JURASSIC CYCLOSTRATIGRAPHY AND PALEONTOLOGY OF THE HARTFORD BASIN

by

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INTRODUCTION

Jurassic age lacustrine strata of the Hartford rift basin (Figs. 1, 2) are profoundly cyclical. Interbedded with the three laterally extensive basalt flow sequences of the Central Atlantic magmatic province (CAMP; Marzoli, 1999), the Shuttle Meadow and East Berlin sedimentary formations show a dominance of the familiar ~20 ky climatic precession cycle as well as the ~100, ~400, and longer eccentricity cycles that are strongly influenced in frequency by the chaotic behavior of the Solar System. Less well-studied, the lower 2 km of strata of the 4 km-thick Portland Formation immediately above the basalts are also cyclical.

In this guidebook, we describe and interpret the cyclicity and biofacies through most of the major Jurassic intervals in the south-central Hartford basin. We use the permeating Milankovitch cyclostratigraphy as the basis for an astronomically calibrated time scale for the Hettangian and possibly early Sinemurian ages, placing into environmental and temporal context the rich paleontological and biostratigraphically useful assemblages in the aftermath of the Triassic-Jurassic mass extinction and the great CAMP flood basalt eruptions.

ENVIRONMENTAL, GEOLOGICAL, AND BIOLOGICAL CONTEXT

With its nearly symmetrical meridional supercontinent, Pangea, the Triassic and Early Jurassic represent an extreme end member of Earth's geography and climate. With no evidence of polar ice (Frakes, 1979), this "hot house" world is marked by coal deposition in polar and equatorial regions and plausibly extremely high $p\mathrm{CO}_2$, as inferred from soil carbonate data (Wang et al., 1998; Ekart et al., 1999; Tanner et al., 2001) stomatal density trends (McElwain et al., 1999; Retallack, 2001), and geochemical models (Beerling and Berner, 2002). Despite vast climate differences from the present, a humid equatorial zone of modern dimensions (Kent and Olsen, 2000; Kent and Tauxe, 2005) existed (Fig. 3). Within the transition zone between this humid region and the arid, central subtropics to the north, a series of continental rifts from Nova Scotia to North Carolina filled with lacustrine and fluvial strata of the Newark Supergroup during the crustal extension that ultimately led to the fragmentation of Pangea. The Hartford basin is one of the largest segments of these extensive central and north Atlantic margin rifts (Fig. 1).

In central Pangea, including eastern North America, continental synrift sedimentation started in the middle Permian (Olsen et al., 2002d) and continued through the Early Jurassic (Olsen, 1997). The synrift sequence is comprised of four tectonostratigraphic sequences (Olsen, 1997; Fig. 4). Tectonostratigraphic sequences (TS) are conceptually similar to marine sequence stratigraphic units in that they are largely unconformity-bound, genetically-related packages, but are controlled largely by tectonic events. Tectonostratigraphic sequence I (TS I) is median Permian in age and while known from the Fundy basin of maritime Canada and various Moroccan basins,

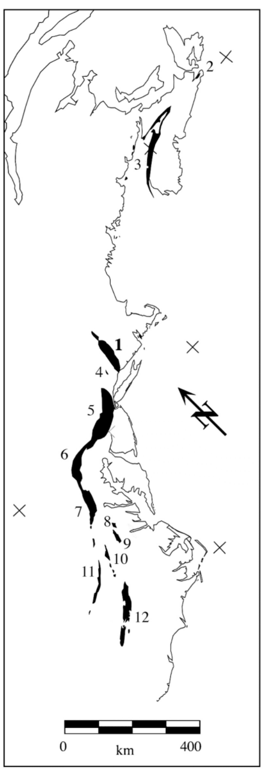

Figure 1. The Hartford basin within the Newark Supergroup. 1, Hartford and Deerfield basins; 2, Chedabucto or Orpheus basin; 3, Fundy basin; 4, Pomperaug basin; 5, Newark basin; 6, Gettysburg basin and mostly buried; 7, Culpeper basin; 8, Taylorsville basin; 9, Richmond basin; 10, Farmville and associated basins; 11, Dan River basin; 12, Deep River basin (modified from Olsen, 1997).

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could also exist in the subsurface in other basins. Tectonostratigraphic sequence II (TS II) is of Middle (Anisian-Ladinian) Triassic to early Late Triassic (Early to early Late Carnian) age and although present in most Newark Supergroup basins, is not known to exist in the Hartford basin. Tectonostratigraphic sequence III (TS III), of early Late Triassic (Late Carnian through early Late Rhaetian) age, is the most widespread sequence, dominating nearly all Newark Supergroup basins, and is represented in the Hartford basin by the lower +90% of the New Haven Formation.

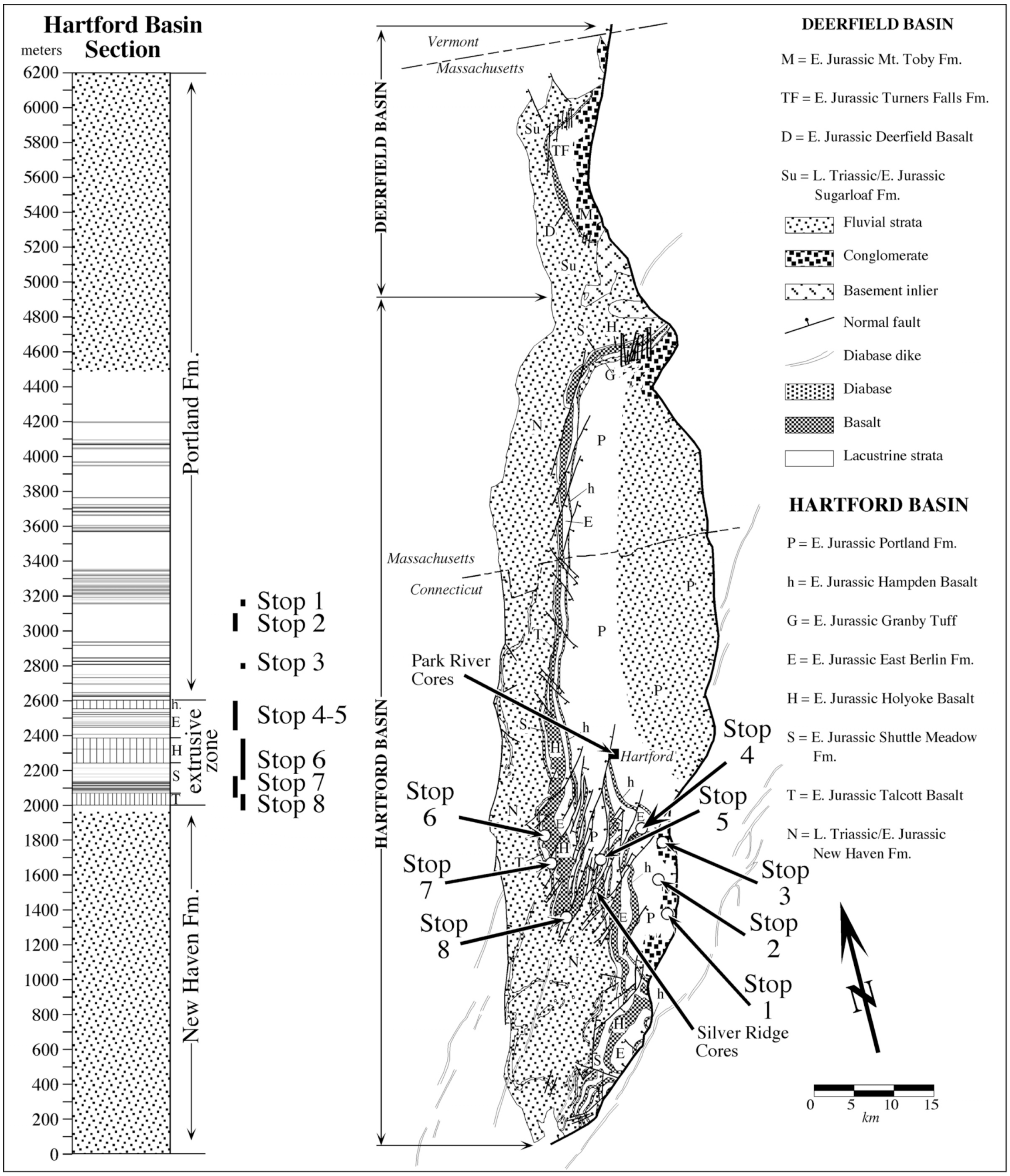


Figure 2. Bedrock geological map of the Hartford basin and basin section showing fieldtrip stops. Modified from Olsen et al., (2003a).

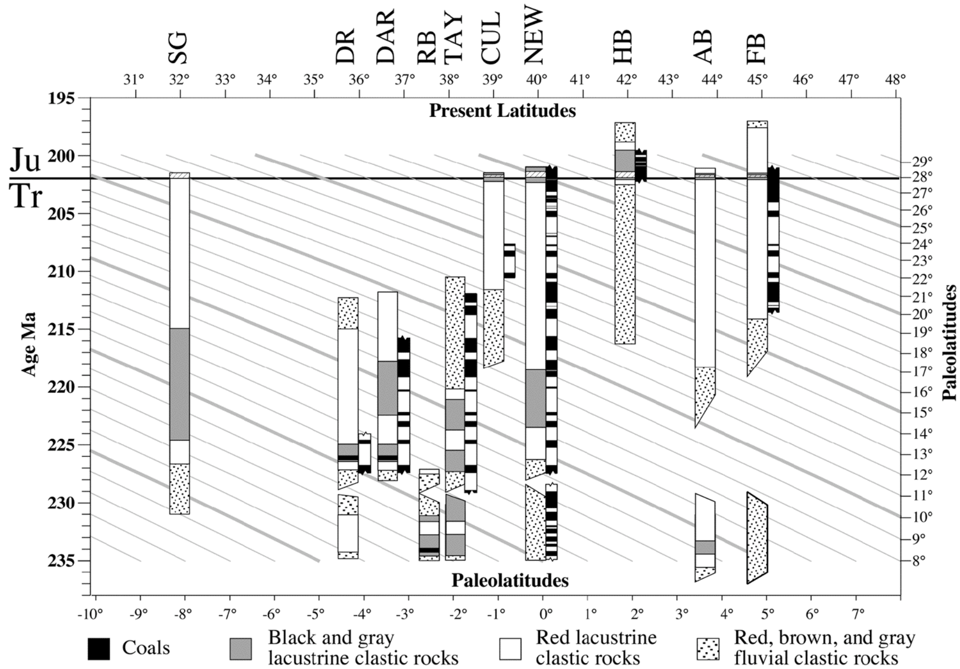


Figure 3. Time-geography nomogram showing the relationship between the main climate sensitive lithologies, age, geography, and latitude. Sections are correlated by magnetostratigraphy as indicated (black, normal; white, reverse). Slightly curved diagonal lines are lines of equal paleolatitude. Modified from Olsen and Kent (2000), Kent and Olsen (2000), and Kent and Tauxe (2005). Basins are: SG, South Georgia Rift; DR, Deep River Basin; DAR, Dan River basin; RB, Richmond basin; TAY, Taylorsville basin; CUL, Culpeper basin; NEW, Newark basin; HB, Hartford basin; AB, Argana basin; FB, Fundy basin.

Tectonostratigraphic sequence IV (TS IV) is of latest Triassic (Late Rhaetian) to Early Jurassic (Hettangian and Sinemurian) age. It contains the Triassic-Jurassic boundary, extrusive tholeiitic basalts of the CAMP, and in some basins extensive post-CAMP sedimentary strata. TS IV is very well represented in the Hartford basin where more Jurassic strata are preserved than elsewhere in eastern North America. The uppermost few meters of the New Haven Formation make up the lowest portions of TS IV, followed by the three basaltic lava formations of the basin, the Talcott, Holyoke, and Hampden basalts, intercalated with and overlain by the profoundly cyclical, lacustrine Shuttle Meadow, East Berlin, and lower Portland formations. The upper Portland Formation, still within TS IV, returns to fluvial deposits.

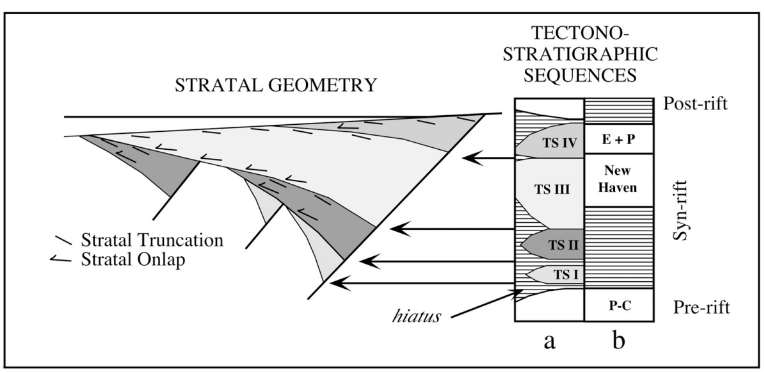


Figure 4. Tectonostratigraphic divisions of the Fundy basin. Adapted from Olsen (1997).

The Triassic and Early Jurassic was a time of evolutionary advent for terrestrial communities. Dinosaurs and mammals along with other major groups of extant vertebrates evolved during the Triassic. The crurotarsians occupied certain key ecological positions, including that of the top predators. Although modern groups had evolved, this was a world largely populated by unfamiliar taxa and with latitudinally distributed communities of different composition. Hence, the terrestrial Late Triassic was not merely an intermediate between the Early to Middle Triassic and Jurassic, it was a fully mature world unto itself, unsuspectingly diverse and unique. In contrast, the Early Jurassic was the dawn of the modern era of terrestrial vertebrate communities, exemplified in TS IV of the Hartford basin. All of the top predatory and herbivorous crurotarsians are gone. The strong biotic provinciality of the

Late Triassic has been replaced by an essentially global distribution of many genera and species. The Jurassic biological record of the Hartford basin features ecological dominance by dinosaurs with crocodylomorphs as the only other remaining archosaurs. Most of the continental tetrapod groups (e.g., lizards, turtles and lissamphibians) that survived the boundary are extant; mammals and the mammal-like tritheodonts and tritylodonts also survived; pterosaurs survived the Triassic-Jurassic boundary, but perished at the Cretaceous-Tertiary boundary.

In both the Triassic and Early Jurassic, seed plants (e.g., conifers and cycadophytes) and various ferns and fern allies including many extant families were abundant. While certainly not plentiful, angiosperms (flowering plants) may have evolved by the Late Triassic (Cornet, 1989a,b; Wolfe et al., 1989). Through the Late Triassic, an extinct conifer group, the Cheirolepidiaceae or cheiroleps became relatively abundant. After the Triassic-Jurassic mass extinction, the cheiroleps became the most conspicuous element of tropical terrestrial communities for 80 million years until angiosperm proliferation. The extraordinary preponderance of the cheirolepidiaceous conifers and the rise dominance of the dinosaurs after the boundary are two of the main features of the biological record in the Hartford basin.

The subject of this field guide is the cyclicity seen in the sedimentary record of the Hartford basin played out against the background of Pangean rifting, tropical climates, and post-Triassic-Jurassic boundary biotic recovery. Given this context, not all of our observations fit neatly into paradigms based on our modern world. Some will certainly reflect grand repetitive patterns driven by incessant climate cyclicity, while others will be completely contingent on the unique peculiarities of the times. This dialectic between the recurring and the historical is a theme of the discussions at all of the field stops.

CYCLICITY AND PALEOECOLOGICAL SUCCESSIONS

Lacustrine rocks of the Newark Supergroup record repetitive and permeating sequences called Van Houten cycles (Olsen, 1986), after their discoverer, Van Houten (1962, 1964, 1969, 1980) (Fig. 5). The Van Houten cycle is comprised of three lithologically distinct divisions that represent lacustrine transgression (division 1), high stand (division 2), and regression followed by lowstand deposits (division 3) controlled by precipitation and evaporation changes attributed to forcing of the 20ky climatic precession cycle. Van Houten cycles are modulated in vertical succession by a hierarchy of four orders of cycles (Fig. 5). These are ascribed to modulation of precession by “eccentricity” cycles, which average approximately 100 ky, 405 ky (named the McLaughlin cycle after a University of Michigan astronomer who mapped 405 ky cycles over much of the Newark basin; Olsen and Kent, 1996), and 1.75 and 3.5 m.y. cycles (Olsen, 2001; Olsen and Rainforth, 2002b). The 405 ky McLaughlin cycle in the Newark basin serves as a basis for an astronomically-calibrated geomagnetic polarity time scale for the Late Triassic (Olsen and Kent, 1996, 1999), and earliest Jurassic (with data added from the Hartford basin), which is pinned in absolute time by radiometric dates from CAMP igneous rocks. Employing the 405 ky cycle for an interval hundreds of millions of years ago is justified because this eccentricity cycle is caused by the gravitational interaction of Jupiter and Venus, a cycle which should be stable on the scale of billions of years (Laskar et al., 2004).

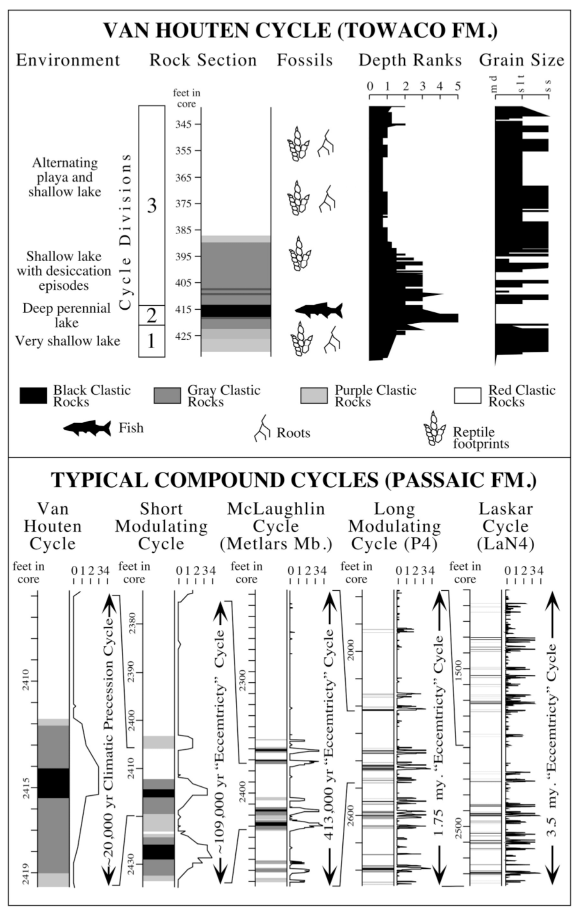


Figure 5. Van Houten and compound cycles. Modified from Olsen and Kent (1999).

The lacustrine cyclicity pervades the lower three quarters of the Jurassic age section in the Hartford basin

(Fig. 6). While understood in broad outline for decades (Hubert et al., 1976), the detailed pattern of this cyclicity has been worked out only recently as a result of detailed fieldwork and study of industry and Army Corps of Engineers cores (Kent and Olsen, 1999a; Olsen et al., 2002c, 2002d, 2003a; Pienkowski and Steinen, 1995). Van Houten cycles in the Hartford basin range from 10 to 30 m in thickness, depending on stratigraphic and geographic position. Within single formations in specific areas of the basin, Van Houten cycle thickness tends to vary only ~25%, but there are consistent differences between formations. The modal thickness of Van Houten cycles in the central Hartford basin is ~15 m in the Durham member of the Shuttle Meadow Formation; ~11 m in the East Berlin Formation; and ~20 m in the Portland Formation.

Six McLaughlin cycles are represented in TS IV in the Hartford basin. The lower two are segmented by the CAMP basalt flow sequences (Figs. 6, 7). The lowest begins in the uppermost New Haven Formation, the lithologic expression of which is termed the Farmington member, interrupted at its top by the Talcott Formation. This oldest McLaughlin cycle continues in the overlying Shuttle Meadow Formation where the lower mostly gray portion is termed the Durham member and the upper mostly red portion the Cooks Gap member. The Holyoke Basalt nearly divides the lowest McLaughlin cycle from the next, most of which comprises the East Berlin Formation. The top of this second McLaughlin cycle is truncated by the Hampden Basalt but resumes in the lower Portland Formation. The uppermost portion of this second McLaughlin cycle we term the Smiths Ferry member. Four more McLaughlin cycles are present in the rest of the lower Portland Formation; we have designated them in ascending order: the Park River member, the South Hadley Falls member, the Mittineague member, and the Stony Brook member. The relatively unknown remaining ~2 km of the Portland Formation appears to be completely fluvial.

The style of the cyclicity shifts through the Jurassic succession of the Hartford basin, in part in response to the longest period cycles (1.75 and 3.5 m.y.), and in part due to tectonic, climatic, and biotic changes related to the rifting history, the CAMP episode, and Triassic-Jurassic boundary phenomena. The major trends include: 1) the unusual prevalence of gray beds with a muted cyclicity in the middle of the profoundly cyclical lower Portland Formation (Whiteside et al., 2005a); 2) the appearance of lacustrine strata in the basin during a 2.5 m.y. interval in the Early Jurassic; and 3) the prevalence of calcareous units in the Shuttle Meadow Formation in association with the fern *Clathropteris*.

Influence of the longer period eccentricity cycles can be seen in the expression of the distinctness of the cyclicity itself. The ~20 ky and 100 ky cyclicity is very obvious during the wetter phases of the 405 ky (McLaughlin) cycles. The oldest 405 ky cycle beginning in the Farmington member of the New Haven Formation is not itself cyclical. Based on correlation between the overlying Shuttle Meadow Formation with the Feltville Formation of the Newark basin, the Farmington member should represent part of the first 100 ky cycle of the first Jurassic 405 ky cycle, the bulk of which is in the overlying Shuttle Meadow Formation. The next 405 ky cycle is comprised of the East Berlin Formation and overlying basal Portland Formation (Smiths Ferry member). These first two 405 ky cycles and the next, represented by the Park River member, have a very obvious cyclicity in which most 20 ky cycles have a black and gray portion and a distinct and thicker red portion. A large proportion of these cycles have a division 2 that is partially microlaminated, which we interpret as the deepest water facies. Thus, although these cycles have the best representation of the deepest water facies, they have a very large proportion of red beds suggesting that they formed during times of maximum precessional variance.

In dramatic contrast, the 405 ky cycle represented by the South Hadley Falls member has relatively muted Van Houten cycles—for the wetter (grayer) intervals, red bed development is poor. The development of the 100 ky cyclicity is very poor as well. Seemingly paradoxically, although the development of gray beds is the greatest of any of the 405 ky cycles in the Hartford basin, suggesting wet conditions, there is also greater development of evaporates than elsewhere and virtually no microlaminated intervals, suggesting drier conditions. This apparent paradox can be resolved if deposition occurred during a time in which precessional and 100 ky eccentricity forcing were at a minimum. In that case, both wet and dry extremes would be mollified. But, as a consequence, the lakes may never have deepened enough to reach the outlet so that solutes concentrated during the previous precessional cycle would not have been flushed from the system, allowing unusual concentrations to build up through succeeding cycles. Just such conditions occurred during the precessional minima tracking the g3-g4 eccentricity cycle that during the Triassic had a period of 1.75 m.y. If we look at the 1.75 million year cycle in light of independent correlation of the Newark and Harford basins, and project forward from the Passaic Formation, the first Jurassic precessional minimum should in fact occur in the South Hadley Falls member.

