FIELD GUIDE TO THE GEOLOGY OF THE PALEOZOIC, MESOZOIC, AND TERTIARY ROCKS OF NEW JERSEY AND THE CENTRAL HUDSON VALLEY

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ATLANTIC MARGIN ENERGY SYMPOSIUM

ATLANTIC CITY, NEW JERSEY
OCTOBER 4-6, 1981

1981 EASTERN SECTION MEETING
AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
ENERGY MINERALS DIVISION OF AAPG

RIFT BASINS OF THE PASSIVE MARGIN: TECTONICS, ORGANIC-RICH LACUSTRINE SEDIMENTS, BASIN ANALYSES

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Introduction

The kinematic model provided by plate tectonics of the earth's lithosphere is helpful in revealing new hydrocarbon and mineral provinces. The distribution of these resources is largely related to the plate tectonic setting of the basin, i.e. proximity to plate boundary, type of plate margin, and the nature of the substrate. Basins currently forming along divergent plate boundaries, e.g. the Red Sea, are the sites of thick accumulation of hydrocarbons and layers of salt, as well as of metalliferous sediments that were concentrated by hydrothermal processes.

The breakup of North America in the Triassic-Liassic was accompanied by transform faulting, igneous activity and the transgression of Tethys into the proto-Atlantic basin. Vast quantities of clastics were deposited on alluvial fans by ephemeral streams, while subaqueous fans and turbidites accumulated in deep-water lakes along the border fault, and subaqueous fissure flows erupted in pull-apart lacustrine basins. Elsewhere platform carbonates formed as the Tethys waters transgressed across eroded Hercynian and Acadian mesetas, and evaporites of salt and potash formed where waters of the juvenile ocean became restricted in narrow basins. In both deep marine and fresh water basins, oxygen-deficient, toxic, near bottom conditions prevailed preserving organic matter as the progenitor of hydrocarbons. Some of these basins have characteristics of potentially important hydrocarbon provinces.

Lake Deposits and Hydrocarbon Provinces: A Brief Review

Today substantial petroleum production comes from lacustrine sequences in China, the Rocky Mountains, Europe and Africa (see Ryder, 1980). Among the most instructive examples from the context of this trip are those basins that formed in a lacustrine setting during the early rifting phases of the south Atlantic, namely: The Gabon, Cabinda, Congo, Brazzaville and Angola Basins of the West African Passive Margin (Brice and other, 1980; and Brice and Pardo, 1980), and the Reconcavo Basin of Eastern Brazil (Chignone and E Andrade, 1970). While production in these basins is mainly from Early Cretaceous fluvial-deltaic sandstones and non-marine carbonates flanking the margins of the basin, organic-rich deep-water lacustrine sediments provide the source for the hydrocarbons.

Organic-rich lacustrine sediments also comprise a major part of the Triassic and Jurassic sections in Newark-type basins of North America and Morocco. In some basins, lacustrine deposits contain up to eight percent organic carbon (Manspeizer and others, 1981). Like the producing horizons of the West African basins, these beds formed in deep lakes with perennial anoxic botton conditions. Laterally they may interfinger with non-marine shelf carbonates and turbidite-generated sediments from near-shore fan-deltas and fluvial-deltaic complexes. Cyclical lacustrine sequences, recording the expansion and contraction of very large lakes, characterize these beds. Like the Green River Shales, micro-laminated sediment with well-preserved whole fish from the center of the basin are widespread. Besides numerous species of fish, these lake beds abound with amorphous algal kerogen, zooplankton, pollen and spores, and plant cuticle (Olsen, 1980). These organic-rich micro-laminated sediments are the result of depressed ecological efficiency in enormous highly productive lakes.

Having formed in pull-apart basins on the passive margin, these rocks display a variety of structural and stratigraphic traps and should be given serious consideration in future exploration programs.

Objectives of the Field Trip

Accordingly, this field trip will focus on the following questions: (1) What are the major trends in sedimentary and volcanic facies?; (2) How can the sedimentologic-volcanic and structural data be understood in terms of major features of Newark Basin genesis?; (3) How can we discriminate among the principal lacustrine models, such playa-lake-sabkha vs. the stratified-deep-lake model?; (4) What are the causes of the lacustrine cycles?; and (5) How can the concepts of energy dynamics in modern lakes be related to the depositional history of Newark Basin's Great Lakes and Potential hydrocarbon production?

Answers to these and other questions will be explored through examination of Triassic-Jurassic stratigraphic sections along two traverses of the Newark Basin (Figure 1).

NEWARK BASIN

Overview

Resting with a profound unconformity, in a series of about 20 elongated basins along the crystalline core of the Older Acadian and Alleghany Orogenes from Nova Scotia to North Carolina, is a thick section of continental clastics and igneous rocks, termed the Newark Supergroup (Figure 2, Table 1). In general, the long axes of these basins parallel the fabric of the basement rock (Rodgers, 1970; Van Houten, 1977). Rocks within these basins are overlain by post-Jurassic sediments of the coastal Plain, Pleistocene deposits or Recent alluvium and soils.

The Newark Basin (Figure 3) is the largest of the exposed basins and covers about 7770 square kilometers, stretching 220 km along its axis. The basin contains the thickest sedimentary sequence of any of the exposed basins and correspondingly contains the most extensive stratigraphic record.

Precambrian and early Paleozoic rocks of the southwestern prongs of the New England Upland border the Newark Basin along its northeast and northwest margins (Figure 3). The southeastern and southwestern portions of the Newark Basin overlie and are bordered by Paleozoic and Precambrian rocks of the Blue Ridge and Piedmont Provinces. Newark Basin sediments rest with a profound unconformity on basement rocks and most dip 5° - 25° to the northwest. The entire stratigraphic column reaches a cumulative trigonometrically calculated thickness of over 10,300 m (the sum of the maximum thicknesses of all the formations), although the total thickness of sediments actually deposited at any one spot was probably much less. Red clastics are the dominant sediments; intrusive and extrusive tholeiites are the dominant igneous rocks.

The oldest sediments are probably middle Carnian (early Late Triassic) in age while the youngest appear to be Sineumurian (middle Early Jurassic) (Cornet, 1977; Olsen, McCune, and Thomson, in press) (Figure 4). Cretaceous and younger Coastal Plain deposits overlap Newark beds with an angular unconformity along the basin's eastern edge. The northern quarter of the basin is mantled by Pleistocene and recent deposits.

Newark supergroup deposits of the Newark Basin (New York, New Jersey and Pennsylvania) are divided into nine formations called (from bottom up): Stockton Formation (maximum 1800 m); Lockatong Formation (maximum 1150 m); Passaic Formation (maximum 6000 m); Orange Mountain Basalt (maximum +200 m); Towaco Formation (maximum 340 m); Hook Mountain Basalt (maximum 110 m); and Boonton Formation (maximum +500 m). Each Formation is characterized by its own suite of rock types, the differences being especially obvious in the number, thickness, and nature of their gray and black sedimentary cycles (or lack thereof).

Fossils are abundant in the sedimentary Formations of the Newark Basin and provide a means of correlating the sequence with other early Mesozoic areas. The Stockton, Lockatong, and most of the Passaic Formation are Late Triassic (Middle and Late Carnian-Rhaetic) while the uppermost Passaic Formation (at least locally) and younger beds appear to be Early Jurassic (Hettangian and Sinemurian) in age. The distribution of kinds of fossils is intimately related to sequences of rock types in sedimentary cycles. The brief descriptions of these formations, extracted from Olsen (1980a), follows:

Stockton Formation

The Stockton Formation is the oldest and most widespread deposit, forming the basal beds of the Newark Basin section everywhere except along portions of the northwest border. The Stockton is thickest near the Bucks-Montgomery county line in the Bucks-Hunterdon fault block (Figure 3), where it reaches a calculated stratigraphic thickness of 1830 m (Willard, et al., 1959). Along its type section (Table 2) along the shores of the Delaware River near Stockton, New Jersey, the Formation is 1500 m thick (McLaughlin, 1945). Measured from the base of the lowest continuous black siltstone unit of the overlying Lockatong formation, the Stockton thins in all directions from this central area (Kummel, 1897). The pre-deformational shape of the Stockton Formation lithosome is an asymmetrical lens with the thickest portion near the center of the Bucks-Hunterdon fault block. McLaughlin (in Willard, et al., 1959) presents evidence that the Stockton Formation in the southern Newark Basin thins by a progressive onlap of younger Stockton beds onto basement.

Stockton lithology is diverse. The dominant sediment types are gray and buff colored arkose and arkosic conglomerate, and red siltstone and arkosic sandstone. In broad view, the Stockton Formation fines upward with the coarsest sediments near the base. As noted by McLaughlin (In Willard, et al., 1959) the Stockton coarsens in the same direction it thins; thus conglomerate bodies and coarse arkose are found high in the section along the eastern edge of the basin.

Red siltstones of the Stockton Formation are characteristically intensively bioturbated by roots and burrows, notably the arthropod burrow Scoyenia (see Olsen, 1977). Purple and Mauve siltstone beds with a markedly disrupted fabric occur near the middle and top of the formation. These beds are usually densely penetrated by roots, but rarely burrowed by Scoyenia. Beds of greenish-gray and brown carbonate-rich pellets occur throughout the Formation. These are often associated with bases of buff arkose beds. Well-bedded gray and gray-green siltstone beds are present locally in the upper Stockton, and these beds are the source of most of the Stockton fossils found so far. How these units, which are unusual compared to the build of the Stockton sequence, fit in the overall facies pattern remains obscure.

Lockatong Formation

The beds of the Lockatong Formation rest conformably on the Stockton Formation over most of the Newark Basin. The Lockatong is composed primarily of gray and black siltstones arranged, as shown by Van Houten (1962, 1964, 1965, 1969, 1977), in sedimentary cycles. In the Bucks-Hunterdon fault block, near the Lockatong's type section along Lockatong Creek, the Formation reaches its maximum thickness of 1150 m (Figure 3). The Formation thins in all directions away from this central area (Figure 5, passing into Passaic and Stockton Formations along exposed edges of the Newark Basin.

Van Houten (1962, 1964a,b, 1965, 1969, 1977) recognizes two end-members to the range of short cycle types present in the Lockatong; he terms these detrital and chemical. In the Delaware River section of the Formation the detrital cycles are an average of 5.2 m thick and consist of a lower platy black calcareous siltstone succeeded upwards by beds of disrupted dark gray, calcareous siltstone, rippled-bedded siltstone, and fine sandstone (Figure 6).In the same area, chemical cycles average 3.2 m. thick. Their lower beds consist of platy black and dark gray dolomitic siltstone, broken by shrinkage cracks, and containing lenses of pyritic limestone. The upper beds are massive gray or red analcime- and carbonate-rich siltstone, intensively and minutely disrupted. The massive beds often contain pseudomorphs after analcime and glauberite.

In the central Newark Basin, the two cycle types occur in clusters; the center of each detrital cycle cluster is about

107 m from the next. Detrital cycle clusters are separated by clusters of chemical cycles. Again, in vertical section, there are more detrital cycles in the lower than in the upper Lockatong. Evidence gathered so far indicates that individual detrital cycles can be traced for over 20 km. Judging from the outcrop pattern of detrital cycle clusters in the upper Lockatong and lower Passaic Formation, it seems likely that individual detrital cycles can be traced basin-wide. Chemical cycles, on the other hand, are predominantly restricted to the central 97 km of the Newark Basin, passing laterally into beds indistinguishable from the Stockton and Passaic Formations. At the southwestern end of the Newark Basin at Phoenixville, Pennsylvania, the Lockatong is 350 m thick; the Formation consists of clusters of detrital cycles separated by red siltstone and some beds of gray sandstone. At the northeastern end of the Newark Basin at Weehawken, the Lockatong is 150 m thick and consists of detrital cycle clusters separated by beds of buff arkosic sandstone. The large number of detrital cycles prevalent in the lower Lockatong in the central Newark Basin strongly suggests that the Lockatong outside of its thickest central portion comprises only the lower 500 m of the Lockatong or less (not including the lower 30 m of red siltstone grouped here in the Stockton). The thickness of the Lockatong decreases away from the central Newark Basin not only by replacement of its upper beds by Passaic Formation but also by the thinning of individual detrital cycles. While the mean detrital cycle thickness is 5.2 m along the Delaware River, for example, it is 1.5 m along the Hudson River (see Olsen, 1980b) (Figure 5).

Passaic Formation

The predominantly red Passaic Formation is the thickest coherent lithologic unit in the Newark Basin, reaching a maximum calculated thickness of over 6000 m (Jacksonwald) Syncline. The Formation outcrops throughout the Newark Basin, although is upper beds are preserved only in the Watchung Syncline (Figure 3), in the smaller synclines preserved along the eastern side of the Flemington Fault, and in the Jacksonwald Syncline (Figure 3). In all other areas, the upper Passaic has been removed by post-Newark erosion.

While in most areas the Passaic Formation rests conformably on Lockatong Formation or, where that is absent, Stockton Formation; in several areas on the western margin of the Newark Basin the Passaic directly overlaps the step-faulted basement without any intervening Stockton or Lockatong. In these areas (Figure 5) the thickness of Passaic Formation present below the Orange Mountain Basalt is comparatively slight.

Facies patterns of the Passaic Formation are a modified continuation of those of the Lockatong, although red beds, not gray are the dominant lithology. As in the Lockatong, periodically spaced clusters of detrital cycles (Figure 5) occur through most of the thickness of Passaic Formation (Van Houten, 1969). The great majority of these non-red units, however, are not as laterally continuous as those of the Lockatong, and as a general trend, it is clear that the number of cycles involved in these clusters decrease in frequency upwards through the Passaic Formation.

Orange Mountain Basalt

The Orange Mountain Basalt is the oldest Newark Basin Formation thought to be wholly Early Jurassic in age, and like similarly aged beds in the Newark Basin, the main area in which the basalt is preserved is the Watchung Syncline (Figure 3). Smaller synclines preserve portions of the Orange Mountain Basalt in several other regions. In the New Germantown and Sand Brook synclines, the overlying Feltville Formation is preserved above the basalt. Correlation by palynomorph assemblages and fossil fish of the overlying Feltville Formation (Cornet, 1977; Olsen, McCune, and Thomson, in press) demonstrate the identity of the underlying basalt. Taken together, these remnants of Orange Mountain Basalt suggest that originally the basalt covered the entire Newark Basin, a minimum of over 7700 km^2. This is comparable to the extent of the Holy Basalt over the Hartford Basin and the North Mountain Basalt over the Fundy Basin. The Orange Mountain Basalt appears thickest in the Watchung Syncline, varying between 100 and 200 m.

Two thick flows are evident in most sections of the Orange Mountain Basalt, at least in the Watchung and New Germantown Synclines. The lower flow is exposed at the type section where it shows a nearly complete Tomkeieff structural sequence (Manspeizer, 1969). Other exposures of the lower flow are abundant. In most places the lower and upper flows are separated by a red volcanoclastic bed which is generally less than a meter thick (Bucher and Kerr, 1948; Johnson, 1957; Van Houten, 1969; Faust, 1975). In the New Germantown Syncline, however, the volcanoclastic bed is over 4 m thick and has numerous beds of purple, red, and gray ripple-bedded and mudcrakced siltstone. The upper flow is extensively pillowed and pahoehoe-like near the type section (Fenner, 1908; Van Houten, 1969) and locally at isolated spots throughout the Watchung syncline. Subaqueous fissue flows and flow lobes are common in the Paterson area, and will be studied on the field trip.

Feltville Formation

The sedimentary rocks above the Orange Mountain Basalt and below the Preakness Basalt are termed the Feltville Formation (Olsen, 1981). The Feltville consists of red siltstone and sandstone, buff, gray, and white feldspathic sandstone, and a thick, laterally continuous non-red unit containing a unique laminated limestone (Figure 6). This formation is named for the old village of Feltville, Union Country, New Jersey, where the type section is located.

The Formation averages about 180 m in the Watchung Syncline, apparently thickening to 300 m in the Sand Brook and 600 m in the Germantown Syncline. More than 200 m seems to be present in the Jacksonwald Syncline.

The Feltville Formation is distinguished from the underlying Passaic Formation and the younger Jurassic Formations of the Newark Basin by the presence of abundant beds of buff, gray, or white feldspathic sandstone interbedded with red siltstone in fining-upwards sequences (Olsen, 1981[a]); thus, much of the Feltville superficially resembles the Stockton Formation. The lower half of the Feltville contains a black to white laminated limestone, calcarenite, and graded siltstone bed (0.4 - 3 m) containing abundant fossil fish. This is sandwiched between two beds (each 1-7 m) of gray, small- to large-scale cross-bedded siltstone and sandstone. As is true for the Formation as a whole, these beds are thickest in the New Germantown Syncline (+14 m).

Conglomerate occurs in the Feltville Formation at Oakland, New Jersey, about 15 m below the Preakness Basalt (Faust, 1975). This conglomerate contains as much as 30% vesicular basalt clasts, in addition to cobbles and pebbles, slate, and limestone. Very little of the section below this unit is exposed, and at this point it is impossible to say how much additional conglomerate is present. Other beds of conglomerate crop out in the New Germantown syncline in association with the non-red laminated beds. The available evidence suggests that the Feltville Formation, like the Orange Mountain Basalt, originally occupied the whole of the area of the Newark Basin; the predeformational shape of the Feltville lithosome seems to have been a wedge, thickest along the western border of the basin. The data are not conclusive, however.

Preakness Basalt

Preakness Basalt consists of the extrusive, tholeiitic basalt flows and interbedded volcanoclastic beds above the Feltville Formation and below the Towaco Formation (Olsen, 1981). Preakness Mountain is the local name of the second Watchung Mountain near Franklin Lakes, New Jersey.

Preakness Basalt is the thickest extrusive unit in the Newark Basin. The calculated thickness is 215 m at its northernmost outcrops at Pomptom and Oaklane, New Jersey.

At its base, the Preakness Basalt is much more variable than the Orange Mountain Basalt. Locally, there are thick sequences of multiple basalt flows making up possible basalt foreset beds (Manspeizer, 1980). In other areas there are thick beds of angular and vesicular basalt breccia resembling aa. In still other areas the thick massive lower flow rests on the flat Feltville Formation surface (Lewis, 1908).

Towaco Formation

The name Towaco Formation is applied to the red, gray and black sedimentary (and minor volcanoclastic) rocks present below the Hook Mountain Basalt and above the Preakness Basalt in the Watchung Syncline (Olsen, 1981).

Laterally continuous symmetrical sedimentary cycles characterize most of the Towaco Formation (Figure 6). These consist of a central black or gray microlaminated calcareous siltstone bounded above and below by gray sandstone and siltstone beds arranged in fining-upwards cycles. These symmetrical cycles are a mean of 35 m thick and bear a close resemblance to the East Berlin Formation (Hartford Basin cycles described by Hubert, Reed, and Carey 1976). Towaco cycles are an order of magnitude thicker than Lockatong or Passaic Formation detrital cycles and differ from the otherwise similar Feltville Formation non-red unit in containing predominantly clastic rather than carbonate laminated portion (Figure 6). In total, six such cycles have been identified in the upper half of the Towaco Formation and most of these have been traced through the Watchung Syncline.

Beds of conglomerate occur at numerous horizons through the Towaco Formation at Pompton, New Jersey. Not only is conglomerate present directly below the Hook Mountain Basalt in this area (Fault, 1975), but thick conglomerate beds also occur at intervals of about 120-150 m, 160-170 m, 185-195 m, 205-229 m, and 270-280 m below the Hook Mountain Basalt (Figure 6).

Hook Mountain Basalt

The uppermost extrusive unit in the Watchung syncline is called the Hook Mountain Basalt (see Baird and Take, 1959. The Hook Mountain Basalt is the thinnest of the three major extrusive Formations of the Newark Basin. At its type section, it is 110 m thick and it retains this thickness throughout the Watchung Syncline. That this basalt extends in the subsurface across the gaps between Hook Mountain and Riker Hill, and between Riker Hill and Long Hill is shown by the bedrock topography maps of Nichols (1968) and the aeromagnetic data of Henderson, et al. (1966). In the area of Bernardsville, New Jersey, what has been mapped (Lewis and Kummell, 1910-1912) as part of the Preakness Basalt is in fact Hook Mountain, as shown by unambiguous exposures of Towaco Formation between it and the underlying basalt.

Boonton Formation

The Boonton Formation is the youngest sedimentary unit in the Newark Supergroup sequence of the Newark Basin and consists of more than 500 m of red, brown, gray and black fine to coarse clastics and minor evaporitic beds (Figure 6).

The stratigraphically lowest beds in the Boonton Formation are well exposed near Bernardsville, New Jersey. In this area, the Formation consists of blocky to finely bedded red, gray, brown and black, often dolomitic siltstone. This 104-meter thick lower unit is riddled with hopper casts (pseudomorphs after gypsum, glauberite, and halite) which are common in sequences of all colors. Similar beds are exposed along Packanack Brook, Wayne, New Jersey. The different colors and textures of these beds do not seem to be arranged in any obvious or consistent cyclic pattern and resemble no other units in the Newark Basin. Stratigraphically above these lower beds is a sequence of well-bedded red siltstones and sandstone beds (mean thickness 35 m) alternating with thinner beds of gray-green siltstones (mean thickness 2 m). The uppermost beds of the type section include a fossil fish bearing calcareous gray microlaminated siltstone at least one meter thick (Smith, 1900). This is the famous Boonton Fish Bed (Newberry, 1888; Schaeffer and McDonald, 1978). Also in this section are gray and brown conglomerate units up to 0.5 m thick. Along the western edge of the Watchung Syncline, northeast of Morristown, New Jersey are thick sequences of red-, gray-, and brown-matrix conglomerate and breccia. The relationships of these units to the finer portions of the Formation are unclear.

Diabase Instrusions

Large diabase and gabbro plutons and sills are emplaced through various portions of the pre-Orange Mountain Basalt section of the Newark Basin sequence. The areal extent, petrography and contact relationships of these masses are, for the most part, well known (Darton, 1890; Kummel, 1897, 1898; Lewis, 1908; Lewis and Kummel, 1910-1912; Willard, et al., 1959; Hotz, 1952) and will not be described in detail here. These bodies generally parallel the distribution of major bodies of gray and black siltstones; thus the largest intrusives are broadly concordant (but locally discordant) to the Lockatong Formation (i.e., Palisade, Rocky Hill, and Sourland Mountain sills) or the Perkasie Member of the Passaic Formation (Haycock Mountain, Coffman Hill, and possibly the Cushetunk

Pluton). The general pattern is for these intrusions to be emplaced progressively higher in the Newark Basin section viewed along an east to west section (Figure 5). Like most Newark Supergroup deposits, Newark Basin beds are cut by a number of narrow, often straight and vertical diabase dikes which, in this area, trend north and northeast. The mapping of the distribution of these dikes is still very incomplete (see King, 1971, and May, 1971, for reviews).

BASIN TECTONICS

Beginning with the studies of Rogers (1858) in Pennsylvania and Davis (1886) and Barrell (1915) in Connecticut, Newark-type basins were considered grabens or fault troughs produced by extension at right angles to the rift axis. Today many of these same basins have been assigned to the initial phase of the Atlantic tectonic cycle, and display tectonic structures and facies characteristic of rhomb-shaped pull-apart basins that formed within transforms due to horizontal shear (see Manspeizer, 1980; and 1981).

As crustal plates move past each other along transform boundaries, different types of pull-apart basins may form in zones of crustal extension. In as much as the crust may have been heated by hot spot activity (e.g. the White Mountain Magma series), the walls and floors of these basins may have been stretched so that in time they sag and collapse forming basins. Where the basement has been pulled apart creating rhombochasms, diapirs of magma may enter the basin floor in the form of dikes and flows. Differential horizontal movement along an active fault zone may create an asymmetric basin, as in the Dead Sea Rift. Continuous wrench faulting along the transform may produce complex transtensional and transpressional structures, such as en-echelon cojugate fractures and folds, and isolated basins with complicated unconformities and sedimentary overlap.

What data can we cite to support this view of the Newark Basin? The following is extracted from Manspeizer (1981, and ms):

1) The fundamental structures of wrench tectonics, including en-echelon folds, conjugate strike-slip faults, the main wrench fault zone, and en-echelon normal faults, are shown on Figure 3. Note particularly the Hopewell and Flemington faults, which are en-echelon right-lateral oblique faults that may have up to 12 miles of horizontal slip, and the Chalfont fault, a possible major left lateral fault.

2) Syntectonic development of both transtensional and transpressional structures occur along the border fault, leading to a complex set of drag folds, unconformities and basins (see Ratcliffe, 1980; and Manspeizer, 1980).

3) Moderately deep-water fissure eruptions with pillow lavas and volcanic flow lobes restricted to rhombochasms (?) near the axis of the basin.

4) Pronounced asymmetry of the sedimentary basin and sedimentary facies with deep-water lacustrine deposits typically along the border fault, and fluvial-deltaic sediments along the eastern Piedmont Province.

5) progressive "younging" of Triassic and Jurassic sediments in the direction of the western margin of the basin.

6) The absence of a continuous system of faults along the margins of the basin, indicating that the

earliest phases of sedimentation may have begun on a downwarped crust prior to faulting.

7) The predominance of slickensides with a horizontal neat along the western border fault.

IGNEOUS ROCKS

Tholeiitic basaltic lavas and intrusives of Early Jurassic age clearly mark and distinguish the upper part of the stratigraphic sequence in the onshore and offshore basins of eastern North America. These rocks were emplaced over a vast area, perhaps 2500 km long and 1000 km wide, during an episode of crustal extension and sea-floor spreading, and therefore exhibit a variety of structures reflecting the complex history of the basin at that time (Figure 7). Some of these structures, studied on the field trip, are described below.

While the intrusive sheets such as the Palisades Sill and the Rocky Hill-Lambertville sheets extend collectively throughout much of the basin, the volcanics are restricted to the Jurassic section (Figure 3). Paleoflow data (Manspeizer, 1969) and geochemical data (Puffer and Lechler, 1980; and Puffer and others 1981) show that the First and Second lava flows, now preserved as erosional remnants in the north, originally extended 80-150 km south to their probable source in the eastern part of Pennsylvania. Field studies also show that these lavas extended west of the Ramapo border fault. While First and Second Watchung lavas erupted from sources in the southwestern end of the basin, vector means calculated from pipe vesicles indicate that the Third Watchung erupted from an unknown area to the northeast of the basin and flowed to the southwest in the direction of the regional sedimentary paleopslope (Manspeizer, 1969). These flows may have fractionated from a typical Mid-Atlantic Ridge basalt magma (Puffer and Lechler, 1980).

Most of the lavas were emplaced as multiple flows through a series of lava tunnels and tubes that occasionally arched and pierced the overlying pahoehoe shell. Some flows were emplaced as deep-water (lacustrine) pillow lavas, fissure eruptions and volcanic breccias in rhombochasms (?) of pull-apart basins (Figures 8 and 9).

