. 6, Marine Minerals, p.151-173.

McCune, A.R., 1987. Toward the phylogeny of a fossil species flock: semionotid fishes from a lake deposit in the Early Jurassic Towaco Formation, Newark Basin. Peabody Museum of Natural History Bulletin, no. 43, 108 p.

McDonald, N.G., 1992. Paleontology of the early Mesozoic (Newark Supergroup) rocks of the Connecticut Valley. Northeastern Geology, v. 14, p. 185-199.

McDonald, N.G., 1996. The Connecticut Valley in the Age of Dinosaurs: A guide to the geologic literature, 1681-1995. Connecticut State Geological and Natural History Survey Bulletin, no. 116, 242 p.

McDonald, N.G., 2010. Window into the Jurassic world: Dinosaur State Park, Rocky Hill, Connecticut. Rocky Hill, Conn., Friends of Dinosaur State Park and Arboretum, Inc., 105 p.

McDonald, N.G. and LeTourneau, P.M., 1988. Paleoenvironmental reconstruction of a fluvial-deltaic-lacustrine sequence, Lower Jurassic Portland Formation, Suffield, Connecticut. U.S. Geological Survey Bulletin, no. 1776, p. 24-30.

McDonald, N.G. and LeTourneau, P.M., 1989. Taphonomic phosphate loss in Early Jurassic lacustrine fishes, East Berlin Formation, Hartford Basin, New England, USA. Washington, D.C., 28th International Geological Congress, Abstracts, volume 2, p. 398.

McDonald, N.G. and LeTourneau, P.M., 1990. Revised paleogeographic model for Early Jurassic deposits, Connecticut Valley: Regional easterly paleoslopes and internal drainage in an asymmetrical extensional basin. Geological Society of America Abstracts with Programs, v. 22, p. 54.

McHone, J.G. and Puffer, J., 2003. Volatile emissions from Central Atlantic Magmatic Province basalts: mass assumptions and environmental consequences. AGU Geophysical Monograph, v. 136, p. 241-254.

Newberry, J.S., 1888. Fossil fishes and fossil plants of the Triassic rocks of New Jersey and the Connecticut Valley. U.S. Geological Survey Monograph, v. 14, 152 p.

Nriagu, J.O., 1983. Rapid decomposition of fish bones in Lake Erie sediments. Hydrobiologia, v. 106, p. 217-222.

Olsen, P.E., 1986. A 40-million-year lake record of early Mesozoic orbital climatic forcing. Science, v. 234, p. 842-848.

Olsen, P.E., 1988. Continuity of strata in the Newark and Hartford Basins. U.S. Geological Survey Bulletin, no. 1776, p. 6-18.

Olsen, P.E., 1999. Giant lava flows, mass extinctions, and mantle plumes. Science, v. 284, p. 604-605.

Olsen, P.E., Et-Touhami, M., and Whiteside, J.H., 2012. *Cynodontipus*: A procolophonid burrow - not a hairy cynodont track (Middle-Late Triassic: Europe, Morocco, eastern North America). Geological Society of America, Abstracts with Programs, v. 44, no. 2, p. 56.

Olsen, P.E., Kent, D.V., Et-Touhami, M., and Puffer, J.H., 2003. Cyclo-, magneto-, and bio-stratigraphic constraints on the duration of the CAMP event and its relationship to the Triassic-Jurassic boundary. *In:* W.E., Hames, J.G. McHone, P.R., Renne, and C. Ruppel, (eds.), The Central Atlantic Magmatic Province: Insights From Fragments of Pangea. AGU Geophysical Monograph, v. 136, p. 7-32.

Olsen, P.E., Kent, D.V., Sues, H.-D., Koeberl, C., Huber, H., Montanari, A., Rainforth, E.C., Fowell, S.J., Szajana, M.J., and Hartline, B.W., 2002. Ascent of dinosaurs linked to iridium anomaly at Triassic-Jurassic boundary. Science, v. 296, p. 1305-1307.

Olsen, P.E. and McHone, J.G., 2003. Part II: Introduction [The Central Atlantic Large Igneous Province]. *In:* P.M. LeTourneau and P.E. Olsen, (eds.), The Great Rift Valleys of Pangea in Eastern North America, Volume I, p. 137-140. New York, Columbia University Press.

Olsen, P.E., and Rainforth, E.C., 2003. The Early Jurassic ornithischian dinosaurian ichnogenus *Anomoepus*. *In:* P.M. LeTourneau and P.E. Olsen, (eds.), The Great Rift Valleys of Pangea in Eastern North America, Volume II, p. 59-176. New York, Columbia University Press.