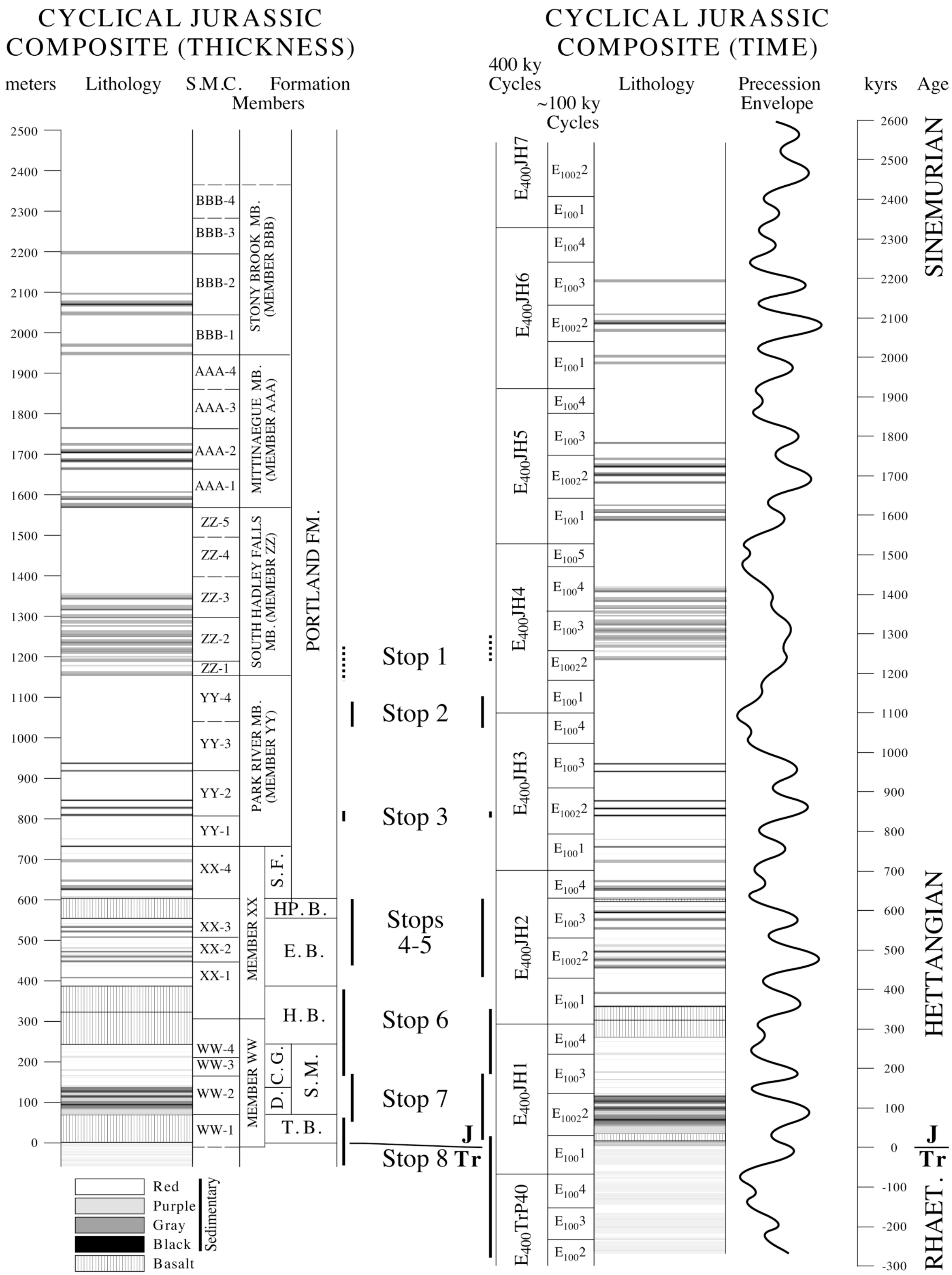
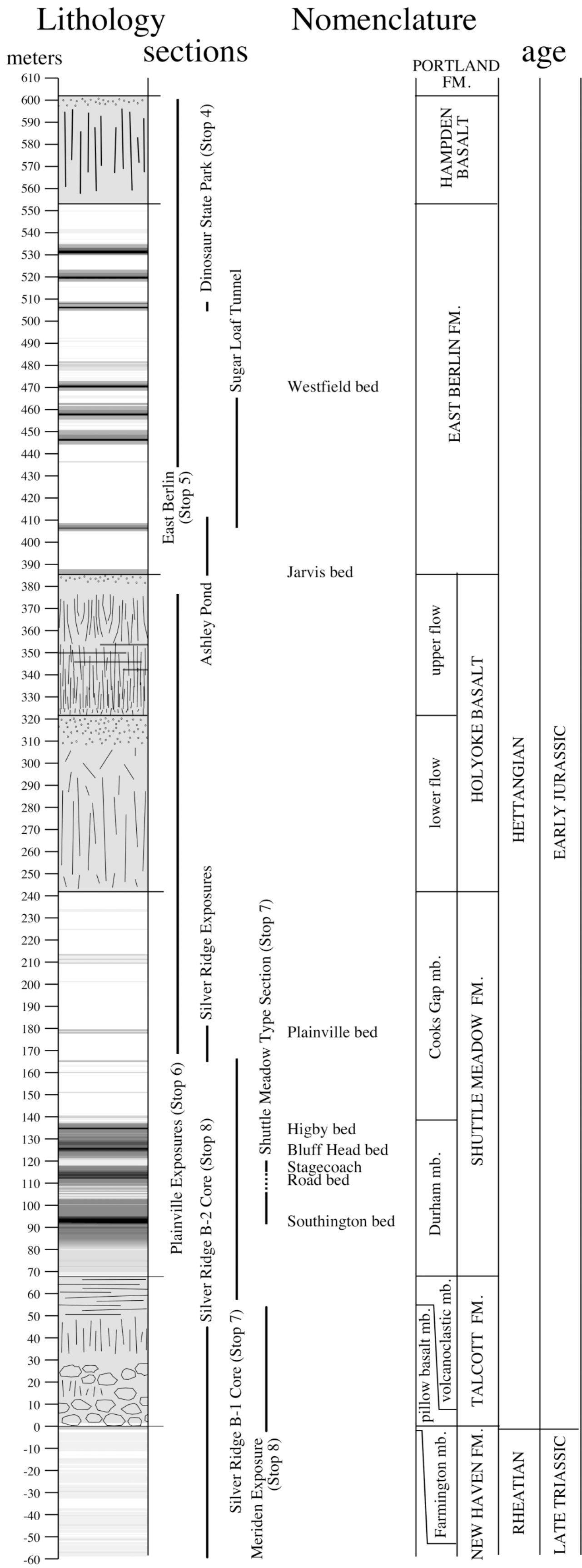


Figure 6. Jurassic cyclostratigraphy expressed as thickness and lithological units on left and in time and astronomical cycles on right, showing stratigraphic and temporal position of stops., Abbreviations are: T.B., Talcott Formation; D., Durham member; C.G., Cooks Gap member; S.M., Shuttle Meadow Formation; H.B., Holyoke Basalt; E.B., East Berlin Formation; HP.B., Hampden Basalt; S.F., Smiths Ferry member;



The largest-scale pattern of the appearance and disappearance of lacustrine strata is clearly of tectonic origin. Accommodation space growth had to first increase and then decrease in order to allow the transition from the fluvial New Haven Formation to the lacustrine deposits of the Shuttle Meadow Formation with an associated increase in sediment accumulation rate, in spite of the additional basin fill represented by the CAMP basalts. Similarly, accommodation space growth had to decrease in the middle Portland Formation to produce the transition back to purely fluvial deposits. As expected in a half graben these transitions are accompanied by changes in paleocurrent direction from largely axial and from the northeast during deposition of the New Haven Formation to largely from the west (hanging wall) during deposition of the Shuttle Meadow through the lower Portland Formation and back from the northeast during deposition of the upper Portland Formation (McInerny, 2003; Hubert et al., 1992), reflecting a pulse of accelerated fault-controlled asymmetrical basin subsidence as explained by the models of Schlische and Olsen (1990) and Contreras et al. (1997.) LeTourneau (2002) termed this predictable sequence of facies caused by a pulse of extension a Schlische cycle.

Characterized by deeper water units rich in carbonates (see Stops 5a and 5b), the cycles of the Shuttle Meadow Formation are amongst the most distinctive in the basin. The carbonates span a range of facies from black to light gray microlaminated deep-water lacustrine carbonates and calcareous mudstones (Cornet et al., 1975) of the Durham member to shallow-water and pedogenicly-modified massive and nodular micrites (Gierlowski-Kordesch and Huber, 1995) of the Plainville limestone bed of the Cooks Gap member. The only other significant carbonate unit in the Hartford basin section occurs at the base of the East Berlin Formation (e.g., Starquist, 1943). Gray and tan sandstones and siltstones of the Shuttle Meadow Formation also tend to have macrofossil remains of the large pinnate-leafed fern *Clathropteris meniscoide*s (Dipteridaceae) sometimes in growth position. The laminated to microlaminated units tend to have fronds of *Clathropteris* as well. Within the Hartford basin, such occurrences are restricted to this one formation, although fragments of the fern are preserved throughout the Jurassic sequence.

Figure 7. Stratigraphy of the extrusive zone in the Hartford basin and sources of stratigraphic data.

The prevalence of carbonates and the abundance of *Clathropteris* characterize the Shuttle Meadow Formation, remarkably similar to homotaxial units in the Culpeper, Newark, Pomperaug, Fundy, and in part Moroccan basins (no *Clathropteris* yet). That these distinctive sequences occur in the same homotaxial position relative to the basalts suggests that they represent deposition during the same time interval within their respective basins. The pattern probably represents a facies syndrome associated with the underlying Triassic-Jurassic boundary, perhaps related to the super-greenhouse conditions postulated for this time by McElwain et al. (1999) (Whiteside et al., 2005b).

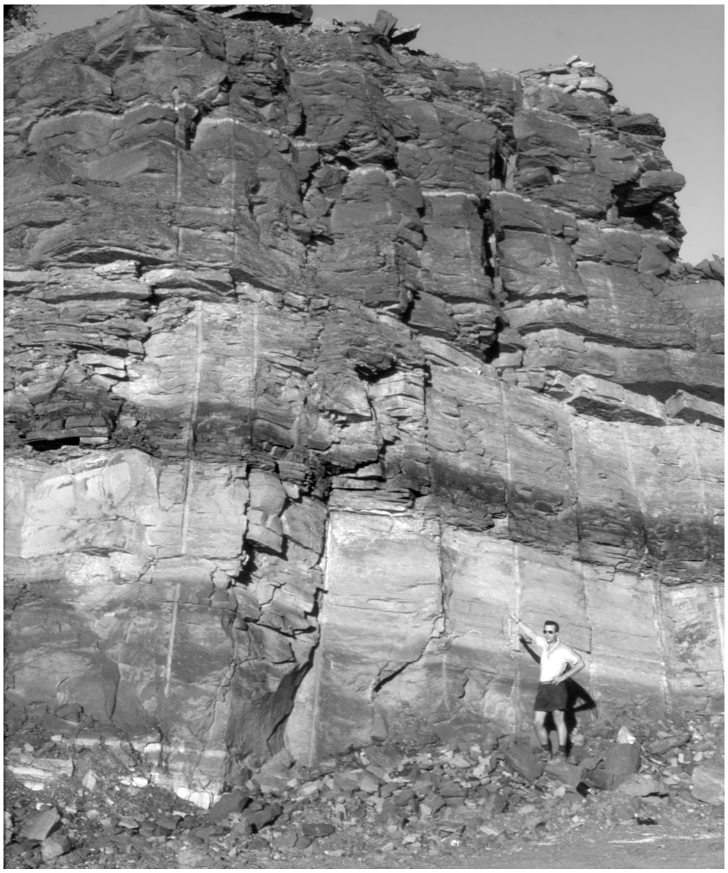


Figure 8. Single Van Houten cycle containing the Westfield bed at Stop 5. This is the uppermost of the second black-shale baring triplet from the top (i.e. short modulating cycle AAA-2 of Fig. 6). PML for scale.

At the opposite scale, Van Houten cycles of the Hartford basin demonstrate a predictable pattern of biofacies and depositional environments, fully developed within only a few of the cycles. These cycles have distinct, informally named microlaminated beds that have produced the bulk of fossil fish in the basin. These cycles contain in ascending order the Southington, Stagecoach Road, Bluff Head and Higby beds (Shuttle Meadow Formation: Stops 7 and 7a), the Westfield bed (East Berlin Formation; Stop 5), and the Middlefield (Stop 3) and Chicopee beds of the Portland Formation. The transgressive division 1 contains mudcracked clastics often with abundant reptile, especially dinosaur tracks deposited on an infrequently exposed shallow lake floor (Stop 5). The transition to division 2 is relatively abrupt with only a few centimeters of fossil-poor non-mudcracked mudstone or claystone. The usually calcareous microlaminated division 2 contains a stereotyped biofacies with articulated fishes, coprolites, occasionally the conchostracan *Cornia*, allochthonous vascular plant material (sometimes spectacularly preserved), and often allocthonous charophyte fragments. These laminites have individual laminae of great lateral extent (Olsen, 1988) and were deposited in perennial lakes exceeding tens of meters in depth (Olsen, 1990) (Stop 5). In fine grained settings. the microlaminated portion of division 2 is often overlain by a post-depositional mudstone mélange consisting of dark gray to black mudstone with microlaminated to laminated clasts derived from the underlying (and occasionally overlying) units. While interpreted by some authors as beds of rip up clasts, Olsen et al. (1989a) interpreted these sequences as a partly penecontemporaneously sheared dewatering phenomenon occurring within the beds after deposition of some thickness of overlying strata. Hence, they cannot be easily interpreted in terms of depositional environments (see Stops 5 and 7a). The upwardly shoaling rest of division 2 of the cycles tends to consist of laminated mudstones and minor sandstone (Stop 5) to sandstones and conglomerates (Stops 2 and 3), and frequently contain abundant conifer remains and reptile footprints (Stops 4, 5, 7, 7a). The succeeding division 3 is usually comprised of fine to coarse red beds, with abundant mud cracks and root structures, and less common reptile footprints (Stops 4, 5, 7).

Laterally, most of the cycles behave in a similar manner; they are thinnest over much of the central Hartford basin, thickening rapidly toward the eastern basin edge, as the cycles in general coarsen. The divisions of the cycles do not increase in proportion, however. Division 2 of the cycles increases at a much faster rate than divisions 1 or 3. This thickening is accomplished by an increase in the individual laminae and increase in the total fraction of the cycle taken up by the beds, and an increase in clastic content. The increase in clastic content is partially because of the presence of numerous small graded beds we interpret as turbidites (Stop 7). A similar pattern characterizes all of the black and dark shale beds of the Hartford basin and was outlined by LeTourneau and McDonald (1985).

Fish preservation within laminites of division 2 also changes along this thickening gradient. At several localities in the central Hartford basin, articulated fish are preserved as organic films with virtually no relief and sometimes as only very faint pyritic halos (i.e. dephos-phatization) (Stop 5). McDonald and LeTourneau (1989) described the trend from these regions towards the eastern basin edge where preservation of bony tissue vastly improves and the fish have progressive higher relief. The better preservation seems associated with higher clastic content, but the mechanism is very poorly understood. A very similar pattern of dephosphatization occurs in the fish-bearing laminites of the Devonian Caithness Flagstone of Scotland (Westoll, pers. comm., 1982).

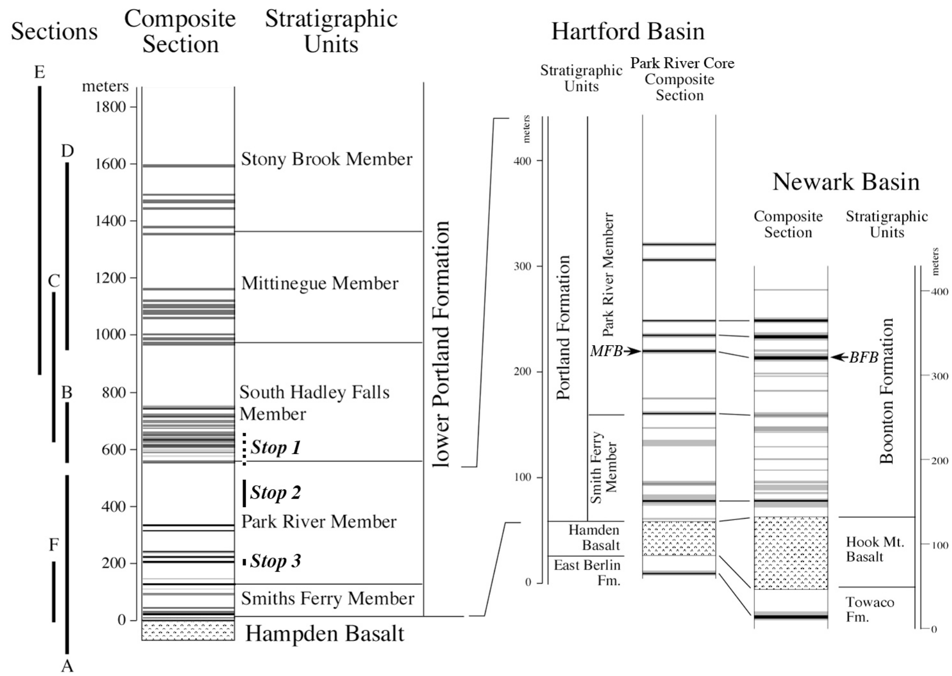


Figure 9. Stratigraphy of the Portland Formation, informal members of the Portland formation, and correlation to the Newark basin. Colors as in Fig. 6.

LITHOSTRATIGRAPHY AND BIOTA OF THE HARTFORD BASIN

New Haven Formation

The New Haven Arkose was named by Krynine (1950) for the thick succession of red, brown, tan, and minor gray siltstone, sandstone and conglomerate that represent the lower portion of the Hartford basin stratigraphic column. These strata were previously called "Western Sandstone" by Percival (1842) and Davis (1898), and in part, "Sugarloaf Arkose" by Emerson (1898; 1917). Krynine attempted a generalized stratigraphy of the formation based on a small number of short (2-20 m thick), scattered outcrops in the vicinities of New Haven and Meriden, CT, that extended through the formation's entire thickness (Krynine, 1950, fig. 10, table 2). Krynine designated 5 type sections, each of which represented what he interpreted to be a distinctive sedimentary facies assemblage, with much of his facies descriptions being based on petrologic data (e.g., heavy mineral assemblages) rather than stratigraphic and/or sedimentological criteria.

Gray (1987), among others, have recognized that the New Haven Formation contains diverse associations of lithofacies and have used the lithologic descriptor "Formation" instead of "Arkose". Several workers since Krynine (1950) have described the stratigraphy and sedimentology of several long stratigraphic sections of New Haven Formation rocks or have attempted generalized characterization of the formation (e.g., Wessal, 1969; Hubert et al., 1978; Lorenz, 1987; McInerny, 1993; McInerny and Hubert; 2002) though no one has attempted a comprehensive stratigraphic synthesis of the formation. The New Haven Formation varies in thickness from ~1500 m in the New Haven, Connecticut region to as much as 2000 m at, and west of Meriden, Connecticut.

Unlike its lacustrine time equivalents in the Lockatong and Passaic formations of the Newark basin, virtually all of the New Haven Formation fluvial strata lack black mudstones. The basal New Haven Formation locally has beds of gray sandstone that at one locality (Forestville, CT: Krynine, 1950; Cornet, 1977) produced a palynoflora closely comparable to that of the lower Passaic Formation. Hence the basal New Haven Formation is conventionally assigned a basal Norian age (Cornet, 1977).

The rest of the lower New Haven Formation consists of cyclical fluvial strata that have been interpreted as meandering river sequences (McInerney, 1993; McInerney and Hubert, 2003; Horne et al., 1993). These have common and locally well-developed pedogenic soil carbonates. Pure pedogenic micritic calcite from one such carbonate provided a U-Pb date of 211.9 ± 2.1 Ma (Wang et al., 1998), a Norian age on most time scales, including the Newark GPTS (Gradstein et al., 1995; Kent and Olsen, 1999). The same exposure has produced a partial skull of the crocodylomorph *Erpetosuchus*, known otherwise from the Lossiemouth Sandstone of Scotland, conventionally assigned a Carnian age (Olsen et al., 2000b). Previously described reptilian skeletal material from the New Haven Formation in the southern Hartford basin comprises the holotype of the stagonolepidid *Stegomus arcuatus* Marsh, 1896. Lucas et al. (1997) considered *Stegomus* a subjective junior synonym of *Aetosaurus*, an index fossil for continental strata that again suggests an early to middle Norian age and referred the lower to middle New Haven Formation to the Neshanician Land Vertebrate Faunachron (Lucas and Huber, 1993, 2003).

Virtually unstudied, the middle New Haven Formation in the central Hartford basin consists of mostly red massive sandstone with much less well-developed pedogenic carbonates (Krynine, 1950). Apart from abundant *Scoyenia* burrows and root casts, the only fossil recovered is a scapula of an indeterminate phytosaur ("*Belodon validus*" Marsh, 1893), indicating only a Late Triassic age. Much more varied lithologies categorize the upper part of TS III and the upper New Haven Formation (Hubert, et al., 1978), including meandering and braided river deposits and minor eolian sandstones (Smoot, 1991). Vertebrates from these strata include an indeterminate sphenodontian (Sues and Baird, 1993) and the procolophonid *Hypsognathus fenneri* (Sues et al., 2000). The presence of *Hypsognathus* indicates correlation to the upper Passaic Formation of the Newark basin and thus a Cliftonian Land Vertebrate Faunachron age (middle to late Norian and Rhaetian age).

We informally coin the name “Farmington member” for the distinctive uppermost 3-20 m of strata of the New Haven Formation (Stop 8, 8a). These strata consist of laterally-continuous, red to gray, well-bedded to laminated sandstone, siltstone and minor shale facies that are interbedded and/or intertongue in places with arkosic conglomerate, and sometimes volcaniclastic strata. The Farmington member is named for exposures of uppermost New Haven Formation strata that outcrop on the north side of Route 4 in Farmington, Connecticut. Davis (1898) and Gray (1982b) described facets of the geology of this locality. The Farmington member has produced a florule of *Brachyphyllum* conifers at multiple localities and in its uppermost few centimeters a palynoflorule of typical Jurassic aspect at one locality (see discussion at Stop 8a). The member plausibly contains the Triassic-Jurassic boundary, unless cut out by a TS III – TS IV unconformity.

Talcott Formation

The Talcott Formation was originally named the Talcott Diabase by Emerson (1917), the lower lava flow of the Meriden Formation by Krynine (1950) and raised in rank to formation by Sanders (1968). The Talcott Formation is a high-titanium quartz normative tholeiitic basalt (HTQ basalt; terminology of Puffer, 1992) that attains a maximum thickness of ~130 m in central Connecticut, and is composed of a variety of textures that display complex relationships. In central and southernmost Connecticut, the lower ~75 m of the Talcott Formation includes ubiquitous pillowed horizons that grade laterally and vertically into columnar-jointed massive basalt. The upper part of the formation is made up of volcaniclastic breccia and thin interbeds of conglomeratic, fluvial sandstone and conglomerate. Locally, the uppermost beds of the New Haven Formation interfinger with the Talcott Formation. This can be seen where forsets of pillow basalts overlie the New Haven Formation and tongues of red beds extend between them such as at Stop 8 in Meriden, CT.

Between the southernmost and central basin areas, the Talcott Formation consists of similar lithologies that can laterally interfinger along strike and throughout the entire thickness of the formation and reflects the proximity to sites of fissure eruptions where Talcott feeder dikes intersected the surface (cf. Philpotts and Martello, 1986). In this region, Sanders (1970) proposed a sweeping lithostratigraphic redefinition of the Talcott Formation to include four basalt and three sedimentary units that possessed a cumulative thickness of 300+ m. Sander’s (1970) proposed scheme relied implicitly upon the assumption that the relevant units were tabular, parallel, conformable lithosomes, but this is not the case. Instead, the outcrop consists of growth structures developed with the feeder system of the Talcott Formation (Philpotts and Martello, 1986; Olsen, et al., 2004).

The nature of the upper contact of the Talcott Formation is variable, and is gradational over a short stratigraphic distances often consisting of volcanoclastics where the largely gray lower Shuttle Meadow Formation (Durham member) is present (see Stop 7). In other areas of the basin in the vicinity of Meriden and also north of Cooks Gap, the Durham member is not present and the contact is a disconformity, and basal Shuttle Meadow strata locally consists of up to 0.5 m of well rounded/well-sorted conglomerate composed exclusively of clasts of Talcott Formation.