Pillow Lavas, Subaqueous Flow Lobes and Rhombochasms (?)

One of the most striking features of moderately deep-water Recent basaltic volcanism is its abundance of pillow lavas (Jones, 1966). Current investigations of the FAMOUS expedition (Heirtzler and Bryan, 1975; Choukrone and others, 1978) show that pillow lavas and pillow rubble comprise an important component of the Mid-Atlantic Rift facies. While the main deeps of the rift are often buried by considerable rubble, pillows form on adjacent highs away from the center of tectonic activity from flows erupting from volcanic vents and fissures.

Pillow lavas occur extensively throughout the upper flow unit of the Orange Mountain Basalt and in the lower flow unit of the Preakness Basalt. They are best exposed in several trap quarries in the Paterson region, where according to Fenner (1908), they formed in the lacustrine setting of Lake Paterson. In the New Street Quarry of Paterson, long a favorite collecting site for mineral hobbyists, pillow lavas are abundant, occurring in two distinctively different facies: (1) a subaqueous flow lobe, and (2) bedded pillow lavas. (Figures 8 and 9).

The subaqueous flow lobe, sketched in (Figures 8 and 9) from the walls of two adjacent quarries and a roadcut, is about 400 m long and 35 m high with an apparent long axis oriented east-to-west. Its upper surface slopes gently westward 5° - 10°, while its distal end and flanks are extremely steep and slope 35° - 40°. Its shape is a broadly flat-topped tongue or lobe that flares out along its distal end to the west. The lobe overlies the vesicular and tuffaceous upper surface of the lower flow unit and appears conformably overlain by an extensive horizon of bedded pillows and massive columnar basalt.

The distal western end of the flow lobe is overlain by the younger set of subaqueous fissure eruptions which feed a younger set of pillows.

Pillows of the bedded and lobe-type form interconnected ellipsoidal masses that are distorted, kneaded and flattened like half-filled sacks in a tight structural framework without matrix but with open interstices. The interstices have irregular shapes and are filled with small angular fragments of basaltic glass that are completely surrounded by and cemented with secondary zeolites, calcite and quartz. It is clear that the clasts were derived from the glassy and checkered rind of the pillows by circulating secondary solutions that displaced the glassy rind by their mineralizations. In transverse section the pillows are almost circular and display well-developed radial and/or concentric joints. Concentric layering and blocky joint patterns accompany longitudinal sections, which are markedly elliptical with long axes to short axes ratios in the order of 3:2. While the exterior rind of the pillows are cracked in the form of checkered glass selvage, the interior is generally massive and only very slightly and minutely vesicular. Vesicularity and vesicle size, according to Moore (1965) and Jones (1969), is an index of the depth of water in the formation of pillows. The pillows of Lake Paterson have few microvesicles and may have formed in moderately deep water. This avenue of research is currently being investigated.

The absence of rubble is an important and notable attribute of the pillows suggesting that the waters of this basin were well-agitated and that the finely comminuted clasts were washed into the deeper part of the basin perhaps along the border fault. (See Choukroune and others, 1978, Figure 6). Considerable volcanic breccia and fissure eruptions are found at the Haledon Quarries north of Paterson (D. Bello, Oral Comm.).

Fenner (1908) determined that the minimum size of the lake basin was in the order of 8 km long, that is from Montclair to North Haledon where the beds are concealed by glacial cover. Field data, however, show that similar rifting and volcanism may have occurred concurrently in isolated basins from Ladentown, New York south to Feltville, New Jersey, a distance of about 75 km. The presence of volcanic vents, subaqueous flow lobes, moderately deep-water pillow lavas within down-dropped blocks causes us to speculate whether a short-lived juvenile ocean basin hadn't formed for a brief moment here during the Early Jurassic (Figure 10).

Zeolites

The trap rocks of the Paterson region with their spectacular array of zeolites and associated minerals have been favored by mineralologists and hobbyists for over 150 years. These minerals enrich museums and private collections throughout the world and their quality and diversity rank with similar collections from Nova Scotia, Iceland and the Deccan of India (Mason, 1960). As early as 1822 Nutall recorded the occurrence of prehnite, natrolite, chabazite, stilbite, and datolite from quarries in the first Watchung Basalts (Mason, 1960). Among the zeolites, Bucher and Kerr (1948), report that stilbite, analcime, natrolite, laumontite, thaumasite, chabazite and heulandite are probably the most frequently found, and that they occur most often with quartz, calcite, datolite, prehnite, pectolite and apopyllite. Of the sulphides, pyrite and chalcopyrite occur more frequently than galena and bornite. Among the sulphates, gypsum occurs rarely.

In the past, as basalt quarries were actively worked for the trap rock, good crystals could be found in newly opened quarry faces. Today there are no operating trap quarries in Paterson, therefore, mineral collecting is almost non-existent.

The presence of cavities and pseudomorphs after glauberite and anhydrite within the pillow complex at Paterson and in the mudstones below the lavas led Schaller (1932) to suggest that the zeolites formed only when the second flow unit entered into a saline lake. Van Houten (1969), however, suggests that the pillowed lava and underlying vesicular lava at Paterson were mineralized after burial by circulating ground water, perhaps derived largely from the compaction and dewatering of the underlying mudstones.

Pillow lavas and pillow-derived debris are important rock components in modern oceans. The absence of debris in the interstices of pillows suggests that it was washed away, leaving open channels for subsequent mineralization by ground water solutions. Therefore, it seems unlikely that the zeolites formed in shallow water playas.

Columnar Jointing

A spectacular joint system, marked by a lower and upper colonnade with a central entablature, is the single most consistent and prominent feature of the lower flow unit of the First Watchung basalts (Figure 7). It is remarkable that this three-fold joint pattern may be observed for a distance of almost 80 km along strike. It marks a uniform flow condition and cooling history over a vast area, suggesting that the lava was ponded. It is unlikely that these ponded lavas could have reached far beyond the northern limits of the current basin. First described almost 100 years ago by Iddings in 1886, these structures are equal in prominence to those described by Bailey (1924) of the Mull Province, Tomkeieff (1940) of the Devil's Causeway, and Waters (1960) of the Columbia River Basalts.

This joint system is most completely exposed along Interstate Route 280 in West Orange, near the site of the O'Rourke Quarry described by Iddings in 1886 (Manspeizer, 1969). The structure, overlying a fluvial red bed sequence of shales and sandstones, consists of: (1) a lower colonnade; (2) an entablature; and (3) an upper colonnade. The lower colonnade, about 15 km thick, is composed of massive 4-5 or 6-sided polygonal subvertical joint prisms up to 13 m high and 0.5 - 1.2 m wide. The entablature consists of long (20 to 30 m), slender, slightly undulating curved polygonal columns that pinch and swell, and radiate from the aspices of wide-angle cones that form upright, inverted and oblique fans and chevron structures (see Spry, 1961, p. 195). Sheafs of curved downward radiating fans and chevrons are significantly more abundant than upward radiating structures by a factor of perhaps 10:1. Cross joints, intersecting the radiating columns at high angle, appear concentrically distributed about the apex of radiation. The density of joints, as manifested by the long slender prismatic olumns, is the key factor differentiating the entablature from the colonnades. While the entablature of the First Watchung is curvi-columnar, in the Second Watchung it is characteristically composed of very long (about 25 m) and fairly continuous, slender (about 10 cm in diameter), non-radiating parallel columns that are perpendicular to the flow surface. Poorly developed blocky columns and massive basalt of the upper colonnade overlie the entablature in most areas.

Petrographically (Manspeizer, 1980) the curvi-columnar joint pattern of the entablature is characterized by an increase in grain size, an increase in the abundance and size of the interstitial glass, and the virtual restriction of olivine to this zone (Figure 11). These relationships suggest that although the rate of cooling of the hot flow interior may have proceeded slowly, once a ground mass capable of transmitting stress was established the remaining silicate melt cooled almost instantaneously. The greater rate of cooling near the center of the flow would produce more fractures per unit volume and a greater release of the total energy in the system (Spry, 1961). The clarity of joint reflection from the lower colonnade into the entablature indicates that joint propagation proceeded along master joints, as suggested by Spry (1961). The obscure joint pattern observed almost everywhere in the upper colonnade may be the result of convective heat loss near the upper part of the flow.Other explanations offered for the origin of the curvi-columnar jointing in the entablature of the First Watchung basalts include: (1) an undulatory upper surface (Iddings, 1886; Manspeizer, 1969); (2) varying rates of cooling at the upper contact (Iddings, 1886); (3) the occurrence of feeder dikes (Bucher and Kerr, 1948); (4) the effects of master joints upon stress in the entablature (Spry, 1971), and a fracture-controlled quenching process whereby temperature and stress distribution are altered by water introduced through joints (Justus and others, 1978). This issue, and the observations by Ryand and Sammins (1978) are further discussed in the Road Log.

LACUSTRINE CYCLES

Lockatong Formation, Detrital Cycles

The Lockatong Formation is composed almost entirely of well-defined sedimentary cycles. Of the two short cycles described by Van Houten, chemical and detrital, only the latter will be discussed here; they resemble not only cycles found higher in the Newark Basin section, but also lacustrine sequences of other Newark Supergroup basins.

As originally noted by Van Houten, Lockatong detrital cycles clearly reflect the expansion and contraction of lakes. Recent study of these cycles shows that each can be split into three lithologically identified divisions (Figure 12) from the bottom up: 1, a thin (0.5 m) platy to massive gray siltstone representing a fluvial and mudflat to lacustrine (transgressive) facies; 2, a microlaminated to coarsely laminated black to green-gray fine, often calcareous siltstone (0.1-1.0 m) formed during maximum lake transgression; and 3, a generally thickly bedded or massive gray or gray-red siltstone or sandstone (0.5-4.0 m) usually showing a disrupted fabric and current bedding and sometimes bearing reptile footprints and root horizons (regressive facies).

If individual detrital cycles can be traced over the extent of the Lockatong Formation, the area of division 2 of each cycle is a measure of the average minimum size of the lake during maximum transgression; this is about 7000 km^2.

Vertical sections through Lockatong cycles show consistent lateral trends in lithology and paleontology. Detrital cycles traced away from the geographic and depositional center of the Newark Basin show changes in faunal and floral assemblages due to deposition in progressively shallower water. In addition to lateral change in facies, there is a correlated change in cycle thickness (see Figure 12). For instance, along the Delaware River (at the geographic and depositional center of the basin), the mean thickness of detrital cycles is 5.2 m (Van Houten, 1969), while in the northern Newark Basin this thins to 1.5 m (Figure 11). The microlaminated sediments of division 2 are made up of couplets of laminae, one of which is more calcareous than the other (in their unmetamorphosed state) (Figure 12). Similar sediments are produced in a variety of modern lakes; in most of the studied cases the couplets are the result of seasonal variation in sedimentation and are thus varves (Nipkow, 1920, 1927; Kelts and Hsu, 1978; Tolonen, 1980)

Fletville Formation

Washington Valley Member -

General Comments

About 3150 m above the early Late Triassic Lockatong Formation, is the first laterally extensive perennial lake sequence in the Early Jurassic (Hettangian) of the Newark Basin. The Feltville Formation contains a limestone-bearing sequence which bears a gross resemblance in vertical sequence to a single Lockatong detrital cycle (Figure 6). It can be split into three basic divisions at most exposures as follows (Figure 13) (from the bottom up): 1, a 0 to 3 m gray to red siltstone and fine sandstone showing current bedding, root zones, abundant reptile footprints, and carbonized megafossil plants (transgressive facies); 2, a 0.5 to 5 m black, gray or red and green-gray microlaminated to massive limestone and calcareous siltstone with abundant fossil fish and graded to massive siltstone similar to division 1 but with fewer footprints (regressive facies). Division 1 grades down into, and division 3 grades up into red and buff clastics. Like Lockatong cycles, the Washington Valley member was deposited by the expansion and contraction of a large lake.

Lateral facies relationships in the Washington Valley member are very different from Lockatong detrital cycles despite the similarity in vertical section (Figure 14). On a small scale, the Washington Valley member shows lateral variation in thickness and lithology far outside the range of Lockatong cycles. Thickness changes markedly along strike as does color. Within 300 m in the Watchung Reservation (type area for the Feltville Formation) the color of the limestone of division 3 changes from gray and black to white and green gray and the color of fish bone changes from black to amber. Siltstones associated with all three divisions change from gray to red in the same area, but all the beds still retain palynomorphs and black coalified plant remains. The thickness of the red siltstone between the Washington Valley member and the underlying Orange Mountain Basalt varies markedly along strike as well; at some localities division 2 rests directly on the basalt (Figure 14). We believe these lateral changes reflect an irregular depositional surface.

On a larger scale, the Washington Valley member thickens towards the New Germantown Syncline, as does the whole of the Feltville (Figure 14). This thickening is in the same direction as the mean paleocurrent vector for the Formation which is southwest. Presumably this indicates that the depositional center of the Feltville, unlike that of the Lockatong, was located near the present western edge of the Newark Basin.

In contrast to the Watchung Syncline exposures, those of the Oldwick Syncline contain little massive siltstones. Instead, the siltstones are well bedded, often sandy, sometimes conglomeritic, and are usually made up of beds 1 to 5 cm thick showing a distinct graded pattern characteristic of turbidites.

Towaco Formation Cycles

The cycles of the Towaco Formation have a mean thickness of 30 m and can be broken into four basic divisions as follows (Figure 15 from the bottom up): 1, a 1 to 5 m gray siltstone and sandstone (or conglomerate) often with root horizons, reptile footprints, and large to small scale crossbedding (transgressive facies); 2, a 1 to 5 m thick gray to black siltstone with a 0.1 to 5.0 m thick gray to black microlaminated calcareous portion often with numerous fish (deep water facies; 3, a 3 to 6 m gray clastic unit similar to division 1 (regressive facies); and 4, a thick 20 - 30 m) red clastic sequence often composed of several fining upwards cycles containing abundant reptile footprints, root horizons, mudcracked surfaces, and beds with numerous carbonate rich nodules (fluvial, flood pain, and flow basin facies).

Individual Towaco cycles resemble the Washington Valley member of the Feltville Formation in lateral facies relationships (Figure 16, again contrasting with the Lockatong [Figure 12]). All divisions of the Towaco cycle coarsen towards the north, and the microlaminated portion of division 2 thickens by more than an order of magnitude towards the Ramapo Fault. This microlaminated portion appears varved, similar to the microlaminated portions of Lockatong cycles and the Washington Valley member. Varve thickness increases in the same general direction as the entire microlaminated sequence (Figure 16), although only by a factor of five. The structures and fossils in these varved beds are consistent with the stratified lake model of deposition. However, the more massive fine siltstone portions of division 2 are more consistent with a model in which the lake experienced at least seasonal overturn; fossil fish are present in these beds but only as isolated bones and scales.

At a number of exposures, division 2 of Towaco cycles contain beds which we interpret as lacustrine turbidites of two types. One series of turbidites, formerly exposed in the Roseland (Riker Hill) quarry, conform to the proximal-to-distal turbidite model developed originally for marine flysche sequences by Allen (1969). The maximum thickness of these Towaco turbidities increases exponentially above the microlaminated siltstones in division 2 of the lower cycle, as might be expected of such a channel approaching a site at a nearly constant rate (Allen, 1969). The slope of the approaching fan would be the source of the slumped beds. In this model, water depth remains constant, but an alternative could involve a decrease in water depth resulting in the encroachment of the shore on the center of the lake. The sense of rotation of the folds in the slumped beds indicates transport from the east; presumably this was the direction from which the channel fan approached. A second series of turbidites is exposed in Towaco cycles near the Ramapo Fault at Bernardsville and Wayne, New Jersey. These are graded beds, 0.5 to 20 m thick, which occur throughout the otherwise microlaminated portions of division 2 and which resemble the turbidites of the Washington Valley member in the New Germantown Syncline. Some of the thicker turbidites are conglomeritic at their base and clearly scour the underlying microlaminated units. The pebbles found in these beds are up to 3 cm in diameter and suggest a source from the west. Thinner sandy turbidites often have casts of tool marks on their lower surface. These turbidites, apart from their clastic composition, resemble units deposited by turbidity currents in meromictic Green Lake, Fayetteville, New York (Ludlam, 1973). These turbidity currents begin along the lake basin margin as slumps, which slide down the basin slope, and liquify as they mix with water.

The picture derived from facies analysis is one compatible with a model of a large perennial stratified lake which was wedge-shaped in cross-section, deepest near the Ramapo Fault, and receiving detritus primarily from the east but with a significant western input at the western lake edge.

Major Depositional Models for Newark Basin Microlaminated Sediments

Numerous authors have for decades interpreted organic-rich microlaminated sediments as having been deposited in a deep-water anoxic environment such as the Black Sea or a stratified lake (Bradley, 1929; David and Ludlam, 1973). Newark Supergroup organic-rich microlaminated sediments have been similarly interpreted (Cornet, Traverse, and McDonald, 1973; Hubert, Reed, and Carey, 1976; Olsen, et al., 1978; Olsen 1980b). Recently, however, the proliferation of information on the sediments of arid environments has led to a new model of deposition for many of these microlaminated sediments; in this model the microlaminated sediments form as living algal mats in very shallow water. There is no doubt that flat agal mat deposits closely resemble microlaminated sediments formed in stratified lakes or seas, especially in box cores or hand samples. Since many of the features explained by the algal mat model are also explained by the deep water mode, we can expect difficulty in deciding which model is applicable to any given deposit. The ambiguity must be resolved for Newark sediments or no further analysis of the microlaminated units and the rest of the sedimentary cycles will be possible.

What specifically are the two models? In the algal mat model, microlaminated sediments are produced by the continuous growth of a surface layer of living algae and bacteria in conjunction with intermittent influxes of allochthonous carbonate or clastic material (Buchheim and Surdam, 1977). The mats form only in very shallow water since the algae must have sufficient light to grow. The laminated sediments thus formed are protected from wave action and scour by the binding action of the algae and bacteria. In the stratified lake model, the laminations are produced by seasonal changes in the kind and amount of fine material settling out of the water column. The laminations are protected by being below wave base and in an oxygen-poor or toxic environment (i.e., an anaerobic hypolimnion) which excludes benthic sediment-burrowing animals. Both models successfully explain the presence of organic-rich microlaminated sediments themselves; differences in corollaries of the models must be sought out or neither model will be useful. Features explained by both models and features unique to corollaries of each model are listed in Table 2.

The algal mat model is based on recent arid environments such as bays and lagoons in Western Australia and the Red Sea (Logan, et al., 1974; Friedman, et al., 1973) and lakes in the Sinai (Cohen, et al., 1977; Krumbein, Cohen and Shilo, 1977), where a diverse suite of algal mat types exist including pinnacle blister, and flat mats. Only flat mats resemble the microlaminated sediments in question; but these occupy only a fraction of the total area in which mats grow. Further, the algal mat zone itself is restricted to a relatively narrow zone in shallow water (1-3m); deeper and shallower water areas have no algal mats. As a lake or bay deepens and shallows, a ring of algal mats presumably expands and contracts as the zone of appropriate water depth migrates laterally. In cross section, the sedimentary record of such an advance and retreat should be a deeper water non-mat unit surrounded in time and space by the laminated algal mat unit which in turn should be surrounded by a non-laminated shallowest water unit (Figure 17) (Krumbein, Cohen, and Shilo, 1977). As a consequence of this pattern, the algal-laminated unit must be fundamentally diachronous and none of the individual laminae, or groups of laminae should be traceable across the unit.

In the case of the stratified lake model, the microlaminated units are deposited in the deepest parts of the water body. The model is based on recent lakes and seas such as Fayettville Green Lake, New York (Ludlam, 1969), Lake Zurich (Nipkow, 1927), and the Dead Sea (Neev and Emergy, 1969). The microlaminated unit expands and contracts with the depth of the lake. In cross section the microlaminated unit should form a central deepest water facies surrounded in time and space by shallower water non-laminated sediments. The unit as a whole should be isochronous and individual laminae should be traceable basin wide and represent true time planes (Figure 17).

Algal mat deposits are uncommon today because they are formed only where grazing by aquatic herbivores is reduced or absent (Golubic, 1973; Friedman, et al., 1973; Logan, et al., 1974) usually due to hypersalinity of high temperatures. An indigenous fish population is essentially excluded, but fish may be washed onto the living mat from less hostile water. To be preserved whole, however, living algae would have to cover these fish before they rotted on the super-oxygenated mat surface or before they floated away because of gas formation. Such a process has never been observed nor does it seem likely, thus algal laminated sediments should not contain abundant whole fish.

In the stratified lake model, however, the same features which lead to the preservation of laminations (i.e. deposition below wave base and exclusion of burrowing organisms) lead to the preservation of whole fish (Shafer, 1972). Fish can be abundant in such water bodies since only the hypolimnion is anoxic. The increased pressure, lowered temperatures, and lack of oxygen in deep water discourage gas formation and flotation of the dead fish (Shafer, 1972). The organic-rich microlaminated sediments produced according to the stratified lake model should contain abundant whole representatives of the indigenous fish populations.

In northern New Jersey (see Stop 1), Olsen, (1980b) has traced a series of microlaminated units over 15 km. These units clearly form the deepest water portion of Lockatong cycles and show every indication of being isochronous. Data are still being collected and studied, but it is apparent that at least some individual laminae can be traced the full extent of the microlaminated unit. There is no sign of associated pinnacle, or blister mat-like structures. The microlaminated units are surrounded above, below, and to the north by non-laminated units. Finally, the microlaminated units contain abundant whole fish while the surrounding non-laminated beds contain disarticulated fish. By these features, the algal mat model may be discounted for these portions of the Lockatong Formation.

Because of the limited areas of Jurassic strata which have escaped erosion (Figure 3) it will never be possible to trace the lacustrine units of the Feltville, Towaco, or Boonton Formations across the Newark Basin. Nonetheless, Towaco cycles have been traced throughout the Watchung Syncline (Olsen, 1980c), and the single thick lacustrine unit in the Feltville Formation (i.e. the Washington Valley Member) has been traced from the southern Watchung Syncline to the Oldwich syncline (Olsen, 1980b and 1980c). Throughout these areas the lacustrine units contain a prominent microlaminated unit. The microlaminated beds in the Feltville, Towaco, and Boonton Formations produce abundant whole fish, thus there is no reason to prefer the algal mat model and good evidence to prefer the deep water lake model for the microlaminated units.

Demonstration that the microlaminated portions of the Lockatong, Feltville, Towaco and Boonton Formations best fit the deep water lake model does not imply that the associated non-microlaminated units were deposited in a deep lake. On the contrary, the presence of reptile footprints, abundant mudcracks, and occasional root zones in beds in the upper parts of some cycles attest to very shallow water deposition: this should not, however, influence the interpretation of microlaminated units just a few meters below. Each characteristic deposit should be interpreted on its own merit and it should never be assumed that any single depositional model should fit such a heterogeneous formation.

The Eocene Green River Formation of Wyoming, Colorado, and Utah is similar in many ways to the Lockatong Formation of the Newark Basin. Both deposits contain cycles of microlaminated, organic-rich beds and non-laminated evaporitic beds. In the Green River Formation the microlaminated units are in many cases rich oil shales of great economic importance. The current very active debate on the environment of deposition of the Green River Formation parallels and inspired the above discussion of Lockatong microlaminated beds.

There is presently no clear consensus on major depositional models for the Green River; some workers (Surdam and Wolfbauer, 1974; Eugster and Hardie, 1975; Buchheim and Surdam, 1977; Buchheim, 1978) adhere to a playa lake model with a subsidiary algal mat origin for the microlaminated oil shale units, while others (Desborough, 1978) adhere to the stratified lake model. We see no reasons why only one of these models should be sufficient for such a complex assemblage of distinctive units as the Green River. As we see it, the playa lake model works best for the microlaminated oil shale units. Non-microlaminated oil shale units need not fit in either model and may be best explained by a model based on Lake Victoria as suggested by Bradley and Beard (1969) and Bradley, 1970).

Major Physical Features of the Lakes Which Produced the Microlaminated Beds in New Basin Lacustrine Cycles

With the algal mat model of deposition excluded from the interpretation of the microlaminated beds of the Newark Basin lacustrine cycles, we can proceed with several more detailed questions: 1) How large in area were Newark Basin lakes during their maximum transgression; 2) How can the minimum depth during maximum lake expansion be estimated; 3) What was the cross-sectional shape of Newark Basin Lakes; 4) What is the periodicity and cause of the lacustrine cycles of the Newark Basin.

The minimum area of Lockatong lakes can be estimated by the area of division 2 of Lockatong detrital cycles. All of the individual detrital cycles studied thus far in the Lockatong of Northern New Jersey (see Stop 1) have been traced from the most southern exposures at Hoboken to the most northern exposures north of the George Washington Bridge (Olsen, 1980b) a total of more than 20 km. Preliminary results from ongoing field work indicate that these same cycles can probably be traced through the entire areal extent of the Lockatong. If so, the minimum area of division 2 of these cycles is near 7000 km^2. The lakes must have been larger than the area of division 2 at their maximum extent and it seems likely some of the largest lakes may have covered the entire exposed extent of the Newark Basin, some 7700 km^2 (Olsen, 1980b).

The areas occupied by the largest Jurassic lakes cannot be approximated the same way as Lockatong lakes because so little of the original extent of the strata are preserved. However, the area over which the microlaminated portion of the Washington Valley Member has been traced suggests a lake which must have been larger than 290km^2 and the area over which Towaco cycles have been traced suggests lakes in excess of 990km^2. We believe that the largest Newark Basin Jurassic lakes may have been much larger in total area than the largest Lockatong Lakes.

Estimating the depth of any ancient water body is speculative and difficult. One trigonometric method of calculating lake depth is to use the distance to shore from the deepest part of the lakes and an angle which describes the average slope of the basin floor. If we assume that the deepest part of the Lockatong lakes was near the geographic center of the Newark Basin (see below), the shortest distance to shore during maximum lake transgression would be in excess of 20 km. If a constant slope toward shore is assumed the minimum lake depth would be 20 km X tan 0, where 0 is the angle of the slope of the lake floor. This relationship is shown in Figure 18. Unfortunately since we have no real way of assessing within several orders of magnitude (i.e. 0.001° to 1.5° seems reasonable) our estimates of lake depth are similarly uncertain. A method which relies more on the character of the sediments themselves would be more useful.