Olsen, P.E., Smith, J.B., and McDonald, N.G., 1998. Type material of the type species of the classic theropod footprint genera *Eubrontes*, *Anchisauripus*, and *Grallator* (Early Jurassic, Hartford and Deerfield basins, Connecticut and Massachusetts, U.S.A.). Journal of Vertebrate Paleontology, v. 18, p. 586–601.

Olsen, P.E., Whiteside, J.H., and Fedak, T., 2005. Triassic-Jurassic faunal and floral transition in the Fundy Basin, Nova Scotia. NAPC Field Guidebook, North American Congress, Halifax, 52 p.

Olsen, P.E., Whiteside, J.H., and Huber, P., 2003. Causes and consequences of the Triassic-Jurassic mass extinction as seen from the Hartford basin. *In:* J. B. Brady and J.T. Cheney, (eds.), Guidebook for Field Trips in the Five College Region, 95th New England Intercollegiate Geological Conference, p. B5-1 to B5-41.

Olsen, P.E., Whiteside, J.H., LeTourneau, P.M., and Huber, P., 2005. Jurassic cyclostratigraphy and paleontology of the Hartford basin. *In:* N.W. McHone and M.J. Peterson, (eds.), Guidebook for fieldtrips in Connecticut. New England Intercollegiate Geologic Conference. State Geological and Natural History Survey of Connecticut, Guidebook No. 8, Trip A-4, p. 55-106.

Ostrom, J.H. and Quarrier, S.S. 1968. The Rocky Hill Dinosaurs. *In*: P.M. Orville, (ed.), Guidebook for Fieldtrips in Connecticut. New England Intercollegiate Geological Conference 60th Annual Meeting, New Haven, Connecticut. State Geological and Natural History Survey of Connecticut Guidebook, Trip C-3, p. 1-12.

Posner, A.S., Blumenthal, N.C., and Betts, F., 1984. Chemistry and structure of precipitated hydroxyapatites. *In*: J.O. Nriagu and P.B. Moore, (eds.), Phosphate Minerals. p. 330-350.

Rainforth, E.C., 2003. Revision and re-evaluation of the Early Jurassic dinosaurian ichnogenus *Otozoum*. Palaeontology, v. 46, p. 803-838.

Rainforth, E. C., 2005. Ichnotaxonomy of the fossil footprints of the Connecticut Valley (Early Jurassic, Newark Supergroup, Connecticut and Massachusetts). Ph.D. dissertation, Columbia University, 1301 p.

Schaeffer, B., Dunkle, D.H., and McDonald, N.G., 1975. *Ptycholepis marshi* Newberry, a chondrostean fish from the Newark Group of eastern North America. Fieldiana Geology, v. 33, no. 12, p. 205-233.

Schaeffer, B. and McDonald, N.G., 1978. Redfieldiid fishes from the Triassic-Liassic Newark Supergroup of Eastern North America. American Museum of Natural History Bulletin, v. 159, p. 131-173.

Thompson, N., 1996. Putting their foot in it: Dinosaurs weren't shy about leaving their tracks all over central Connecticut. The Hartford Courant, p. H1, June 23. Available from: The Hartford Courant Archives (1764–1986); http://pqasb.pqarchiver.com/courant/advancedsearch.html

Warner, E. and Fowler, L., Sr., 1966. Industries. *In*: E. Burnham et al., (eds.), A History of Middlefield: Written for the Centennial Celebration 1866–1966. Portland, Connecticut, The Eaverly Printing Co., pp. 19–28.

Wenk, W. J., 1984. Seismic refraction model of depth of basement in the Hartford rift basin, Connecticut and Massachusetts. Northeastern Geology, v. 6, p. 196-202.

Whiteside, J.H., Olsen, P.E., Eglinton, T.I., Cornet, B., McDonald, N.G., and Huber, P., 2011. Pangean great lake paleoecology on the cusp of the end-Triassic extinction. Palaeogeography, Palaeoclimatology, and Palaeoecology, v. 301, no. 1-4, p. 1-17.

Whiteside, J.H., Olsen, P.E., Kent, D.V., Fowell, S.J., and Et-Touhami, M., 2007. Synchrony between the central Atlantic magmatic province and the Triassic-Jurassic mass-extinction event? Palaeogeography, Palaeoclimatology, Palaeoecology, v. 244, no. 1-4, pp. 345-367.

Yang, W, Gludovatz, B., Zimmmermann E.A., Bale, H.A., Ritchie, R.O., and Meyers, M.A., 2013. Structure and fracture resistance of alligator gar (*Atractosteus spatula*) armored fish scales. Acta Biomaterialia, v. 9, p. 5876-5889.