Shuttle Meadow Formation

The Shuttle Meadow Formation was named by Lehmann (1959) to replace the anterior shales of Percival (1842) and Davis (1898) and the lower sedimentary division of the Meriden Formation of Krynine (1950); it is the oldest of the Hartford basin sedimentary formations that is entirely of Jurassic age and the oldest unit expressing well-developed lacustrine cyclicity (Figs. 6, 7). The type section is near the Shuttle Meadow Reservoir and was described by Krynine (1950). The formation attains a maximum estimated thickness of ~250 m near the border fault, and is herein defined to consist of two member-rank units: a lower sequence of gray, black and red strata, up to ~100 m thick that we informally designate the Durham member after outcrops comprising the famous fossil fish locality of the same name in Durham, CT (Newberry, 1888; Davis and Loper, 1891; McDonald, 1975); and an upper mostly red sequence we informally call the Cooks Gap member, named after the exposures at Cooks Gap, Plainville, CT.

Having produced fossil fish for over a century, the Durham member is exposed at many locations in the Hartford basin, but no section revealed the complete succession of beds until the recovery of the Silver Ridge B-1 core (see Stop 7). We recognize three well-developed Van Houten cycles in this member, each with a distinctive and laterally recognizable division 2 to which we give informal names.

The contact of the Durham and Cook's Gap members is defined by the transition of gray- green shale and siltstone of the Higby cycle into red, finely laminated similar lithologies which pass into red, ripple cross laminated siltstone. Where the Durham member is absent, redbeds of the Cooks Gap member rest directly on basalt of the Talcott Formation. The Cooks Gap member is overlain everywhere by the Holyoke Basalt. We hypothesize that the pinching out of the Durham member between the Talcott Formation and the Cooks Gap member is accomplished by progressive onlap of the Durham member against the Talcott Formation, rather than a dramatic thinning of its component parts or a lateral change in facies of the Durham member to that of the Cooks Gap member. The striking changes in thickness laterally of the Shuttle Meadow Formation along strike along the western outcrop belt of the formation is thus largely due to a onlap of progressively younger strata onto the Talcott Formation.

The sequence of Van Houten cycles seen in the Durham member as well as the transition into red beds as seen in the upper parts of the Silver Ridge B1 core (Fig. 7; Stop 7) is typical of a short modulating cycle (Fig. 5). We regard the top of this short modulating cycle (WW2; Fig. 6) to be at the base of the weakly variegated beds at the top of the Silver Ridge Core. The largest continuous exposure of the Cooks Gap member is at Cook Gap, Plainville, CT (Stop 6), where virtually the entire member is exposed. As described by Gierlowski-Kordesch and Huber (1995) most of the section consists of red and red-brown ripple-cross-laminated siltstone and sandstone and interbedded red, mostly massive, mudstones. The red units have abundant desiccation cracks and dinosaur tracks, as well as some locally abundant burrows and root casts. There are a series of gray, purplish, and tan beds that mark out successive, very weakly developed Van Houten cycles, and one set of limestone beds near the base of the member that we designate informally, the "Plainville limestone bed" (see Stop 6). This bed is laterally continuous and has been identified at all sections where the suitable interval is exposed. It falls stratigraphically at the appropriate place for the peak of the next short modulating cycle (WW3; Fig. 6) after the cycle containing the Durham member.

Lateral facies changes in the Cooks Gap member are poorly known due to limited outcrop as well as the lateral variability of beds as seen in the Cooks Gap section. At East Haven the Cooks Gap member is much coarser. Pebbly sandstone and conglomerate beds are abundant, reflecting the proximity of the eastern border fault 1.2 km to the southeast. Here the Plainville limestone bed is well developed, containing macerated plant debris and isolated fish scales and bones.

Overall, in the Shuttle Meadow Formation, microfloral assemblages are present in most gray claystones and siltstones, which is not the case in the other formations. In all cases the palynoflorules are dominated by the cheirolepidiaceous pollen genus *Corollina* (Cornet, 1977). Floral macrofossils are often present in the same units. Assemblages bearing *Clathropteris* and *Equisetites* are common throughout the Shuttle Meadow Formation. The Bluff Head bed has produced a relatively diverse macroflora of ferns, cycadeoides, ginkophytes, and cheirolepidiaceous conifers (Newberry, 1888) (See Stop 7).

Invertebrates are represented by burrows and walking and crawling traces of arthropods, along with locally by common clams, ostracodes, the conchostracan *Cornia*, and the beetle larva *Mormolucoides* (McDonald, 1992; Huber, et al., 2003). Articulated fossil fish, often beautifully preserved and very abundant, occur in the five named beds with the formation and pertain to four taxa: the ptycholepid palaeonisciform *Ptycholepis marshi*, the redfieldiid palaeonisciform *Redfieldius gracilis*, the holostean neopterygian *Semionotus* sp., and the coelacanth *Diplurus longicadatus* (Newberry, 1888; Cornet et al., 1975; Schaeffer et al., 1975; Schaeffer and McDonald, 1978; Olsen and McCune, 1991). Additionally, two isolated possible theropod teeth were recovered from the lower Shuttle Meadow Formation (McDonald, 1992).

While the Jurassic strata of the Hartford basin comprise the type area of the famous Connecticut Valley footprint assemblage (e.g., Hitchcock, 1836, 1848, 1858, 1865; Lull, 1904, 1915, 1953; Olsen et al., 1998; Olsen and Rainforth, 2002a; Rainforth, 2005), footprint assemblages from the Shuttle Meadow Formation are amongst the most poorly known in the Jurassic of eastern North America. However, the assemblage is clearly of Connecticut Valley aspect. The theropod dinosaur tracks *Eubrontes giganteus*, and a variety of smaller forms traditionally called *Anchisauripus* and *Grallator* are present along with much less common *Anomoepus* (ornithischian dinosaur: Lull, 1953; Olsen and Rainforth, 2002a), *Batrachopus* (crocodylomorph), and a recently discovered example of the synapsid track *Ameghinichnus* (found by G. McHone). The only significant Connecticut Valley genus missing is the prosauropod dinosaur track *Otozoum* (Rainforth, 2003).

Holyoke Basalt

The Holyoke Basalt is the most widespread of the CAMP flow sequences in the Connecticut Valley, always being present at the appropriate stratigraphic level (Stop 6). It was named the Holyoke diabase bed by Emerson (1891) for what previously had been called the main trap sheet by Percival (1842) and Davis (1898), and renamed the Holyoke Basalt by Lehmann (1959). The Holyoke Basalt is an HFQ-type (high-iron quartz normative) basalt, essentially identical in chemistry to the lower three flows of the Preakness Basalt of the Newark basin (Puffer et al., 1981; Puffer, 1992). It reaches a maximum thickness in excess of 200 m (Philpotts and McHone, 2004). Two flows are present in central Connecticut, but only the upper extends throughout the basin (Davis, 1898; Gray, 1987). The lower flow tends to be very massive with a thick and reddened vesicular top. The second has a colonnade with a characteristic splintery jointing, and a curvicolumnar upper entablature (Philpotts and McHone, 2004). Prevot and McWilliams (1989) identified an anomalous paleomagnetic direction (an excursion) in the lower part of the Holyoke Basalt at several localities in northern Connecticut and Massachusetts where the lower flow is absent. The excursion is recorded in the second flow of the Preakness Basalt of the Newark basin (P2 and P3 units of Tollo and Gotfried, 1992), characterized by the same kind of splintery fracture, and again in the upper flow of the Deerfield Basalt. The presence of this excursion in these different basins strongly suggests that these flows were erupted simultaneously, within hundreds of years. It also implies that the lower flow of the Holyoke Basalt is represented in the Newark basin by the thin discontinuous unit at the base of the formation (unit P1 of Tollo and Gotfried, 1992), or the lowest, pillowed flow of the Deerfield Basin.

East Berlin Formation

Lehmann (1959) named the sedimentary unit between the Holyoke and Hampden basalts, the East Berlin Formation, replacing the informal name middle shale of Percival (1842), posterior shales Davis (1898), and upper sedimentary division of the Meriden Formation of Krynine (1950). It was the first Hartford basin unit in which cyclical strata were described (Krynine, 1950; Klein, 1968; Hubert and Reed, 1978, Hubert et al., 1976, 1978; Demicco and Gierlowski-Kordesch, 1986; Olsen et al., 1989a). The formation is ~200 m thick in its type area, thickening toward the east (Figs. 6, 7).

The Van Houten cycles and short modulating cycles of the East Berlin Formation are the most obvious in the basin, due partly to the excellent exposures at which they are displayed (e.g., Stop 5), and partly to the thick red bed-dominated division 3 that contrasts obviously with the gray divisions 1 and 2 and the black deepest water portion of division 2 (Fig. 8). The two or three Van Houten cycles of each short modulating cycle divisions 1 and 2 that are gray purple or red, make the longer frequency cycles obvious as well.

Three short modulating cycles comprise the East Berlin Formation (Figs. 6, 7). The lowest has Van Houten cycles in which each has a relatively poorly developed division 2, lacking a microlaminated bed, while the upper two have a two Van Houten cycles each with a microlaminated division 2. The thickest microlaminated bed is within division 2 of the third Van Houten cycle of the middle short modulating cycle (Westfield bed). Hence, the middle of the East Berlin Formation marks the wettest phase of a McLaughlin cycle. Fourier analysis of depth ranks of the section at Stop 5 reveals a clear hierarchy of periodicities in thicknesses of 12.0 m and 68.3 m. Assuming that the 12.0-m-thick cycles are the 20 ky precession cycles, the 68.3-m-thick cycles have periodicities in time of 113 ky, consistent with a Milankovitch interpretation (Olsen et al., 1989a).

The lateral continuity of Van Houten cycles in the East Berlin Formation was demonstrated by Hubert et al, (1976, 1978) who showed the strong stratigraphic relationship between the mapped distribution of the Hampden Basalt and the underlying Van Houten cycles over much of the Hartford basin. Olsen et al. (1989a) elaborated upon the lateral correlation of the cycles and showed that correlation of the microlaminae and turbidites in polished slabs from the Westfield, providing compelling independent evidence of the lateral continuity of the cycles (Olsen, 1988). Changes towards the border faults are much like in the other cyclical units (e.g., Shuttle Meadow Formation), as is the fish dephosphatization pattern, best exemplified in the Westfield bed (McDonald and LeTourneau, 1989).

Despite the abundance of gray beds in the East Berlin Formation, palyniferous units are rare. This is not a function of the thermal maturity of the strata, because even those that are of very low thermal maturity ($R_o = 0.5$; Pratt et al., 1988) have rare preservation of pollen and spores. Nonetheless some palynofloules have been recovered and all are typically Early Jurassic in aspect being very strongly dominated by *Corollina meyeriana* (Cornet, 1977; Cornet and Olsen, 1985). While macrofloral remains are common in the gray beds, they are almost totally dominated by shoots of *Brachyphyllum* (see Stop 5) with scraps of *Otozamites* and even more rare *Clathropteris*, making a dramatic contrast with the underlying Shuttle Meadow Formation.

The fish assemblage is similar to the underlying Shuttle Meadow Formation. *Semionotus*, *Redfieldius*, very rare *Ptycholepis* and *Diplurus* are present (McDonald, 1975, 1992, pers. comm.), as well as the abundant *Diplurus* coprolites. In addition, six or more, slightly recurved, non-serrated conical reptile teeth have bee found in the Westfield bed that cannot yet be attributed to any taxon with confidence (H. D. Sues, pers comm., 1995).

As usual, invertebrates are represented by burrows and walking and crawling traces of arthropods, along with locally by common examples of the conchostracan *Cornia*, and rare insect body fossils, specifically the beetle larva, *Mormolucoides* (Lull, 1953; McDonald, 1992; Huber, et al., 2003).

Although the East Berlin Formation is justifiably famous for the spectacular display of large theropod dinosaur tracks (*Eubrontes giganteus*) at Dinosaur State Park (Stop 4), the overall assemblage is actually relatively poorly known. Like the underlying Shuttle Meadow Formation, the usual Connecticut Valley taxa (*Eubrontes*, *Anchisauripus*, *Grallator*, *Anomoepus*, and *Batrachopus*) are present, with the exception of *Otozoum*.

Hampden Basalt

Emerson (1898) named the Hampden Diabase for the posterior sheet of Percival (1842) and Davis (1898) that was later termed the upper lava flow of the Meriden Formation by Krynine (1950) and finally the Hampden Basalt by Lehmann (1959). The Hampden Basalt is a high-TiO, high-Fe, quartz-normative tholeiite (HFTQ) identical in composition to the Hook Mountain Basalt, which appears to be its exact temporal correlate. According to Chapman (1965), there may be as many as eight flow units based on the presence of thin vesicle zones, although Gray (1982a) suggested that the maximum is two flows in Massachusetts (Colton and Hartshorn, 1966), which agrees with our observations and one flow in central Connecticut (Stop 5). The flows are typically massive but can be very vesicular at the base and top. Tilted pipestem vesicles are common at the lower contact and indicate a northeasterly flow direction (Gray, 1982a). The Hampden Basalt is the thinnest of the extrusives in the Hartford basin, reaching a maximum thickness of 30 m, and thinning and disappearing near the Massachusetts border where it is largely replaced by the equivalent Granby Tuff (Emerson, 1898; Robinson and Lutrell, 1985), reappearing again on the back slope of the Mount Tom and Holyoke ranges at the northern end of the Hartford basin.

Portland Formation

Krynine (1950) coined the name Portland Arkose to apply to all sedimentary rocks above the Hampden Basalt and its equivalent, the Granby Tuff. Previous names for these strata include the eastern sandstone of Silliman (1826), Percival (1842) and Davis (1898), and Longmeadow Sandstone (in part) and Chicopee Shale (in part) of Emerson (1898, 1917). Krynine's (1950) stratotype was designated at the Portland brownstone quarries along the east bank of the Connecticut River in Portland, Connecticut (see Stop 2). Leo et al., (1977) recognized that the Portland contains a diverse range of lithofacies, and modified the unit name to Portland Formation. The Portland Formation ranges in thickness from ~450 m in southern Connecticut, to ~1 km in the vicinity of Middletown, to as much as 4 km thick in the central portion of the Hartford basin north of Hartford and in south-central Massachusetts (Fig. 2).

The Portland Formation is composed of a lower half consisting of cyclical lacustrine and marginal fluvio-lacustrine red, gray and black clastic rocks closely comparable to the East Berlin Formation, and an upper half made up almost entirely of fluvial red mudstone sandstone and conglomerate and minor red eolian strata (total maximum thickness ~5 km). Olsen et al. (2002c, 2003a) divide the lower Portland Formation into members in a parallel manner to the Passaic Formation of the Newark basin. They recognize four full McLaughlin cycles in the lower Portland, and one continuing from the underlying East Berlin Formation. These mappable units are proposed as informal members as follows (from the bottom up): "Smiths Ferry", "Park River", "South Hadley Falls", "Mittineague", and "Stony Brook" members (Figs. 6, 9). These units are critical to establishing the cyclostratigraphy and time scale for the Hettangian and Sinemurian sites and hence reconstructing the sedimentologic and structural history from the Triassic-Jurassic.

We recognize five members in the lower, 2 km-thick lacustrine-dominated portion of the Portland Formation. The upper 2 km-thick interval of the formation, dominated by fluvial and alluvial-fan facies is undivided. As the cyclicity of the lower Portland strongly resembles the lithologic expression of cyclicity displayed by the Passaic Formation in the Newark basin, we have modified McLaughlin's (1933) and Olsen et al.'s (1996) approach by adopting a lithostratigraphic nomenclatural convention for the Portland Formation from the Passaic Formation in which lithologically identified McLaughlin cycles are given formal member names (e.g., McLaughlin, 1933; Olsen et al., 1996) (Fig. 6). In this convention, we divide the Portland Formation into a series of lithologically identified members, each consisting of a lower cyclical portion with significant amounts of gray and black strata, and an upper portion that is predominately red. While these members do broadly correspond to McLaughlin cycles, they are defined by purely lithological criteria, and each member has, in fact, has its own lithologic and boundary characteristics that do not necessarily correspond to the natural peaks or troughs of cycles derived from Fourier analysis.

During the Park River diversionary tunnel project, the Army Corps of Engineers cored the lowermost ~500 m of the Portland Formation the near Hartford (Pienkowski and Steinen, 1995). These cores, a number of much less extensive cores and borings as well as outcrops along Stony Brook River, the Connecticut River, the Westfield River, and the Chicopee River in south central Massachusetts (Fig. 9) provide the most significant stratigraphic information on the Portland Formation. Combined with other outcrops and exposures, these sections allow us to compile a composite stratigraphy for the lower half of the Portland Formation, the informally designated members of which are described below.

Smiths Ferry member: We define the base of the Portland Formation as the stratigraphically lowest sedimentary bed that lies above the Hampden Basalt or Granby Tuff. The 110 m of the lower Portland Formation as seen in the Park River cores comprise the Smiths Ferry member, named for extensive outcrops at, and in the vicinity of, the Dinosaur Footprint Reservation at Smiths Ferry, Massachusetts. The Park River cores penetrated the entire thickness of the Smiths Ferry member including its contact with the Hampden Basalt, and provide an excellent reference section that allows correlation of other lengthy exposures in different areas of the basin.

Depending on basin location, the Smiths Ferry member ranges between 100-150 m-thick. In the Park River cores, the member begins with thin, red basal strata followed by a series of three Van Houten cycles each with gray to dark gray division 2. The basal red strata and triplet of gray shales up to the top of the third shale unit have a cumulative thickness of 40 m, and are in turn overlain by 30 m of entirely red siltstone and sandstone which contain two red Van Houten cycles. The upper Smiths Ferry member includes two additional Van Houten cycles, each with a gray or purple division 2, and intercalated red siltstone and sandstone with a cumulative thickness of 30 m. The top of the Smiths Ferry member is defined as the base of the prominent black shale marking the overlying Park River member in the Park River cores.

The lower Smiths Ferry member constitutes the uppermost, short modulating cycle of the ~400 ky McLaughlin cycle that began in and comprises the East Berlin Formation. The last two Van Houten cycles within the upper 30 m of the member (as seen in the Park River cores) actually belong to the basal short modulating (~100 ky) cycle partially contained within the overlying Park River member, but the non-red parts of those two cycles are too indistinct to be practical for field recognition as an upper boundary for the Smiths Ferry member.

At its type section, the Smiths Ferry member consists of well-exposed, basal red siltstone and sandy siltstone that include the main dinosaur track-bearing surface of the Holyoke Footprint preserve described by Ostrom (1972). It is also the locality for the type specimen of *Eubrontes giganteus*, the first dinosaur footprint to be described and figured (Hitchcock, 1836; Buckland, 1836; Olsen et al., 1998). Above the aerially-extensive footprint horizons, only the next two Van Houten cycles of the member are in part exposed. The gray strata of these cycles contain abundant oscillatory ripples, dinosaur footprints, and oriented plant debris. Laterally-equivalent exposures include extensive outcrops in the Middletown and adjacent quadrangles mapped and described in part by Lehman (1959) and Gilchrist (1979). The Smiths Ferry member is well-represented within the confines of Wadsworth Falls State Park and nearby in the bed and banks of the Connichaug River in Middletown. Most of the gray and dark gray lakebeds visible in the Park Cores can be readily identified in the field.

Park River member: We informally name cyclical lacustrine strata between the Smiths Ferry member and the overlying South Hadley Falls member the Park River member after the type section contained by the Park River cores (Fig. 9). In the cores, the type Park River member is represented by 280 m of section, and begins at the base of the first prominent black mudstone above the mostly red beds of the upper Smiths Ferry member as discussed above. Its top is defined as the base of the first well-developed black shale of the succeeding South Hadley Falls member, which is not represented in the cores. The lower half of the Park River member is profoundly cyclical, with a pattern remarkably similar in lithology and overall properties to the East Berlin Formation, but different than overlying members.

The upper half of the Park River member is represented by extensive outcrops in the Middletown area first documented in detail by McDonald (1975) and LeTourneau (1985a). The most distinctive portion of the Park River member is the second short modulating cycle, the lowest Van Houten cycle of which has a microlaminated division 2, termed the Middlefield bed after outcrops along Laurel Brook in Middlefield, Connecticut. Known since at least the 1820's (Redfield, 1836; Davis and Loper, 1891; McDonald, 1975, 1992), this unit has produced the holotype of *Redfieldius gracilis* Hay 1899 (Schaeffer and McDonald, 1978) along with several morphotypes of neopterygian *Semionotus* (possibly "species flocks" similar to those of McCune (1986) and Olsen and McCune (1991). Other exposures of this bed and the enclosing Van Houten cycle include outcrops in Bachelor Brook, South Hadley, Massachusetts (Hubert et al., 1992), Long Brook, Cromwell, Connecticut, the foundation excavations (now covered) for the One State House Square building, Hartford, Connecticut, and the unit uncovered in a gravel pit at Glastonbury, Connecticut described by LeTourneau and McDonald (1997) (Stop 3). These locations have collectively produced a wealth of fossils including fish and coprolites and most importantly conchostracans, plants and dinosaur footprints.

The third short modulating cycle of the Park River member contains a doublet of Van Houten cycles each with black shale-bearing division 2 (Figs. 6, 9). These lack a microlaminated portion and as a rule are not well exposed. One outcrop that is probably of this short modulating cycle is exposed along Long Hill Brook, Middletown, Connecticut and one of the thin black mudstones of division 2 of the upper Van Houten cycle of this doublet does contain associated if not completely articulated fossil fish (McDonald, 1975).

The sandstone facies of the Park River member in the northern and southern portions of the Hartford basin are distinctive in preferentially being used for building stone, compared to other members of the cyclical portion of the formation. These include quarries in South Hadley, Massachusetts that produced the type of *Otozoum moodii, Grallator parallelum* (Hitchcock, 1847; Olsen et al., 1998; Rainforth, 2003), and numerous other footprint taxa of dubious validity. Red beds in the fourth and uppermost short modulating cycle comprise the extensively exposed sandstones in the famous Portland Brownstone Quarries (Hubert et al., 1982, 1992, McInerney, 1993; Guinness, 2003) that have produced very abundant and well-preserved reptile footprints (i.e., Hitchcock, 1865) as well as one example of dinosaur bone casts (Colbert and Baird, 1958) (Stop 2).

Lateral changes in the Park River member are comparable to those seen in the East Berlin Formation, again with a disproportionate increase in the thickness of division 2 of Van Houten cycles – best seen in the cycle bearing the Middlefield fish bed (Stop 3). Extensive conglomerates are present in this member in southern Connecticut and have been described by LeTourneau and McDonald (1985, 1997), Smoot et al. (1985) and Smoot (1991).

South Hadley Falls member: We informally designate the largely gray strata and succeeding red beds between the underlying Park River member and the overlying Mittineague member the South Hadley member after its type section along the Connecticut River at South Hadley Falls and adjacent Holyoke, Massachusetts (Olsen et al., 2003a).

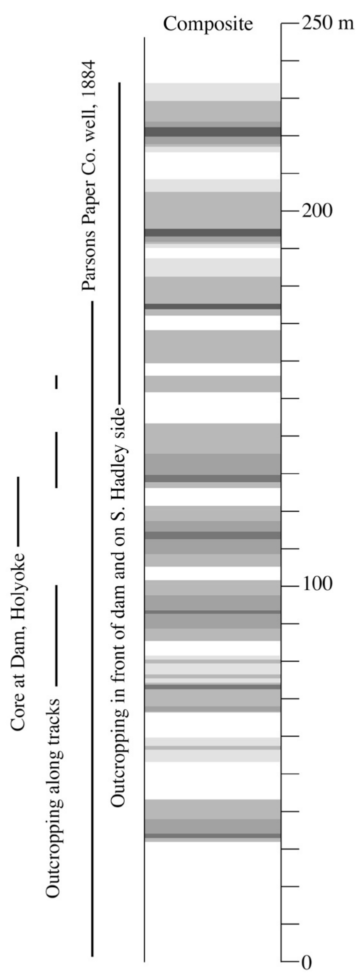


Figure 10. Composite section in vicinity of the Holyoke dam. Parsons Paper Co. well data from Emerson (1898). Rock color as in Fig. 5.