Another, perhaps more reasonable, way to estimate lake depth can be derived from the familiar relationship between lake fetch and depth of wave base (as suggested by Hubert et al., 1978). If we assume that the microlaminated portions of division 2 of Lockatong cycles were deposited below wave base, the minimum extent of these units must approximate the minimum area of the lake over which non-depth-limited waves could be propagated by winds blowing over the lake surface. The major and minor axes of an elipse defined by the extent of the microlaminated units in the Lockatong Formation (Figure 19) can be used as minimum estimates of the greatest fetches for winds blowing along the axis of the Newark Basin or across the Newark Basin. In this case these two fetches are 170 and 40 km. There is an empirical relationship between wind speed, fetch and wave length (Bretscheider, 1952; Smith and Sinclair, 1972) given by the equation (from Smith and Sinclair, 1972, p. 389):

$$g\ T/w = 0.46\ (g\ F/w^{2})^{0.28}$$

Here g is acceleration by gravity (9.8 m/sec^{2}), T is wave period, w is wind speed in m/sec, and F is fetch in m. since for deep water, wavelength (λ) is equal to 1.56 T^{2} amd wave base is approximated by $\lambda/2$, the relationship can be restated in terms of depth of wave base as follows:

$$\lambda/2 = 0.0062\ w^{0.88}F^{0.56}$$

To use this equation to estimate the depths of Lockatong Lakes we would need to know the greatest wind speed which blew over Lockatong Lakes during the deposition of the microlaminated beds--a fact we will never know. Nonetheless, it seems reasonable to assume that there were winds in the Triassic, even strong winds; as the Triassic dune sands described by Hubert and Mertz (1980) attest. The relationship between depth of wave base for fetches of 170 and 40 km and a range of plausible wind speeds is given in Figure 20. It seems likely that gale force winds (ca. 20m/sec) were occasionally funneled down the axis of Lockatong Lakes during the several thousand years or more it took to deposit each microlaminated bed, just as powerful winds are funneled down the length of the African Rift Valley Lakes today; Lake Tanganyika is often mixed to a depth of 100 to 200 m by winds (Beadle, 1974). These assumptions seem robust; if so, Lockatong Lakes were probably a minimum of 40 to 90 meters deep during their high stands. No doubt even more powerful winds blew over the surface of Lockatong Lakes, and we believe that these estimates are low minimums.

Some information on the cross-sectional shape of Newark Basin lakes can be gained from variations in the thicknesses of lacustrine units over the basin. If we assume that fine sediments reaching the Lockatong Lakes were preferentially distributed to the deepest parts of the lake, the area in which Lockatong cycles are thickest represent the deepest part of the lakes and the depositional center of the Newark Basin during Lockatong deposition. The thickest Lockatong cycles are found in the geographic center of the Newark Basin in the Hunterdon Plateau Fault Block (see Stop 5, Sunday). In this area the mean thickness of Lockatong cycles is

4.2 m (Van Houten, 1964, 1969, 1980) while around the edges of the basin the mean thickness of cycles decreases to 2 to 1.5 m (Olsen, 1980b). The area where Lockatong cycles are thickest also corresponds to the area where chemical cycles are most abundant (Van Houten, 1964). In fact, outside of this central area, most chemical cycles are replaced by red beds identical to typical red beds of the Passaic Formation. The cross-sectional shape of Lockatong lakes during their maximum extent, can thus be inferred to have been a gentle dish, perhaps best approximated by a very flat trapezoid. Of course this assumes that Lockatong lakes ended somewhere near the current limits of the Newark Basin. If lake level rose so that lake waters lapped against the bordering highlands, the cross-sectional shape of the lakes could have approached a steep sided trapezoid or a rectangle. The apparent termination of microlaminated siltstones of Lockatong cycles within the basin (notably at the northeastern and southwestern ends) and the replacement of these microlaminated units laterally by non-laminated siltstones and finally by gray and buff arkose and sandstone, suggests that the shores of Lockatong Lakes may indeed have approximated the presently preserved edges of the Newark Basin. The shallower cross section, therefore, seems more likely.

Towaco cycles and the Washington Valley Member of the Feltville Formation show a pattern of thicknesses completely different from the Lockatong, and from this we infer a different cross-sectional shape for these ancient lakes. In both the Towaco and the Feltville Formations, microlaminated units are an order of magnitude thicker along the northwestern edge of the Newark Basin than along their easternmost outcrops. In some areas along the Newark Basin's northwestern edge the microlaminated units slice through thick conglomerate beds and show no sign of ending within .5 km of the Ramapo Fault (Olsen, 1980b). In these same areas the microlaminated beds themselves contain thin graded conglomerate beds which we interpret as lacustrine turbidites. These features suggest that Towaco and Feltville lakes were markedly asymmetrical with their deepest portions near the northwestern margin of the basin. During maximum transgression these lakes may well have lapped well up the scarps at the basin's edge.

Van Houten (1962, 1964, 1969, 1980) has estimated the duration of Lockatong cycles by assuming that the microlaminated units of division 2 are varved, and extrapolating the rates of sedimentation derived from varve thickness counts to the entire cycles. His counts, based on the cycles in the center of the Newark Basin, suggest a periodicity of about 20,000 years. As noted by Van Houten this suggests control of the depth of Lockatong lakes by precipitation in turn governed by the precession of the equinoxes. New data on varve counts (Olsen, 1980b) support Van Houten's data for the central Newark Basin. Where the cycles thin to a mean of 1.5 meters, as at Weehawken, much shorter durations for each cycles are indicated, on the order of 5,000 to 10,000 years. This presumably indicates significant bypassing or erosion in the marginal areas (Olsen, 1980b).

Cycles nearly identical to Lockatong detrital cycles occur in the contemporaneous upper member of the Cow Branch Formation of the Dan River Group. Floral remains from these cycles suggest changes in climate during the expansion and contraction of the lakes which produced the cycles (Olsen, et al., 1978). Floral remains are much less common in Lockatong cycles but studies of spores and pollen are now underway by one of us (Olsen).

As Van Houten (1962, 1964, 1969, 1980) has described, Lockatong cycles are arranged into higher order cycles in the Newark Basin. Clusters of detrital cycles and of chemical cycles occur at about 25 m intervals. Very thick clusters of chemical cycles occur at 100 m intervals and this corresponds to the thickness periodicity of the alternations of red and gray units higher in the Passaic Formation. It is interesting that each set of a cluster of detrital cycles plus the succeeding cluster of chemical cycles contains from five to six cycles; at 20,000 years per cycle this gives an average of 100,000 to 120,000 years for each 25 m larger cycle. Of course 100,000 years is the principle periodicity of the glacial-interglacial cycles of the Pleistocene (Hays, Imbrie, and Shackleton, 1976), and finding an obvious periodicity of similar magnitude in the Lockatong Formation is very suggestive. The largest cycles of about 100 m have a calculated periodicity of about 44, 000 years Van Houten (1964). Cycles of this periodicity are the most obvious in the Passaic Formation and they comprise the gray and red units mapped by McLaughlin (1946) throughout the Hunterdone Plateau Fault Block.

Ponding by lava flows has been suggested to account for the lacustrine units of the Jurassic strata of the Newark Supergroup (Krynine, 1947). It is not necessary to invoke this mechanism for the Newark Basin since strata far below the extrusive units contain extensive lake deposits. Lacustrine units of the Feltville, Towaco, and Boonton Formations most likely developed because of increased precipitation, although the closure of the basin drainage system and the cross-sectional shape of the lakes were certainly controlled by basin tectonics which in turn was under the same control as the volcanism.

The duration of Towaco cycles cannot be estimated the same way as the duration of Lockatong cycles since the upper parts of Towaco cycles are very much coarser and individual units show extensive downcutting making extrapolation of varve counts to the whole cycle unreasonable. If, however, Towaco cycles were of the same duration as Lockatong cycles, deposition of the Towaco Formation proceeded at roughly 6.7 times that of the Lockatong, that is at an average rate of 1.5 mm/yr.

Notes on Ecological Dynamics in Newark Basin Lakes

Obvious changes in total organic carbon content follow the microscopic textural and bedding features and fossil content in Newark Basin lacustrine sequences. These are easily seen in the color of non-metamorphosed rocks; the few analyses done so far indicate the following rough association of color and carbon content--red (0%), gray (0.5%), black (.508%). Thus sedimentary cycles such as those in the Lockatong show correlated cycles in total organic carbon. Many authors have considered the amount of organic carbon in sediments to be a good reflection of the productivity of the lake ecosystem (Hutchinson and Wollack; 1940; Deevey, 1942; Lindeman, 1942). A consideration of the large scale energy dynamics of lakes shows total organic carbon content of sediments can be deceptive as an indicator of primary production but it also reveals some fundamental relationships between a lake's ecological history, the production of organic sediments, and ultimate hydrocarbon production. The cycles in organic carbon seen in Newark Basin lacustrine sequences can probably be better understood in terms of changing energy dynamics than simply as a record of changing primary productivity.

The source of virtually all usable energy in ecosystems is primary production by plants. In large lakes the bulk of usable energy comes from photosynthesis within the lake. Photosynthetic plants fix carbon, and this reduced carbon is the source of energy for all other organisms in the lake (chemosynthetic bacteria are here considered to be ultimately dependent on compounds resulting from photosynthesis--Cole, 1979). Consumer and decomposer organisms oxidize the reduced carbon and thus obtain energy.

Obviously, organic carbon in sediments has its origin in primary production. In lakes, the organic carbon locked in sediments represents a net loss of energy from the lacustrine ecosystem. This relationship is what suggests reading carbon content as a record of productivity. But the loss to the sediments depends on what proportion of the energy of primary production is dissipated by the living ecosystem.

The ratio of dissipation (by respiration) of reduced carbon by all the organisms of an ecosystem (Rs_E) to the gross productivity of reduced carbon of the ecosystem (GP) (times 100) we can loosely term the ecosystem efficiency:

($\underline{Rs_E}$/GP) 100 = ecosystem efficiency

This concept is suggested by Lindeman's (1942) development of the concept of ecological efficiency carried to the ecosystem level and Wetzel's (1975) emphasis on the role of detritus. The difference between the rate of production of reduced carbon by the ecosystem and the rate of loss by respiration is equal to the net ecosystem productivity (NEP) and it is this last quantity of carbon which can be preserved in the sediments.

In a perfectly efficient ecosystem all of the energy captured by photosynthesis would be dissipated by the rest of the organisms of the ecosystem as CO_2 and heat (Rs_E = GP and $\underline{Rs_E}$ x 100 = 100%); there will be no "waste." If this perfect system were a lake there would be no accumulation of organic material in the sediments (i.e. GP Rs_E = NEP = 0). Of course real ecosystems must be less efficient than this. This concept of ecosystem efficiency emphasizes that two equally important factors (GP and Rs_E) contribute to the sedimentary record of an ecosystem such as a lake, and that the ratio of these two terms need not be constant.

A demonstration of the crucial role of ecosystem efficiency is given by a comparison of a tropical forest and a north temperate bog. The well-drained soils of tropical forests are often very poor in organic material; the sedimentary record of such a forest soil might plausibly be a series of red beds riddled with rootcasts, much like portions of the Passaic Formation. The bog on the other hand, has a waterlogged soil composed almost entirely of the remains of dead plants. The sedimentary record of this soil might be a peat or coal. If sediment carbon content were "read" as a literal record of productivity, the peat or coal would be interpreted as the product of an ecosystem much more productive than that which produced the red beds. This interpretation would be wrong; tropical forests are among the most productive ecosystems on earth while north temperate bogs are among the least. The important difference lies in the high rate at which the well-drained tropical soil recycles plant debris, and other dead organisms. The bog, on the other hand, recycles at a low rate, tending instead to preserve organic material. In this case the ecosystem efficiency of the tropical forest is many times that of the bog.

Similarly there is no reason to postulate unusually high levels of primary production in the Carboniferous to account for the abundant coal. Production levels could have been lower than modern environments if ecosystem efficiency was lower. The decrease in frequency of coals above the Carboniferous might well be due to the evolution of soil organisms which increased the rate at which organic matter was dissipated.

There are three interrelated controls on lacustrine ecosystem efficiency: 1) actual gross primary productivity; 2) extrinsic physical factors such as basin morphology, water depth, salinity, and wind conditions; and 3) the diversity, abundance, and nature of consumers and decomposers. As detailed below all three of these factors play roles in determining both differences between lakes and changes in lakes through time.

Cultural eutrophication of lakes is a process in which nutrients added by man, usually in the form of sewage, industrial waste, or agricultural runoff, increase lacustrine primary productivity often with undesirable consequences (Hutchinson, 1969). Primary production usually increases to a point where it exceeds the rate at which it can be balanced by aerobic consumption and decomposition. A surplus of organic material builds up which can exhaust the oxygen at depth; anaerobic decomposition then becomes dominant at the lake bottom. Anaerobic decomposition occurs at a slower rate than aerobic (Wetzel, 1975; Cole, 1979) and energy rich organic material accumulates at an even faster rate. The process of eutrophication thus lowers ecosystem efficiency (Lindeman, 1942).

Physical Factors

Studies of two lakes in Michigan by Newcombe and Slater (1950) and Cole (1954) point up the role of physical factors, in this case water depth, in otherwise similar lakes (Cole, 1979). In the deeper lake a permanently anoxic hypolimnion is present and thus a larger proportion of organic material undergoes anaerobic decomposition with presumably a correspondingly lowered ecosystem efficiency.

The Kind of Organisms Present

Today, tubificid worms and chironomid fly larvae act to transport material across an oxygen gradient at the sediment-water interface (David, 1974) in highly productive lakes with low oxygen concentrations at the bottom. By irrigating sediments with water which is relatively more oxygenated they increase the rate at which organic material is metabolized. Essentially, they mine the sediment under conditions where nothing else can, and in the process they increase the ecosystem efficiency. There are very few reasons, however, for thinking that these groups were present in the Triassic. If these organisms were absent from those ancient lakes, with no replacements, a given level of primary production could be associated with a lower ecosystem efficiency and hence a larger proportion of gross production would end up in the sediments. The degree of bioturbation of lake sediments is thus an indirect measure of lacustrine efficiency; organic rich microlaminated sediments showing no signs of bioturbation indicate low ecosystem efficiency while bioturbuted sediments indicate higher efficiency.

In the stratified lake model of the production of microlaminated sediments, bioturbating organisms are excluded by the perennial presence of an anoxic hypolimnion (Bradley, 1929; Twenhofel, 1932; David and Ludlam, 1973; Cornet, Traverse, and McDonald, 1973; Olsen, Cornet, Remington, and Thomson, 1977; Olsen, 1980b and Wilson, 1980). If, however, such organisms as tubificids and chrinomids were absent in the distant past, many lakes with low ecosystem efficiency but without a perennial hypolimnion, could produce microlaminated sediments (Olsen, 1980b).

Shallow lakes can be just as productive as deep lakes if not more so (Cole, 1979; Beadle, 1974; and Wetzel, 1975), and there are no reasons for supposing that the shallower lakes which deposited division 3 of Lockatong cycles, or the terrestrial and fluvial systems which deposited division 4 of Towaco cycles were any less productive than the lakes which deposited division 2 of the same cycles. The change in carbon content through these sedimentary cycles probably reflects changing ecosystem efficiency through time as the lake changed in depth (see Figure 32).

There are three factors of possible importance not considered in the above discussion: 1) loss of reduced carbon by abiotic oxidation in the water column, in the sediments during deposition, and as part of later diagenesis; 2) addition of allochthonous carbon and direct outflow of reduced carbon, both as particulate and dissolved matter but not including that part lost into the sediments; and 3) migration of reduced carbon compounds into and out of the sediments after deposition. The first of these, abiotic oxidation, seems to be inconsequential in most lake systems compared to the magnitude of loss by biological processes (Wetzel, 1975). Allochthonous imports and direct outflow can be very important in small or very shallow lakes (Wetzel, 1975) but these factors are presumably of less importance in large lakes. Carbon compound migration is of great importance to geologists and palaeoecologists for it distorts our ability to read the record of carbon losses to the sediment. It is also the process of hydrocarbon migration. The search for the origin of hydrocarbon source rocks must therefore concentrate not only on environments of originally high primary production, but also environments of low ecosystem efficiency.

Newark Supergroup deposits, in general tend to have thicker accumulations of organic rich sediments in the more southern basins (Olsen, McCune, and Thomson, In Press; Hubert and Mertz, 1980; Cornet, 1977). Several Basins south of the Fundy Group contain very thick (500-2000 m) sequences of organic-rich sediments that can plausibly be regarded as hydrocarbon source rocks. These deposits represent the accumulated net loss of energy from periodically cycling lacustrine ecosystems. Many of the sequences show resemblances both in fossil content and facies patterns to the Eocene Green River Formation. A major difference, however, is that most, if not all, Newark Supergroup sequences have been buried to a depth of from 1000 to 6000 m and thus hydrocarbon migration has already occurred (Hunt, 1979). Indeed, few Newark Supergroup deposits contain beds that could be considered oil shales; most of the organic-rich sediments are too mature. But, are there reservoir facies and suitable traps? Certainly the prevailing monoclinal nature of most Newark Supergroup strata is not encouraging. However, Newark facies relationships and structure are complex, and Newark Supergroup strata should not be overlooked in the search for hydrocarbons.

Finally, we know virtually nothing about the offshore Newark Supergroup equivalents. If they are similar to the onshore souther basins they may contain large volumes of suitable source rocks perhaps in favorable migration and accumulation settings. However, as long as they are thought of as "barren Triassic red bed sequences" we will never know.

ROAD LOG (Saturday)

Mileage

0.0 Rutgers University, Newark, New Jersey.

Left turn onto Warren Street, leaving University parking lot.

0.1 Left turn onto Washington Street.

0.5 Turn left onto Broad Street.

0.8 Right turn onto ramp leading to N.J. 58E and interstate 280E.

3.1 Bear left, taking N.J. Turnpike North towards G.W. Bridge.

4.9 Snake Hill, a Triassic volcanic neck, appears to the east.

5.0 The low-lying cliff to the west is the site of the historic Schuyler Copper Mine, where copper was initially discovered in 1712 or 1713, and mined in 1739. The cupriferous minerals at the mine are chalcocite, chrysocolla, minor amounts of malachite and azurite, and rare particles of cuprite and native copper. Chalcocite is the only potential ore mineral. The origin of the ore is explained by hydrothermal solutions that accompanied the intrusion of small diabase dikes (probably Jurassic) found below the ore body. While the mine has had a long history, it has produced little since the Revolutionary War (see H.P. Woodward, 1944, for an enlightening account of copper mining in New Jersey).

5.1 Hackensack Meadowlands. Agron (1980) reports that this region was covered by at least three glacial advances in the Pleistocene. About 15,000 years ago, the entire region was submerged by proglacial Lake Hackensack, which was impounded behind the terminal moraine to the south. About 10,000 years ago the terminal moraine was breached, and the lake was drained into the Atlantic. During the time the lake existed more than 200 feet of varved clays were deposited. Over 2,500 varves have been counted from this horizon. About 3,000 to 5,000 years ago, rising sea level accompanying the melting of the ice sheets exposed the river to the tides. Estuarine conditions extend north into the Hackensack River Valley, producing the salt marsh environment that has existed into the present.

The Meadowlands is one of the most intensely used land areas in the world. As we travel across the region for the next 11 miles, we will observe the diverse utilization of the land in the form of high-rise condominiums, town houses, sanitary landfills, industrial and recreational parks, the Sports Complex, marinas, Liquid Natural Gas Storage Facilities, Sewage Treatment Plant, generating plant, and so forth (see Agron, 1980).

5.3 Sanitary landfill to the west.

7.6 Harmon Cove Development, Hartz Mountain Industries with high-rise apartments, town houses, marinas, etc.

9.0 New Jersey Complex with race track, Giant's Stadium, etc.

9.5 Two LNG storage tanks to the northeast.

10.0 View of the backslope of the Palisade Sill to the east.

11.0 Granton Quarry, exposes the lower Lockatong Formation and the overlying sill (see Van Houten, 1969; Olsen, 1980).

12.5 Bergen Generating Station, P.S.E.& G. Co. to the west; Bergen County Sewage Treatment Plant to the east.

16.0 Crossing the Hackensack River.

16.2 Climbing the backslope of the Palisades Sill.

16.5 Palisades Sill in contact with the Lockatong hornfels in roadcut.

17.7 Bear right, exiting at "last exit in New Jersey"; continue east on Bridge Plaza Square Road.

18.2 Right turn at "T" intersection onto Hudson Terrace.

18.4 Stop sign; continue traveling south on River Road.

18.5 Left turn into the entrance of the Palisades Interstate Park. Follow park road around to north. A significant portion of a large phytosaur skeleton was found in upper Stockton beds near here in 1911. The skeleton, named <u>Rutiodon manhattanensis</u> by Friedrich von Huene is not really generically determinate because it lacks a skull. It is now on display at the American Museum of Natural History in New York.

Reentrant in Palisade escarpment at this point is due to a few east dipping normal faults.

18.6 Olivine zone of palisade Sill on left. Diabase on left has a distinct finely laminated appearance.

19.0 Irregular contact of Palisade Sill with Lockatong Formation on left (Figure 21).

19.1 Pass under George Washington Bridge.

19.2 Additional exposures of the contact between the Lockatong Formation and the Palisades Sill. Here the contact is conformable. On the right, at the base of the hill, is a footpath along which there are good exposures of buff arkose and red and purple siltstones of the upper Stockton Formation.

Circle in park road at base of shear face of Palisades Sill. Take road which veers off on right towards Ross Dock.

<u>STOP 1.</u> Ross Dock, palisade Interstate Park. Extensive exposures of detrital cycles of Lockatong Formation and irregular lower contact of Palisade Sill.

Park in lot then walk up stone steps up the hill (west) to the road at the level of the circle (River road in Park) and walk north along road to exposures of the Lockatong (Figure 22).

Proceed north along road walking slowly down section. All ten of the detrital cycles exposed here (Figures 22 and 23) have been traced more than 15 km to the south (Olsen, 1980b). These cycles are informally designated 0, 1', 1, 2, 3, 4, 5, 6, and a, b, c. Cycles 1', 1, 2, 5 and 6 contain beds which are prominantly microlaminated. Cycles a, b, and c are not microlaminated here but become so in the exposures further south (Olsen, 1980b). Cycles 2, 5 and 6 contain numerous fossil fish (see Figures), and cycle has produced scattered remains of the little lizard-like reptile Tanytrachelos (Figure 24). At Kings Bluff, 15 km south a team of Yale paleontologists opened a quarry in cycles 5 and 6 and recovered over 4,000 fish and reptile skeletons in the years 1978-81. At these more southern outcrops the fossil fish are more abundant and tend to be better articulated than to the north. The gradual facies changes from Kings Bluff to the George Washington Bridge in cycles 5 and 6 are show in Figure (25). Note decreasing frequency in the presence of articulated reptiles and fish. The detailed differences in lithology and faunal content allow for relatively easy cycle-by-cycle correlation.

At these exposures, cycles 3 and 4 have been replaced by buff, cross-bedded arkose and the upper parts of cycles 5 and 6 have developed calcareous and nodular beds resembling caliche. A thick bed of arkose cuts down into cycle a, nearly cutting it out. The mean paleocurrent direction for these arkose beds is N 59° W (based on 8 readings).

Cycle a is penetrated by numerous burrows called Scoyenia. Scoyenia type burrows are extremely abundant in Triassic Newark Basin strata and seem to be the work of a small arthropod, perhaps a crayfish (Olsen, 1977). These Scoyenia burrows are not present in this same cycle to the south. We are clearly in the shallow water facies of cycles a–c at this point but only just leaving the deep water facies of division 2 in cycles 2, 5, and 6. Cycle a shows a well developed facture cleavage in division 1. Cleavage dips 25° to 30° W and strikes S 78° W. The cleavage is strata-bound but discontinuous, passing laterally into breccia or non-cleaved beds. What is the significance of these structures?

The facies trend in the Lockatong from Kings Bluff to this stop is from a more central basin facies to a more marginal facies. The monotony in horizontal continuity in detrital cycles gives way laterally to heterogeneity (Figure 25). Those cycles with the best developed microlaminated units and the best preserved fish in division 2 are those which persist the longest with the least change to the north.

Note that the horizontal distribution and faunal content of the microlaminated portions of division 2 of cycles 2, 5, and 6 are incompatible with an algal mat origin.

20.9 Return to park entrance. Leave park and turn right.

21.0 Turn left onto Main Street (Bergen County Route 11), proceed west.

21.5 Turn right onto Lemoine Avenue, continue north crossing over west portal George Washington Bridge.

21.8 Turn left (west) onto Cross Street. Keep left.

23.2 Veer left onto entrance ramp for Route 95-80. Proceed on Route 95 S.

24.2 Open cut in Palisades Sill and Lockatong hornfels. According to Van Houten (1969), hornfels include grossularite-andradite, prehnite, and diopside varieties. The Lockatong cycles are fossiliferous, as usual, and may tie in with Granton Quarry cycles.

24.8 Veer right onto exit for Route 80.

25.3 Beginning of type section of Passaic Formation.

33.0 Garrett Mountain visible on left (south), Passaic Falls is on the right (north). The upper Passaic Formation of Rhaetic age (latest Triassic) has produced near here a series of well preserved skeletons of the highly specialized procolophonid reptile Hypsognathus (Colbert, 1946). About one skeleton or skull is found per decade.

33.7 Contact of Passaic Formation with overlying Orange Mountain Basalt on left (south). Columnar basalts of the lower flow unit are well exposed in the roadcut. A series of faults cut the Orange Mountain Basalt here, some of which are visible in the cut on the left, just west of the Passaic-Orange Mountain Basalt contact. Triassic-Jurassic boundary is somewhere within a few meters below contact.

34.0 Beginning of the upper flow unit with its characteristic ropy pahohoe-pillowed surface.

34.2 Transverse cross-section of subaqueous flow lobes. Note the arcurate pattern of the pillow lava complex. These structures will be examined in the lower and upper New Street Quarries at Stop 2.

34.5 Exit at Squirrel Woods Road, bearing left at exit.

34.6 Bear left at road signs onto Route 80 overpass. (Do not enter Route 80).

34.8 Left turn into New Jersey Bank parking lot. Drive east through the lot, exiting on New Street.

35.5 Left turn onto New Street. Park in the Richardson parking lot.

STOP 2. Orange Mountain Basalt: Upper Flow Unit, New Street Quarry.

Our objective at this stop is to examine subaqueous volcanic structures including: pillow lavas, flow lobes, fissure eruptions, a volcanic cone (?), and zeolite mineralization. Caution should be exercised in the quarry and participants should not climb the upper quarry walls.

The walls of this quarry and an adjacent quarry, long favorites of mineral collectors for their beautiful and diversified suite of zeolites, also exhibit a splendid array of subaqueous volcanic structures (see Figure 8). Participants should first examine the structures of the east (or far) wall, noting the amygdaloidal and vesicular upper contact of the lower flow unit and the overlying Tomkeieff sequence, which is overlain by bedded pillow lavas and a second Tomkeieff sequence. Note also spiracles in the lower colonnade and cross-sections of polygonal-joint sets of the entablature. Follow the structures along the south wall, walking west, and note the increase in pillow lavas with a concomitant decrease in massive basalt. On the west wall we may observe the characteristic concave-downward arcuate form of overlapping flow lobes in transverse section. Pinching and swelling pillow buds elongated N-S in arcuate bundles distinguish the flow lobes from the overlying bedded pillows which appear to be stacked one on the other and elongated E-W.