The South Hadley Falls member distinctively has a very large proportion of gray strata, a relatively muted expression of the short modulating cycles, and a high frequency of evaporite pseudomorphs in the lower half of the member (Fig. 10, 11). The base of the South Hadley Falls member is defined by the base of the first well-developed gray Van Houten cycle above the red bed sequence that comprises the upper Park River member. The top is defined by base of the gray strata of the overlying Mittineague member. The type section consists of exposures that comprise four transects along the Conrail railroad cut in Holyoke, Massachusetts and adjacent exposures in the bed and banks of the Connecticut River (and canals) in Holyoke and South Hadley Falls, Massachusetts. These outcrops are augmented by a short core (DH-1, Holyoke Power and Light) and records of a water well drilled for the Parsons Paper Company (documented by Emerson, 1898).

As seen at the type section, most Van Houten cycles have an unusually thick and gray division 2 composed of laminated mudstone but generally lack a microlaminated portion (see Stop 3). Division 1 tends to be relatively thin and silty as does division 3, with relatively uncommon desiccation cracks and footprints. Most of division 2 tends to be dominated by thin-bedded mudstones with macroscopic pyrite and delicate pinch and swell lamination. Evaporite pseudomorphs, probably after halite and gypsum, or glauberite and halite, are abundant in many layers, especially in the transition between division 2 and 3, sometimes constituting more than 50% of a bed by volume (Fig. 11). Some of these evaporite pseudomorphs have been described by Parnell (1983) and were commented on much earlier by Emerson (1898; 1917). Because of the relatively thick and gray division 2 in many Van Houten cycles, the short modulating cycles are relatively muted although still discernable compared to other parts of the Hartford Jurassic section.

Other areas in Connecticut that expose the lower South Hadley Falls member include those at Prout Brook (Stop 3) and Petzold's Marina where LeTourneau (1985a) and LeTourneau and McDonald (1988) first documented the apparent thickening of individual Van Houten cycle black shale beds across the basin apporaching the border fault system. In Massachusetts, the member is exposed along streams in northern West Springfield, and in northeastern South Hadley (M. McMenamin, pers. comm..) and Granby, Massachusetts, where the entire member coarsens.

The red beds that comprise the upper South Hadley member are very poorly exposed. The only good outcrops are along Stony Brook at West Suffield (Chard Pond), Connecticut and at Granby, Massachusetts. Almost nothing is known about lateral changes in the red upper portions of this member because there are virtually no outcrops.

The thick-fine grained division 2 of the gray cycles have abundant conifer shoots and isolated cone scales to complete cones, equisetalian stems, and large, pieces of wood. Fragmentary fish are also present, and at least one bedding surface contains a mass mortality accumulation of insect larvae (Huber, et al, 2003). Division 3 of the mostly gray Van Houten cycles tend also to be thin- to flaggy-bedded and often have shallow and poorly preserved reptile footprints, especially brontozooids. The red beds at Granby have produced a large number of tridactyl dinosaurian footprints, mostly brontozooids, from a small but productive dinosaur footprint quarry (William Gringas Granby Dinosaur Museum).

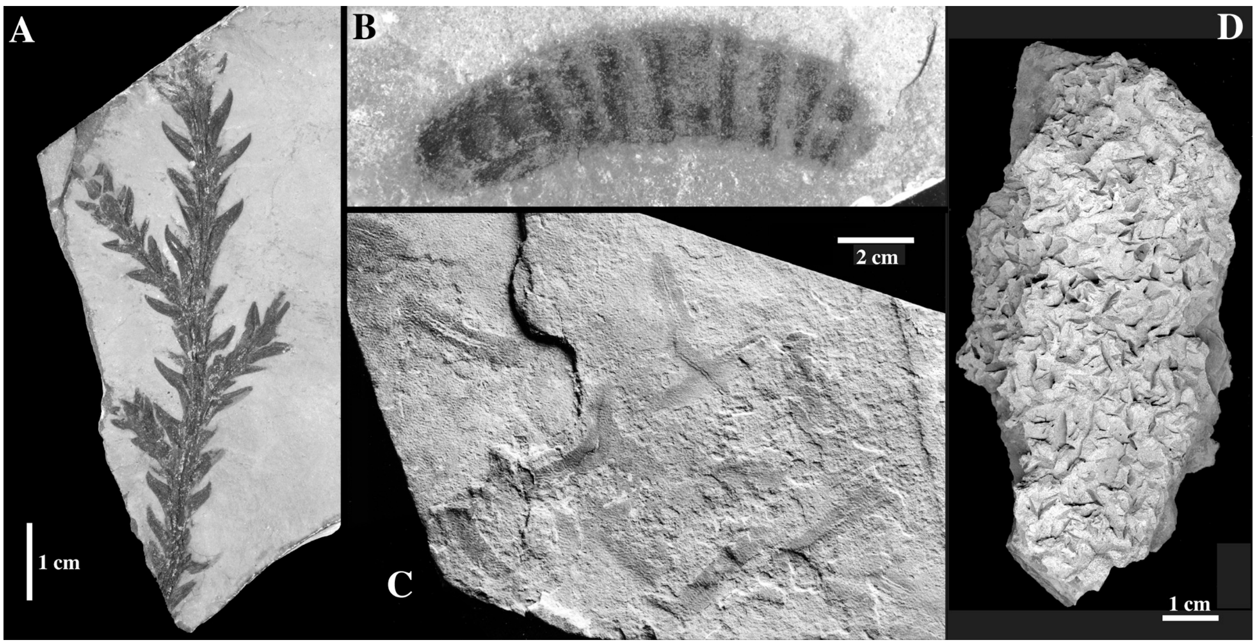


Figure 11. A, large-leafed conifer, south side of canal, Holyoke dam (N.G. McDonald collection); B, unidentified larva, collected by B. K. Emerson in 1901 near Holyoke, Massachusetts; C, Unidentified larvae, downstream from the Holyoke dam, Portland Formation, Holyoke, Massachusetts; D, evaporite pseudomorphs after a ?sulfate, railroad cut near dam, Holyoke. B and C from Huber et al., 2003.

Mittineague member: We informally name the cyclical strata between the South Hadley Falls member and the Stony Brook member the Mittineague member after the village adjacent to the type section along the banks of the Westfield River (Figs. 6, 9). Strata of the Mittineague member to some extent resemble the Park River member and the East Berlin Formation, except that the Mittineague member tends to be more calcareous in both its lower and upper parts. This member, like the overlying member of the Portland Formation, is known almost entirely from outcrops, and although there are no long continuous sections a composite section can be readily constructed because of the distinctiveness of individual beds, in particular, the Chicopee bed.

Van Houten cycles of the lower half of the Mittineague member differ from those in the underlying South Hadley Falls member in having a much smaller proportion of gray strata, very much like the Park River member. The basal short modulating cycle of this member has a triplet of Van Houten cycles each with a gray and black division 2 lacking microlaminations. The base of the black shale in the lowest cycle of the triplet defines the base of the member. Red beds in this short modulating cycle have abundant septarian nodules that characterize much of the rest of the red beds of the lower half of the Mittineague member. Thin red claystone beds with conchostracans and ostracodes are also present. The second short modulating cycle of the member has a basal Van Houten cycle with a thick black, but not microlaminated division 2. The second Van Houten cycle has a very distinctive division 2 that is very calcareous and microlaminated informally called the Chicopee bed (Olsen et al., 1989b).

Overall, the Chicopee bed lithologically resembles portions of the Westfield fish bed of the East Berlin Formation, but it contains a unique fossil fish assemblage dominated by the probable pholidophoridiform holostean "*Acentrophorus*" *chicopensis* (Newberry, 1888). It is easily recognizable at the three major sections of the Mittineague member and microlaminae are traceable for at least 12 km, assuring correlation of the sections.

Divisions 1 and lower parts of division 3 of Van Houten cycles in the lower part of the Mittineague member tend to have abundant beds of climbing ripple cross laminated siltstone and fine sandstone usually with abundant dinosaur footprints of the "leptodactylus" form (penetrating deeply into the bed). Desiccation cracks are usually present as well as septarian and other carbonate nodules.

The upper strata of the Mittineague member are characterized by meter-scale (sub-Van Houten cycle-scale) alternations of red mudstones and thin but laterally continuous gray claystones and associated carbonate layers. These palyniferous (Cornet, 1977) gray layers usually have abundant conifer fragments, conchostracans and ostracodes.

Stony Brook member: The unit we informally designate the Stony Brook member is the uppermost recognized cyclical member of the Portland Formation falling between the underlying Mittineague member and the overlying coarse clastic rocks of the undivided upper Portland Formation. It is named for the outcrops in the eponymous creek in Suffield, Connecticut near its mouth on the Connecticut River. Its base is defined as the base of the lowest black shale of the basal short modulating cycle of the member above the largely red beds of the upper Mittineague member.

Unlike the underlying members, Van Houten cycles of the Stony Brook member often have well-developed inclined beds (delta forests) even in the central portion of the basin. McDonald and LeTourneau (1988) described the geometry of one of the cycles. None of the cycles have microlaminated strata. As a whole, the member is less well-cemented than lower units and locally was used in brick making. The last active pit, the Kelsey-Ferguson quarry, closed in about 1992 and is now reclaimed.

Fossils tend to be abundant and vary in the laterally variable division 2 of the Van Houten cycles. Carbonate pellet lags at the base of inclined strata include bivalve escape structures, unionid bivalves, fish scales and bones, and oncolites (McDonald and LeTourneau, 1988). Red and gray claystones locally have abundant and well-preserved plant remains, fragmentary fish, conchostracans, ostracodes, and insects (Cornet and McDonald, 1995; Huber et al, 2003). The macrofloral assemblages are dominated by cheirolepidiaceous conifers, notably *Brachyphyllum* and *Pagiophyllum* and their reproductive structures (Cornet, 1977; Olsen et al., 1989a; Olsen et al., 2003a). Ripple crosslaminated siltstones and fine sandstones associated with divisions 1 and 3 of Van Houten cycles tend to have abundant leptodactylus dinosaur footprints. Footprints are also present as impressions, usually collectable as natural casts (sole marks).

The upper red strata of the Stony Brook member are substantially coarser than the lower members in the same basinal position with abundant interbedded bioturbated sandstone and thin beds of massive red mudstone. The best exposure of this facies is the CT Route 190 cut at Thompsonville, Connecticut. No Van Houten cycles are readily visible in this outcrop and this facies seems transitional into the overlying, yet coarser clastic rocks of the upper undivided Portland Formation.

Upper Portland Formation (undivided); The upper ~2 km of the Portland Formation is dominated, or perhaps composed exclusively of red fluvial strata (Hubert et al., 1982; McInerney, 1993). Very little is known about these strata otherwise. Several localities in the upper Portland have produced fragmentary to nearly complete skeletons of the prosauropod genera *Anchisaurus* and *Ammosaurus* and the crocodylomorph genus *Stegomosuchus* (Lull, 1953).

ACKNOWLEDGEMENTS

We would like to thank the landowners of the field stops for permission to visit their property. This manuscript benefited from discussions with Emma Rainforth on ichnotaxonomy, Bruce Cornet on cheirolepidiaceaous conifers and angiosperm evolution, Nicholas McDonald on Hartford basin stratigraphy and fish samples, and with Sterling Nesbitt on basal dinosaurs. Partial funding of this project was provided by the US NSF EAR 00-00922 and EAR 04-46843.This is a contribution to International Geological Correlation Programme Projects 458 and 506 and is Lamont-Doherty Earth Observatory Contribution 6814.

ROAD LOG

We have arranged the field trip to go downsection through the composite stratigraphy of the Hartford basin as if we were drilling a scientific corehole. The uppermost two members of the cyclical part of the basin section, the Mittineague and overlying Stony Brook members do not crop out in southern or central Connecticut, and time constraints do not allow us to see the latter two members in the same day. We therefore begin where the South Hadley Falls member crops out at Prout Brook, the lowest point of a 1.75 m.y. eccentricity cycle (Stop 1) and then look at the fossiliferous fluvial and eolian strata in the Park River member, the upper part of which is exposed in the Portland Brownstone (Stop 2) and its lower part at the exposure at the sand pit off Old Maids Lane in Portland (Stop 3). Stop 4 is the classic exposure of dinosaur footprints in the Upper East Berlin Formation at Dinosaur State Park and Lunch. Stop 5 details the Hampden Basalt and a superb pattern of Van Houten and short modulating cycles at the East Berlin road cut, followed by a view of the two flows of the Holyoke Basalt at Cooks Gap (Stop 6.) Outcrops and cores of the Shuttle Meadow Fm. reveal that the cyclostratigraphy of the lower Shuttle Meadow Formation and its associated rich faunal and floral remains are the focus of (Stop 7) and our final stop (Stop 8) is a spectacular view of the pillowed Talcott Formation and underlying uppermost New Haven Formation, which represent the initiation of CAMP and associated basin tilting.

Mileage (Courtesy of Mapquest TM)

Field trip begins in front of the Peabody Museum, 170 Whitney Ave., New Haven, CT.

0.0	Start out going SOUTH on WHITNEY AVE toward BRADLEY ST
0.1	Turn LEFT onto TRUMBULL ST.
0.2	Merge onto I-91 N via the ramp on the LEFT toward HARTFORD
15.2	Take the CT-68 exit- EXIT 15- toward YALESVILLE / DURHAM.
15.5	Turn RIGHT onto CT-68 / BARNES RD. Continue to follow CT-68.
20.6	Turn LEFT onto CT-17 / MAIN ST.
20.7	Turn RIGHT onto MAIDEN LN.
21.9	Turn SLIGHT RIGHT onto JOHNSON LN.
23.7	JOHNSON LN becomes FOOT HILLS RD.
23.9	FOOT HILLS RD becomes MILLBROOK RD.
25.8	Turn LEFT onto PROUT HILL RD.
25.9	Stop west of culvert for Prout Brook, Middletown follow path along east sloping hill to outcrops along ravine and in Prout Brook.

STOP 1. PROUT BROOK OUTCROPS OF THE SOUTH HADLEY FALLS MEMBER (60 MINUTES) SE Middletown Quadrangle, (approx.) 40°31.50' N, 72°38.25' W; Tectonostratigraphic sequence TS IV; South Hadley Falls member, Portland Formation; Hettangian age, 200 Ma. Main points are: thick dark gray beds in South Hadley Falls Member; muted cyclicity; coarse facies close to boarder fault system; very low thermal maturity with biomarker preservation.

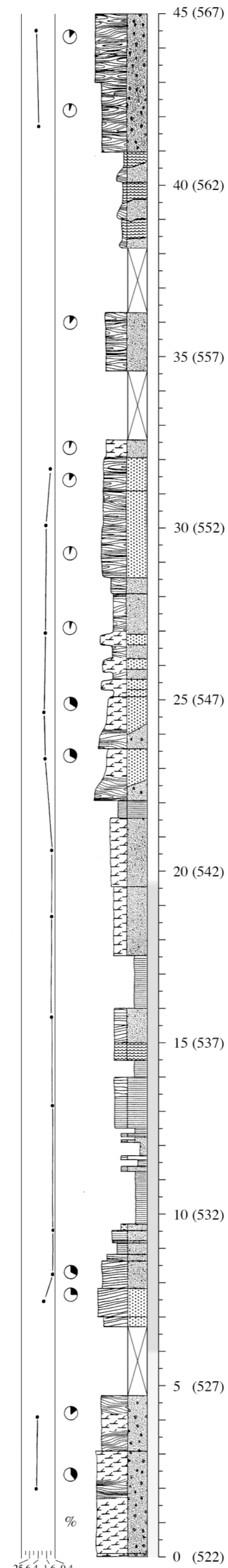


Figure 12. Right. Measured section at Prout Brook. Modified from LeTourneau (1985).

Prout Brook flows east through a gorge from the dam near north end of Crystal Lake, Middletown, CT. Exposed in the beds of the brook and in the walls of the gorge is a 39 m thick section of mostly gray sandstone, pebbly sandstone, and dark gray mudstone overlain red mostly coarse clastics (Fig. 12). These outcrops were briefly mentioned by Rice and Foye (1927) and were described by LetTourneau (1985).

According to LeTourneau (1985a), the Prout Brook section lies about 530 m above the Middlefield bed outcrops at Laurel Brook (its type section) lying within the lower Park River member. The intervening strata are mostly red, coarse clastics with an intervening set of gray intervals that best outcrop along Long Hill Brook that almost certainly correlate with the two well-developed Van Houten cycles above the triplet that contains the Middlefield bed. Assuming no thickening, this would place the Prout Brook section within the South Hadley Falls member, with which it is lithologically consistent Assuming 25% thickening towards the border fault, the Prout Brook section would fall somewhere in the mostly gray portion of the South Hadley Falls member.

The lower part of the Prout Brook section consists predominantly of planer to trough cross-bedded grayish brawn conglomerate overlain by fining up cross-bedded gray sandstone (Fig. 13). This is followed by a dark gray to black laminated mudstone and siltstone sequence with abundant microfaults (sensu Olsen et al., 1989; Ackermann et al., 2003) and conifer fragments, that coarsens up through a series of beds alternating sandstone and siltstone beds, with ripple cross-lamination upwards. The upper half of the section is red with abundant planer and trough cross-bedded sandstone and some ripple cross-laminated siltstone, with the uppermost exposed section consisting of cross-bedded red conglomerate.

The finer-grained gray part of the section is characterized by both an unusually small amount of evidence for desiccation and no microlaminated unit. Unfortunately the outcrops do not permit us to determine what part of the lower South Hadley Falls member this section represents. However, the fact that the adjacent underlying section exposed along the shores of Crystal Lake consists entirely of red strata, plausibly of the upper Park River member, suggests that the Prout Brook section represents the lowest short modulating cycle within the lower South Hadley Falls member. A similar outcrop is present at Petzold's Marina in northern Portland, along the Connecticut River and this section presumably correlates with the Prout Brook member. These are amongst the only known outcrops of the South Hadley Falls member in Southern Connecticut.

Return to vehicle.

25.9 Start out going EAST on PROUT HILL RD toward SUNNYSLOPE DR.
26.0 Turn LEFT onto MILLBROOK RD.
26.8 MILLBROOK RD becomes E MAIN ST.
27.5 Stay STRAIGHT to go onto MAIN ST EXT.
28.1 MAIN ST EXT becomes CRESCENT ST.
28.2 CRESCENT ST becomes MAIN ST.
28.9 Turn SLIGHT RIGHT onto CT-66 / CT-17 / ARRIGONI BRIDGE. Continue to follow CT-66 / CT-17.
29.7 Turn LEFT onto SILVER ST.
29.9 Turn RIGHT onto BROWNSTONE AVE.
30.0 Turn right into viewing area for Portland Quarries, Portland, CT

STOP 2. BROWNSTONE QUARRY, PORTLAND FORMATION (30 MINUTES) Central Middletown Quadrangle, (approx.) 41°34.50' N, 72°38.50' W; Tectonostratigraphic sequence TS IV; upper Park River member, Portland Formation; Hettangian age, 200 Ma. Main points are: extensive exposures of red and brown fluvial and eolian of the dry phase of a 405 ky cycle; strata quarried for building stone for over two centuries; abundant and very-well preserved reptile footprints and other fossils.

Location, Stratigraphy, Sedimentology (contributed by Peter M. LeTourneau)

Located less than 3 kilometers from the eastern border fault of the Hartford basin, the Portland quarries occupy a position on the western edge of the Crow Hill Fan complex that has its depocenter near the high school on the top of Crow Hill. The eastern edge of the fan complex is observed along Route 17 in Portland, near the golf course, where boulder conglomerate is exposed in road cuts and natural outcrops. The southern margin of the fan complex is observed along the north side of Route 66 in the vicinity of the miniature golf course where thinning and fining wedges of the fan conglomerate lithosomes are observed. The Connecticut River laps against the northern flank of the fan complex in the vicinity of Petzold's Marina where a long stratigraphic section of interbedded alluvial fan and dark gray to black, relatively deep water lacustrine deposits of the South Hadley Falls member, reminiscent of the Hales Brook Fan-Delta (Stop 3), but correlative to the lower South Hadley Falls member (Stop 1) are exposed.

Brownstone is the trade name for the Portland Formation arkosic sandstone ("Portland arkose"), which is made of quartz and feldspar sand with calcite and hematite cement. Re-examination of sedimentary features reveal that eolian deposits are a significant component of this sequence. These rocks contain sedimentary features attributable to sand sheets, low angle dunes, and linear "coppice" dunes. The eolian beds were apparently preferred for building stone because of their grain size and texture. The eolian beds alternate with fluvial beds in intervals about 15 m thick indicating possible cyclic climatic control on deposition, tracing out subtle Van Houten cycles.

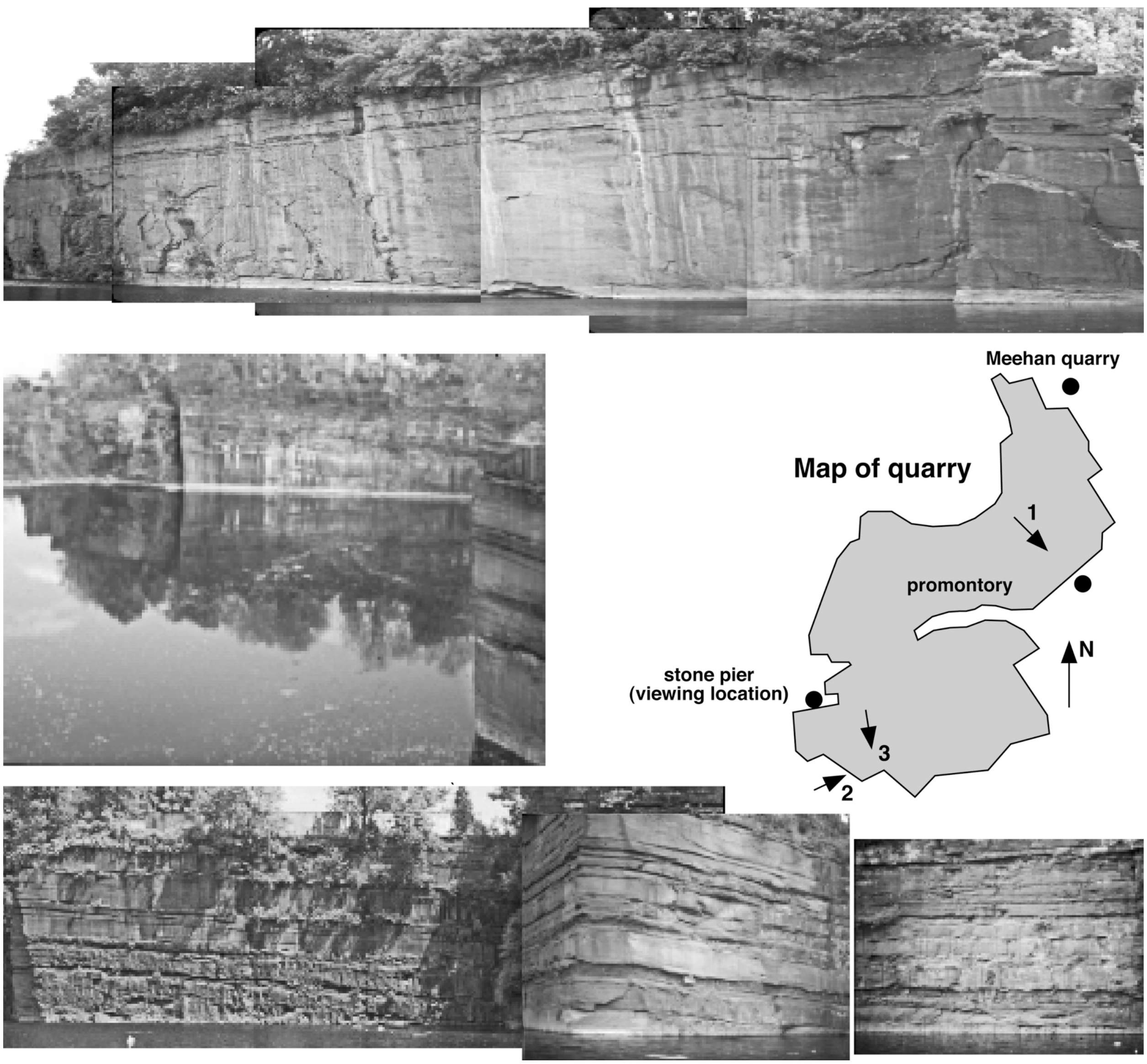


Figure 13. Portland brownstone quarries. Top, view of southeast wall, Middlesex pit (see map for direction of view); center left, view of northeast wall, Brainerd pit (see map for direction of view); center right, map of quarry; bottom; View of southwest wall, Brainerd pit (see map for direction of view),

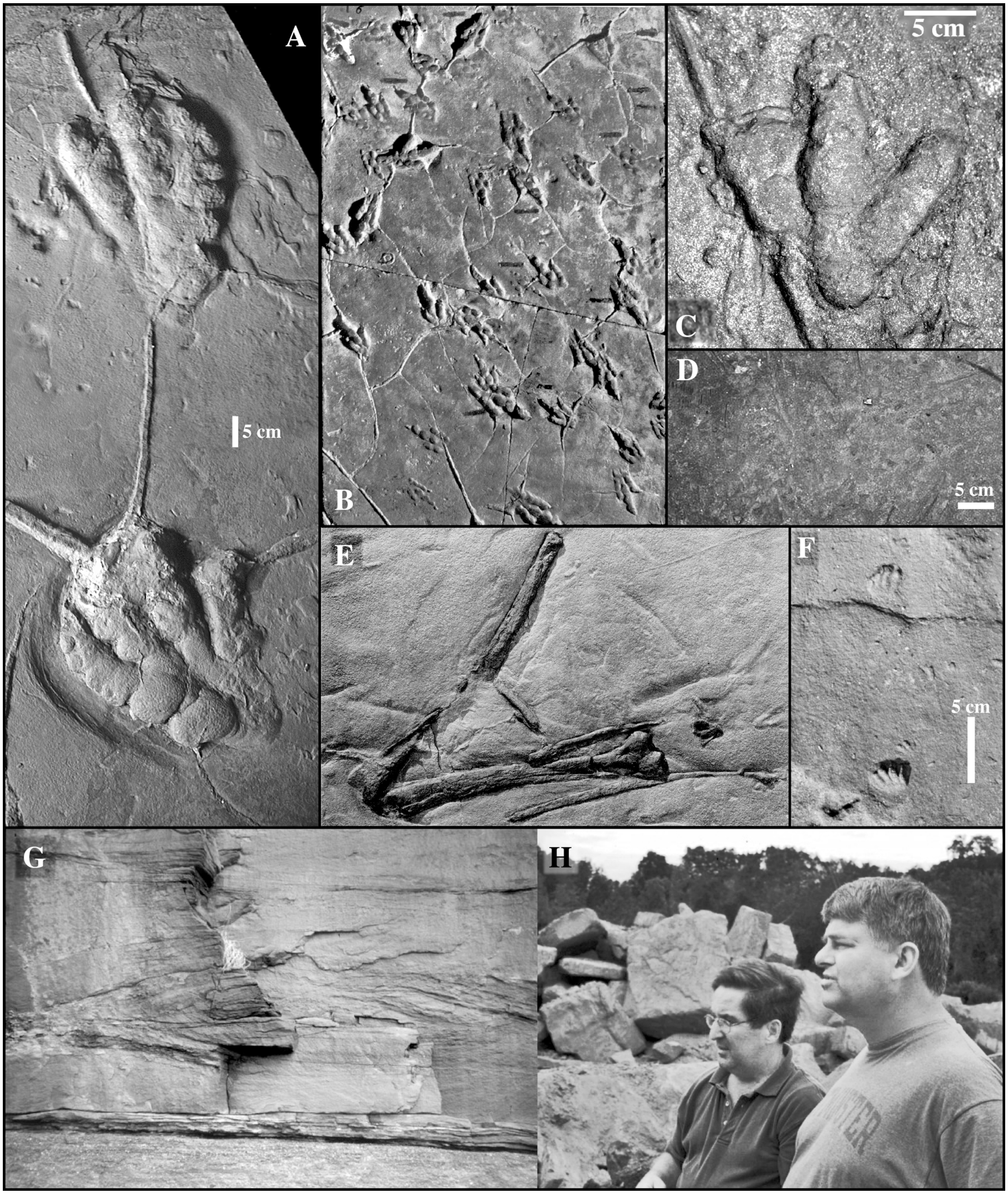


Figure 14. Portland quarries: A, *Otozoum*, trackway on exhibit at Dinosaur State Park (Stop 4); B, slab of numerous *Anchisauripus* that was a sidewalk stone in Middletown, CT (Amherst College, Pratt Museum, AC 9/14), probably from the Portland quarries; C, The largest known eastern North American *Anomoepus* on display at Dinosaur State Park (Olsen and Rainforth, 2003a); D, plant impressions, float, Meehan Quarry; E, natural cast in sandstone of the impression of a partial hind limb and pelvis of a theropod dinosaur (from Colbert and Baird, 1958); F, *Batrachopus* cf. *deweyii*, on block at quarry site; G, coppice dune in quarry wall; H, quarryman Michael Meehan (left) discusses the finer points of brownstone with paleontologist Nick McDonald.

The Portland brownstone quarries presently consist of two large, water-filled pits. The main (northern) pit, where we will focus, consists of 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. It is suprising that, given their obvious appeal to geologists, relatively little work has been done on the sedimentology and structure of the rocks, perhaps due to difficulties in approaching the towering quarry walls in the water-filled pits. Nevertheless, several studies including Krynine (1950), Lehmann (1959), Gilchrist (1979) and Hubert, Gilchrist and Reed (1982) provided partial descriptions of the Portland Formation rocks exposed in the quarries. The type section for the Portland Formation (Arkose), atypical though it is for the formation as a whole, was described by Krynine (1950). A detailed and captivating account of the history of the brownstone quarries may be found in Guiness (2003). LeTourneau (1985a, 1985b) discusses the rocks of the vicinity in context of the paleogeographic distribution of alluvial fan complexes located along the rift margin in central Connecticut.

The main pit ranges in depth from about 25 to 150 ft and is separated by a promontory that emerges from the eastern side of the quarry. South and upsection of the promontory the quarry walls consist of alternating layers of sandstone and sandy siltstone deposited mainly in a fluvial environment. LeTourneau (2002) and LeTourneau and Huber (2005) describe thin eolian beds intercalated with the fluvial rocks in the southern part of the main pit.

A view to the north and east shows the dramatically different character of the downsections rocks in the Middlesex pit, particularly the massive sandstone forming the large wall on the eastern side. Notably, the intercalated fine-grained rocks are nearly absent in this part of the quarry. A close view of the large east wall of the Middlesex pit reveals an abundance of inverse-graded low-angle inclined planar stratification indicative of migrating wind ripples (pin-stripe lamination) (Fig. 13). In additional several enigmatic large-scale convex-up dune forms may be observed. LeTourneau (2002) ascribed these unique sedimentary structures as “coppice dunes” formed around clumps of plants. Evidence for the coppice dune origin of these features includes, complex internal stratification with root traces, inverse-graded wind ripple lamination. The eolian beds were apparently preferred for building stone because of their grain size and texture. A modern model for the Portland brownstone eolian deposits is the Stovepipe Wells dune field in Death Valley, California. There a relatively thin sheet of dune sand overlaps alluvial fan and fluvial deposits on the edge of the extensional basin. Small coppice dunes anchored by plants are found in the interdune areas.

North of the Middlesex pit, Michael Meehan (Fig. 14) has brought the quarries full circle from early development, to abandonment, to renewed extraction of the historic brownstone. The Meehan quarry uses modern, non-explosive methods of extraction, and rather than the horse- and steam-powered equipment of the past, uses electric and diesel power to cut, shape, and transport brownstone. Standing on the promontory at the Meehan quarry we can peer into the geologic and historic past in the old quarries and see the modern re-emergence of layers than have not basked in the sun for over 200 million years.

Now the quarries enter yet another phase as well. In the 1990’s the Town of Portland purchased the brownstone quarries and in 2000 the quarries were designated a National Historic Landmark. Currently, plans are underway to develop the quarries as a center for deep-water SCUBA training, rock-climbing, education, and outdoor recreation. Where, once, steam whistles signaling the start of the day for immigrant stone workers climbing steep ladders into the shadowed pits, shouts of “on-belay!” may soon reverberate from sun-drenched climbers clinging to thin holds on the sheer rock faces. From small crocodilomorphs scampering across sand flats in the Early Jurassic, to wind-blown dunes, to the peak of brownstone production, to the now placid waters of the abandoned pits, the geologic and historic story of the Portland brownstone quarries is truly remarkable.

Eolian sedimentation in the upper Park River member of the Portland Formation at Portland was promoted by both favorable paleolatitudinal position, deposition within the dry climatic interval of a 405 ky cycle, and proximity to fan-related sand.. These deposits formed at about 22° paleolatitude, on the transition between the relatively humid tropics and the arid subtropics. The high-resolution correlations with arid to semi-arid intervals in the nearby Newark basin and the reinterpretation of paleomagnetic data of Kent and Tauxe (2005) support the hypothesis that the eolian sandstones are indicators of regional paleoclimate conditions, rather than just local depositional environments (Fig. 3).

Paleontology

Quarrying of the brownstone in the Portland quarries revealed many fine reptile footprints, many of which are among the best preserved of their kind (Lull, 1953; Guinness, 2003; Olsen et al., 1998; Rainforth, 2003). Footprint taxa of biological significance from the quarries include the stratigraphically lowest occurrence of the sauropodomorph track *Otozoum* (Rainforth, 2003), the small brontozooids (*Anchisauripus* and *Grallator*), representing theropods, and the crocodiliomorph ichnite *Batrachopus* (Fig. 14). *Otozoum* is relatively abundant in these strata possibly correlated with that, the large theropod track, *Eubrontes giganeteus* so abundant elsewhere, is conspicuous by its absence. A similar pattern is seen at least two other occurrences: first at the Moody Homestead locality (Olsen et al., 1998) also in the Park River member that produced the type of *Otozoum* (Rainforth, 2003); and at the McKay Head and Blue Sac localities in the McCoy Brook Formation of the Fundy basin (Olsen et al., 2005). This suggests ecological segregation of the track makers of the largest herbivore, represented by *Otozoum* and the largest carnivore *Eubrontes*, during the Early Jurassic.

The vast majority of footprints were collected as natural casts. The tracks themselves were made in thin mud layers, but lithified, the mud layers proved incompetent, crumbling away during the quarrying process. The sedimentological events that these mud layers represent is unclear. They may represent flooding events from adjacent streams, or the trangression of playas. The overlying sandstone beds that preserved the tracks as natural casts could crevasse splays or sheet floods. Despite the abundance of these tracks in numerous institutions their sedimentology remains essential unexplored.

In addition to footprints, the Portland quarries also has produced a fragmentary skeleton of a theropod dinosaur represented by a natural cast in sandstone of parts of the hind limb(s) of a small theropod (Colbert and Baird, 1958) (Fig. 14). Evidently, bones of a small theropod settled into a mud surface, were washed away leaving a natural mould, and like a footprint, were buried by sand washed in at a later time. This specimen was long thought to be lost, but it is archived at the Museum of Science in Boston (formerly, Boston Natural History Museum) (Rainforth pers. comm., 2003). Plants are represented by natural casts of tree limbs and trunks (Newberry, 1888; Guinness, 2003) and natural casts of root traces (Fig. 14).

Return to vehicle.

30.0 Start out going SOUTHWEST on BROWNSTONE AVE toward SILVER ST.
30.1 Turn LEFT onto SILVER ST.
30.3 Turn LEFT onto CT-66 / CT-17 / MAIN ST. Continue to follow MAIN ST.
32.7 MAIN ST becomes CT-17A / MEADOW RD.
33.3 Turn LEFT onto CT-17 / GLASTONBURY TURNPIKE. Continue to follow CT-17.
36.0 Turn LEFT onto OLD MAIDS LN.
36.7 Turn left into dirt road leading to sand pit, northern Portland, CT, walk to end.

STOP 3. FAN DELTA OF THE HALES BROOK FAN, PORTLAND CONNECTICUT AND MIDDLEFIELD FISH BED OF THE PARK RIVER MEMBER (60 MINUTES). Central Middletown Quadrangle, (approx.) 41°38.00' N, 72°37.25' W; Tectonostratigraphic sequence TS IV; lower Park River member, Portland Formation; Hettangian age, 200 Ma. Main points are: very coarse alluvial fan conglomerate and microlaminated, fossiliferous black shale of the wet phase of a 405 ky cycle; proximity to border fault; Middlefield fish bed.

Stratigraphy and Sedimentology (contributed by Peter M. LeTourneau)

In 1991 an extraordinarily illustrative exposure of very coarse alluvial fan conglomerate and microlaminated, fossiliferous black shale was uncovered in a sand and gravel quarry in northern Portland, Connecticut. This exposure is an unsurpassed example of fan-delta deposition at the faulted margin of the Hartford Basin. The purpose of this stop is to illustrate this remarkable fan delta sequence within the context of lower Jurassic depositional environments of the Portland Formation in central Connecticut.

Stratigraphically, the section lies about 100 m above the projection of the Hampden Basalt. The exposures therefore lie within the expected position of the lower Park River member. Lithologically, only the Middlfield bed

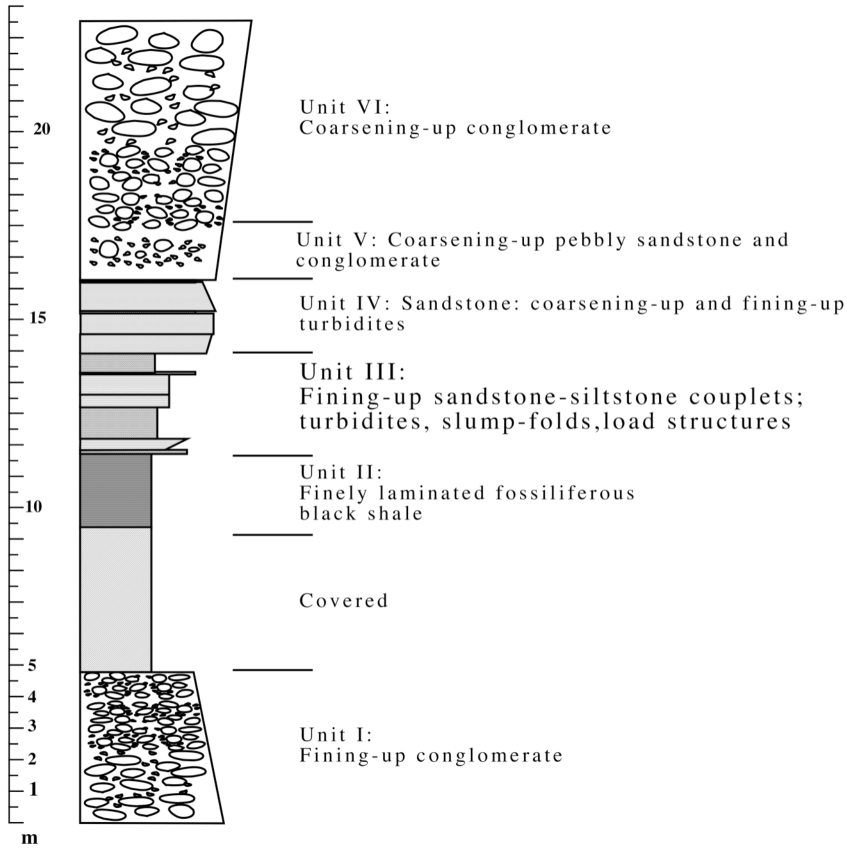


Figure 15. (Right) Measured section at Stop 2.

within the Park River member resembles the exposed fish-bearing unit and therefore we conclude that the exposed unit represents that bed and the overlying portions of the same cycle.

In the context of previous studies of the alluvial fan deposits of the Portland Formation, this new occurrence 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 extraordinary slump folds; 4) abundant fossils including fish, conchostracans, and plants; 5) dramatic coarsening-up sequence; 6) one of the few well-exposed fan-lake sequences found within 1 km of the eastern fault margin of the basin; and 7) extraordinary three-dimensional exposure showing bedding plane, along-strike and along-dip views of beds and sedimentary structures.

The exposure has great utility for educational purposes for demonstrating diverse geological principles including the following:

- *Sedimentology*: finely laminated lake shale, 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 exposure was uncovered during routine excavation of glacial outwash for sand and gravel. Previous geological reconnaissance revealed the presence of small scattered outcrops of boulder conglomerate at elevations above 200 ft (msl) on the small isolated hill located east of the sand and gravel quarry, but no dark shale beds were previously found in the area (LeTourneau, 1985a).

The exposure is about 150 - 200 ft. long and consists of a north-facing vertical section of dark shale, sandstone and conglomerate and a broad, south-facing dip slope of boulder conglomerate. Bedding strikes N 55° E and dips about 25° SE (110-25). 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 envelope bedrock surfaces. The glacial striations also wrap around the eastern and western ends of the exposure, providing dramatic evidence that bedrock influenced the local flow path of the base of the overlying ice sheet.

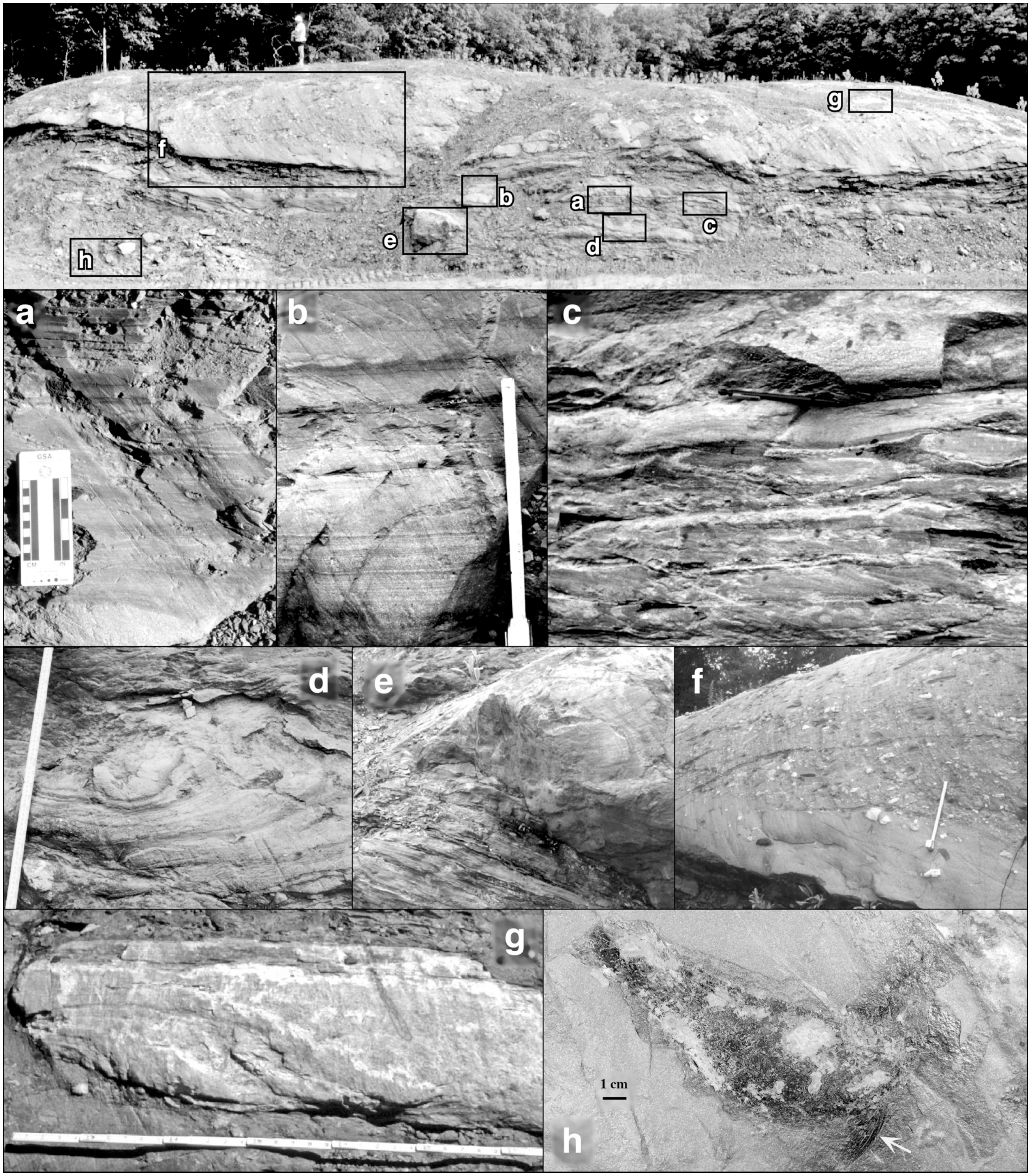


Figure 16. Fan delta sequence at Stop 4: Top, composite of view of units II – VI and key to following; a, turbidite layers; b, Fining-up turbidite thin beds and laminae with pseudo-flame structures caused by loading; C, Contorted turbidite layers caused by loading and possible shear; d. Large turbidite load slump (Note fining-up layers within); e, large turbidite load slump with highly contorted internal structure; f, coarsening-up conglomerate of unit V; g, gneiss boulder from unit VI; h, articulated *Redfieldius* from Middlefield bed (unit II), McDonald collection.

The exposed strata coarsen dramatically upward and exhibit an extremely wide range of grain sizes and bedding style, from thin-bedded finely laminated dark shale to crudely stratified boulder conglomerate within the relatively thin, but continuous vertical section. The depositional environments represented include deep-water lacustrine, shallow or littoral lacustrine, sub-aqueous fan-delta, and sub-aerial alluvial fan. A measured section (Fig. 15) shows the stratigraphic succession from very fine grained lacustrine beds through exceedingly coarse boulder conglomerate beds.

Hales Brook Fan Delta: This outcrop is located within eastern fault margin of the basin in an area of very coarse conglomerate previously termed the Hales Brook Fan (LeTourneau, 1985b). The fan delta sequence is divided for reference into 6 units (Fig. 15), from base to top. Unit I at the base of the section is a poorly exposed pebble and cobble conglomerate more than 4 m thick. The exposed portion of conglomerate is undoubtedly part of a larger conglomerate sequence as suggested by bedrock "float" and the east-west oriented resistant ridge that contains Unit I. A covered interval of approximately 4.5 m overlies Unit I and forms the base of Unit II; 2.2 m of finely laminated, fossiliferous black shale. Unit III is about 4 m thick and consists of three fining-up sub-units of interbedded sandstone and siltstone. Unit IV is a 0.5 m bed of coarse to pebbly sandstone with a sharp basal contact and gradational upper contact. Unit V forms the top of the exposed section and consists of very coarse boulder conglomerate. The sedimentary features and paleoenvironmental interpretation of these units are discussed below.

Unit I: The base of the outcrop consists of poorly-sorted, poorly-stratitified conglomerate with few thin silty sandstone partings or thin beds. Although the exposure of this bed is poor, a fining-up trend can be observed in the sized of the major conglomerate clasts. Clast composition is polymict and reflects the varied low- to high-grade metamorphic rocks and plutonic igneous rocks. Clasts are sub-rounded to sub-angular; no preferred orientation could be observed. Unit I is interpreted as an alluvial fan deposit based on comparision with other well-known ancient examples including the Hartford Basin (e.g., Steel, 1976; Nilsen, 1982; Letourneau, 1985a) and analysis of modern depositional enviroments (e.g., Bull, 1972; Nilsen, 1982).