Although the contact between the two types of pillows appears to be comformable, the absence of the eroded pillows along the contact indicates that they are conformable. Note the manner in which the younger pillows cascade off the flow lobe, building up slopes of about 40°. In general, the pillow buds are very dense with radial joint structures and few minute vesicles, indicating that they formed in deep water. The absence of pillow-derived debris within the interstices of pillow complexes indicates that the debris was washed out of these pockets in a well-agitated lake. The occurrence of interstitial angular basaltic fragments (surrounded with quartz, calcite, prehnite and other zeolites) indicates that the fragments were derived from the checkered exterior rinds of the pillows by circulating fluids, perhaps ground water. The original debris was probably redeposited in a deeper part of the basin, along the border fault. The flow lobe appears to flare out and to plunge westward, where it may be studied in the walls of the lower New Street Quarry. At some appropriate time we shall enter that quarry as a group. Figure 9, a field sketch of its east wall, shows three distinct episodes of vulcanism:
(1) an older episode of flow lobe:
(2) a medial phase of massively bedded, moderately coarse-grained igneous rock that slopes away from a central point and overlaps the distal and advancing end of a flow lobe; and (3) a younger zone of bedded pillow buds that overlie both the steep slope of the subaqueous volcano (?) and the flow lobe. The origin of these features should encourage a lively discussion.

35.5 Turn right leaving the parking lot.

35.6 Turn right into New Jersey Bank parking lot. Drive west through the lot exiting onto Squirrel Wood Road.

36.1 Turn right out of Bank lot on Squirrel Wood Road.

36. Turn right into Route 80 E; note the pillow lavas in the roadcut.

37.0 Exit onto Route 20 South towards the Garden State Parkway

39.0 Bear left, entering the Garden State Parkway.

48.5 Exit the Garden State Parkway at exit 145, taking Interstate 280 East towards Newark.

50.2 Exit in Newark, making a left turn at "T" intersection.

50.3 Left turn at light.

50.4 Enter Interstate 280 West.

50.6 Alternating beds of red sandstone and mudstone with a few thin interbeds of gray siltstone and dark gray to black micaceous shale, occurring below the first overpass. These siltstones yield a probable Upper Norian palynoflora and occur about 1100 m below the First Watchung Mountain Basalt (Cornet and Traverse, 1975, p. 27). Sporadic exposures of sandstones and mudstones with fining-upward sequences, characteristic of meandering streams, occur along Interstate 280 for the next 4.4 miles.

51.3 Bear right for the Garden State Parkway.

51.5 Park in service lane approaching East Orange, Exit, and walk west to outcrop in exit ramp.

STOP 3. Passaic Formation: Central Basin Facies

Figure 26, a stratigraphic section of this stop, shows characteristics of the fining-upward sequence, namely: cut-and-fill channels, channel lag concentrates, cross-bedded arkosic sandstones, overbank deposits of reddish-brown mudstone with calcrete paleosols, gray-green to green shales with plant fragments, Scoyenia, roots, (?) and copper mineralization (chrysocolla and malachite.) Petrographic and paleoccurent studies along this highway, and elsewhere in this stratigraphic horizon, indicate that the sediment was derived from a deeply weathered metamorphic terrane to the north and east, and transported to the basin across a broad southwest-sloping pediment.

51.5 Continue on I 280 westbound

54.2 Dike intrusion and offset into fluvial channel sandstones of the upper Passaic Formation.

54.5 Cuts in uppermost Passaic Formation here have produced phytosaur footprints called Apatopus and the possible crocodilio-morph tracks called Bactrachopus. The Triassic-Jurassic boundary lies somewhere within the upper few tens of meters of the Passaic Formation here.

55.0 STOP 4. Orange Mountain Basalt; lower flow unit. Our objective here is to examine a Tomkeieff sequence of colonnades and entablatures near the classical site of O'Rourke's Quarry.

When built in 1969, this road cut was the deepest federally-financed highway cut east of the Mississippi River. About 33 m deep, the cut exposes a complete section of the lower flow unit of the Orange Mountain Basalt, and a broad array of joint patterns that formed as the basalt cooled. The large "basin" structure on the southeast wall was first described about 100 years ago by J.P. Iddings (1886) of the U.S. Geological Survey in John O'Rourke's Quarry, about 300 m south of the roadcut. While such complete structures have not been observed elsewhere in the Watchungs, similar joint structures, e.g. chevrons, oblique and reverse fans and rosettes (terminology of Spry, 1962) may be studied in this roadcut and in almost every quarry along strike for a distance of 80 to 100 km.

This structure (about 33 m thick) conformably overlies a fluvial red bed sequence of shales and sandstones and, when first exposed, displayed a complete Tomkeieff sequence of: (1) a lower colonnade (10-15); (2) entablatures (20-30m); and (3) an upper colonnade (1-2 m) (Fig. 17). While the lower colonnade is composed of massive 4-5 or 6-sided polygonal and subvertical prisms, the entablature is composed of long (25-30 m) slender narrow joint prisms that radiate from an apparent focus. Several juxtaposed bundles or sheafs of radiating prisms may be observed in the roadcut, comprising fan and chevron-like features. Cross joints, intersecting radiating prisms at high angles, are prominent and appear to be concentrically arranged about the apex of radiation. An incomplete section of pseudo-columns overlie the entablature.

Petrographic studies (Figure 11) show an increase in grain size, an increase in the abundance and size of the interstitial glass, and an increase in the olivine content in the entablature. This suggests that although cooling may have proceeded very slowly from the sediment-volcanic interface, once a groundmass capable of transmitting stress was established the remaining melt cooled almost instantly. The obscure joint pattern in the upper colonnade may form from convective heat loss near the upper part of the flow. The early cooling history of the magma is manifested by well-developed horizontal striations observed on the joint surfaces of the lower colonnade. While Iddings (1886) may have been the first to report horizontal striations on joint surfaces (from O'Rourke's quarry), James (1920) speculated that these striations represent successive stages or pulses in which the rock broke and the columns formed. Recent studies by Ryan and Sammis (1978), and Justus and others (1978) at this site show that the striations are records of discrete thermal events, characterized by sudden periods of crack advance in the cooling basalt. Features such as chisel marks, pinch and swell and kink structures on the curvi-columnar joints may also represent an episodal cooling history. Each of these features may be observed on the walls of the highway cut.

The striations reported by Iddings (1886) show up on joint surfaces of the lower colonnade as cyclical bands of smooth and rough zones, about every 5-7 cm. Ryand and Sammis (1978) report that as the crack growth proceeds, the first formed zone is smooth and associated with a thermal shock event; the second zone is rough, has positive relief, and is associated with the halting of each crack advance. Joints of the entablature are also cut by concave-upward "dish-like" joints that are cut by strike-slip faults. While the origin of this structure is debatable it trends N 50° E and evidently formed after the basalt cooled and before faulting occurred.

55.7 Backslope of the first Wachung lava flow; outlines of pahoehoe toes may be studied in roadcut.

56.7 Contact of the Second Watchung lava flow with the underlying Feltville Formation. Note the fine-textured joints of the entablature, and the large number of strike-slip (left-lateral) faults with little or no dip-slip offset. When exposed, during road construction, the formation consisted of cross-bedded feldspathic sandstone (10m) underlain by thin stringers of coal with underclay. A similar section may be studied in the parking lot of the Daughters of Israel Nursing Home, 1155 Pleasant Valley Way, West Orange (about 3/4 mile south).

57.4 Backslope of the Second Watchung

lava flow. Coarse-grained diabasic texture may be examined near upper part of the exposure.

59.0 Looking west across the Passaic River Valley you can observe the low hills of the Third Watchung lavas, the New Jersey Highlands on the horizon, and the lake bed of Glacial Lake Passaic. The lake formed when the meltwaters of the Wisconsin Glacier became empounded between the N.J. Highlands on the west, the Second Watchungs to the east and south, and the moraine to the south. At its maximum extent, the lake was 30 miles long, 10 miles wide and 240 feet deep (Kummel, 1940).

60.0 Exit I 280 at Eisenhower Parkway South. Continue south on the Parkway.

61.1 Excellent exposures on left (east) of contact between Towaco Formation and Hook Mountain Basalt in Nob Hill Apartment Complex (former east half of Roseland Riker Hill Quarry). Two flows of Hook Mountain Basalt visible here (cumulative thickness 110 m).

61.4 Turn left onto Beaufort Avenue. Take Beaufort Avenue south following along the back slope of Riker Hill.

61.8 Turn left into entrance road for Riker Hill Park of Essex County Department of Parks, Recreation, and Cultural Affairs (former Essex County Park Commission). Follow road up dip slope of Hook Mountain Basalt. Follow signs to Geology Museum.

62.2 <u>STOP 5.</u> Geology Museum and Walter Kidde Dinosaur Park (former west side Roseland Riker Hill Quarry). Park in lot and look over exhibits at Geology Museum. Then take access path from Geology Museum over the crest of Riker Hill and down, through wooded area into Dinosaur Park. Always get permission before entering park.

As it stood in 1975, the Roseland Quarry occupied 55 acres, exposed 95 m of upper Towaco Formation--including two complete Towaco cycles, and exposed about 50 m of the overlying Hook Mountain Basalt (Figure 27). The quarry became very well known in the late 1960's and early 1970's for its prolific dinosaur footprints. Because of the scientific and educational potential of the site the then owners, Walter Kidde and Co., Inc. donated the most productive 15 acres to the Essex County Park Commission. The site now awaits development.

Before the other 40 acres were developed as the Nob Hill development, the following features could be seen:

1, lateral changes in facies within division 1-3 of the lower cycle (Figure 28). The microlaminated beds of division 2 produced many fossil fish, all <u>Semionotus</u>, as did a number of the thinner (30 cm) turbidites.

2, two upwards coarsening turbidite sequences, the lower being by far the larger. The lower sequence shows large scale slumped beds resembling "wild flysche" associations. Some of the "roll over" structures are 2 to 3 m in diameter. Transport was from the east.

3, abundant dinosaur footprints in possible crevasse splay (in division 3) of channels about 70 m to north of tracks. Orientation of trackways proved to be parallel to paleocurrent directions derived from ripple marks within the footprint-bearing bed and oriented plant debris in overlying beds.

4, Series of 7 fining-upwards cycles of division 4 of the lower Towaco cycle in the Quarry. Middle 3 cycles had extensively developed dolomitic nodules and deeply mudcracked beds. Second fining-upwards cycle from the bottom with laminated silty beds (? flood basin) with abundant clay filled root casts, many of which are surrounded by dolomitic nodules.

In the presently exposed beds the following can be seen:

1, uppermost fining-upwards cycle of lower Towaco cycle still exposed along eastern boundary of park. The upper and middle parts of this cycle have the best reptile footprints in the quarry and hold the key to the park's development. Footprints are especially abundant in interbedded sequences of possible crevasse splay sandstone and flood basin siltstone. Basal sandstone portions of cycle are usually deeply down cut into underlying beds and contain beds of mud-chip conglomerate and casts of tree limbs and roots. Uppermost portions of the cycle consist of fine siltstone transitional into the lower parts of division 1 of the upper Towaco cycle. Transitional beds with numerous red siltstone roots surrounded by greenish halos.

2, exposure of complete Towaco cycle. Division 1 contains prominent fine sandstone beds with large calcareous concretions which weather out to form limonite filled cavities and extensive large (1-4 cm) coalified roots which probably belong to confier trees. Crevasse splay beds in division 1 covered with little dinosaur footprints. Identical beds occur in division 2 of this cycle exposed in Chatham, New Jersey, 13 km south of here.

3, microlaminated portion of division 2 has very well developed white-black microlaminae, however no fish have been found here yet. Upper parts of microlaminated beds contain distinctive nodules of black chert. The black, coally-looking siltstone surrounding the chert bed has several bedding thrusts similar to those seen in the Lockatong at Stops 1-4. Microlaminated beds locally involved in disharmonic folds. Like the beds of division 1, these portions of division 2 look exactly the same in the Chatham exposures.

4, casts of salt present in coarse siltstone beds above microlaminated portion of division 2.

5, massive fine gray siltstone in upper parts of division 2 have well-preserved conifer foliage, pollen and spores, individual fish scales (Semionotus), and rare insect fragments.

6, complex series of sandstones and siltstones of division 3 showing features suggestive of both laterally migrating channels and prograding deltas.

7, lowest fining-upwards cycle in division 4 (Figure 49) shows slip-off faces of point bar and beds of intraformational conglomerate with coprolites, fish scales, reptile bone fragments, and abundant dinosaur footprints. The latter features could represent a dinosaur "wallow".

8, 10 successive fining-upwards cycles of division 4. Rill marks very well developed in bank portions of one of the middle cycles. These sorts of rill marks, typical of channels with rapidly dropping water levels, have long been confused with plant remains (it is easy to see why) and have received the name Dendrophycus (Newberry, 1888).

9, unique small reptile footprints with structure highly suggestive of advanced mammal-like reptiles or mammals are present in upper fining-upwards cycles. If they do represent mammals, they will be the oldest North American record.

10, very badly weathered "tuff"

between normal Towaco Formation and Hook Mountain Basalt. This unit is enigmatic but very widespread at this stratigraphic position. Fresh exposures were described by Lewis in 1908 and Olsen, 1980a.

62.2 Leave Walter Kidde Dinosaur Park and Riker Hill Park returning to Beaufort Avenue. Turn right (north) onto Beaufort.

63.0 Turn right off Beaufort onto Eisenhower Parkway heading north.

64.4 Enter I 280 westbound.

64.8 Crossing the Passaic River. For approximately the next 6 miles we will be crossing the lake beds of Glacial Lake Passaic.

68.2 Merge with Interstate Route 80 westbound; bear right, follwoing signs for Interstate 287, Boonton.

70.7 Enter Interstate 287 northbound, following signs for Boonton. Take Interstate 287 to the end of the highway.

75.4 Right turn at exit onto Route 202.

47.4 At Montville Inn, bear left and enter onto River Road. Caution--this is a dangerous intersection!

47.7 Park car on "paper" street on left-hand side of road (opposite Dahl Ave.). Walk east to outcrop.

48.4 STOP 6. Boonton Formation (Fanglomerate). Marginal Border Facies (Figure 29).

Objective: To examine an alluvial fan facies within a fan delta sequence (Figure 30).

Background: Field descriptions and photographs of this section are included in the text under, "Boonton Formation: Marginal Border Facies."

Because the section has been polished by glacial scour, conglomeratic structures are displayed in great detail. Cyclical and laterally continuous beds of poorly sorted debris flows grading upward into cross-bedded and ripple marked sheet-flood deposits are characteristic of the section (Figure 29). Many of the cycles are incomplete, having been partially eroded by a subsequent debris flow. Each section is about 2 to 3 cm thick and occurs within larger cyclical units of about 1.5 m thick. The clast population has a graphic (Folk, 1974) mean size of -3.3 phi, and an inclusive graphic standard deviation (Folk, 1974) of 2.2 phi (Figure); it is, therefore, very poorly sorted. In general, the grains are angular and primarily composed of a quartzite, gneiss and vesicular basalt with subordinate amounts of amphibolite, slate and greenstone schists. They appear to have been derived from a local source.

Some of the primary structures seen at the section include: ripple drift cross-lamination, dessication cracks, cut-and-fill channels, normal and inverse grading, sand waves, parting lineations, antidunes (?), random fabric, sand shadows, dreikanters and oriented clasts.

Particle orientation was determined from clasts having a length to width ratio of at least 1.3:1. The prevailing long axis orientation is west-to-east with clast imbrication to the west. This is incompatible with a preliminary paleocurrent study showing that the clasts were transported to the basin by east-flowing streams. The occurrence of aligned vertifacts indicates that the wind was an effective agent of erosion, and may explain the deficiency of fine sand and clay size particles on the alluvial fan.

Turn around and go back to 202 northbound (right-turn at Montville

Inn). Enter Route 287, southbound. Boonton Formation pebbles along roadbank.

Boonton Reservoir on left--site of famous Boonton fish fossils.

Continue on Interstate 287 and the route 202 south to New Hope, Pa., via Sommerville, Flemington and Lambertville, N.J.

End of Day One

ROAD LOG (Sunday)

Note: The Sunday field log begins 2.5 miles north of Milford, N.J., along N.J. Route 29 at RR milepost 37. Our trip from New Hope, Pa. to Miford, N.J., via Pa. Route 32 north, takes us through the scenic and historic Delaware River Valley. We will be traversing the Triassic Province, going up-section. Descriptions of field stops 1-3 are taken directly from Van Houten (1980)

0.0 STOP 1. Hammer Creek Conglomerate, Pebble Bluffs at culvert.

0.5 STOP 1B. Conglomerate in steep roadcut at RR milepost 37 (0.5 mi S). Southward projection lobe of quartzite-rich fanglomerate dipping 10-15° NW. Most clasts are imbricated. Bedding is very poorly developed; cross-bedding is virtually absent.

The poorly sorted detritus is arranged in crudely fining-upward sequences about 7-9 m thick with a scoured base, multi-storied units of conglomerate, and calcareous patches and nodules (calcrete paleosol) in the upper sandier part.

Significant items:

1. Outcrop less than 5 mi. from border fault.

2. Source probably less than 25-30 mi. to N.

3. Clasts and matrix derived from Paleozoic rocks now stripped from the uplands.

4. Fining-upwards sequence and calcrete common in alluvial fans.

5. Lensing and channeling well-displayed at south end of bluffs.

6. Rapid gradation southward into distal, finer-grained facies.

7. Fault in ravine between two major outcrops.

1.1 STOP 2. Long roadcut in essentially horizontal middle Brunswick Mudstone south of Spring Valley Road. Bright reddish-brown mudstone in patterned sequences about 950 m above base of formation (Picard and High, 1963)

Items along 0.2 mi traverse:

1. Normal fault at E end of exposure down to E. conspicuous jointing.

2. Succession of about 30 massive mudstone and hackly claystone alterations averaging 1.5-3 m thick (Picard and High, 1963). Few units with persistent 1-2 cm beds of siltstone.

3. Abundant burrowing has destroyed lamination in mudstone. Absence of bedding in claystone may be result of small-scale physical disruption.

4. Distinct 2-6 cm layers filling abandoned channel (Figure 6). Fine-to-medium grained feldspathic sandstone in lower part of each layer derived from Southeastern Na-feldspar rich source areas. Some layers are graded. Tops are marked by burrows and shrinkage cracks. Abandoned channel may have been part of interfluvial drainage of extensive alluvial plain (Allen and Williams, 1979) or a shallow waterway in a clay-flat playa.

5. Hammer Creek tongue of dark reddish-brown Paleozoic quartzite-clast lithic-rich sandstone 3 m above road E and W of ravine and culvert.

1.8 Dark gray Perkasie and L and M members of Brunswick Formation 930 m above Lockatong Formation. These are highest of 8 recurring gray units in the Delaware Valley region, centered at 120-137 m intervals. Several have been traced to NE into Hammer Creek Conglomerate, as well as 25 km to SW where they interfinger with reddish-brown mudstone. Gray units consist of black, pyritic platy muddy limestone and calcareous mudstone. The Perkasie Member apparently is about 1400 m below the 1st Watchung flow. Intervals of reversed magnetic polarization have been identified below both the Perkasie and L and M units, as well as just below and above the Graters Members lower in the Formation (W.C. McIntosh).

2.5 Milford. Turn E on Main Street, then S at traffic light on Rt 627.

4.5 STOP 3. Middle Brunswick Mudstone, roadside excavation. Well-displayed bedding surface markings, including several sizes of shrinkage crack-patterns, burrows, and small tracks and trails, many probably made by small crustaceans (Boyer, 1979).

6.1 Frenchtown. Turn E on Main Street, than S on N.J. 29.

9.5 Gray units E and F exposed in ravine and along side road. Gray units G and H above 100 m higher in section constitute the Graters Member (40 m thick).

STOP 4. Warford Creek exposures of member D of the Passaic Formation.

The gray members of the Passaic Formation mapped by McLaughlin (1946) consist for the most part of bundles of short sedimentary cycles very similar to detrital cycles of the Lockatong Formation (Van Houten, 1969; Olsen, 1980a, 1980c). The exposures along Warford Creek consist of one complete cycle (Figure 31). On the basis of the same criteria as are used for Lockatong detrital cycles, this Passaic Formation cycle can be cut into three divisions. At these exposures, the organic rich lower parts of division 2 are microlaminated although this is obvious only in thin section. These microlaminated beds contain poorly preserved partly articulated Semionotus and very small conchostracans. The lower parts of division 3 contain Scoyenia - type burrows, numerous tool marks and possibly very poor reptile footprints. The lateral extent of individual short cycles within Passaic Formation gray members is unknown.

10.7 Lowermost Brunswick Formation, Tumble Falls. Ravine and high roadcut in lowest reddish-brown unit and lowest gray unit C (40 m thick) about 75 m above base of Formation.

11.1 Top of Lockatong Formation (top of gray unit B). Base of Brunswick Formation has been placed arbitrarily below the lowest thick reddish-brown unit even though its lower part is more like upper Lockatong deposits than the upper part of the Brunswick Formation.

11.4 Double Red unit exposed in creek to East is uppermost reddish-brown sequence of analcime-rich chemical cycles assigned to the Lockatong Formation. The reddish-brown intervals of this sort are the most analcime-rich and recur in a 105-120 m pattern of long cycles in phase with thick reddish-brown units in the Brunswick Formation.

12.0 Triple Red unit in abandoned building-stone quarry to East about 1000 m above base of Lockatong Formation. Red units were favored for building blocks because of their more interesting variegated colors.

12.3 STOP 5. Long road cut in upper Lockatong Formation and Byram diabase sheet, a section described in detail in Van Houten (1962, 1964, 1969). Well marked patterns of detrital and chemical cycles and their groupings into 25 m and 100 m higher order cycles can be easily seen here. (Figure 32). Van Houten (1969) has marked cumulative stratigraphic thicknesses on the outcrop starting at the 0 mark on the southernmost exposures of this section. Base of section in Figure is about 21 m above faulted contact with Byram diabase sheet and about 450 m above the Stockton-Lockatong contact. According to Van Houten (1969) nepheline is absent above the 11-foot mark and cancrinite and albite diminish while analcime and thomsonite increase towards the 370-foot mark.

Large abandoned quarry is at 150- to 300-foot mark. Exposures consist of cancrinite hornfels principally in chemical cycles (Van Houten, 1969). Two well developed detrital cycles are exposed at the north end of the quarry. The section between 300 to 1020 feet is especially well exposed showing very clearly alternating bundles of detrital and chemical cycles.

Chemical cycles are on the average 5 meters thick and consist of two major varieties. One type resembles detrital cycles in having a lower black or gray platy siltstone. Generally, however, fissility is not as well developed in this unit as in division 2 of detrital cycles. And even the darkest siltstone units contain tan weathering dolomitic beds (Van Houten, 1969). The middle parts of these cycles contain more massive dolomite beds and the upper parts contain even more massive beds of gray very hard and blocky siltstone (argillite) speckled with analcime and dolomite.

The other variety of chemical cycle has a lower platy gray to gray-green often dolomitic siltstone which is usually disrupted by numerous shrinkage cracks. This basal unit grades upward into a deep mauve, blue-gray, or red massive siltstone with abundant analcime. These sorts of chemical cycles are most common in the upper part of this section (Figure 32) and these red chemical cycles make up the "first thin red" unit mapped by McLaughlin. This type of chemical cycle passes laterally into typical Passaic Formation red beds outside of this central area. Some of the thicker chemical cycles which have a lower black siltstone, lose their analcime laterally and so become detrital cycles.

Detrial cycles are an average of 4.5 to 6 meters thick at this section. Each cycle can be divided into three divisions. (Figure 32). The lower massive to platy dark gray siltstones of the previous cycle. Prominent, easily weathered laminated black siltstone (division 2) is sometimes microlaminated (only once in this section). In non-microlaminated parts of division 2, very small burrows and delicate shrinkage cracks are common. Division 3 is more massive and consists of feldspathic siltstone and fine grained sandstone. The siltstones are almost always intensively disrupted by shrinkage cracks and also show a variety of sole marks including reptile footprints. These divisions record the development, maintenance, and extinction of very large lakes.

Above Van Houten's 720-foot mark (Figure F) is the only cycle in this section with a well developed microlaminated division 2. As is the case with virtually all microlaminated bed in the Newark Supergroup, this one is rich in organic carbon, whole fossil fish (in this case, <u>Turseodus</u>), coprolites, and conchostracans. A small rock fall, apparently from division 3 of this cycle has exposed several poor phytosaur footprints (Figure 33). Some bedding planes in this shrinkage cracked unit are covered with small concostracans.

The lower part of the Lockatong (very poorly exposed in this area) has a much higher frequency of detrital cycles (Van Houten, 1964) with many more microlaminated units, and more fossils than the upper part of the Lockatong. Some of the lower beds of the Lockatong are exposed in small ravines further to the south. It seems likely that the cycles exposed and mapped in northern New Jersey correlate with detrital cycles in the lower parts of the Lockatong along the Delaware.

17.5 <u>STOP 6.</u> Active quarry in upper part of Prallsville Member of the Stockton Formation. Section is about 61 m thick and begins about 760 m above the base of the Formation (Van Houten, 1969, 1980).

Four major sediment types are obvious at these outcrops:
1) massive, well sorted medium grained gray to buff arkose with faint to prominent large scale cross bedding.

2) massive to crudely cross bedded thin (2 m) arkosic conglomerate units some of which are locally kaolinized.

3) well bedded red coarse siltstone, intensely and obviously bioturbated.

4) blocks and massive red siltstone resembling much of the Passaic Formation.

The intense bioturbation seen in the red coarse siltstone clearly extends into the massive arkose as can be seen on the lower surfaces of the arkose beds. Two main types of bioturbation are dominant. One is the arthropod burrow <u>Scoyenia</u>, and the other is large and small roots. Large roots are especially abundant in the massive arkose beds where they are replaced by an iron-rich carbonate mineral which weathers to limonite. All of the sediments at this exposure show roots.

Both the roots and the abundant burrows attest to high productivity in a very shallow water or terrestrial environment. Presumably this represents a fluvial to deltaic environment in which all the sediments become soils sooner or later before burial. The complete lack of organic carbon in all the sediment is a testimony to the high ecosystem efficiency of this primarily terrestrial ecosystem.

Return to bus and travel to the Stockton Inn for a fine lunch and good cheer.