Unit II: The base of Unit II is a 2 m covered interval. The upper 0.75 m consists of microlaminated to finely laminated, thin bedded black to dark gray, organic-rich, fossiliferous shale (Fig. 16). Bedding contacts are sharp and planar and laminations may be traced through the exposed portion of Unit II. The upper portion of Unit II contains a few fining-up siltstone interbeds or lenses. Laminations consist of clastic and carbonate couplets (*varves*, sensu Olsen, 1986). Evidence of subaerial exposure such as mud cracks or root burrows is not present nor are invertebrate burrows observed. Fish fossils are whole and articulated, but are in some cases disrupted by normal faults and bedding plane faults of small displacement that penetrate portions of the outcrop. These features correspond to those described by Olsen (1986, 1990) for deep water lacustrine strata within the Newark Supergroup. The sedimentary structures and preservation of whole articulated fish are indicative of deposition below wave base and the thermal or chemical stratification of the lake water column. Therefore, Unit II is interpreted as a perennial, stratified lake deposit based on comparison to examples of modern and ancient rift lakes (e.g., Olsen, 1990; Dean, 1981; Trewin, 1986).

Fossils from Unit II include the holostean *Semionotus*, conchostracans, and plants. The excellent preservation of bone in the wholly articulated fish is typical of fossil fish found within a lateral distance of 1 to 2 km of the eastern basin margin. McDonald and LeTourneau (1989) attribute geographic trends in fossil fish preservation to relatively high rates of sedimentation adjacent to the basin margin. The relatively rapid burial of fish carcasses prevents microbially mediated dephosphatization of bones (Nriagu, 1983) that is occurs in lake beds located in central and western areas of the Hartford Basin. In addition, the size of Unit II conforms the bed thickness predicted by the previously determined relationship of the thickness of division 2 and distance from the faulted basin margin for the Hartford Basin (Fig. 17).

Unit III: Unit III consists of 1.3 m 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 (e.g., Hubert et al., 1978) beds and nodules. The 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 large fold is observed in the central portion of the exposure. The recumbent fold is about 1 m thick and 1.5 m wide with a rounded lower boundary and a shallow, convex upward upper surface. Laminations of fine and coarse sand, often as normal-graded couplets, within the slump are crenulated, recumbent, and of different attitude than the laminations on the outermost portion of the slump fold, indicating that the internal deformation was somewhat independent of the shear forces that shaped the outer boundaries of the slump fold. 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. This fold is also has complex internal deformation and recumbant, multiply folded laminations. The slumps appear to be part of a formerly continuous coarse sandstone wedge that tapers toward the west, away from the basin margin.

Beds overlying the folded horizon are thin bedded and laminated gray mudstone 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. 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. The normal-graded couplets and folds are intebedded with gray mudstone as opposed to finely laminated fossiliferous black shale, indicating the progradation of the fan-delta over organic-rich lake bottom sediment.

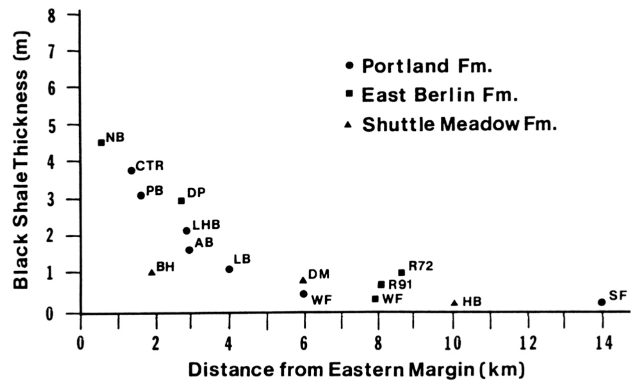


Figure 17. Relationship between “black shale” thickness (division 2) and distance from the boorder fault (from LeTourneau, 1985a).

Unit IV: Unit IV is similar to the underlying Unit III but overall 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 observed. The upper surface is hummocky to irregular and is "onlapped" by normal-graded sandstone beds in the western portion of the outcrop. Internally, the sand bed is massive to laminated; cross stratification is not observed. The normal-graded sandstone beds that overlie the massive sandstone wedge are about 20 to 30 cm thick and consist, internally, of thin, 10 to 3 cm, normal-graded couplets. The apparent "onlap" of these beds on the massive sandstone bed is caused by the westward thickening of the normal-graded beds.

Unit V: Unit V is an abrupt grain-size transition from the underlying turbidite sandstone. Very coarse sand and fine gravel predominate 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. Typical fluvial sedimentary structures are missing from Unit V, including crossbedding and lag gravels, nor are typical deltaic features, such as, climbing ripple cross-laminae, load casts, or sorted layers and lenses, present. Furthermore, features of typical sub-aerial alluvial fans, including fining-up layers and lenses with silt drapes, or debris-flow lenses are not in evidence. Therefore the depositional environment of the Unit remains somewhat enigmatic, although a sub-lacustrine origin seems likely.

Unit VI. Unit VI is a spectacular, coarsening-up cobble and boulder conglomerate. The conglomerate may 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, are observed in 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 one basalt clast was observed. Stratification within Unit VI is obscure. In many places grain size segregations suggestive of bedding are observed, but, except in a few locations, crossbedding 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 likely deposited at and below the lake margin where rapid sedimentation below water resulted in poorly sorted and poorly segregated, amalgamated conglomerate with faint bedding.

Paleoenvironments - <u>Alluvial fans</u>: Well-developed alluvial fan deposits are found along the eastern fault margin of the Hartford Basin from North Branford to South Glastonbury, Connecticut, specifically at this stop. In particular, the alluvial fan deposits of the lower Portland Formation in Durham, Middletown, and Portland have been extensively studied (Gilchrist 1979, LeTourneau, 1985a, 1985b). These deposits consist of coarse sandstone and conglomerate in coarsening- and fining-up sequences with intercalated, fossiliferous, finely laminated lacustrine dark shale. The alluvial fan deposits form discrete prisms of coarse-grained rocks within finer-grained fluvial sandstone and siltstone, and dark shale lacustrine mudstone deposits of the basin floor. The alluvial fan deposits can be separated into two general types of facies associations. The relatively large (1 to 4 km radius) basin margin alluvial fans, typically show evidence of fluvial activity, such as cross stratification, channels, and thin fining-up beds and features of wave reworking and shoreline modification of fan sediment is often observed.. Large boulders may be found, but these are generally a small percentage of the total conglomerate clast population and they occur in discrete boulder layers, including debris flows, or as isolated clasts. In contrast, the smaller radius fans (0.5 - 1 km), perhaps more related to steep talus fans, are: characterized by extremely poor stratification and internal fabric organization; are exceedingly coarse-grained, and are thick bedded with little cross-stratification or channelization evident. Large boulders comprise a significant percentage of the conglomerate clasts often within a fine sand and silt matrix.

The contrast in the two fan types indicate differences in the dominant depositional processes (e.g., stream-flow, debris-flow, colluvial) which are linked to source area drainage basin size, catchment and fan slopes, and stage of fan development (Blair and McPherson, 1994, fig 20, pg. 474). For reference, the alluvial fan deposits of the Portland Formation in central Connecticut have been identified by their assocation with modern geographic features, e.g., Round Hill Fan, Reservoir Brook Fan (LeTourneau, 1985b). The alluvial fan - lacustrine sequence described here is located within the Hales Brook Fan complex.

<u>Paleoenvironments - Perennial Lakes</u>: The intercalated dark shale beds are typically very finely laminated, lack evidence of bioturbation or sub-aerial exposure, contain fine carbonate (calcite and dolomite) laminae, often contain exquisitely preserved fish fossils, and are laterally continuous over broad areas of the Hartford Basin. The dark shale beds are the result of sedimentation in deep-water, stratified, perennial lakes (Olsen, 1984) Stratification of the water column promotes anoxic bottom water conditions which in turn allows the preservation of abundant organic matter and excludes benthic epifauna and infauna resulting in finely laminated, organic-rich black shale with fully articulated fish fossils. As demonstrated in the Newark basin and the East Berlin Formation in the Hartford Basin (Stop 5), the periodic occurrence of perennial lakes within the vertical stratigraphic section of these basins is a result of astronomical forcing (Milankovitch cycles) of regional climate in the late Triassic and early Jurassic (Olsen, 1986, 1990; Olsen et al. 1989a). Therefore, the presence of fossiliferous dark shale beds within conglomerate beds as seen at this stop represent the climatically controlled transgression, high stand, and regression of perennial lakes over coarse basin margin alluvial fan deposits.

<u>Fan Deltas</u>. Fan delta deposits are formed where alluvial fans intersect marine or perennial lake waters (Wescott and Ethridge, 1990). Distinct from wholly sub-aerial alluvial fans, fan deltas consist of two portions: 1) the sub-aerial alluvial fan deposited above mean water level and: 2) the sub-aqueous portion deposits below standing water (Nemec and Steel, 1988; Blair and McPherson, 1994). Although alluvial fans are deposited by water-laden mass flows, ephemeral to perennial stream flow, and sheetfloods, in this context "sub-aerial" means all deposition above mean water level of a perennial lake. The sub-aqueous portions of fan deltas show evidence of coarse-grained deposition into profundal waters dominated by fine grained sedimentation, and typically contain turbidite beds and soft sediment slumps and folds generated on unstable sub-aqueous slopes (Postma, 1984). Fan delta sequences typically coarsen-upward as a result of the progradation of coarse-grained littoral, shoreline, and alluvial fan sediment. These features are well represented in the Hales Brook Fan fan delta sequence. A progradational sequence may result from sediment deposition on the alluvial fan during relatively static lake levels or from the "forced" regression of lake margin deposits during receding lake levels. We interpret the Hales Brook Fan delta as the progradation of an alluvial fan *into* deep water during a lake high stand because of the intimate association of exceedingly coarse grained deposits with anoxic, profundal lake water and the absence of features indicative of sub-aerial exposure. Other alluvial fan deposits in the lower Portland Formation show evidence of progradation *following* climate-driven lake regression.

Paleoecology and Evolution

Characteristic of the fish assemblage of the Middlefield bed is the large amount of variation seen in individuals of the holostean genus *Semionotus*. Most of this variation is apparently attributed to morphological differences between different species. The presence of many endemic species of the same genus (in closely related genera) is termed a species flock. This *Semionotus* species flock are akin to their counterparts in the Westfield bed of the East Berlin Formation, and the Bluff Head bed of the Shuttle Meadow Formation (Stops 5 and 7) and are analogous to species flocks of cichlid fishes of East African great lakes (Olsen, 1980; McCune et al., 1984; Olsen and McCune, 1991; McCune, 1996). In this case, all the species seem to belong to one limited clade (the *S. elgans* species flock of Olsen and McCune (1991), which is also the case in the precisely correlative Van Houten cycle in the Boonton Formation of the Newark basin. *Semionotus* species flocks are limited to Newark Supergroup strata above the Triassic-Jurassic boundary, although fish assemblages are abundant in older Newarkian strata, and suggesting that perhaps the evolution of the species flocks was fostered by the extremely low post-Triassic-Jurassic boundary fish diversity in the watersheds of the rift basins.

The only other fish genus found in the Middlefield bed here or elsewhere is the palaeonisciform *Redfieldius*. However, the presence of abundant phosphatic coprolites strongly suggests the presence of the coelacanth *Diplurus longicaudatus* that has been found with such coprolites within its body (Gilfillian and Olsen, 2000). The conhcostracan *Cornia* is also abundant as are various plant fragments, including large stems.

Return to vehicle.

36.7 Start out going EAST on OLD MAIDS LN toward CT-17 / MAIN ST.
37.4 Take CT-17 N.
42.9 CT-17 N becomes CT-2 W.
43.8 Merge onto CT-3 S via EXIT 5D toward WETHERSFIELD.
46.8 Merge onto I-91 S via the exit on the LEFT toward NEW HAVEN.
50.9 Take the WEST STREET exit- EXIT 23- toward CT-3 / ROCKY HILL.
51.1 Turn LEFT onto WEST ST.
52.0 Turn right into parking lot for at Dinosaur State Park, 400 West St Rocky Hill, CT

STOP 4. DINOSAUR STATE PARK, EAST BERLIN FORMATION (LUNCH - 60 MINUTES) SE Hartford South Quadrangle, (approx.) 41°39.03' N, 72°36.48' W; Tectonostratigraphic sequence TS IV; East Berlin Fm.; Hettangian age, 201.5 Ma. Main points are: Abundant large theropod dinosaur tracks (*Eubrontes*) in regressive portion of upper gray and black Van Houten cycle of East Berlin; extreme rarity of herbivores; post boundary ecological release; no evidence for herding in theropod dinosaurs.

This site was discovered in 1966 during excavation for the foundation of a state building. Exposures here have revealed nearly 2000 reptile tracks, most of which have been buried for preservation and future exhibition. The present geodesic building at the park houses approximately 500 tracks (Fig. 18). The tracks are found in the gray arkoses, siltstones, and mudstones of the East Berlin Formation. The stratigraphic position of the main track-bearing horizon has been a bit of conundrum. Byrne (1972) correlated the track-bearing unit with the uppermost Van Houten cycle that has black mudstone in the East Berlin Formation, placing it about 20 m (17.4 m) below the contact with the Hampden Basalt, a correlation followed by Olsen et al. (2003a). However, close examination of these sections through Byrnes' descriptions of the cores shows that the thickness of red beds below the track level is too great to be accommodated by Byrne's proposed correlation. In fact, the only interval with such a long red bed sequence in the upper East Berlin is the third black shale-bearing cycle from the top. In outcrop along Rt, 9 (Stop 5) this cycle also has a second dark shale unit in the upper part of division 2, a feature matched at the track site. Given the extremely slow lateral change in thickness of Van Houten and short modulating cycles observed laterally, the latter is the most parsimonious hypothesis, and that would place the track horizon at about 38 m below the Hampden Basalt.

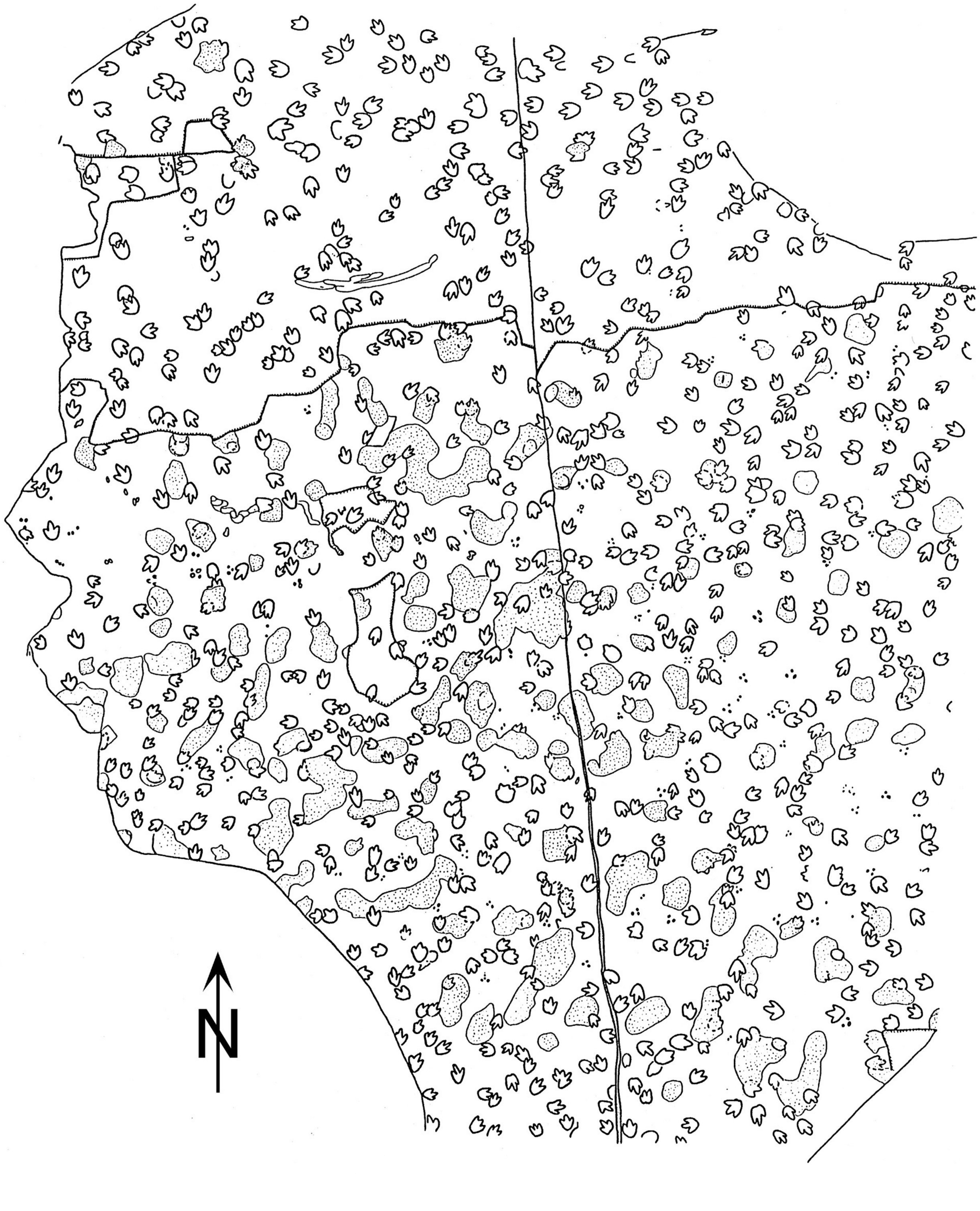


Figure 18. Dinosaur footprints on display *in situ* at Dinosaur State Park (from Farlow and Galton, 2003). Most footprints are 30-40 cm long. Stipple illustrates where overlying rock did not separate cleanly from the upper track-bearing layer, cross-hatched lines indicate boundary between the upper and the lower track-bearing layers (cross-hatches directed toward the lower layer). Groups of circles in a triangular pattern indicate footprints made by swimming (?) dinosaurs.

Thus, the track-bearing surface in the enclosure is part of the regressive portion of a Van Houten cycle in part of the wettest phase of a short modulating cycle. Ripple marks, raindrop impressions, mudcracks, and the footprints indicate shallow-water conditions and some subareal exposure. The track-bearing beds grade upward into dark gray mudstone followed by red sandstone and mudstone, suggesting a return to slightly deeper water conditions prior to conversion of the lake into a playa.

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, early, fully terrestrial protosuchian crocodilian. *Eubrontes giganteus* tracks are the most common and are the only clear tracks visible in situ within the geodesic dome. Because of the popularity of this site, *Eubrontes* is now the Connecticut state fossil. 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. This is yet another example of the low diversity, theropod dominated assemblages typical of strata only a few hundred thousand years younger than the boundary.

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. (2002a) 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. The largest Triassic theropods *Gojirosaurus* and *Liliensternus* were less than 80% the size of the larger *Dilophosaurus*, despite statements to the contrary by Lucas (2002). This size difference compares well to the disparity between the largest Newarkian Triassic *Anchisauripus* (25 cm) and *Eubrontes giganteus* (35-40 cm) Olsen et al., 2002a). This difference in length scales to roughly more than a doubling of mass. As described by Olsen et al. (2002a, 2003a), the appearance of these larger 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 the phytosaurs), allowed a very rapid increase in size in the absence of competitors.

52.0 Start out going WEST on WEST ST toward GILBERT AVE.
52.9 Merge onto I-91 S via the ramp on the LEFT toward NEW HAVEN.
54.5 Merge onto CT-9 N via EXIT 22N toward NEW BRITAIN.
57.5 Take EXIT 22 toward US-5 S / NEW HAVEN / CT-15 S.
57.6 Turn RIGHT onto FRONTAGE RD.
57.7 Turn RIGHT onto CT-372 / WORTHINGTON RDG.
57.8 Go straight onto ramp for CT-9 S
57.9 Park on dirt on right, off road.

STOP 5. CT RT 9 ROAD CUTS IN EAST BERLIN AND HAMPDEN BASALT, BERLIN, CT. (60 MINUTES). Northeast corner Meriden Quadrangle **(**41°37.37'N, 72°44.33'W); Tectonostratigraphic sequence TS IV; East Berlin Fm. and Hampden Basalt; Hettangian, ~201.5 Ma. Main points are: cyclical middle and upper East Berlin Formation; remarkably close match to Towaco Formation; deep-water lacustrine carbonate with dephospatized fish; superb pattern of Van Houten and short modulating cycles; "Dead horses" dewatering? structures; very thin basaltic crystal tuff; HFTQ-type quartz basalt of the Hampden Basalt.

Stratigraphy and Cycles

The intersection of US 15 and CT 72 reveals over 120 meters of the upper two-thirds of the East Berlin Formation and almost the entire thickness of the Hampden Basalt (Figs. 19, 20). The exposure consists of cyclical red, gray, and black lacustrine units and subordinate fluvial strata that document dramatic changes in the depths of the lakes over relatively short periods of time. Krynine (1950) first recognized the lacustrine cycles here; later work was carried out by Klein (1968), Hubert and Reed (1978), Hubert et al. (1976, 1978), Demicco and Gierlowski-Kordesch (1986), Suchecki et al. (1988), and Kruge et al. (1990). The Van Houten cycles are virtually identical in form, but not in all fabrics, to the Van Houten cycles described from the Towaco Formation (Olsen, 1980, Olsen et al., 1996b).

Hubert et al. (1976) demonstrated the lateral continuity of the Van Houten cycles. The three cycles in the upper part of this section correlate with the three cycles exposed a few hundred meters to the north on CT 72 and the three cycles exposed at the I-91/CT-9 cloverleaf, ~2 km to the east (Hubert et al., 1978). Visible at this stop and on CT 72, a 35m thick section of red and minor gray and purple clastics separates the upper cycles from three underlying cycles in the middle East Berlin Formation. The uppermost of these cycles contains a black, microlaminated carbonate called the Westfield bed. The most distinctive bed in the East Berlin Formation, it preserves a characteristic assemblage of fishes that include *Semionotus*, *Redfieldius* and surprisingly common large coelacanths (*Diplurus* cf. *D. longicaudatus*). Correlation of the microlaminae and turbidites in polished slabs from the middle of the fish-bearing carbonate is further evidence for lateral continuity of these units (Olsen, 1988).

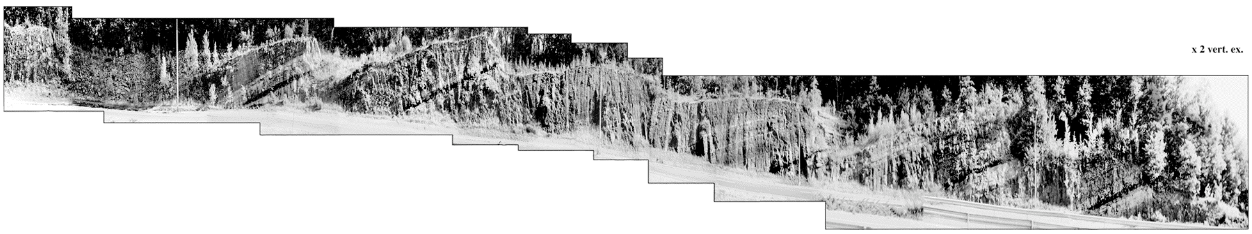


Figure 19. Photo mosaic of exposures on south side of southbound entrance ramp for CT Rt. 9, Stop 5.

Fourier analysis of proxies of water depth of this section reveals a clear hierarchy of periodicities in thicknesses of 12.0 m and 68.3 m. Assuming that the 12.0-m-thick Van Houten cycles are the 21,000-year precession cycles, the 68.3-m-thick short modulating cycles have time periodicities of 119,000 years. There is a clear hierarchy of cycles similar to that seen in the Lockatong and Passaic Formations. This sequence represents the wet part of a McLaughlin cycle within the wet part of long modulating cycle. Evidently, the lakes that produced these cycles in the Newark and Hartford basins rose and fell synchronically, controlled by regional climatic change, without necessarily being contiguous bodies of water (e.g., Fig. 9).

During the deposition of TS III of the underlying New Haven Arkose, sediment and water supply were mostly from the footwall (east) side of the basin. During Early Jurassic time, in TS IV the drainages reversed with the western hinge side of the basin becoming the source for the bulk of the sediment fill. This can be seen in the cross bedding at this outcrop (LeTourneau and McDonald, 1988). The reversal of drainage probably reflects increased asymmetry of the basin and correspondingly high rates of footwall uplift during an Early Jurassic pulse of increased extension associated with the igneous episode and TS IV. Extensive lacustrine deposition occurred in the Hartford basin only during this period of increased extension. Lacustrine deposition is favored by high extension rates, whereas low extension rates favor fluvial deposition.

"Dead Horses": The black portions of division 2 of these Van Houten cycles show some of the deformation features common to Newark Supergroup lacustrine strata. Small-scale thrust fault complexes associated with bedding-parallel shear zones are commonly developed in the microlaminated black shales of division 2 as seen here. At this outcrop and in the East Berlin and Towaco formations, black mudstone units above and sometimes within the microlaminated intervals contain what termed by Olsen et al., (1989a) "dead horses", small (usually <20 cm long) quadrangular pods of rock composed of laminae and layers oblique to the bedding surface. Similar structures occur in the Eocene Green River Formation and in a variety of other laminated shale sequences (J. Stanley, pers. comm., 1988; M. Machlus, pers. comm., 2002). We interpret the "dead horses" as compacted and dissociated blocks, after the term "horse" for a fault-bounded sliver of rock and their "dead" or dismembered condition. Most commonly, these "dead horses" float in a matrix of massive black mudstone; however, there is a progression from jumbled and partly associated masses of these blocks with no matrix, to isolated blocks in layers composed mostly of matrix. The associated massive mudstone suggests that partial liquefaction accompanied the deformation that produced the dead horses. Beds composed of these black massive mudstones and "dead horses" have usually been interpreted as depositional units, but we interpret them as a form of low-pressure structural mélange.

Depending on depth of burial and pore-fluid pressure, we suggest that bedding plane-parallel shear lead to three intergradational types of deformation: 1) shallow burial bedding plane shear with the development of plastic folds,

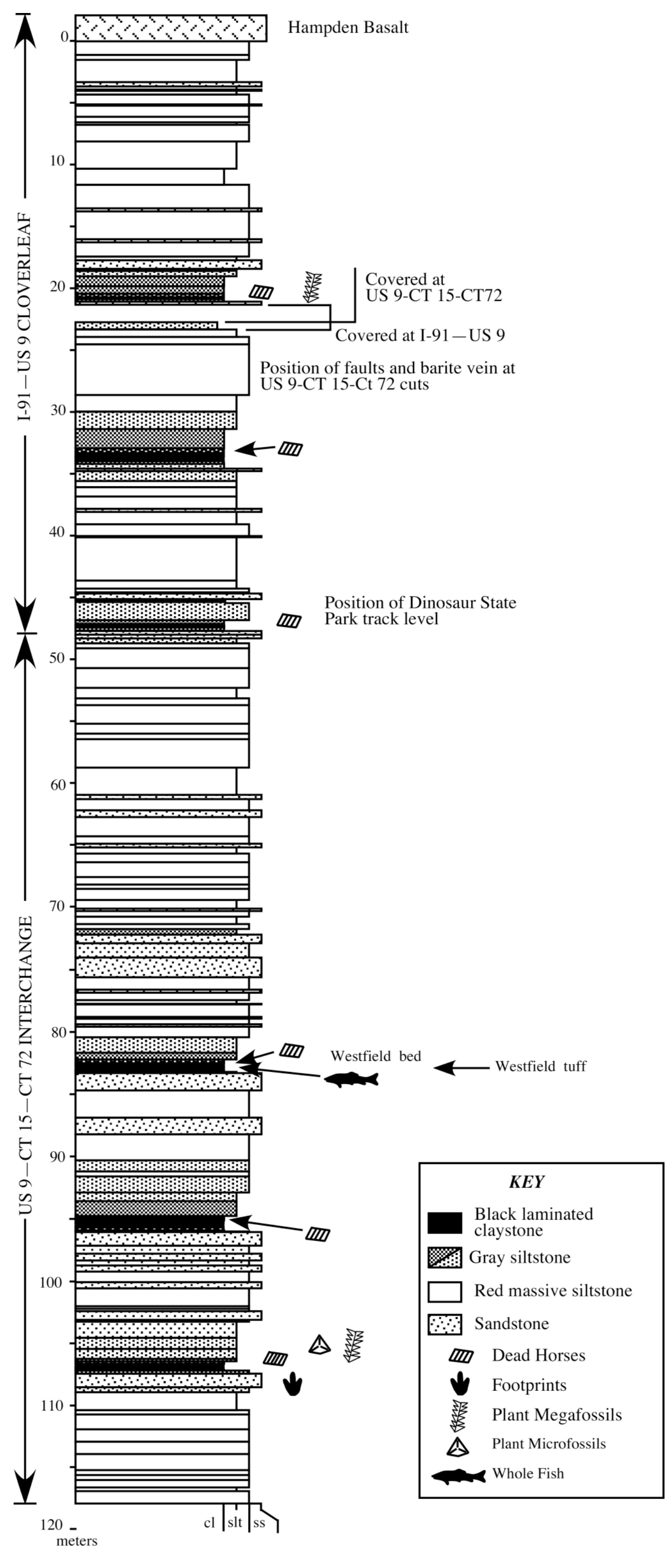


Figure 20. Section exposed at Stop 5. Modified from Olsen et al. (1989).

duplexes, considerable liquefaction, and the production of "dead horses;" 2) intermediate depth bedding-plane shear with abundant slickenside formation, some brecciation, some mineralization of voids, and small amounts of liquefaction; 3) completely brittle shear with extensive slickensiding and decalcification, with the production of platy, polished horses. All of these structures involve at least small-scale thrust faults and concomitant fault-bend folds. However, the sense of shear of the brittle bedding plane faults is up to the west, consistent with late, probably related to tectonic inversion-related compression (e.g., Withjack et al., 1998). In contrast, the dead horses and associated folding seem to indicate down to the east shear, consistent with syn-rifting tilting. All of these structures can easily be confused with "slump" structures, which require a free upper surface, and are usually interpreted as indicators of paleoslope. Although the ultimate tectonic origin of these bedding-parallel shear-related structures is not fully worked out, the folds cannot be assumed to be related to depositional paleoslope.

Westfield Tuff (contributed by Anthony Philpotts): A very thin (3 mm) bed tends to erode proud of the surrounding basal portion of the Westfield bed (Fig. 20). This unit resembles thin airfall tuffs in microlaminated units in the Eocene Green River Formation (P.E.O., pers. obs.). A photomicrograph of this layer (Fig. 21) shows that the only detectable particles in the layer are all euhedral plagioclase laths with a high aspect ratio. They show no signs of rounding. They must have originally been enclosed in glass that is now converted to a red clay or to what appears to be chalcedony.There are small circular areas that contain a mottled gray birefringent material that looks very much like chert. In addition, large areas of interstitial carbonate all go into extinction at the same time (poikioblastic?). The laths in Fig. 21 are 0.1 mm long that is typical of the rest in the section. As soon as you move into the material immediately above or below the layer, angular fragments of quartz and muscovite are found, but none is present in the layer itself.

These observations are entirely consistent with the small laths of plagioclase being part of a basaltic crystal tuff. The question is where did it come from? The camptonite dikes on Higby Mountain (Charney and Philpotts, 2004) are vesicular and probably exploded onto the surface, but the plagioclase in those rocks was the last mineral to crystallize and does not form crystals like the ones in the tuff. They can't be the source. The tuff would seem to represent an explosive eruption of the CAMP that is separate from those that produced the stereotypical sequence of known CAMP flows.

Hampden Basalt: The Hampden Basalt is a high titanium, high-iron, quartz-normative tholeiite (HFTQ) identical in composition and age to the Hook Mountain Basalt of the Newark basin (Puffer et al., 1981). The basalt is typically massive but is vesicular at its base. Tilted pipestem vesicles are common at the lower contact and indicate a northeasterly flow direction (Gray, 1982a). The visible thermal effects of the flows are minimal, restricted to the upper meter of the East Berlin. The Hampden Basalt is the thinnest of the extrusives in the Hartford basin, reaching a maximum thickness of 30 m.

Figure 21. Photomicrograph of Westfield tuff. Laths are about 0.1 mm long.

Paleontology

The gray mudstones and gray-black shale beds have generated most of the fossils at this site. The gray units are somewhat palynologically productive and have also yielded carbonized leaf and twig fragments of the conifers *Brachyphyllum* and *Pagiophyllum* and the cycadophyte *Otozamites* (Cornet, 1977a). Other fossils include the conchostracan *Cornia* sp., coprolites, articulated but dephosphatized *Semionotus* and *Redfieldius* (in the Westfield bed), dinosaur tracks, and burrows and invertebrate trails in various gray and red lithologies (McDonald, 1982, McDonald and LeTourneau, 1988a).

Return to vehicle.

57.9 Continue Merge onto CT-9 S toward MIDDLETOWN.
60.6 Merge onto I-91 N via EXIT 20N toward HARTFORD / SPRINGFIELD.
62.7 Take the WEST STREET exit- EXIT 23- toward CT-3 / ROCKY HILL.
63.2 Turn left onto West Street
63.3 Merge onto I-91 S via the ramp on the LEFT toward NEW HAVEN.
64.9 Merge onto CT-9 N via EXIT 22N toward NEW BRITAIN.
75.9 Merge onto I-84 W / US-6 W via EXIT 32 on the LEFT toward WATERBURY.
Begin drive by of locations at Cooks Gap.

STOP 6. COOKS GAP, UPPER SHUTTLE MEADOW FORMATION (Drive by-10 MINUTES). North-central New Britain Quadrangle (very approx. 41°40.50'N, 72°49.25'W). Tectonostratigraphic sequence TS IV; Holyoke basalt, Shuttle Meadow Fm.; Hettangian age, 200 Ma. Main points are: two lava flows; paleomagnetic excursion; Cooks Gap member of Shuttle Meadow Formation; Plainville bed, red beds; footprints; conchostracans; dry phase of 405 ky cycle with muted cyclicity.

The two flows of the Holyoke Basalt are obvious in the road cuts along I-84 and quarries at Cooks Gap, one of the best places to see them in clear superposition. The poorly known lower flow is massive with a thick and purple to red upper vesicular zone. The second flow displays a colonnade with the splintery fracture characteristic of the upper flow. Just north of Cooks Gap, Irving and Banks (1961) reports paleomagnetic directions from outcrops of the lower flow at CT Rt. 10 similar to the Talcott and Hampden. Prevot and McWilliams (1989) sampled the upper flow in Northern Connecticut and Massachusetts, where the lower flow does not extend (Gray, 1982a) and found that it had anomalous directions compared to the other Hartford basin flows. The Cooks Gap section would be perhaps the best place to further examine the paleomagnetic and geochemical properties of the two flows in the Holyoke, where they can be seen in superposition. These anomalous directions imply a magnetic excursion of very short interval (a few thousand years at most) that provides a time marker within the basalts (Prevot and McWilliams, 1989).

Continuous exposures of the upper 55 m of the Shuttle Meadow Formation and its contact with the overlying Holyoke Basalt are well exposed along an old quarry face at the north side of Cook's Gap in Plainville. This section was shown on Simpson's (1966) Bedrock Map of the New Britain Quadrangle), and was first described by Hubert et al. (1978), and since has been a popular field trip stop (e.g., Gierlowski-Kordesch and Huber, 1995). At this location near the western edge of the Shuttle Meadow outcrop belt, the formation is relatively thin when compared to downdip areas such as Silver Ridge, or farther southeast and adjacent to the eastern border fault where this same stratigraphic interval is as much as ~200 m thick.

The base of the section begins at the northwest corner of the small parking lot behind the basket shop, and consists of 10 m dominated by decimeter-scale fining upward packages of ripple cross laminated siltstone and thin mud drapes. At the northeast corner of the parking lot, a prominent, ~ 1 m thick bench of buff, massive limestone and bracketing green and gray shale and siltstone are exposed on the small cliff face. The limestone has been described by Hubert et al. (1978), Gierlowski-Kordesch and Huber (1995) and DeWet et al. (2002) to consist of micritic carbonate, locally with a brecciated or cracked texture with tubules of varying diameter, gradational into immediately underlying and overlying units. The latter are brecciated as well, but more clastic-rich with more obvious rhizoliths and some thin bedding. The limestone contains ostracodes and fish fragments and possible poorly preserved charophyte debris. We refer informally to these beds as the Plainville limestone, and recognize the unit to be traceable over at least the southern half of the Hartford basin. Other outcrops of the Plainville limestone are found at Silver Ridge on Lamentation Mountain, along I-91 below Higby Mountain, along an unnamed stream at the northern tip of Totoket Mountain at Durham, and on the north side of U.S. Route 1 in East Haven, at the southern end of Lake Saltsonstall. The unit contains isolated to patches of scales of semionotid fossil fishes at several localities and the Higby Mountain section produced the skull of a large coelacanth (cf. *Diplurus* sp.), along with clams and the fern *Clathropteris*. We interpret the Plainville limestone as a division 2 of Van Houten cycle 2, the best developed of those in the second short modulating cycles within the Shuttle Meadow Formation (Figs. 6, 7).

The remaining ~40 m of section is largely composed of ripple cross laminated and massive siltstone with clay interbeds of various thickness and four thicker and more finely bedded intervals we interpret as the division 2 of weakly developed Van Houten cycles. Locally, the upper two intervals are gray, the lowest having been described by Hubert et al. (1982). The uppermost beds in the Cooks Gap section consist of slightly metamorphosed siltstone to pebbly sandstone.

These predominately red beds of the upper Cooks Gap member contain abundant reptile footprints and invertebrate trails. Large and small brontozooids, including *Eubrontes giganeteus*, are the most common dinosaurian forms and *Batrachopus* is the only other reptilian track form present. Fragmentary plant remains are present in the gray beds and conchostracans are present in the lower two thicker claystone intervals.

82.3 Take unnumbered exit on right toward CT-372 / NEW BRITAIN AVE / PLAINVILLE.
82.5 Turn right onto CT-372 / NEW BRITAIN AVE
83.2 Turn right onto CROOKED ST.
83.3 Turn RIGHT onto WHITE OAK AVE.
83.4 Turn LEFT onto LEDGE RD.
84.7 LEDGE RD becomes SHUTTLE MEADOW RD.
85.8 SHUTTLE MEADOW RD becomes LONG BOTTOM ST.
86.5 Turn RIGHT onto ANDREWS ST.
86.6 Park next to overgrown small quarry on left, Southington, CT

STOP 7. SILVER RIDGE CORE B-1 AND TYPE SHUTTLE MEADOW FORMATION (30 MINUTES). Stop location in north central New Britain Quadrangle (41°37.694' N, 072°50.013'W); core location in northeastern Meriden Quadrangle (41°35.102'N, 072°45.388'W). Talcott Formation, and Shuttle Meadow Fm.; Hettangian age, 200 Ma. Main points are: type section of Shuttle Meadow Formation correlated to complete stratigraphy derived from core; core with continuous section of uppermost volcanoclastic Talcott Formation upward into cyclical Durham Member; cyclicity of Durham member with fish-bearing carbonates; lateral persistence of cycles; fauna and flora of Durham member.

This small, long-abandoned quarry comprises the section described by Krynine (1950) near the Shuttle Meadow Reservoir that was designated the type sections of the formation of the same name. The stop consists of two parts: 1) examination of the Silver Ridge B-1 core that displays a complete section of the Durham member of the Shuttle Meadow Formation; and 2) examination of the type section that proves to be the lowest Van Houten cycle in the formation, containing the Southington bed.

The Silver Ridge B-1 core, representative portions of which will be on displayed at this stop, penetrates nearly the entire lower half of the Shuttle Meadow Formation as well as most of the volcanoclastic equivalent of the Talcott Formation (Fig. 22). This core revealed for the first time the stratigraphy of the lower, mostly gray and black, highly fossiliferous portion of the Shuttle Meadow Formation that we call the Durham member.

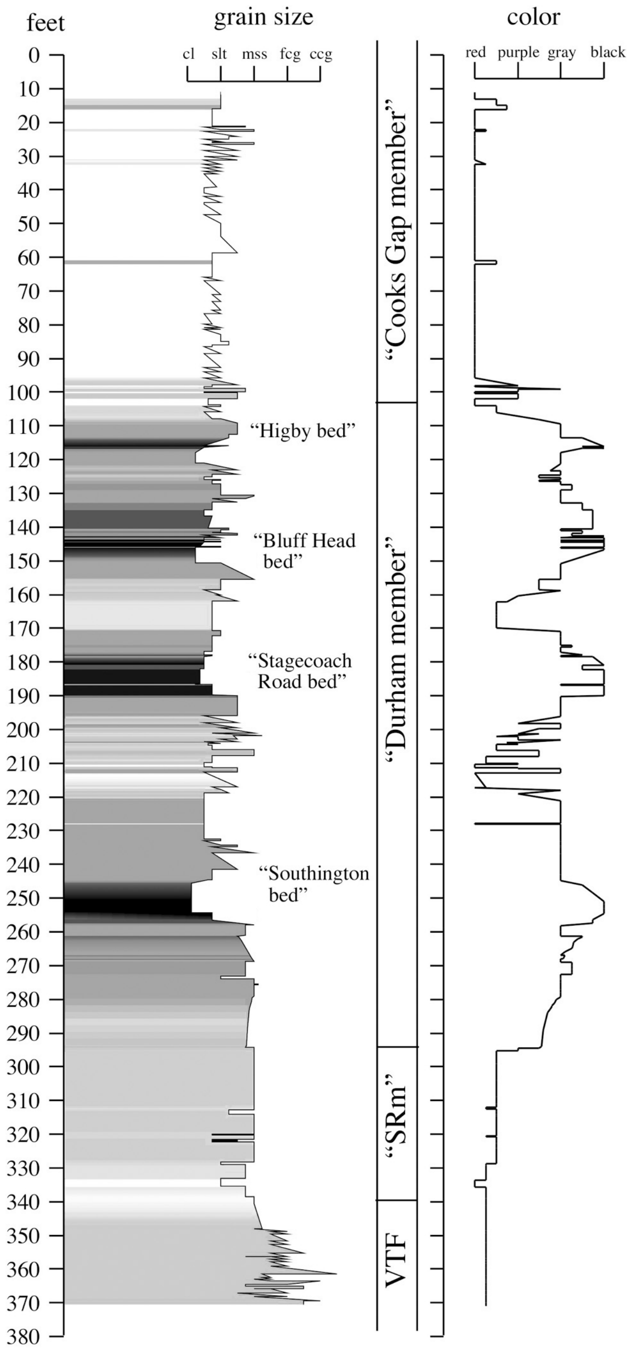


Figure 22. Silver Ridge Core B-1 (Stop 7).

The lowest Van Houten cycle has a distinctive black and dark gray division 2 bearing a limestone with rather thick and distinctive laminae with a pelleted or flocculent appearance (254.6-251.0 ft.). This bed, which we call the "Southington bed", crops out in a variety of places, most importantly at small, long-abandoned quarries to the south in Southington, Connecticut and this stop that is the section described by Krynine (1950, p. 61) near the Shuttle Meadow Reservoir. Rather poorly preserved (partly dephosphatized), but articulated fish are present in this core (e.g., at 252.7 ft, Fig. 23) and adjacent temporary exposures. We believe that the "Southington bed" is the lateral equivalent of the Coe Quarry limestone near Northford, Connecticut described by Krynine (1950), Mooney (1979), Steinen et al. (1987) and DeWet et al. (2002).

The second Van Houten cycle lacks a well-developed limestone bed but does have a division 2 with significant black shale (186.7-175.0 ft, Fig. 23). This shale is distinctive in that there are many silty interbeds with some of them bearing reptile footprints (as seen in adjacent exposures, to the core). We correlate this interval with the lower fish-bearing black shale (the "crinkle bed") that crops out at the Durham fish locality and name it the "Stagecoach Road bed" after the road immediately east of the stream on which the latter locality is located.

The third Van Houten cycle has two distinctive dark gray to black intervals (Fig. 22). The lower bed (146.5 – 132.8 ft) is highly calcareous and finely microlaminated and contains abundant fish and coprolites (Figs. 23, 24). This bed is evidently the main fish-bearing unit that crops out at the famous Durham and Bluff Head fish localities (McDonald, 1992), and we thus call it the "Bluff Head bed". Some of the best-preserved fish in the Newark Supergroup (Fig. 24) have been recovered from this unit, including the subholostean *Semionotus*, redfieldiid palaeonisciforms *Redfieldius* and *Pycholepis* and the coelocanth *Diplurus longicaudatus* (McDonald, 1992.) The Bluff Head bed also provides the best example of a *Semionotus* species flock in the Hartford basin.

The upper of the two dark gray to black beds (118 – 113.6 ft: Fig. 22) is neither clearly microlaminated nor as calcareous. It apparently correlates with a black shale that crops out along Highland Brook on the East face of Higby Mountain, and we term this bed the “Higby bed”. At the latter locality, the “Higby bed” produces articulated fish and conchostracans.

The Silver Ridge B-1 core unveiled for the first time the surprisingly complex stratigraphic relationships of the numerous black shale-and carbonate-bearing localities in the lower Shuttle Meadow Formation. In addition, the core showed that the cyclostratigraphy of the Durham member is profoundly similar to the homotaxial portion of the Feltville Formation of the Newark basin, known from multiple cores (Olsen et al., 1996a) (Fig. 25), suggesting that three Van Houten cycles exist in the lower Feltville Formation, rather than the two reported in Olsen et al. (1996b; 2003b.) The total duration of the CAMP basalt flows is thus extended ~20ky, totaling ~610ky (Whiteside et al., 2005).

The carbonate-rich nature of the “Durham member” is distinctive compared to most Jurassic age strata in the Newark Supergroup. There is a strong cyclostratigraphic similarity between the sections above these initial flows throughout eastern North America and Morocco (Olsen et al., 2003b; Whiteside et al. (2005). A similar stratigraphy of two HTQ flow sequences with two sedimentary cycles is also present in eastern Morocco; however, there the entire interbed is limestone-dominated. The apparent relationship between the initial HTQ CAMP flows, the underlying Triassic-Jurassic boundary and the overlying carbonate rich sequence suggest to us two possible interpretations (Olsen et al., 2003b; Whiteside et al., 2005): 1) The limestone deposition is a response to a super-greenhouse effect at Triassic-Jurassic boundary with effects tapering off over some hundreds of thousands of years; 2) the limestones are weathering products of vast drainage areas newly floored by relatively Ca-rich basalt, and the ferns are a consequence of unusually heterogeneous depositional environments caused by the accelerated tilting and subsidence associated with the eruption of the basalts (and the initiation of TS IV. These scenarios are not mutually incompatible, but they do predict completely different far field effects that can be looked for in other regions far from the CAMP.

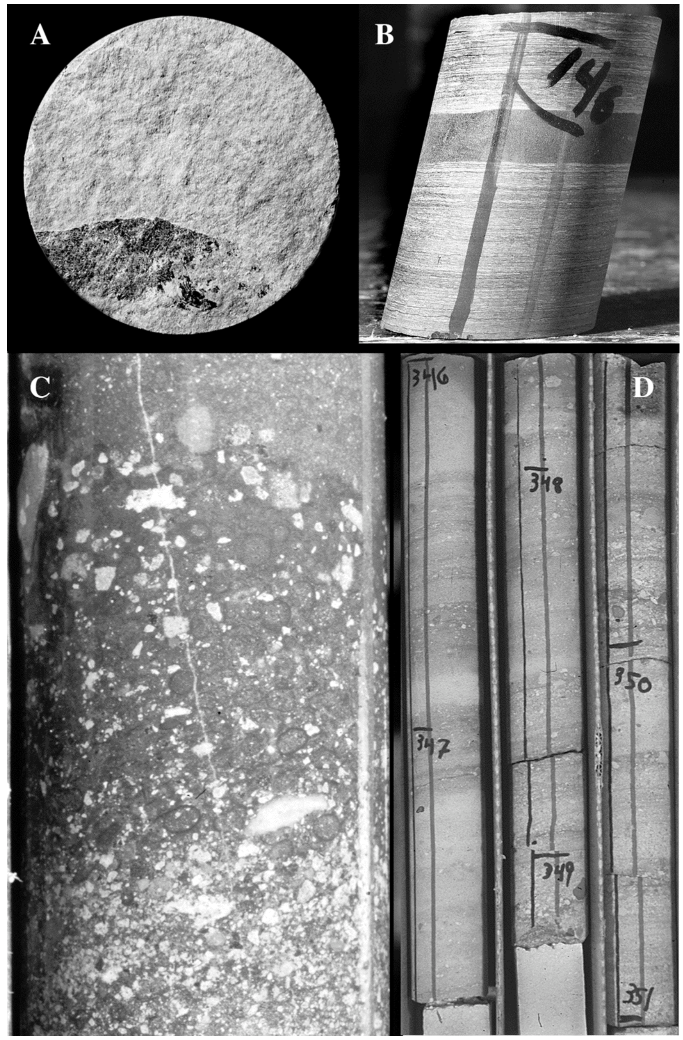


Figure 23. Silver Ridge B-1 core: A, Fish (*Redfieldius*) at 146 ft; B, lateral view of microlaminated calcareous mudstone with fish (“Bluff Head bed”) at 146 ft – note small turbidite; C, spherules from 349 ft. (examples at arrows); D, typical Talcott volcanoclastics (footage on core). From Olsen et al. (2003a).