END OF FIELD TRIP

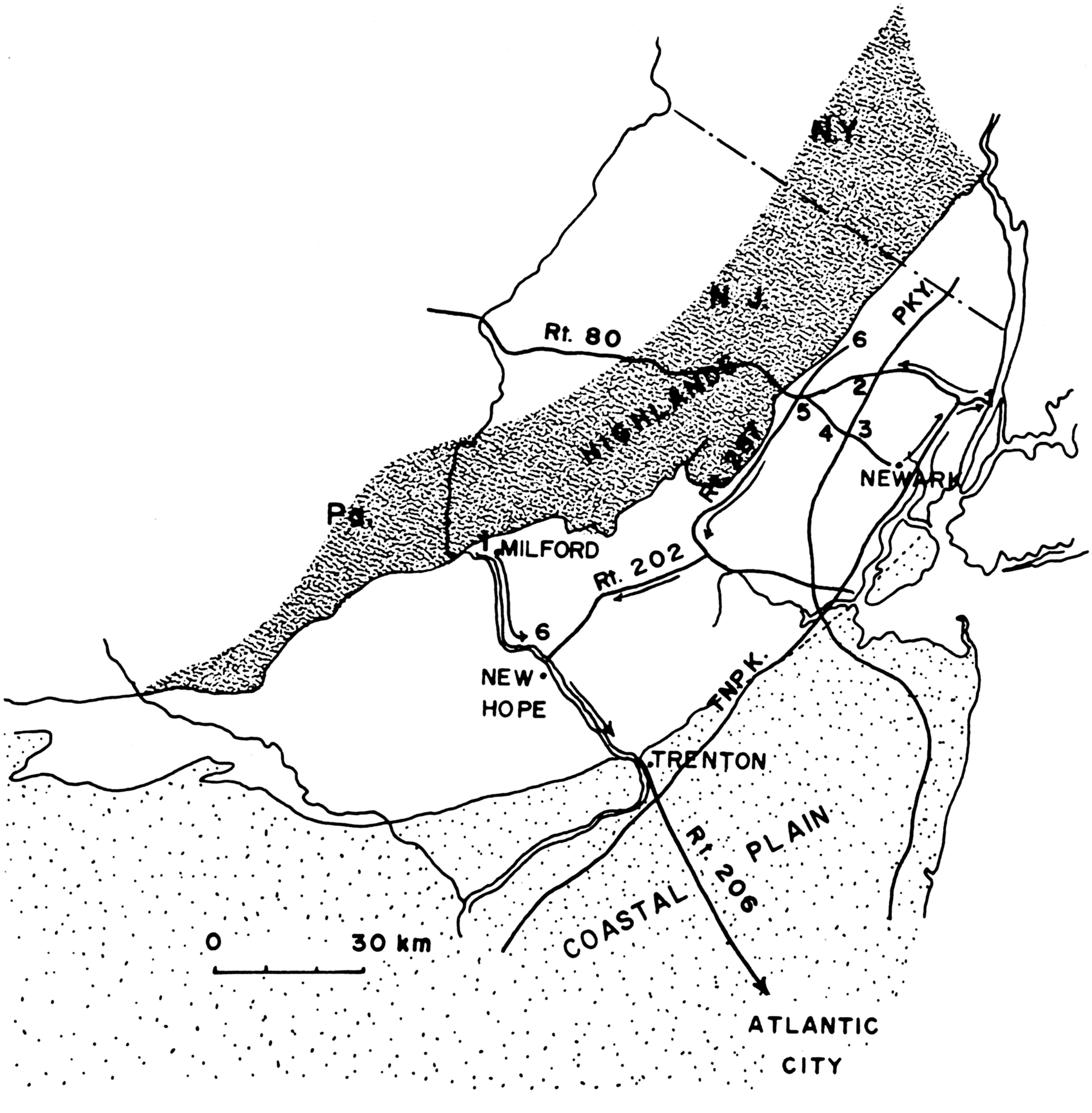


Figure 1

Map of the Newark Basin showing route of field trip and field stops.

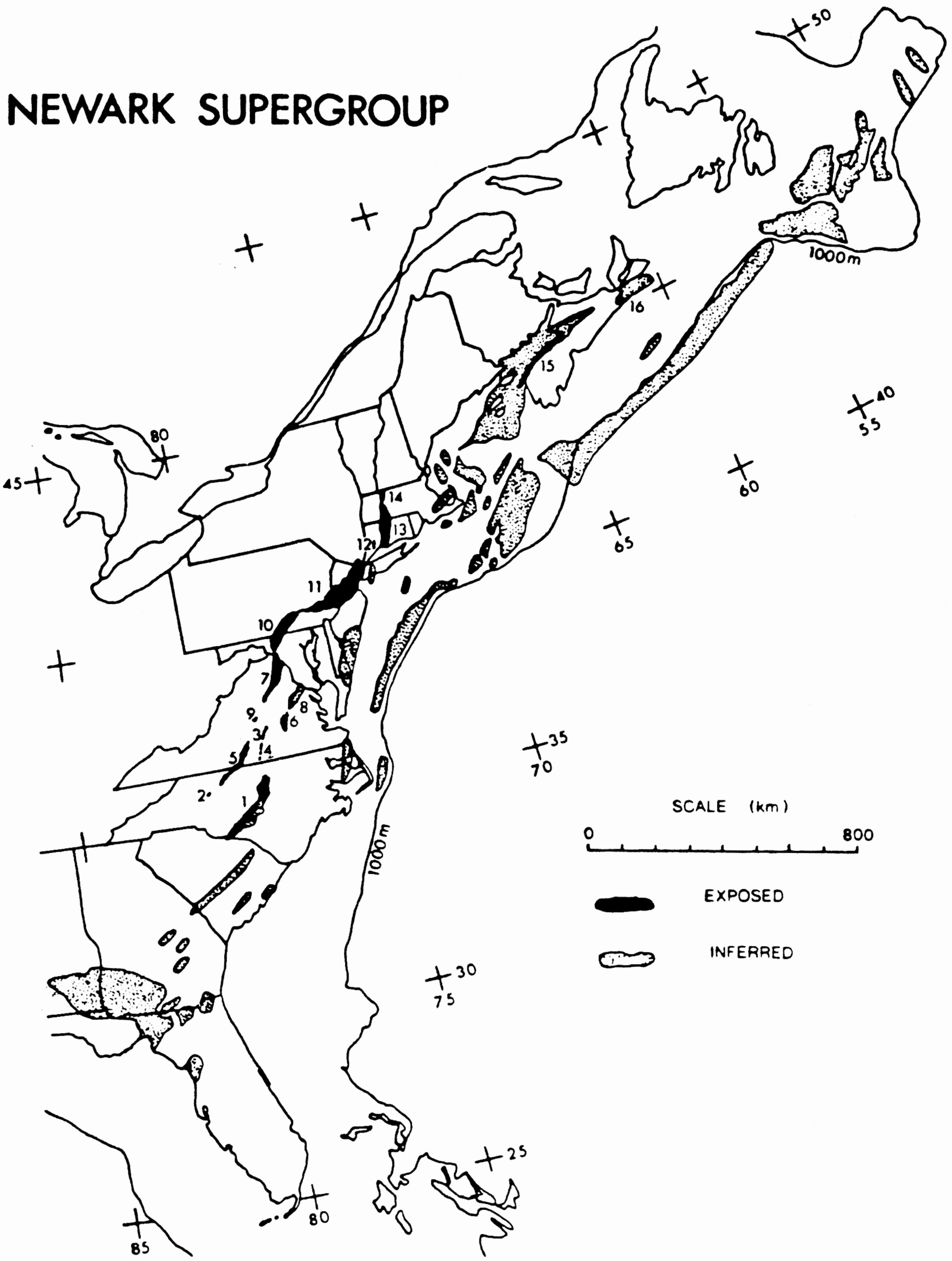


Fig. 2 Newark Supergroup of eastern North America. Key to numbers given in Table 1. The Newark Basin is 11. Data from Olsen, 1978.

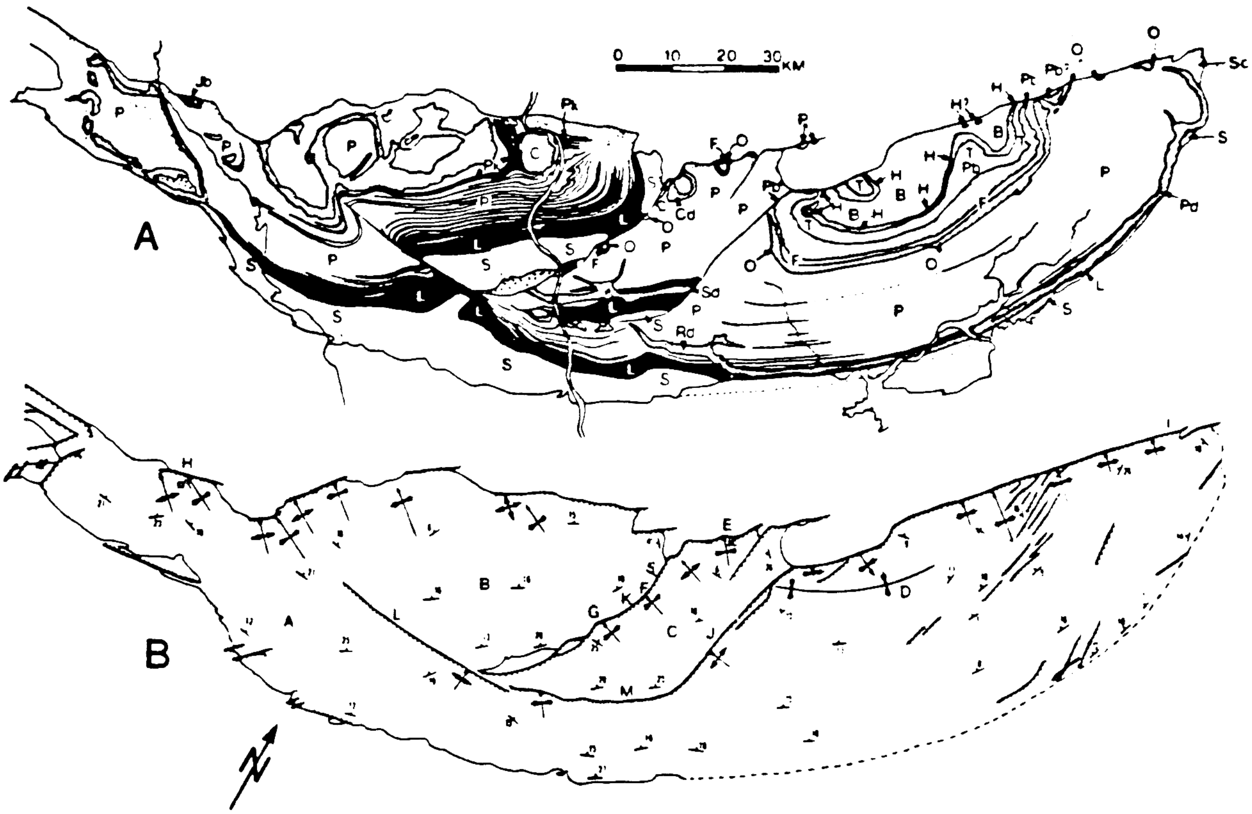


Fig. 3 The Newark Basin.

A. Geologic map showing distribution of formations, conglomeritic facies (irregular stipple), and major clusters of detrital cycles in Passaic Formation (parallel black lines) – abbreviations of formations and diabase bodies as follows: B, Boonton Formation; C, Coffman Hill Diabase; Cd, Cushetunk Mountain Diabase; F, Feltville Formation; H, Hook Mountain Basalt; Hd, Haycock Mountain Diabase; Jb, Jacksonwald Basalt; L, Lockatong Formation; O, Orange Mountain Basalt; P, Passaic Formation; Pb, Preakness Basalt; Pd, Palisade Diabase; Pk, Perkasie Member of Passaic Formation; Rd, Rocky Hill Diabase; S, Stockton Formation; Sc, carbonate Facies of Stockton Formation; Sd, Sourland Mountain Diabase; T, Towaco Formation.

B. Structural features of the Newark Basin. Faults are all drawn as normal with dots on the down-thrown side; portions of basin margin not mapped as faults should be regarded as onlaps. While all the faults are mapped here as normal, it is clear many, if not all of them, have some component of strike slip, although the significance of this component is unclear. Symbols for the names of structural features used in this paper are as follows: A, Montgomery-Chester fault block; B, Bucks-Hunterdon fault block; C, Sourland Mountain fault block; D, Watchung syncline; E, New Germantown syncline; F, Flemington syncline; G, Sand Brook syncline; H, Jacksonwald syncline; I, Ramapo fault; J, braided connectoin between Ramapo and Hopewell faults; K, Flemington fault; L, Chalfont fault; M, Hopewell fault.

Data for A and B from Kümmel, 1897; Lewis and Kümmel, 1910-1912; Darton, 1890, 1902; Darton, et al., 1908; Glaeser, 1963; Sanders, 1962; Van Houten, 1969; McLaughlin, 1941, 1943, 1944, 1945, 1946a, 1946b; Bascom, *et al.*, 1909; Willard, *et al.*, 1959; Faille, 1963; Manspeizer, pers. comm.; Olsen, in press, and personal observation.

Table 1

Key to Figure 1	Rock-stratigraphic term	Basin name	Age range
1	Chatham Group	Deep River Basin	Carnian-?Norian (Late Triassic)
2	undifferentiated	Davie County Basin	?Late Triassic
3	undifferentiated	Farmville Basin	?Carnian (Late Triassic)
4	undifferentiated	4 small basins south of Farmville Basin	?Carnian (Late Triassic)
5	Dan River Group	Dan River and Danville Basins	Carnian-?Norian (Late Triassic)
6	Tuckahoe and Chesterfield Groups	Richmond Basin and subsidiary basins	Carnian (Late Triassic)
7	none	Culpeper Basin	Norian-?Sinemurian (Late Triassic-Early Jurassic)
8	none	Taylorsville Basin	Carnian (Late Triassic)
9	undifferentiated	Scottsville Basin and 2 subsidiary basins	?Late Triassic-Early Jurassic
10	none	Gettysburg Basin	Carnian-Hettangian (Late Triassic-Early Jurassic)
11	none	Newark Basin	Carnian-Sinemurian (Late Triassic-Early Jurassic)
12	none	Pomperaug Basin	?Late Triassic-Early Jurassic
13	none	Hartford Basin and subsidiary Cherry Brook Basin	Norian-?Bajocian (Late Triassic-?Middle Jurassic)
14	none	Deerfield Basin	?Norian-?Toarcian (Late Triassic-Early Jurassic)
15	Fundy Group	Fundy Basin	?Middle Triassic-Early Jurassic
16	Chedabucto Formation (=Eurydice Formation?)	Chedabucto Basin (=Orpheus Basin?)	?Late Triassic-Early Jurassic

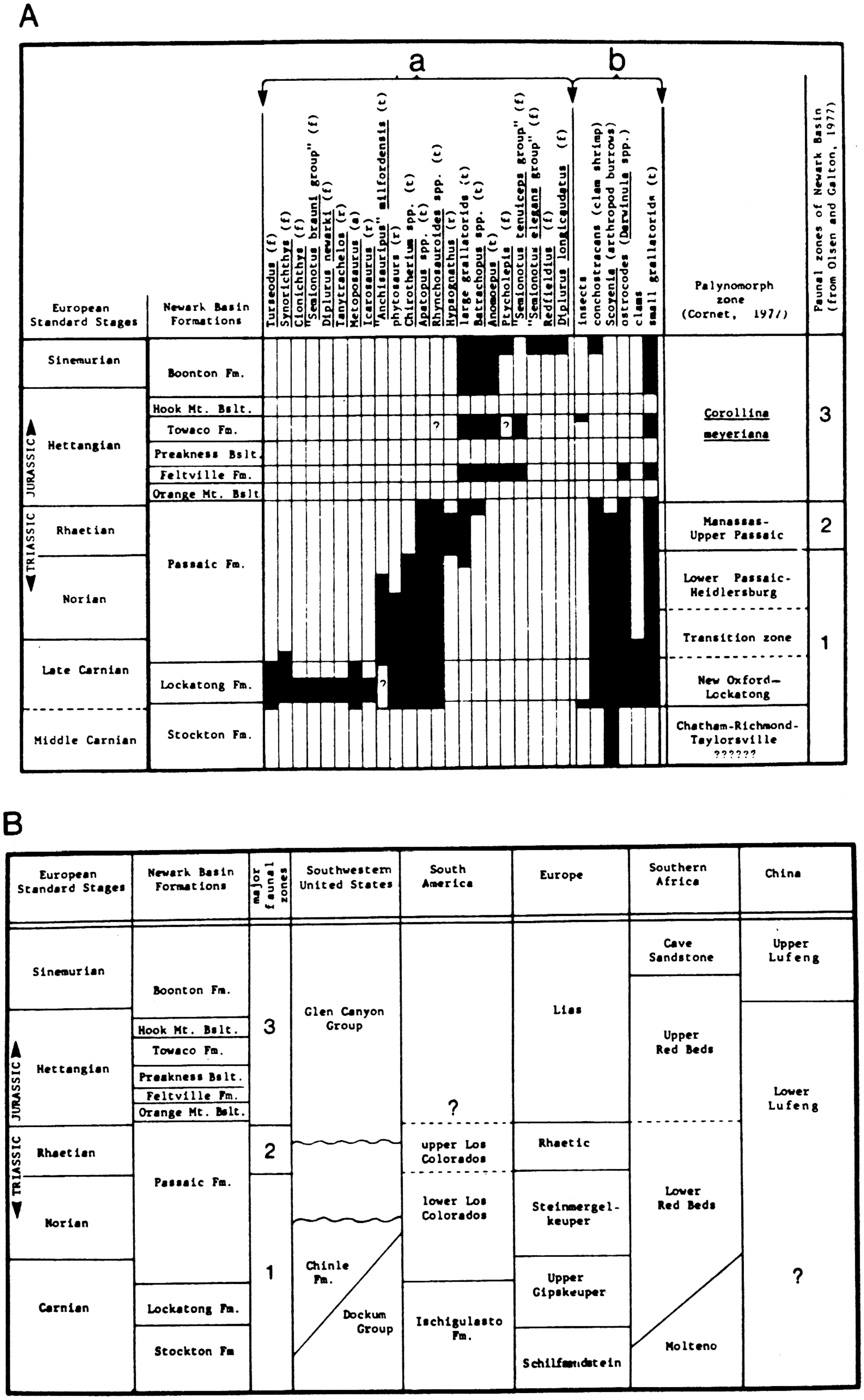


Fig. 4

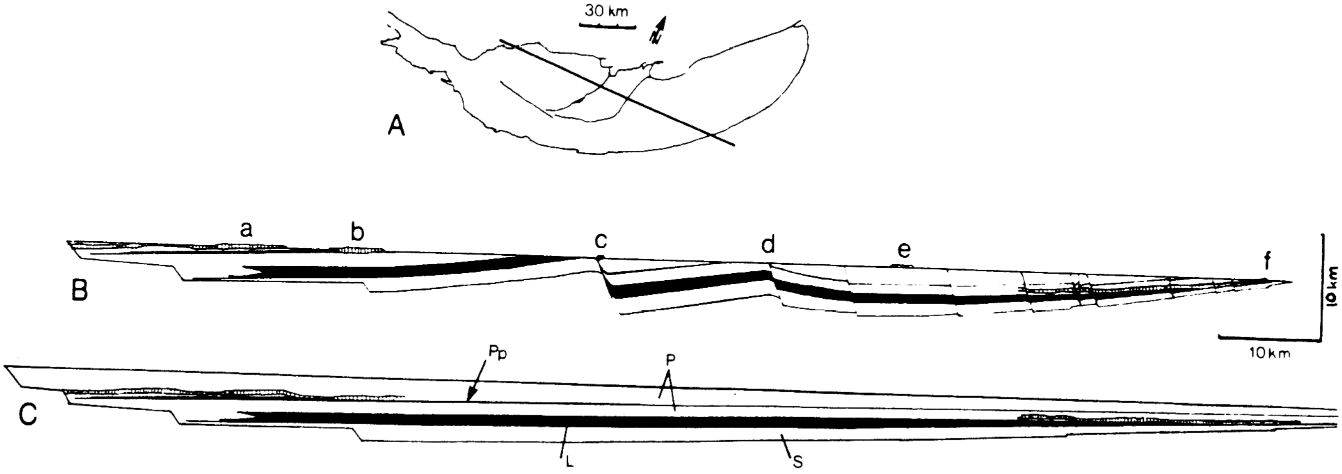
A. Distribution of most abundant vertebrate and invertebrate fossils in the Newark Basin; a, taxa thought to be biostratigraphically important; b, taxa thought to be of little or no stratigraphic value. Letters in parenthesis--(f), (r), (a), (t)--indicate nature of fossils: (a) amphibians; (f) fish; (r) reptiles; (t) reptile footprints.

B. Correlation of the formations of the Newark Basin with other Mesozoic sequences.

Data for A and B from: Cornet (1977); Olsen (in press; Olsen and Galton (1977); Olsen, McCune, and Thomson (in press); Olsen, Baird, and Salvia (MS); and Olsen and Colbert (MS).

Fig. 5 Cross-section of the pre-Orange Mountain Basalt portion of the Newark Basin: A, position of section in Newark Basin; B, present cross section--note that the vertically ruled band represents diabase and gabbro sills and plutons; C, reconstructed section with Passaic Formation-Orange Mountain Basalt contact as horizontal--note thinning to east and ramping to west.

Abbreviations as follows: a, Haycock Mountain Pluton; b, Coffman Hill Pluton; c, Flemington syncline outlier of Orange Mountain Basalt and to the immediate left the Flemington Fault; d, Hopewell Fault; e, Orange Mountain Basalt of Watchung syncline; L, Lockatong Formation; P Passaic Formation; P;. Perkasie Member of Passaic Formation; S, Stockton Formation. Note that the trigonometrically calculated thickness of Passaic Formation east of the Watchung syncline has been reduced by 25% as a correction for dip slip faults.



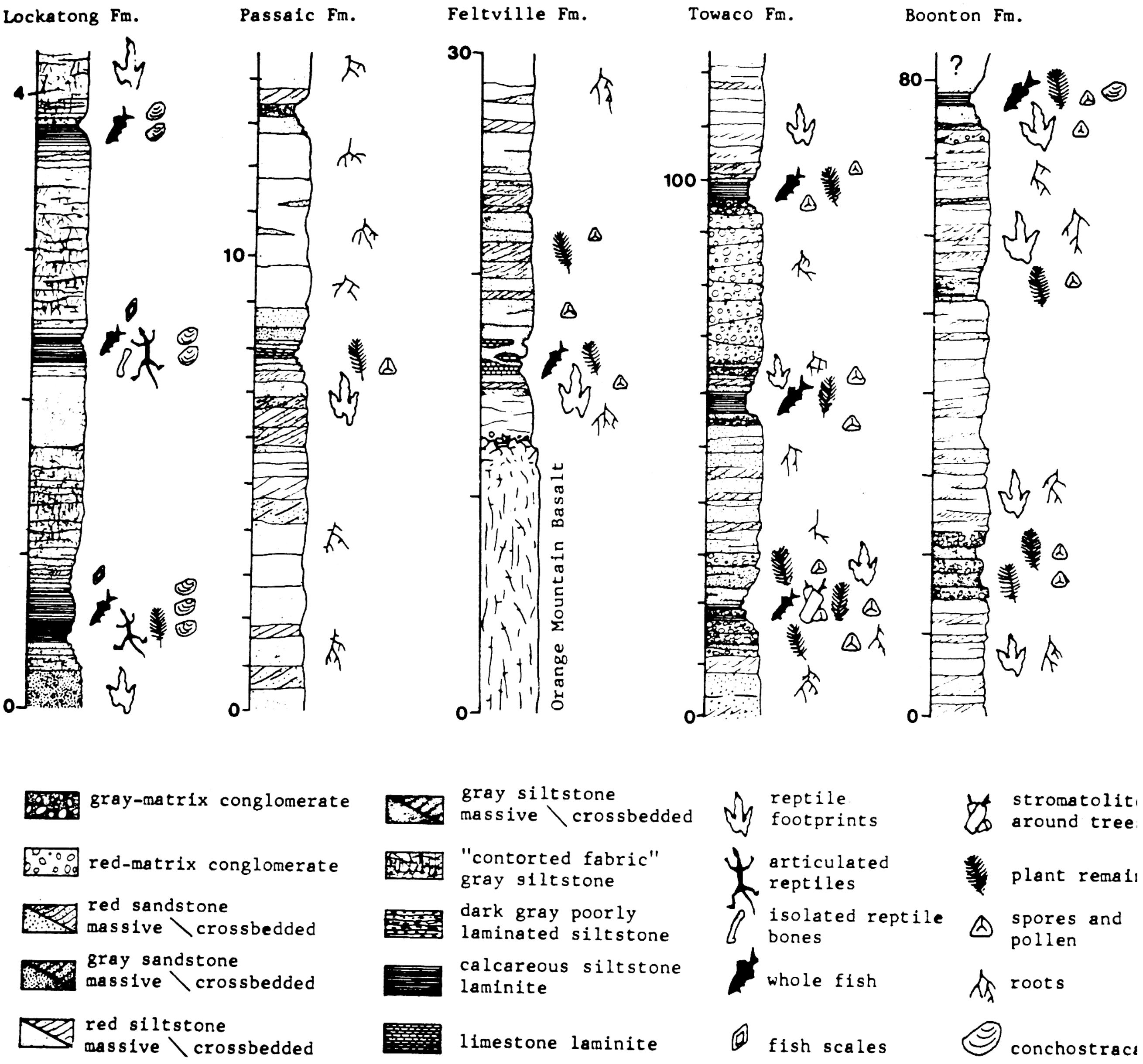


Fig.6 Major types of sedimentary cycles of the formations of the Newark Basin. Note that the approximate center of the symbols for the major types of fossils found is placed about where they occur in the section to the left. Note the change in scale (in meters) from section to section.

Lockatong Formation section measured at Kings Bluff, Weehawken, New Jersey and represents three detrital cycles. The Passaic Formation section measured along Nishisakawick Creek and Little Nishisakawick Creek, northeast of Frenchtown, New Jersey; the two cycles shown represent the lower portion of McLaughlin's Graters Member (i.e., Member G) and are characteristic of most of the detrital cycles of the Passaic Formation. The upper cycle develops a dark gray siltstone a kilometer to the south. Feltville Formation section measured along East Branch of Middle Brook, Martinsville, New Jersey--there is only one such "cycle" in the Feltville Formation. Towaco Formation section measured along stream 2 km southwest of Oakland, New Jersey; three cycles are shown. Boonton Formation section is upper part of type section (see Figure 12); section not clearly cyclic.