There are 13.5 m (339.0 to 294.6 ft) of largely red beds between the largely gray "Durham member" and underlying volcanoclastics (Fig. 22, 23). The volcanoclastics begin as a few clasts of basalt in sandstone at 339 ft but rapidly becomes downward a conglomerate of basalt clasts and basaltic sandstone to the base of the core at 371 ft. At 362.5 ft and 367 ft there are well-developed layers of reddish spherule layers (Figs. 23, 24) that might represent basaltic lapilli. These are well-displayed at the adjacent outcrops (Olsen et al., 2003a).

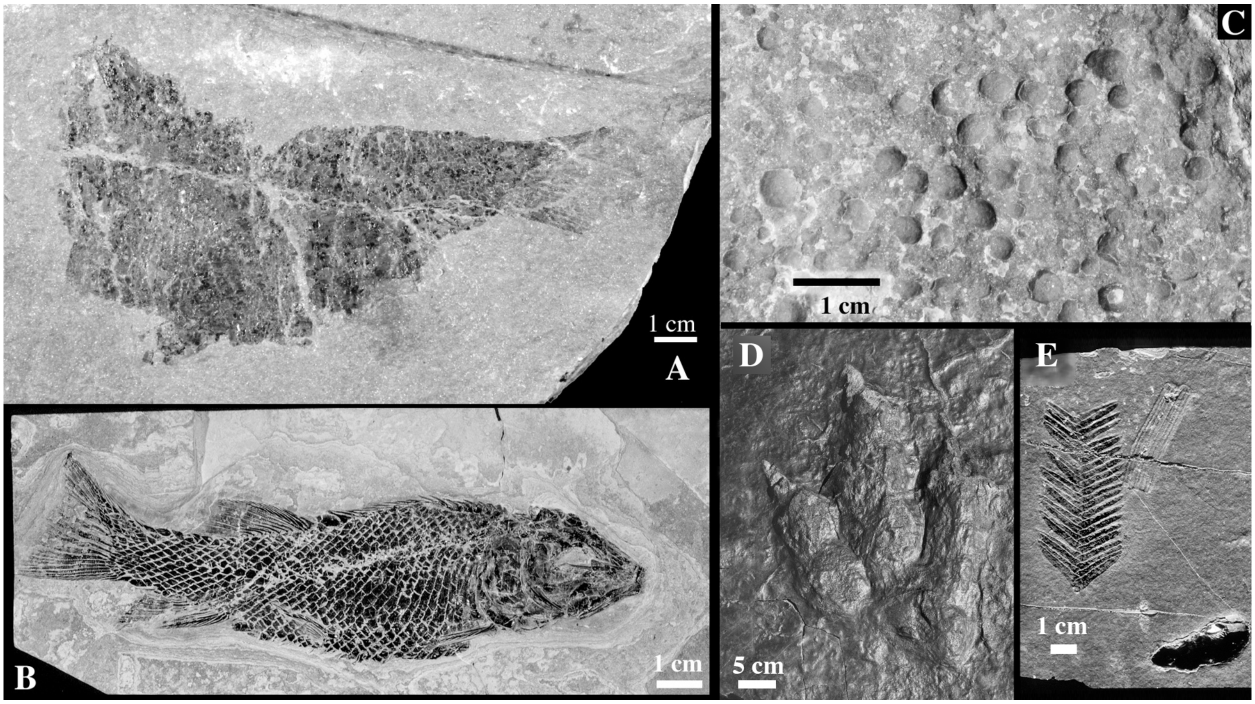


Figure 23. A, *Semionotus* from the "Southington limestone bed" in exposure, Silver Ridge; B, *Semiontous* from the "Bluff Head bed", Bluff Head, North Guilford, CT N.G. McDonald Collection; C, Spherules from Talcott vocanoclastics, Silver Ridge, (Stop 6) (N.G. McDonald collection); D, *Eubrontes giganeteus*, Highland Brook, between Higby and Bluff Head beds, Huber collection; E, *Otozamites* and coprolite, Bluff Head bed, Durham locality, Durham, CT.

At this field stop, as presently exposed, Krynine's (1950) type section consists of about 5 m of laminated and thin-bedded dark to medium gray clay- and siltstone with plant fragments (mostly conifers). This is followed upward by 0.6 m of thin-bedded gray mudstone that grades upward into flaggy-bedded red siltstone which is overlain by 3.6 m of red mudstone to the top of the exposure. Small exposures along Andrews Street to the northwest and in the woods reveal an additional 4 m of gray grading upward into red siltstone beginning about 9.6 m above the top of the type section exposures, The character of the gray laminated units is consistent with the gray beds above the Southington member and the gray-into-red siltstone higher up is consistent with the cycle bearing the Stagecoach Road bed as seen in the Silver Ridge B-1 core and adjacent outcrops. To test these hypotheses, we excavated at the base of the type section and uncovered a black limestone with a pelleted appearance characteristic of the Southington bed. Although Krynine (1950) mentioned a fish-bearing limestone at this section, it had not been identified. It seems clear that the type section does indeed represent the cycle that bears the Southington bed.

The relationship between the accelerated tilting in the lower part of TS IV can be seen in a comparison of the stratigraphy in the lower Shuttle Meadow Formation across the various fault blocks in the Meriden area. At Higby Mountain, gray siltstones and sandstones of the "Durham member" rest directly on the Talcott Formation. In the next fault block east with Lamentation Mountain, there are 10 m of intervening red beds, suggesting additional accommodation due to syndepositional subsidence along the intervening fault. On the next major fault block to the west with Cathole Mountain and Stop 8, the Durham member is missing entirely and the entire formation is much thinner. Based on outcrop width, this thinning continues further to the west. To the northwest the Shuttle Meadow thins, then thickens to this field stop and then thins again towards Plainville and is only 14 m thick at Tarrifville, CT with the Durham member again missing. In contrast there appears to be much less variability of the Talcott Formation along this same interval. The simplest interpretation of these observations is that considerable structurally controlled depositional relief developed between the emplacement of the Talcott Formation and the deposition of the upper Shuttle Meadow Formation, an interval of time probably no more that a couple of hundred thousand years.

Return to vehicle.

86.6 Start out going SOUTH on ANDREWS ST toward SMITH ST.
87.8 Turn SLIGHT LEFT onto CAREY ST.
88.2 CAREY ST becomes RESERVOIR RD.
89.6 Turn RIGHT onto CHAMBERLAIN HWY / CT-71A. Continue to follow CHAMBERLAIN HWY.
94.0 Turn right into parking lot for TARGET (474 Chamberlain Hwy Meriden, CT)
94.1 Drive to southwest cornet of parking lot.

STOP 8. TALCOTT PILLOW BASALT SEQUENCE ON NEW HAVEN FORMATION. (45 MINUTES). Central Meriden Quadrangle, (approx.) 41°33.12'N, 072°48.91'W and Silver Ridge Core B-2 (41°35.053'N, 072°45.647'W)**.** Tectonostratigraphic sequence TS IV; New Haven and Talcott formations; Hettangian age, 200 Ma. Main points are: northeast prograding pillow lava forsets and flow lobes in the; onlapping red sandstones; graded beds altered pyroclastics; gray beds in the upper New Haven in the Silver Ridge B-2 core; and transition downward into typical New Haven Formation.

This spectacular exposure reveals nearly the entire thickness of the Talcott Formation as well as the uppermost few meters of the New Haven Formation. Most of the lower half of the Talcott Formation here consists of forsets and tongues of pillow lava, while most of the upper part consists of non-pillowed flow lobes and vesicular basalt. It is unclear how many eruptive events are represented.

The base of the Talcott Formation at this exposure displays an extremely informative relationship to the underlying Farmington member of the New Haven Formation (Fig. 26). Northeast tapering wedges of pillowed basalt onlap each other in the lower 10 m of the flow complex. These are easily traced by following the red sandstone and siltstone beds that extend upward from the underlying New Haven Formation into the basalt. In several places these beds are internally stratified and contain numerous large to small clasts of basalt and highly altered basalt. Tracing the red beds downward, they merge with the underlying New Haven Formation. Beneath the pillow forsets and associated red beds there is well-bedded red sandstone and mudstone of the New Haven Formation. In its upper few decimeters, there are beautiful graded beds comprised of basaltic gravel and sand (Fig. 27). The basalt and what presumably was basaltic glass is generally altered to a yellow or tan material, superficially resembling a carbonate. All stages of alteration from unquestionable nearly unaltered basaltic material to the tan to yellow clasts seem to visible. Based solely on macroscopic examination, the lowest beds of the New Haven Formation at this outcrop seem to lack basaltic material.

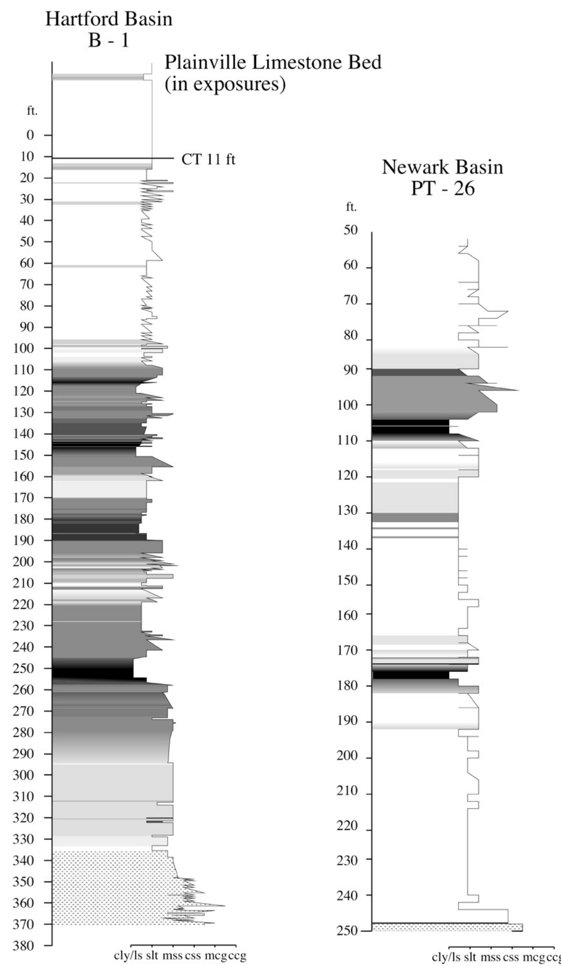


Figure 24. Comparison of the Silver Ridge B-1 core and core PT-26 from the lower Feltville Formation of the Newark basin. Note the homotaxiality of the black units.

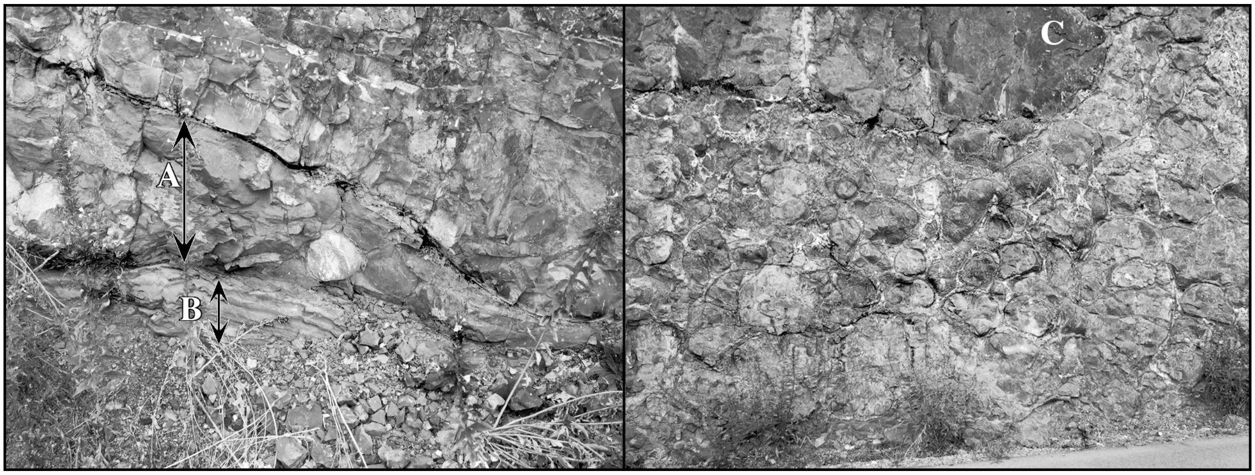


Figure 25. Exposures of Talcott Formation and underlying Farmington member of the New Haven Formation at Stop 8: left, pillow forests and onlapping red siltstone (A) and underlying New Haven Formation with tuff layers (B); right, pillowed basalt in forests with overlying massive flow lobe.

basalt pillows are larger lobes of massive basalt without pillows. Yet higher in the Talcott Formation, some of these are over 6 m thick and scores of meters long. These are almost certainly flow lobes that were the sources of the pillowed wedges. The uppermost Talcott here is highly vesicular, not pillowed and appears to have been deposited subareally.

Although locally deformed by the overlying pillow wedges, the series of graded volcanoclastics beds can be traced across the admittedly limited exposure of the New Haven Formation. Very similar graded volcanoclastic beds have been observed in the uppermost New Haven (by PH) at Hubbard Park at approximately 41°33'22"N and 072°49'33"W. These volcanoclastics would appear to be relatively proximal altered air-fall(?) pyroclastics from a CAMP eruption that began some time before the flows that we see here. This interpretation is different than that given in Olsen et al. (2003a) in which these graded beds were assumed to be related to the basalt pillow wedges.

We interpret the observations on the pillow forsets to indicate that the basalt was flowing to the east and north into a large lake as a series of lava streams. At the advancing front of these lava streams the cooling crust constantly ruptured, sending basalt pillows tumbling down in front, making cones and wedges of pillows. These wedges shed hyaloclastite into muds onlapping the pillow wedges. Hyaloclastite is a hydrated tuff-like rock composed of angular, flat fragments 1 mm to a few cm across formed by granulation of the lava front due to quenching when lava flows into, or beneath water. It would be good to know how much of the red matrix is composed of locally derived, very fine grained hyaloclastite and how much is sediment derived from the highlands or reworked older sedimentary strata.

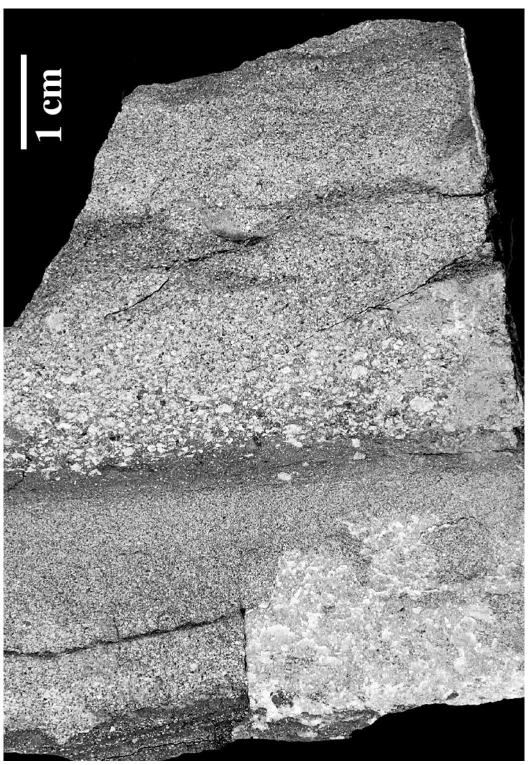


Figure 26. Graded volcanoclastic (tuff) beds in uppermost New Haven Formation at Stop 8 at the Target.

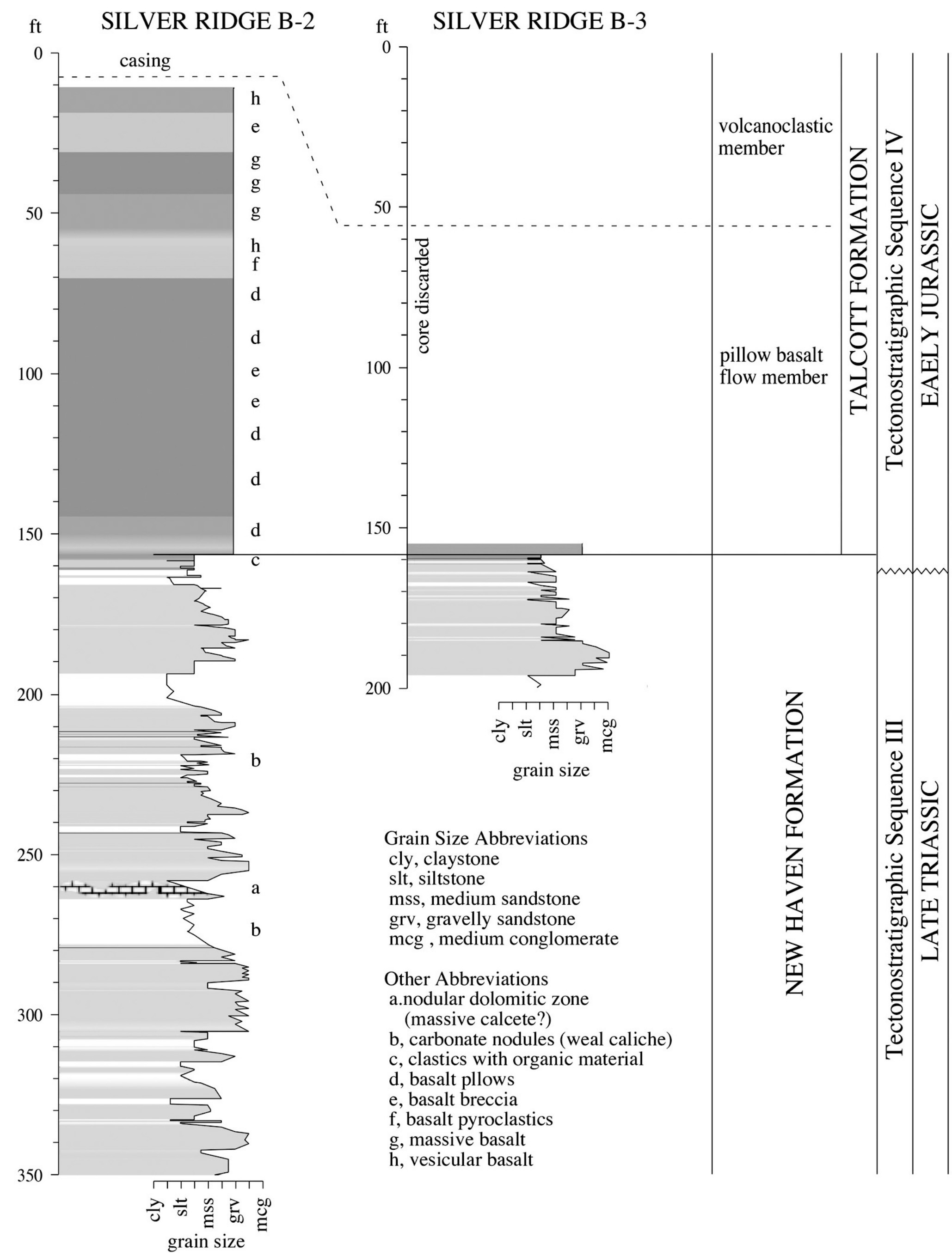


Figure 27. Cores B-2 and B-3 from Silver Ridge on display at Stop 8. From Olsen et al. (2003a).

Assuming that the various pillow wedges and flow lobes represent one major eruptive event constrains the accumulation rate and water depth of the uppermost New Haven Formation. The couple or so meters of basalt-bearing sedimentary strata obviously took no more time to accumulate than the flow complex took to advance over the site, which would seem to be on a time scale of years to at most hundreds of years. The lake into which the lava poured had to be at least the depth of the high points of the individual wedges of pillowed basalt (i.e., 5 m or so), but probably not the depth of the entire Talcott Basalt because lava displaces water. We have found no desiccation cracks in the basalt-bearing red beds, suggesting the lake did not locally dry up during the advance of the Talcott Basalt. It is worth noting, however, that no sedimentological criteria indicates that these red beds were deposited under a significant body of water, or even that they are lacustrine strata, yet they were and are.

Core B-2, portions of which will be on display at this stop, samples 44.5 m (146 ft) of the lower Talcott Formation and the 58.8 m (193 ft) of the upper New Haven Formation and hence the Triassic –Jurassic and TS III – TS IV boundaries (Fig. 28). In core B-2 the lower 56.5 m (below 164.5 ft) is typical of the New Haven Formation and characteristic of the alternating “Red stone” and Lamentation facies of Krynine (1950), itself typical of the Meriden area. The “Redstone” facies consists of red micaceous feldspathic sandstone and interbedded bioturbated mudstones that can be seen in the exposures along near by I-691, while the Lamentation facies consists of often conglomeritic coarse gray or purplish white arkose. To the east, the Lamentation facies predominates; to the west the “Redstone” facies is dominant (Krynine, 1950). Both facies tend to be heavily bioturbated with roots and the burrow *Scoyenia,* and consequently there is very little preservation of fine sedimentary structures (e.g., ripples).

Above 164.5 ft, the New Haven Formation facies change abruptly to finely interbedded, red and tan fine sandstone that grades upward into gray fine sandstone and minor mudstone with abundant plant fragments, including conifer shoots. This facies is much more similar to the overlying Shuttle Meadow Formation in the preservation of small-scale sedimentary structure, the reduction of bioturbation, and the preservation of organic matter. We have not yet extracted pollen from these gray beds, however, just below the Talcott Formation, a similar sequence of conifer-bearing gray beds produced a palynoflora of earliest Jurassic aspect, strongly dominated by *Corollina* (Robbins, quoted in Heilman, 1987; pers. obs.), and therefore we believe the gray beds to be earliest Jurassic in age. The abrupt facies change at 164.5 ft and 166.9 ft in cores B-2 and B-3, respectively, is best interpreted at the TS III – TS IV boundary. The same facies transition could also represent the Triassic-Jurassic boundary.

The contact with the overlying Talcott Formation at 156 ft in core B-2 is sharp, but there is some deformation of the uppermost New Haven Formation. From 156 ft to 70 ft, the Talcott is pillowed and brecciated, looking very much like the exposures at this stop. Radial pipe vesicles are evident as are the chilled margins of pillows. From 70 ft to 32 ft there is massive locally vesicular basalt. This is overlain by breccia unit to 19 ft, which itself is overlain by vesicular basalt to the top of the core (11 ft). It is impossible to tell whether the contacts at 19 ft and 70 ft are contacts between different major flows or contacts between lobes of one eruption, although we favor the latter interpretation based on the geometry visible at this stop.

There is a dike trending towards the Berlin area in Meriden (mapped as present near Hanover Pond). This could be a local feeder for the pillowed basalts, pyroclastics, and volcanoclastics seen at this stop and the Silver Ridge cores and outcrops. Such a feeder, graben system, and associated Talcott flows, has been described in East Haven, CT by Philpotts and Martello (1986) and Olsen et al. (2003a). Assigning the Meriden dike to the feeder system, in a less speculative fashion, however, requires much additional work. It is clear however that there is much to be learned about the dynamics of the Talcott eruption in southern Connecticut.

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