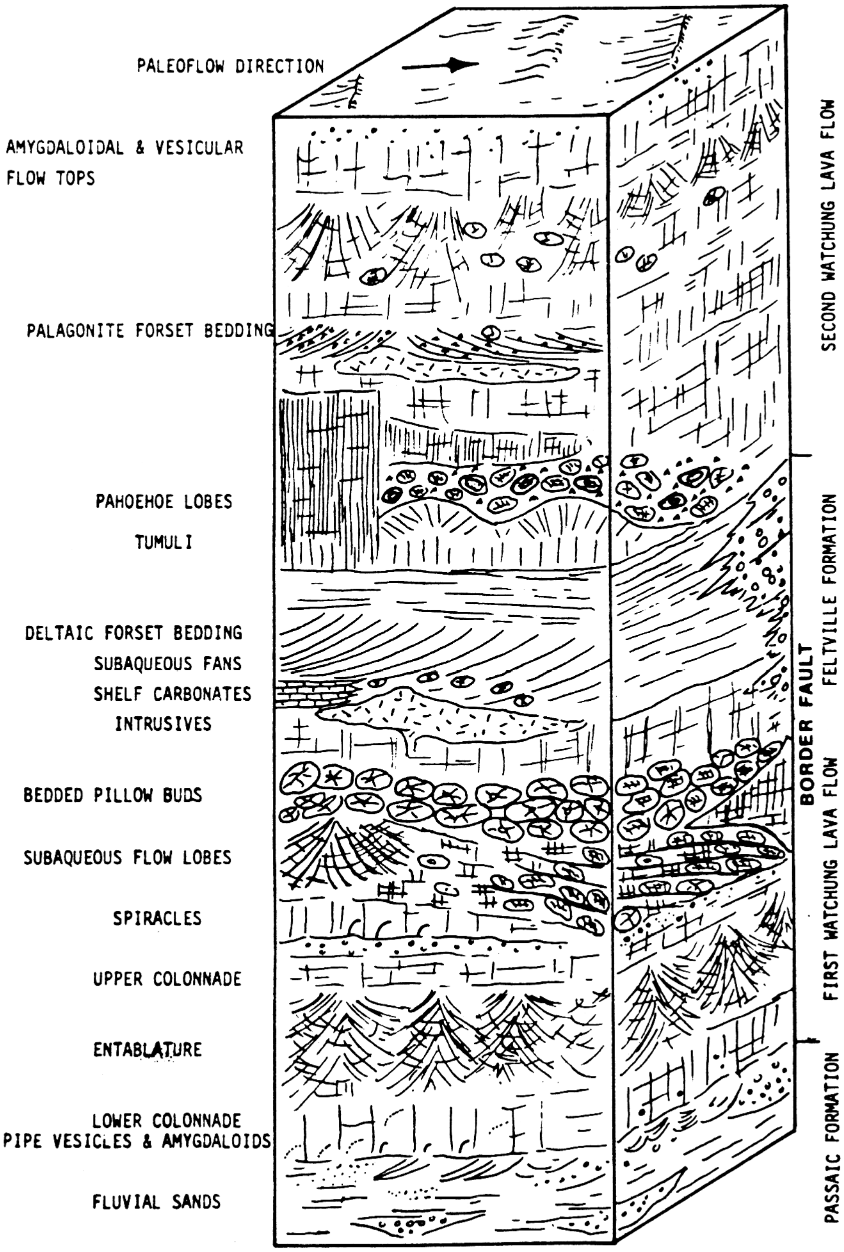


Fig. 7 Schematic diagram of the volcanic and sedimentary structures to be studied on the field trip.

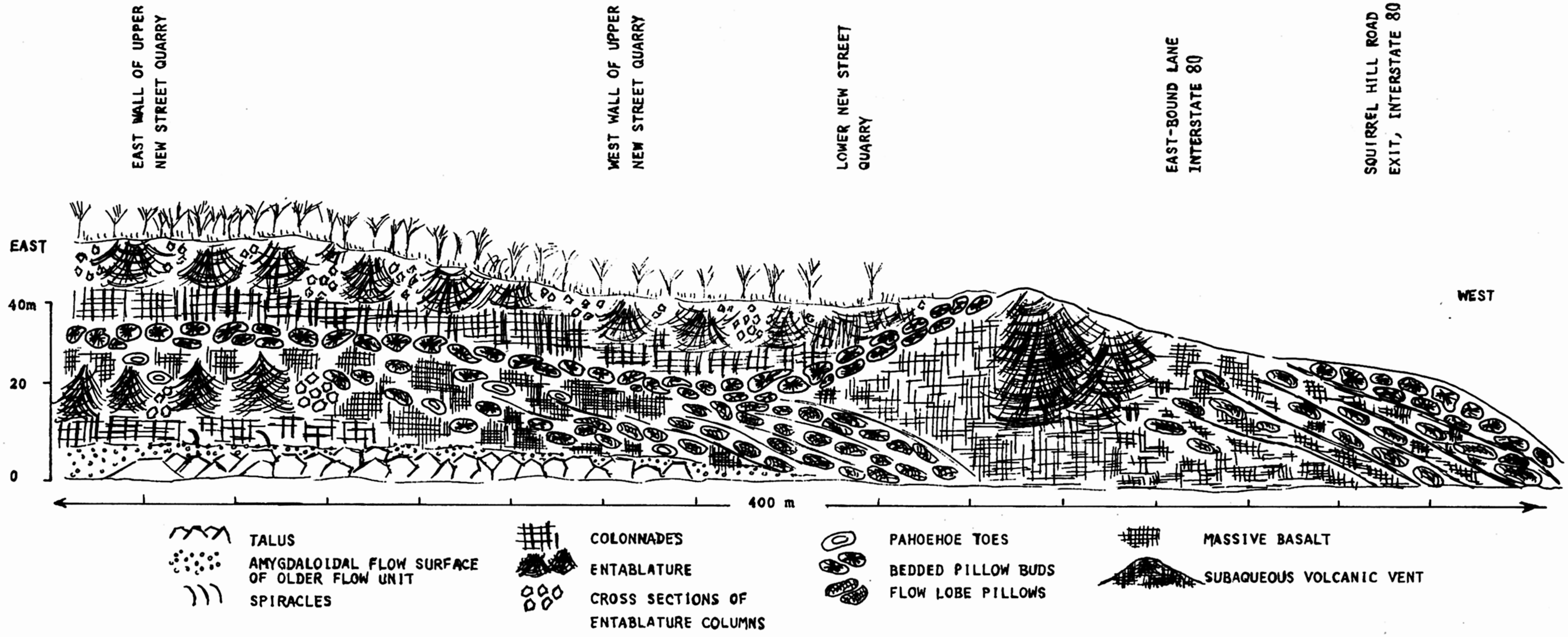


Figure 8

Field sketch of volcanic structures studied in the second flow unit of the Orange Mountain Basalt in the Upper and Lower New Street Quarries and along I-80; note: longitudinal section of the subaqueous flow lobe, volcanic vent, bedded pillow lavas, an overlying Tomkeieff sequence and underlying amygdaloidal flow top.

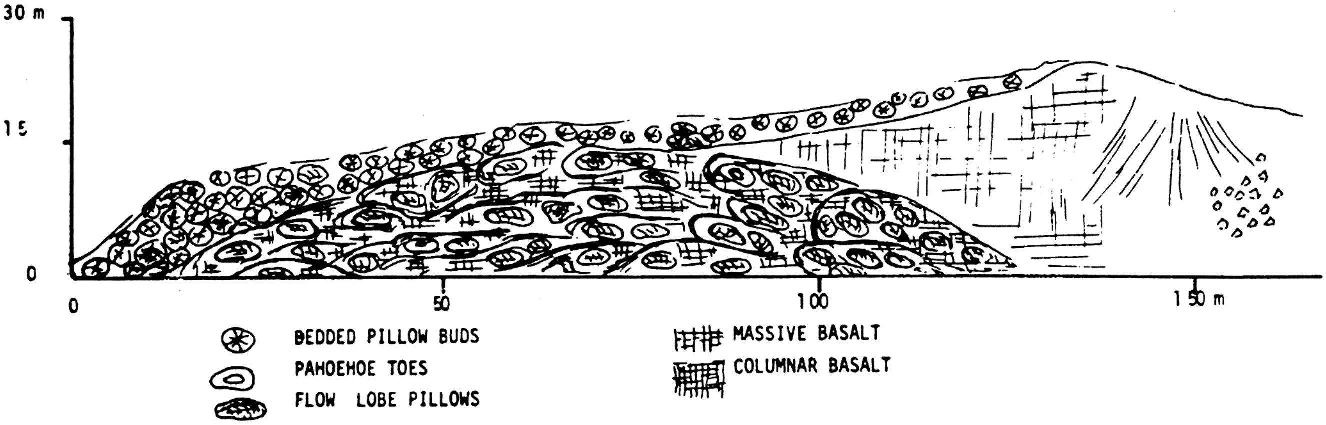


Fig. 9 Field sketch of the lower New Street Quarry, showing transverse section of the subaqueous flow lobe, volcanic vent, and overlying bedded pillow lava.

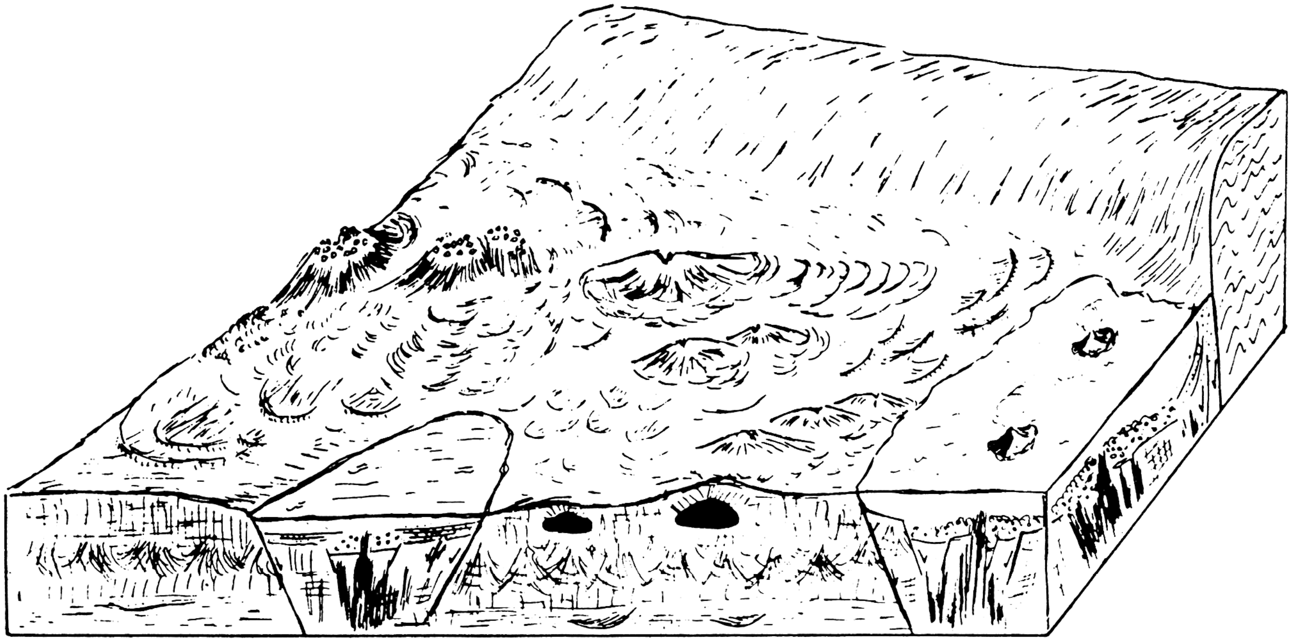


Fig 10 Schematic block diagram illustrating volcanic structures and paleogeography of the Newark Basin during the extrusion of the First and Second Watchung lavas.

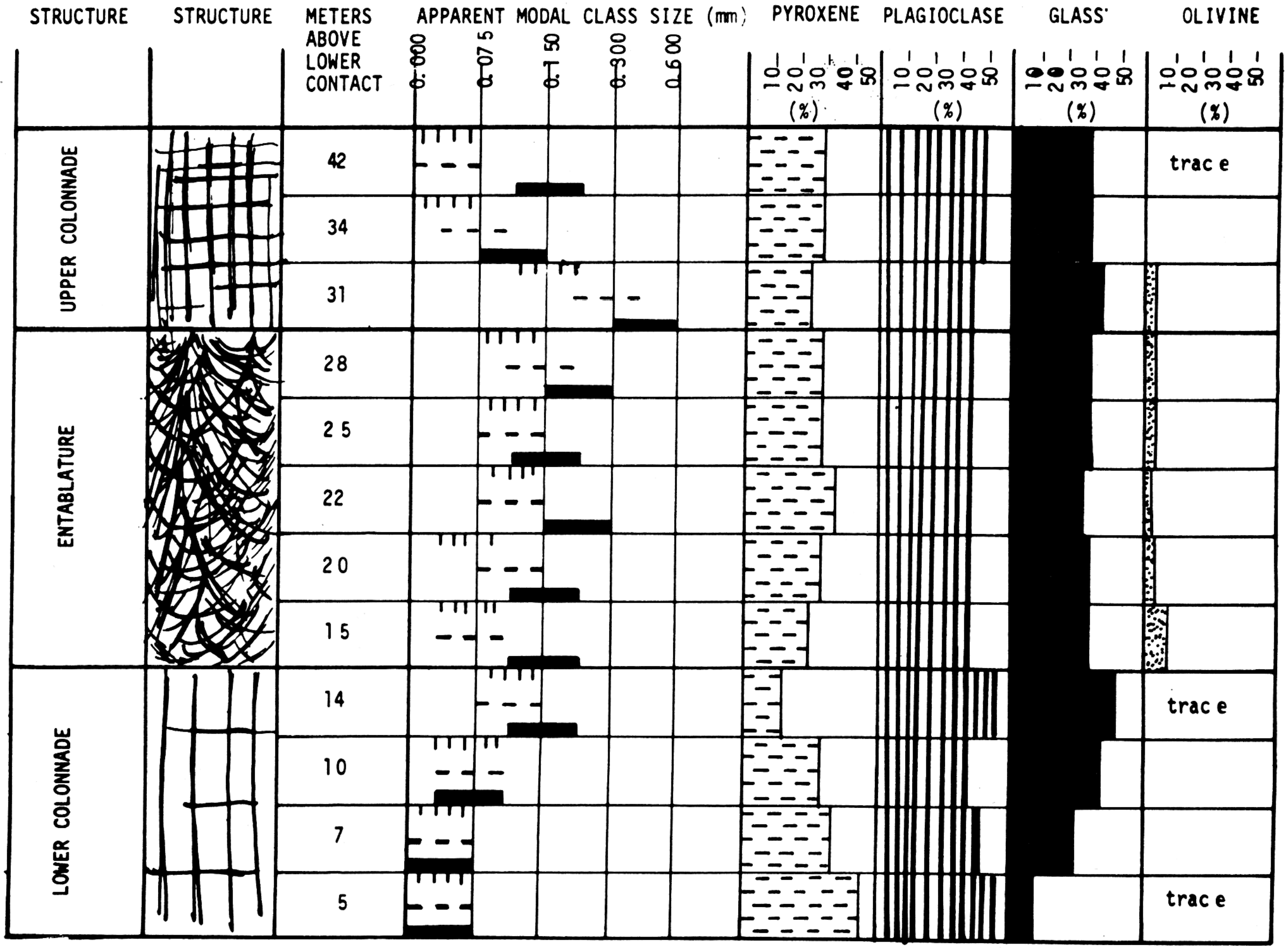


Fig. *11* Plot of mineral and glass content and texture against the Tomkeieff sequence of colonnades and entablature, Orange Mountain Basalt, I-280, West Orange.

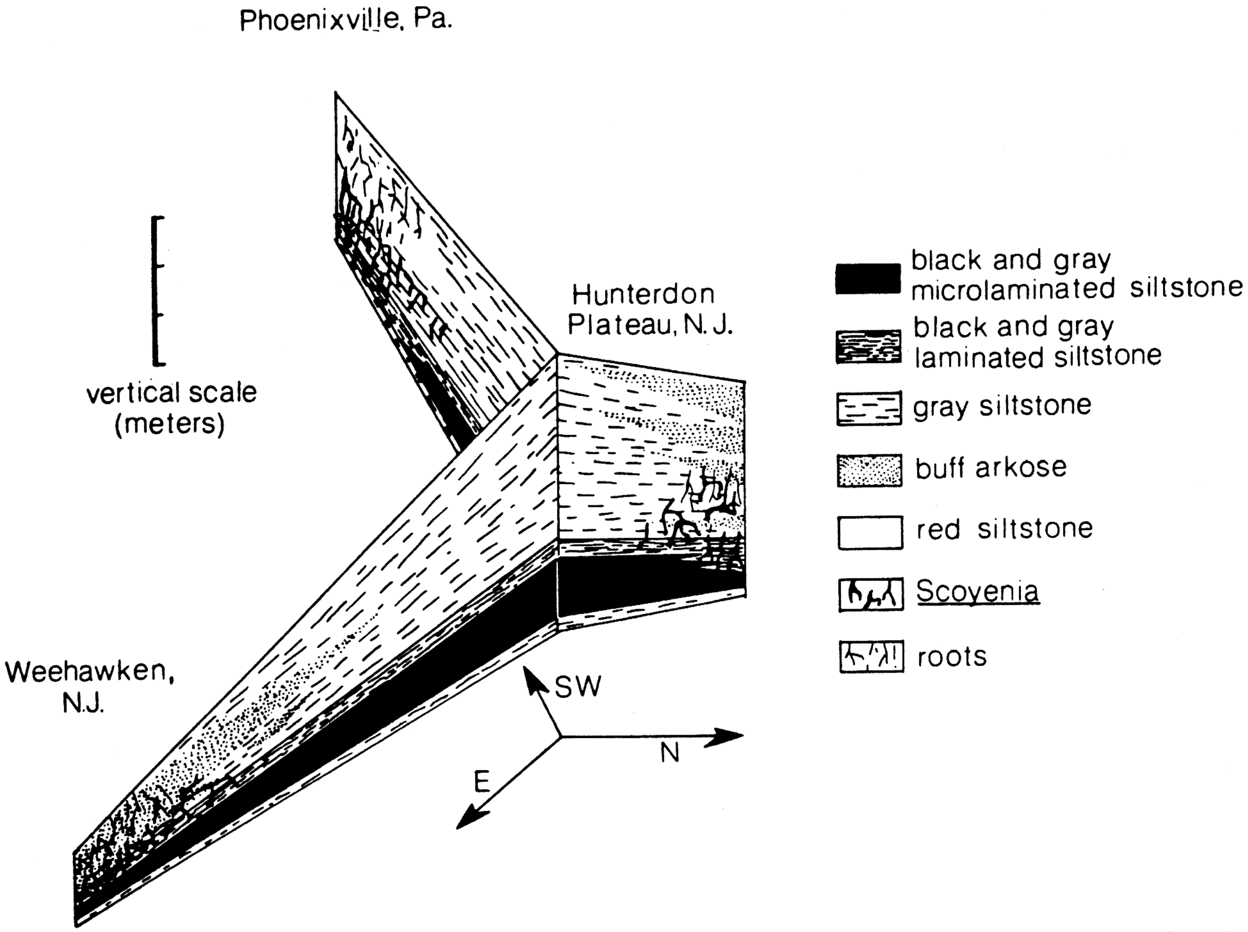


Fig. 12 Generalized facies relationships of Lockatong detrital cycles (horizontal distances not to scale); Phoenixville is 50 km from the southern portion of the Hunterdon Plateau (Stockton, New Jersey), which in turn, is 27 km from the northern corner of the plateau and 105 km from Weehawken, New Jersey.

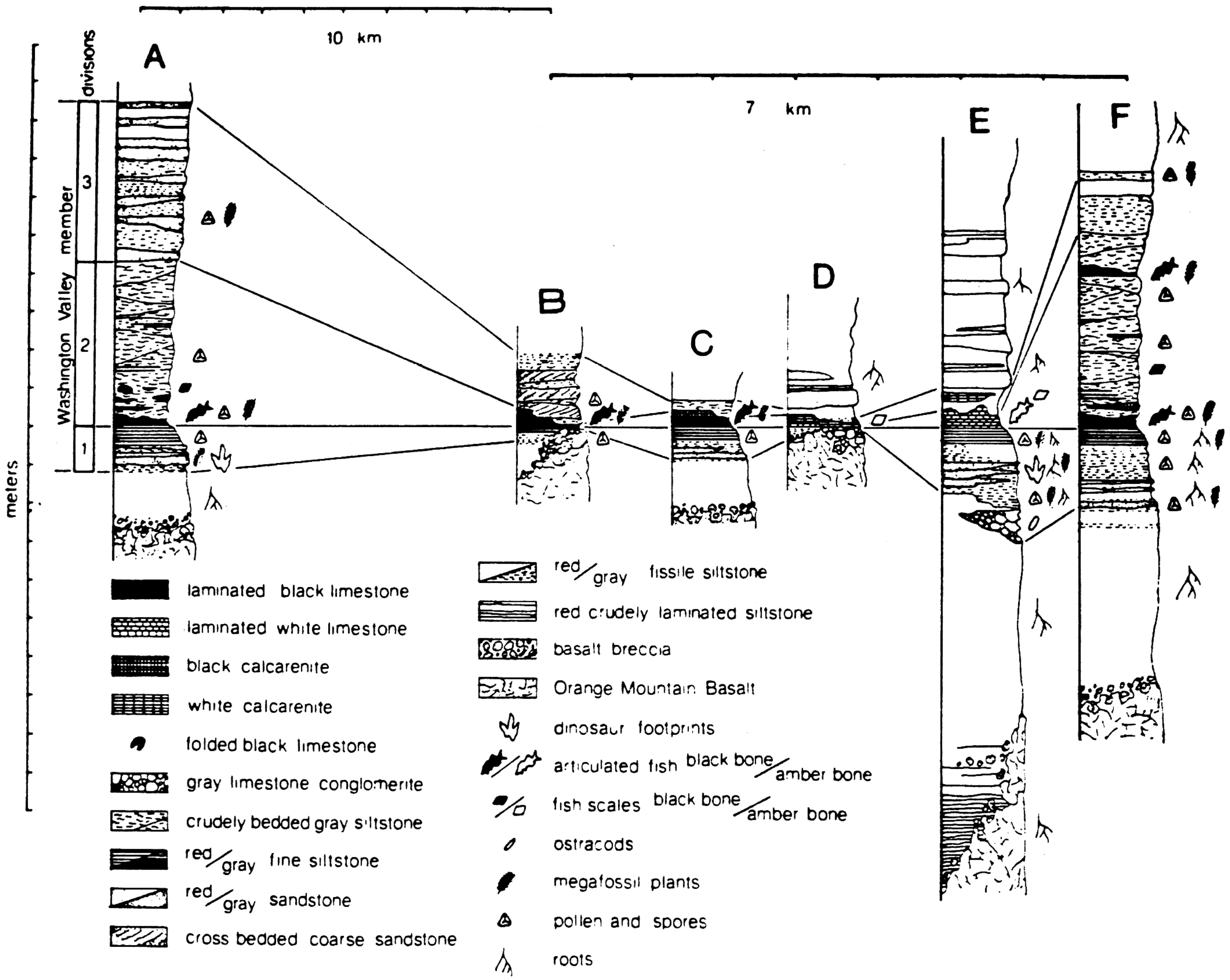


Fig. 13 Small scale lateral change in Washington Valley member: A, outcrop along East Branch about 145 m northwest of Vosseller Road near intersection with Roberts Road, Somerset County, New Jersey; B, banks of small stream running parallel to and on the southeast side of Valley Road, 1.6 km north of Watchung, New Jersey rotary (Somerset County). Elsinore Drive crosses this stream 80-100 m down stream from locality; C, bluffs and pool exposures along Green Brook about 400m northeast of intersection of Plainfield Avenue, Valley Road, and Bonnie Burn Road and about 618m down brook from overpass of Plainfield Avenue over brook (outcrops at boundary of Union and Somerset Counties); D, outcrops along Green Brook north of (c) above and about 200m, south of the Plainfield Avenue bridge over Green Brook; E, two combined sections, 400m apart, one on the south, one on the north side of Blue Brook about 1.9km and 2.3 km respectively, upstream from the crossing of Sky Top Drive over Blue Brook, Watchung Reservation, Union County, New Jersey — type section of the Feltville Formation; F, outcrops in bluff of small tributary of Blue Brook, 260m south of Lake Surprise, Watchung Reservation, Union County, New Jersey.

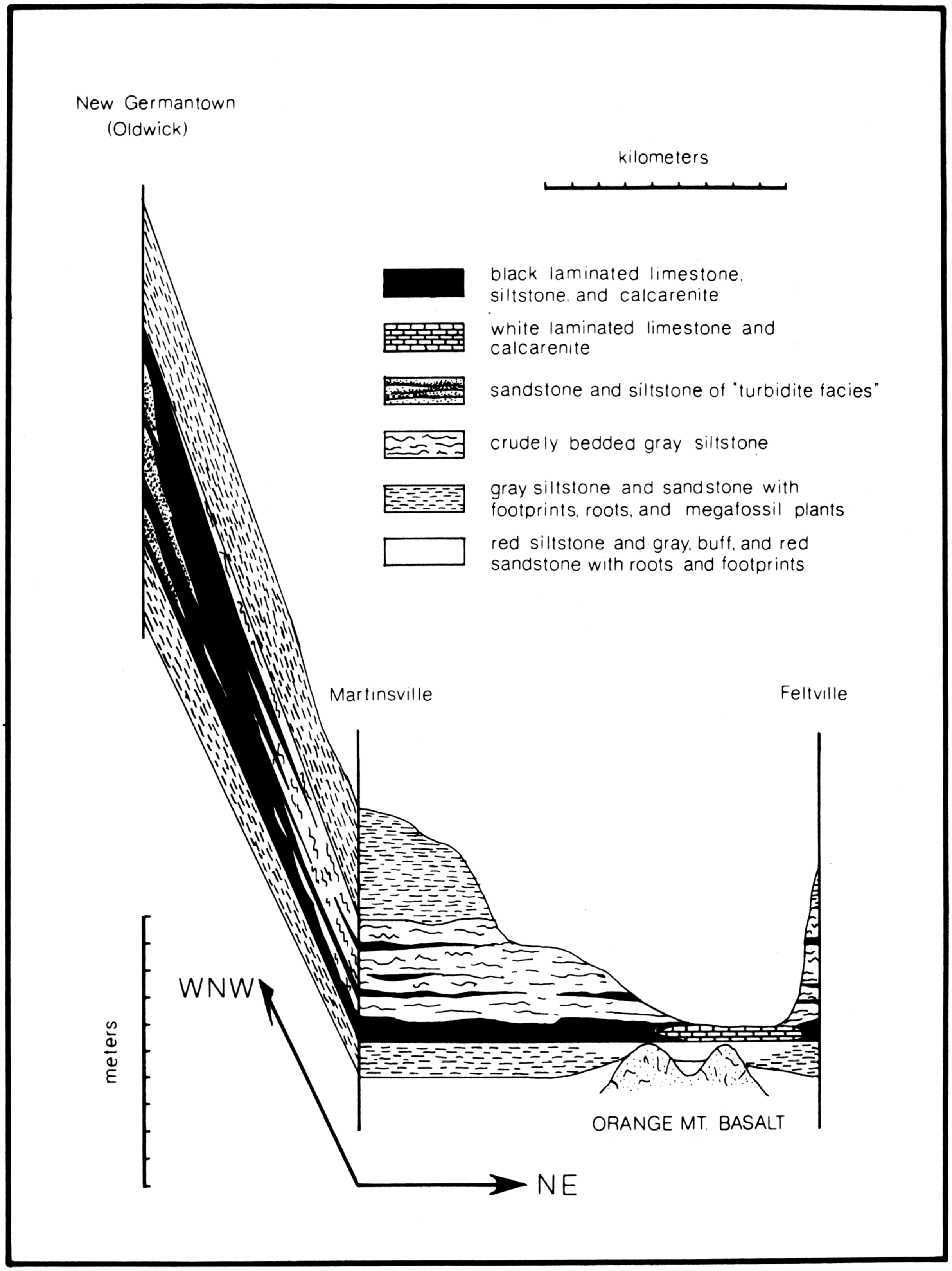


Fig.14 Lateral facies relationship in Washington Valley member.

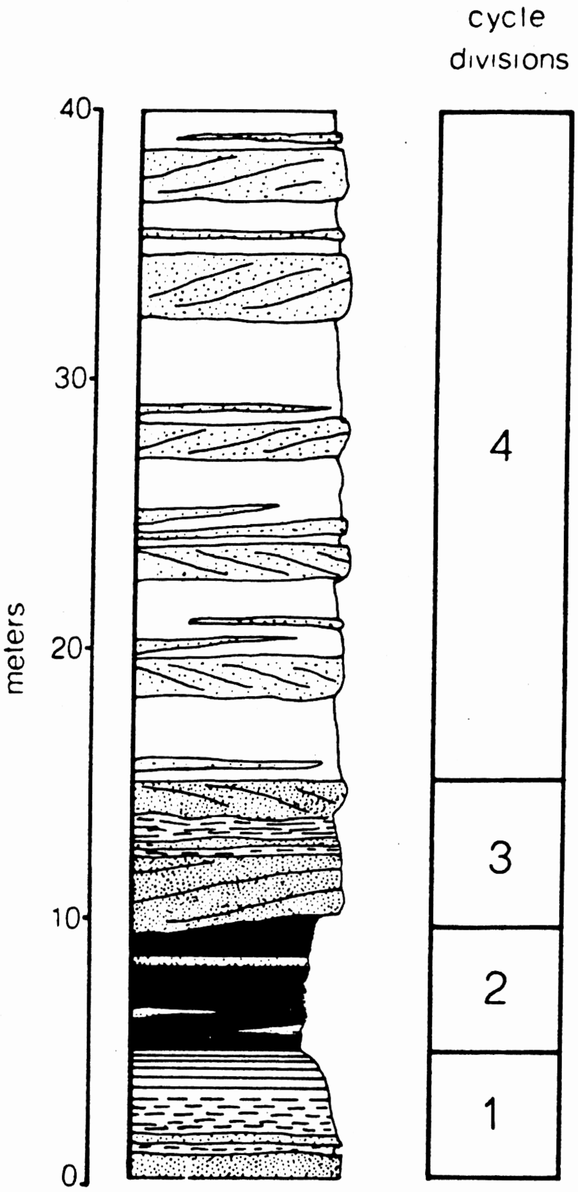


Fig. 15 Generalized Towaco Formation cycles. Description in text.

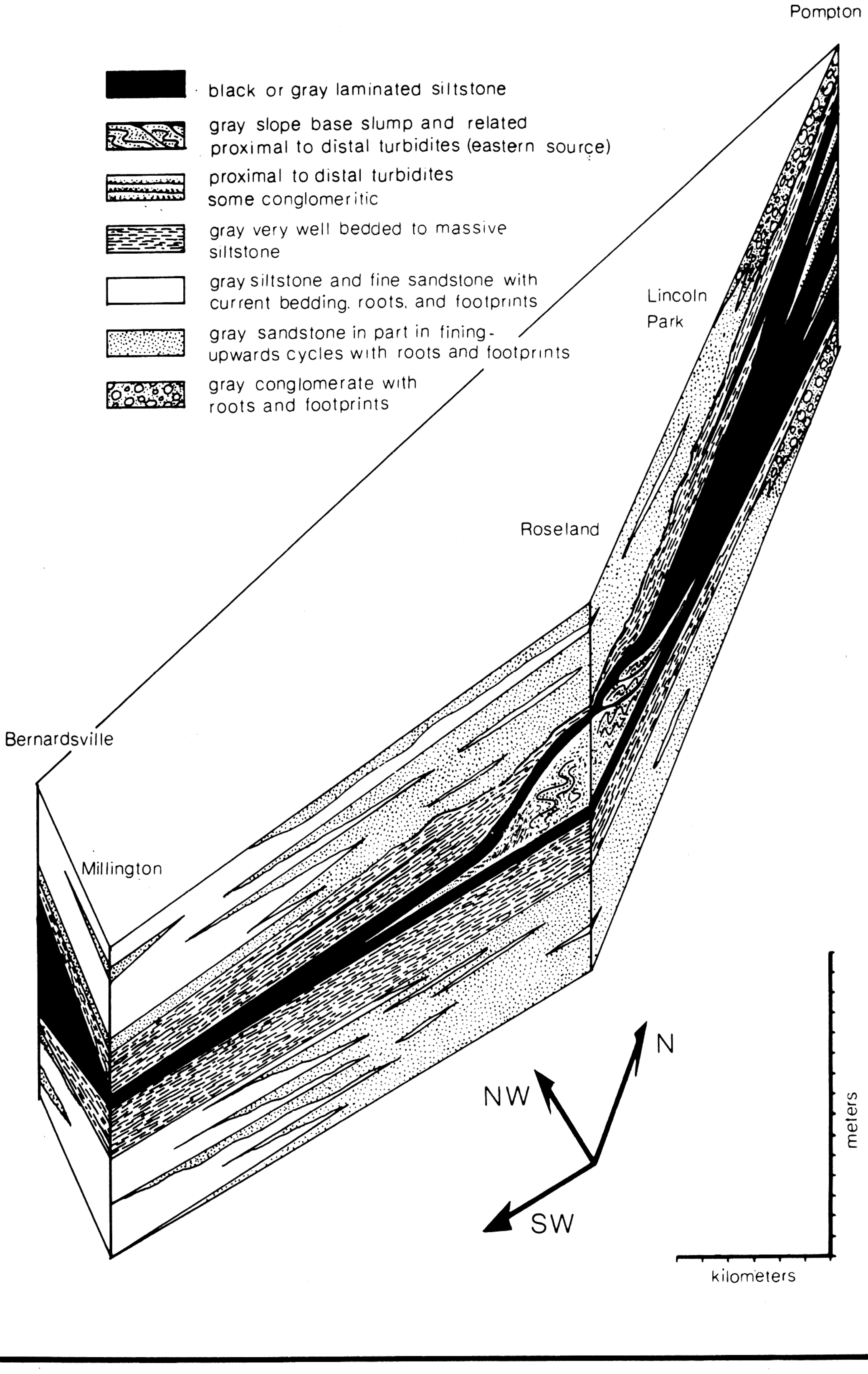


Fig. 16 Lateral facies relationship within divisions 1—3 of Towaco cycles.

Table 2

__Features explained by both the algal mat model and the stratified lake model__

1. production and preservation of microlaminated sediments
2. laminations composed of carbonate plus organic-rich couplets
3. organic component of laminae algal in origin at least in part

__Features unique to each model__

A. Algal mat model

   1. laminations of limited extent laterally
   2. few if any fish
   3. shallow water microlaminated zone surrounds in time and space a deeper water non-laminated zone
   4. associated blister and pinnacle mats

B. Stratified lake model

   1. laminations traceable over large area
   2. abundant whole fish
   3. laminated lithosome is deepest water deposit and lacks a central non-laminated portion
   4. blister and pinnacle mat structures absent

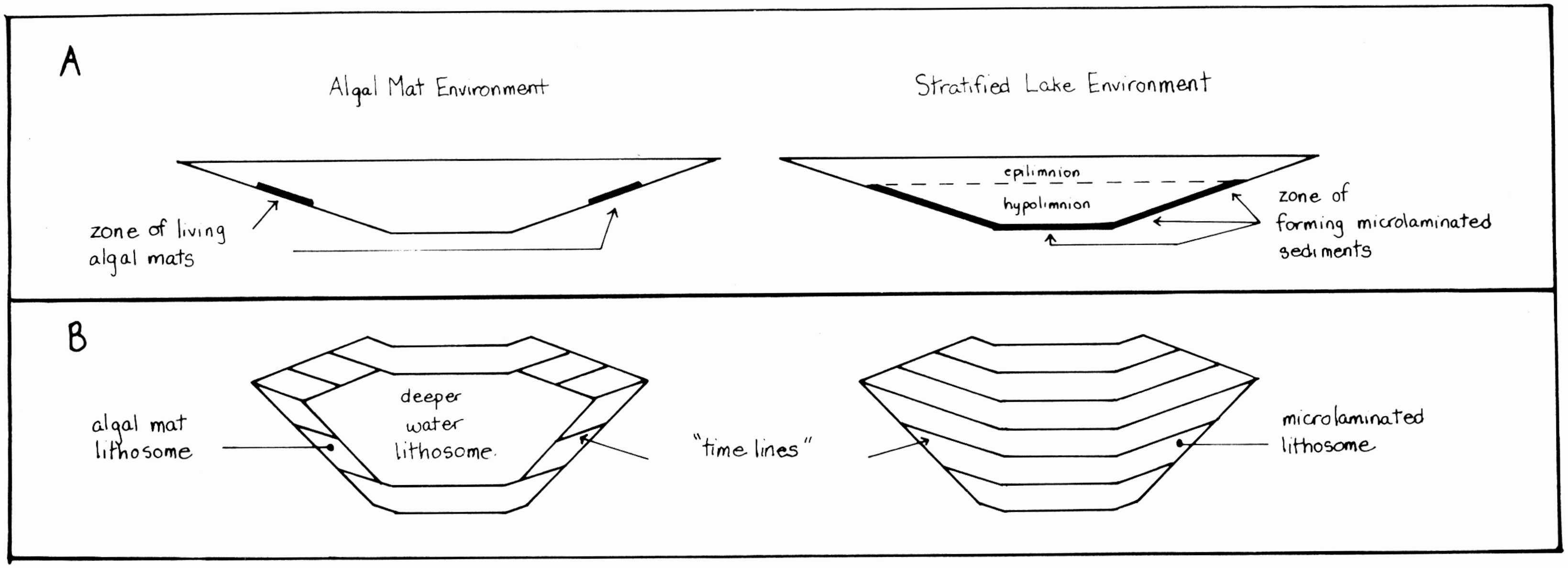


Figure 17

Diagram contrasting lakes conforming to the Agal Mat Model and the Stratified Lake Model (A) and the shape of the sediment lithosomes they should produce (B) after one episode of expansions and contraction of the lake. For construction of the shapes of the lake sediment lithosomes the shape of the lake basin was held constant throughout sedimentation as water level changed. Each "time line" marks off equal thicknesses of sediment deposited during a constant unit of time and marks off a plane deposited over the lake simultaneously.

Note that in the Algal Mat Model lithosome "time lines" are discontinuous while in the Stratified Lake lithosome they are continuous. In the Stratfield Lake Model "time lines" can be considered microlaminae or varves.

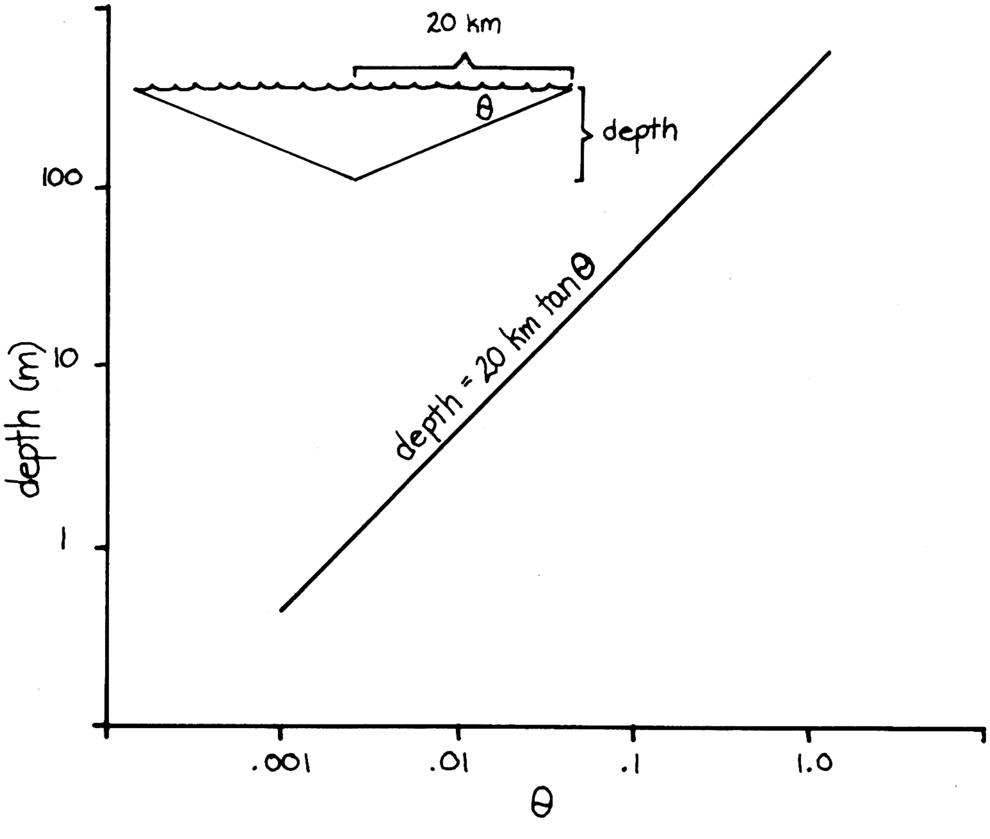


Figure 18

The relationship between lake depth and the angle of slope of the basin floor assuming a 20 km distance from the deepest part of the lake to the shore and a triangular cross section of the lake.

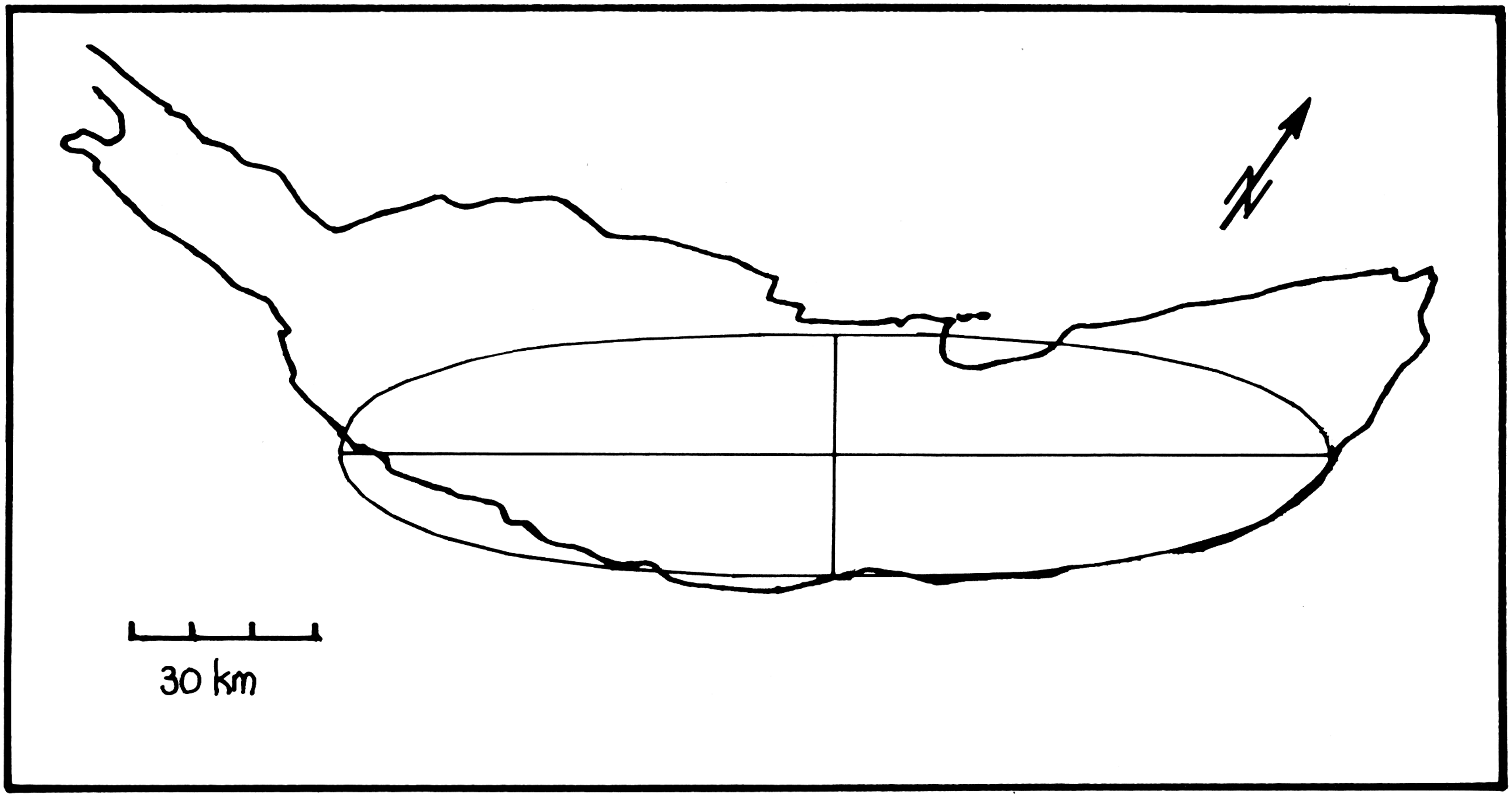


Figure 19

Elipse encompassing most of the known distribution of the microlaminated beds in the Lockatong Formation. The major and minor axial diameters are 170 and 40 km respectively, which correspond to the greatest and least possible fetches for winds blowing across the part of the lake which is assumed to be deeper than the depth of wave mixing.

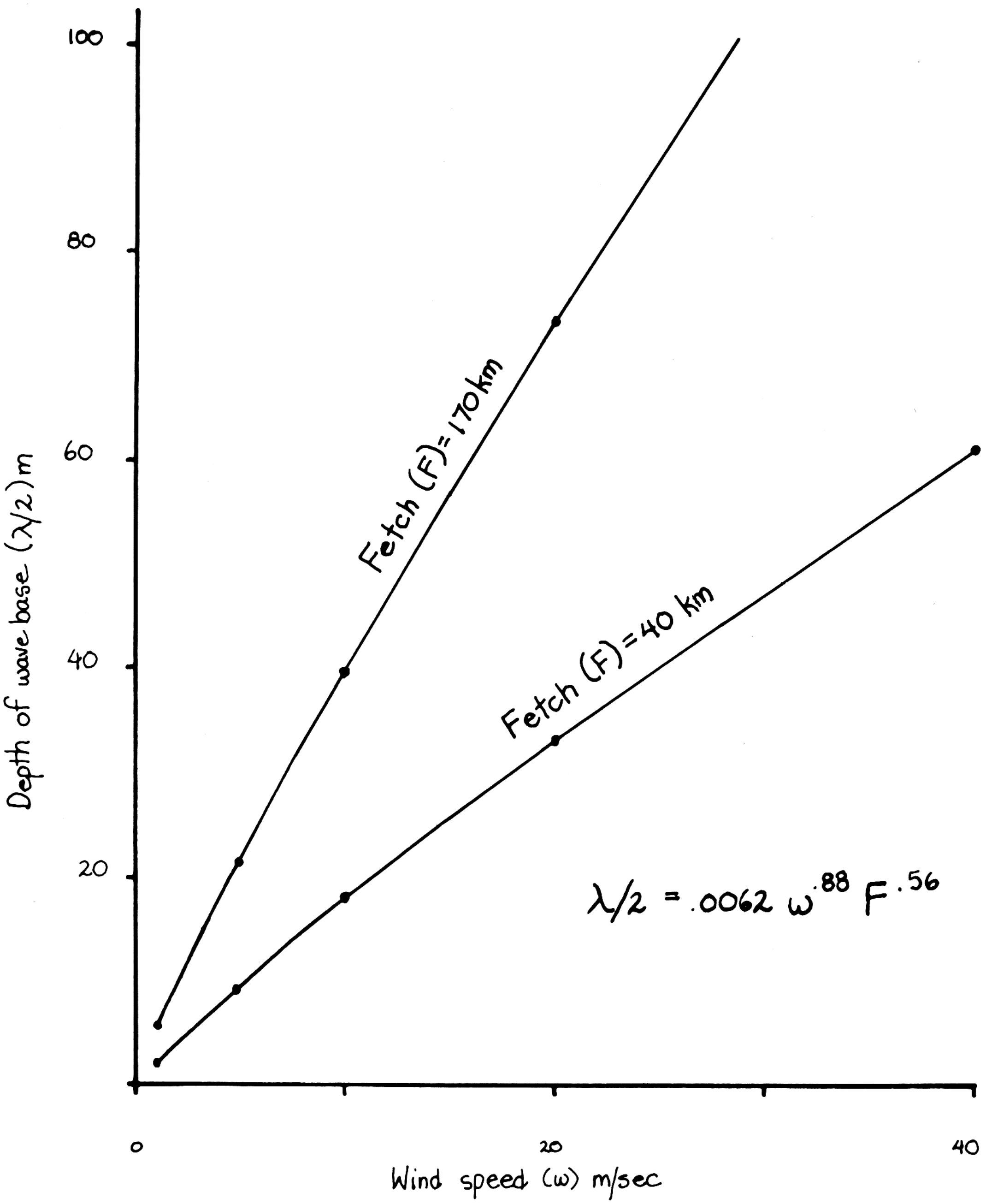


Figure 20

Graph of the relationship between wind speed (W) and depth of wave base ($\lambda/2$) for the greatest and least fetches of Figure 19.

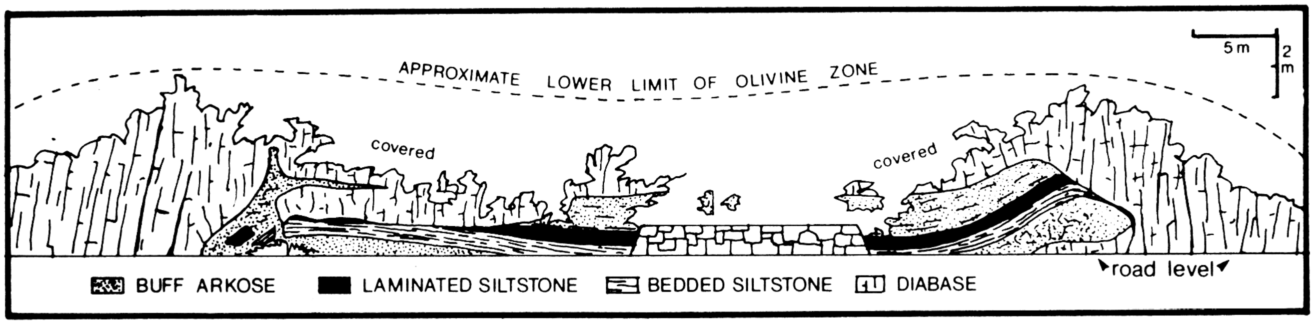


Fig. 21 Exposures of discordant contact of Palisade Diabase and Lockatong Formation, south of George Washington Bridge on road from River Road to Ross Dock in Palisades Interstate Park, Fort Lee.

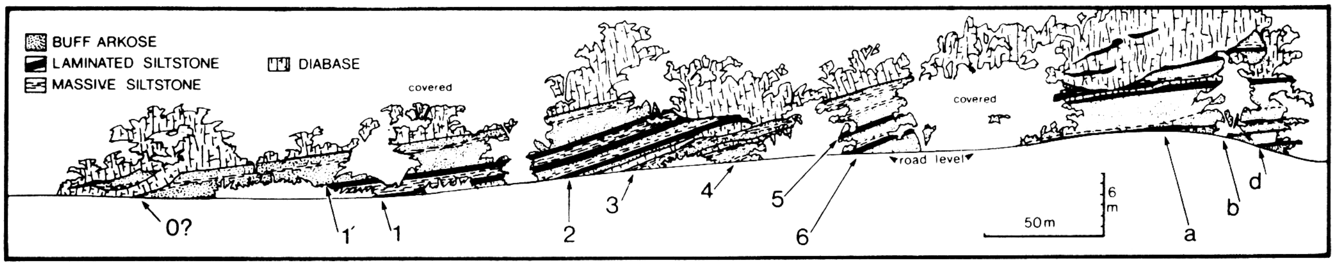


Fig. 22 Exposures of Palisade Diabase and cycles 0-d west of Ross Dock, Palisades Interstate Park, Fort Lee.

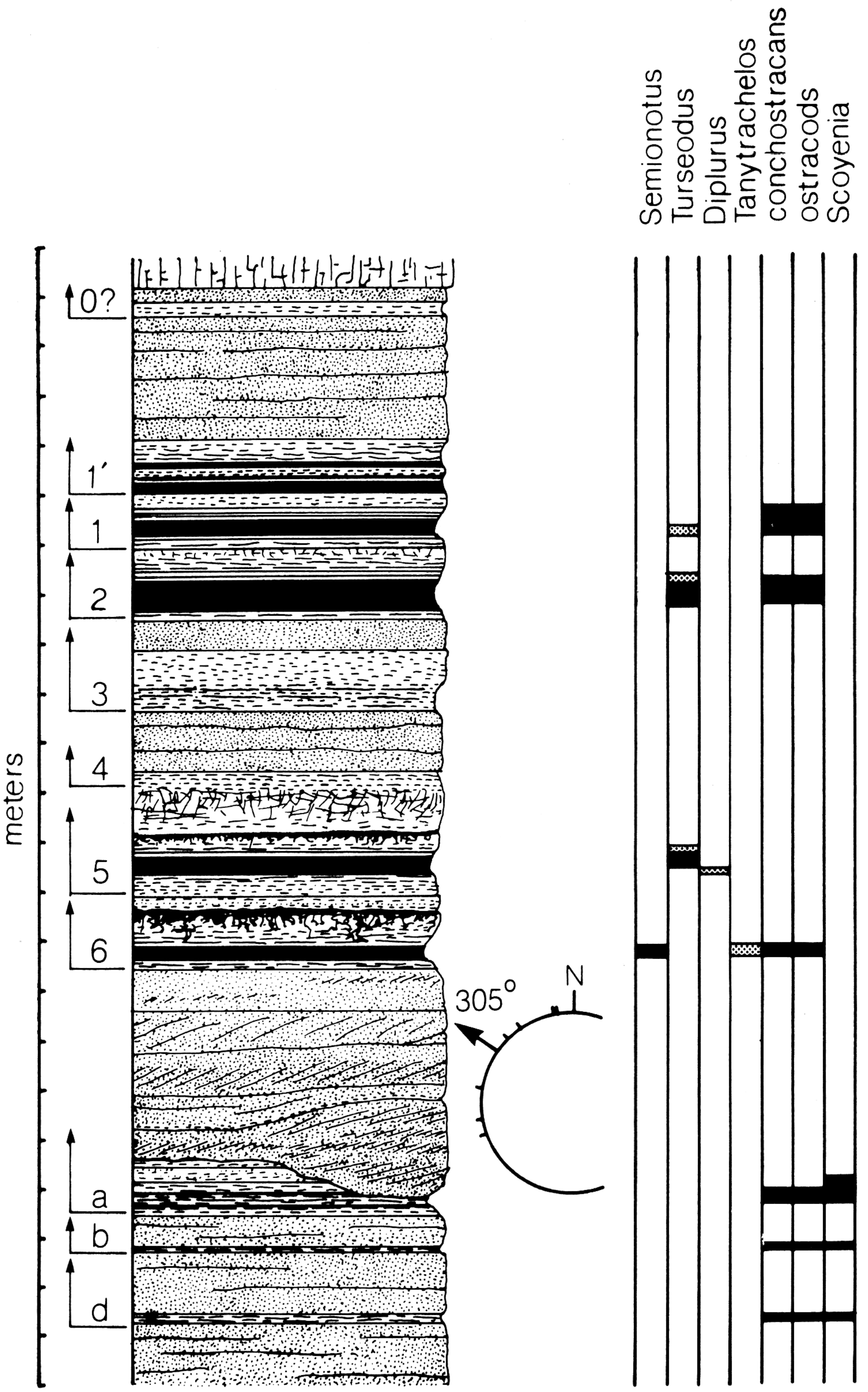


Figure 23

Section west of Ross Dock, Palisades Interstate Park, Fort Lee showing distribution of major fossils and paleocurrent data (n-7) for crossbedded buff arkose between cycles 6 & a.

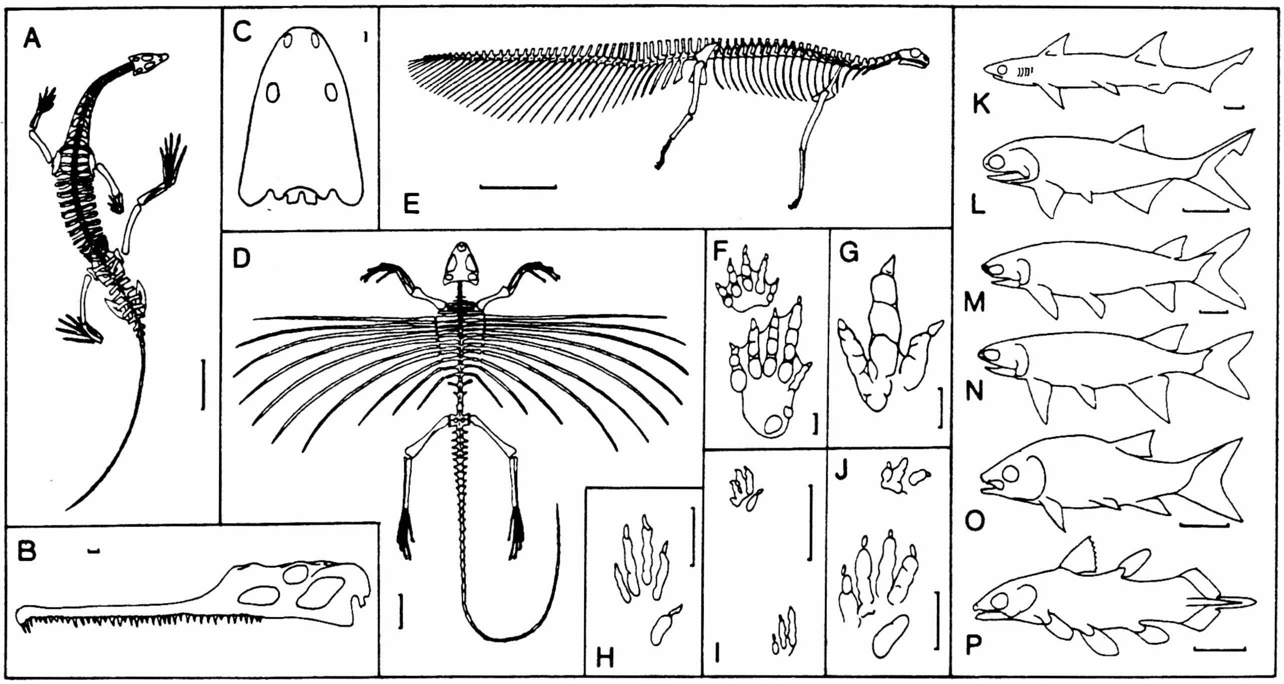


Fig. 24 Lockatong Formation vertebrates and reptile footprints from the upper Stockton, Formation (for repository abbreviations see Olsen, this Fieldbook) (From Olsen, In prep.); A, *Tanytrachelos* cf. *ahynis,* reconstruction; B, Rutiodon carolinensis, reconstruction; C, *Eupelor durus,* reconstruction; D, *Icarosaurus siefkeri,* reconstruction; E, "deep tailed swimmer", tentative reconstruction; F, *Apatopus lineatus,* composite right manus and pes; G, *Grallator* sp., left pes; H, *Gwyneddichnium minore,* right pes; I, *Rhynchosauroides brunswicki,* right manus and pes; J, *Chirotherium* cf. *eyermani,* right manus and pes; K, *Carinacanthus jepseni,* reconstruction; L, *Turseodus* sp., reconstruction; M, *Synorichthys* sp. reconstruction; N *Cionichthys* sp., reconstruction; O, semionotid of the *"Semionotus brauni* group", reconstruction; P, *Diplurus newarki,* reconstruction. Scale 2 cm.

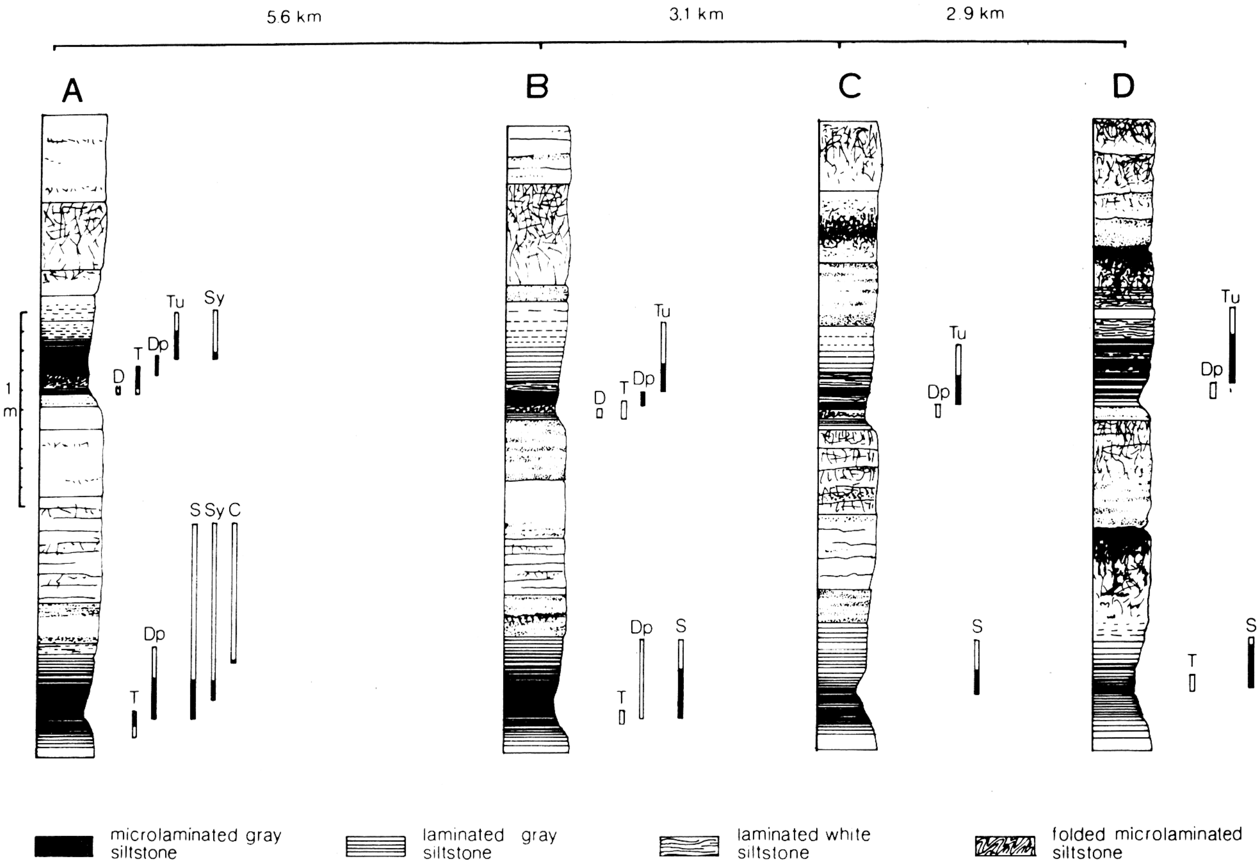


Fig. 25 Comparison of section of cycles 5 and 6 showing distribution and preservation style of fish: A, Kings Bluff, Weehawken; B, Gorge and River Roads, Edgewater; C, "old trolley route", Fort Lee, D, west of Ross Dock, Palisades Interstate Park, Fort Lee.

Abbreviations for fossils as follows: D, "deep tailed swimmer"; Dp, *Diplurus;* C, *Cionichthys:* T, Tanytrachelos; TU, *Turseodus;* Sy, Synorichthys; S, *Semionotus.* Open column under abbreviation of taxon stands for presence of dissarticulated fish while solid column indicates the presence of complete specimens.

Lithogic symbols as in Figures 29 and 30 except as shown.

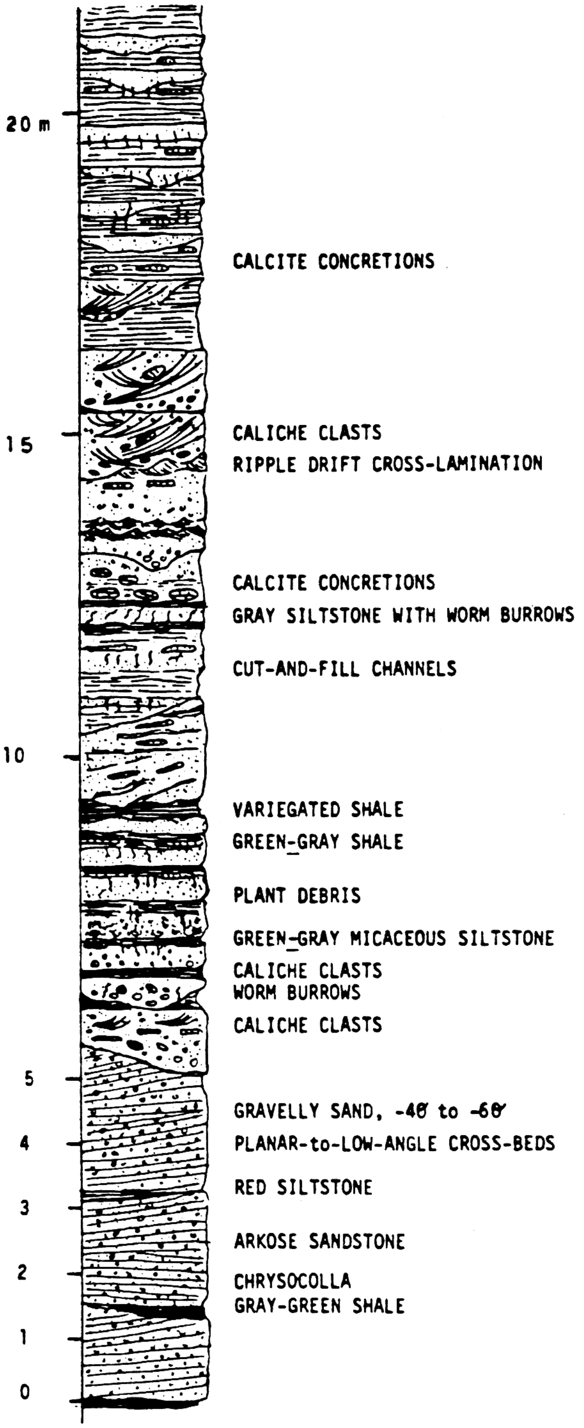


Fig. 26 **Columnar section through part of the Passaic Formation, an inferred fluvial-playa sequence; I-280, East Orange.**

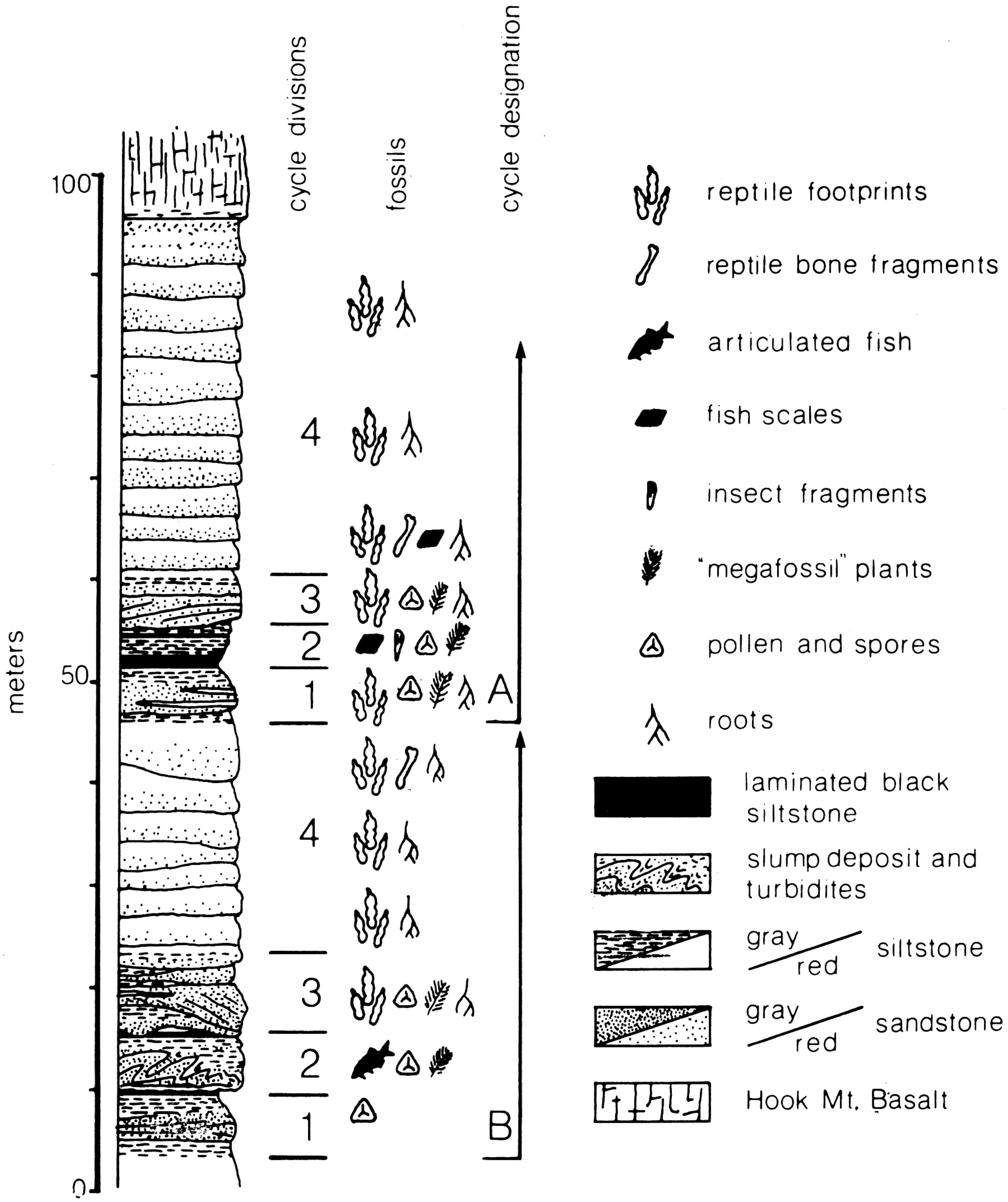
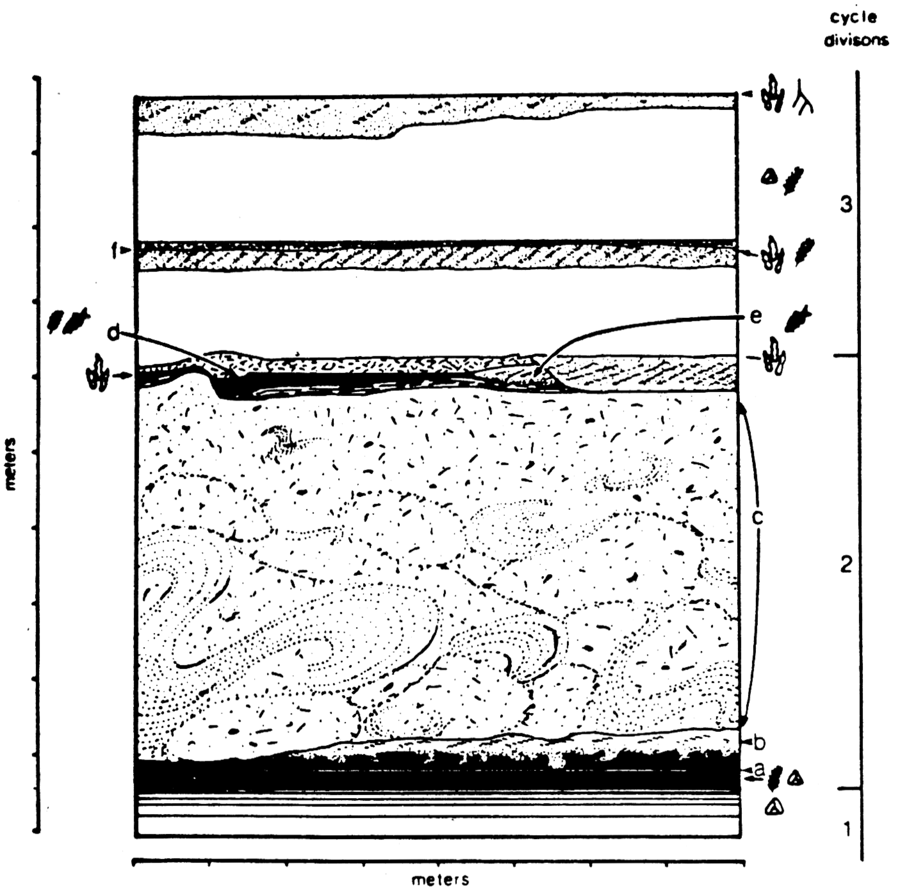


Figure 27

Section at Roseland Quarry. Only cycle A and Hook Mountain Basalt are presently exposed.



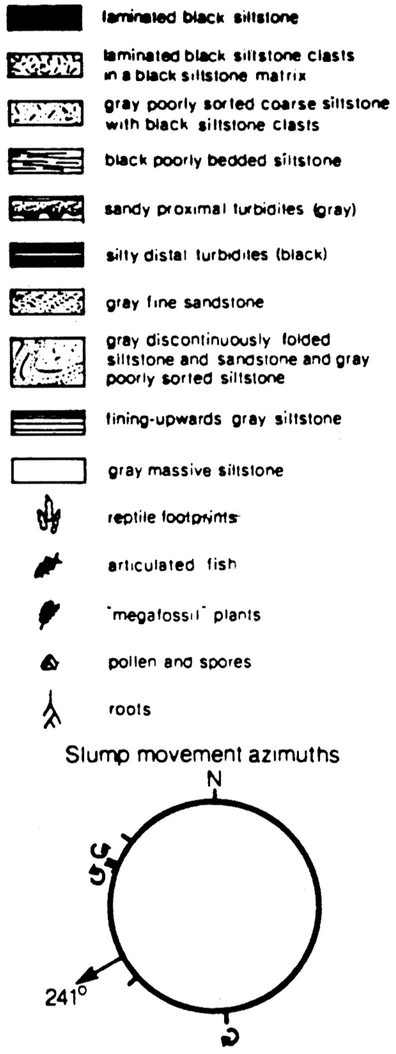


Fig. 28. Section along strike of upper part of division 1, all division 2, and lower division 3 of cycle B Roseland Quarry.

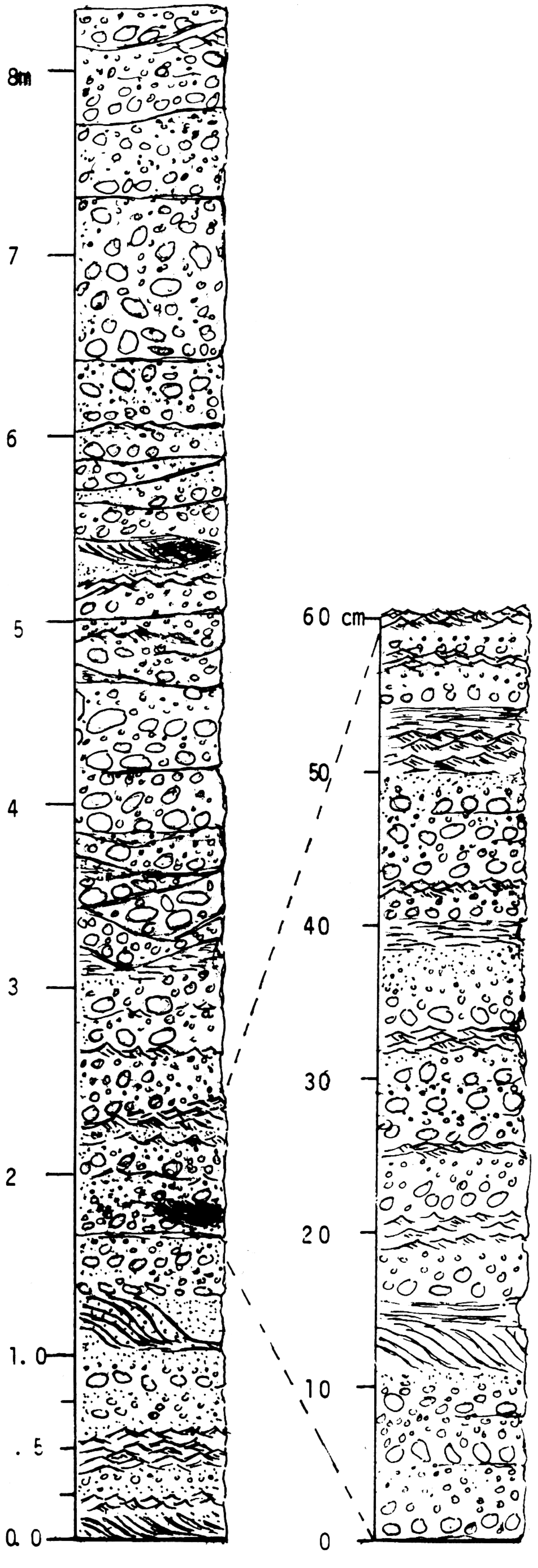


Fig. 29 Stratigraphic section through that part of the Boonton Formation inferred to represent an alluvial fan prograding eastward from the western border fault.

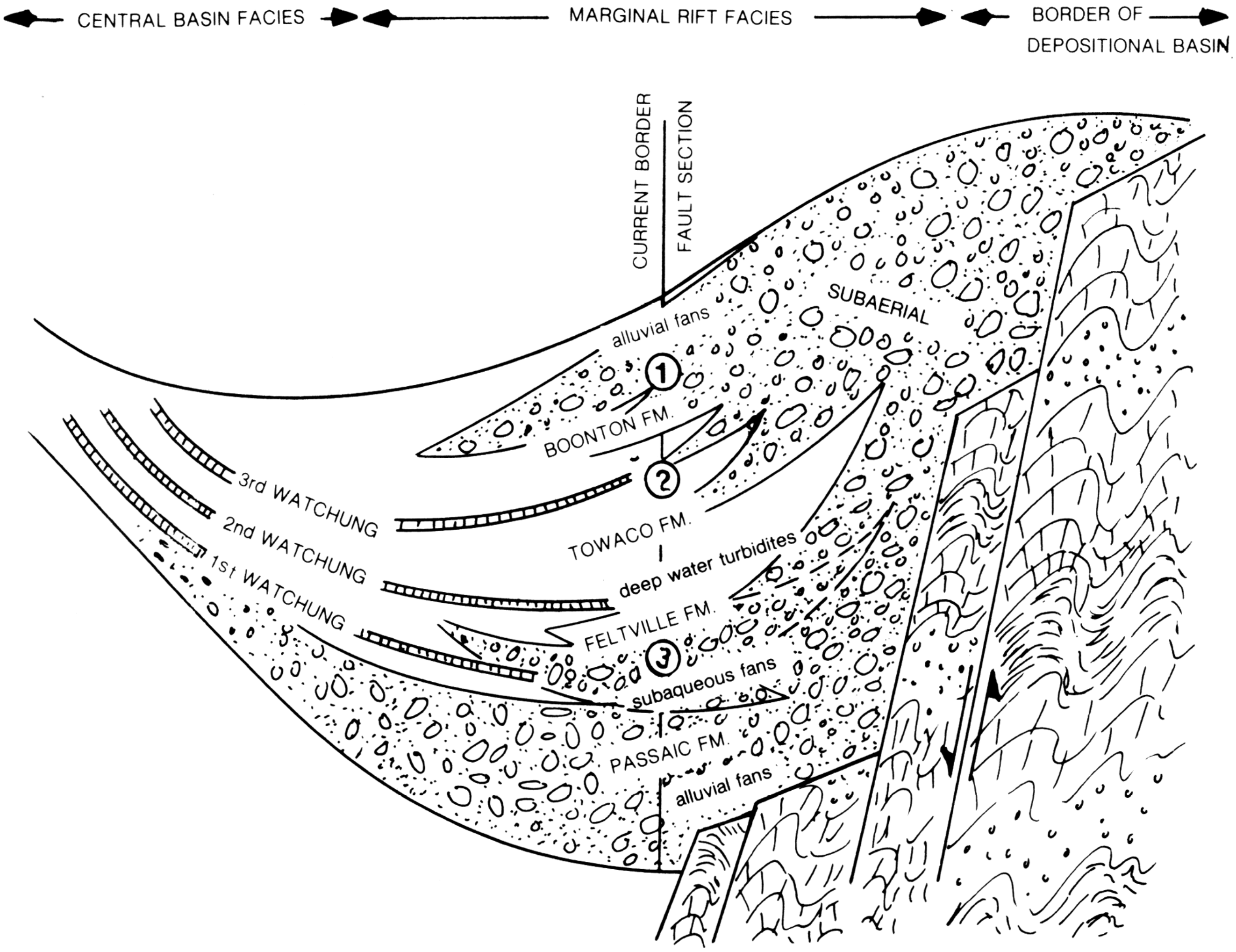


Fig 30 Fan delta sequence, showing the distribution of facies in the basin.

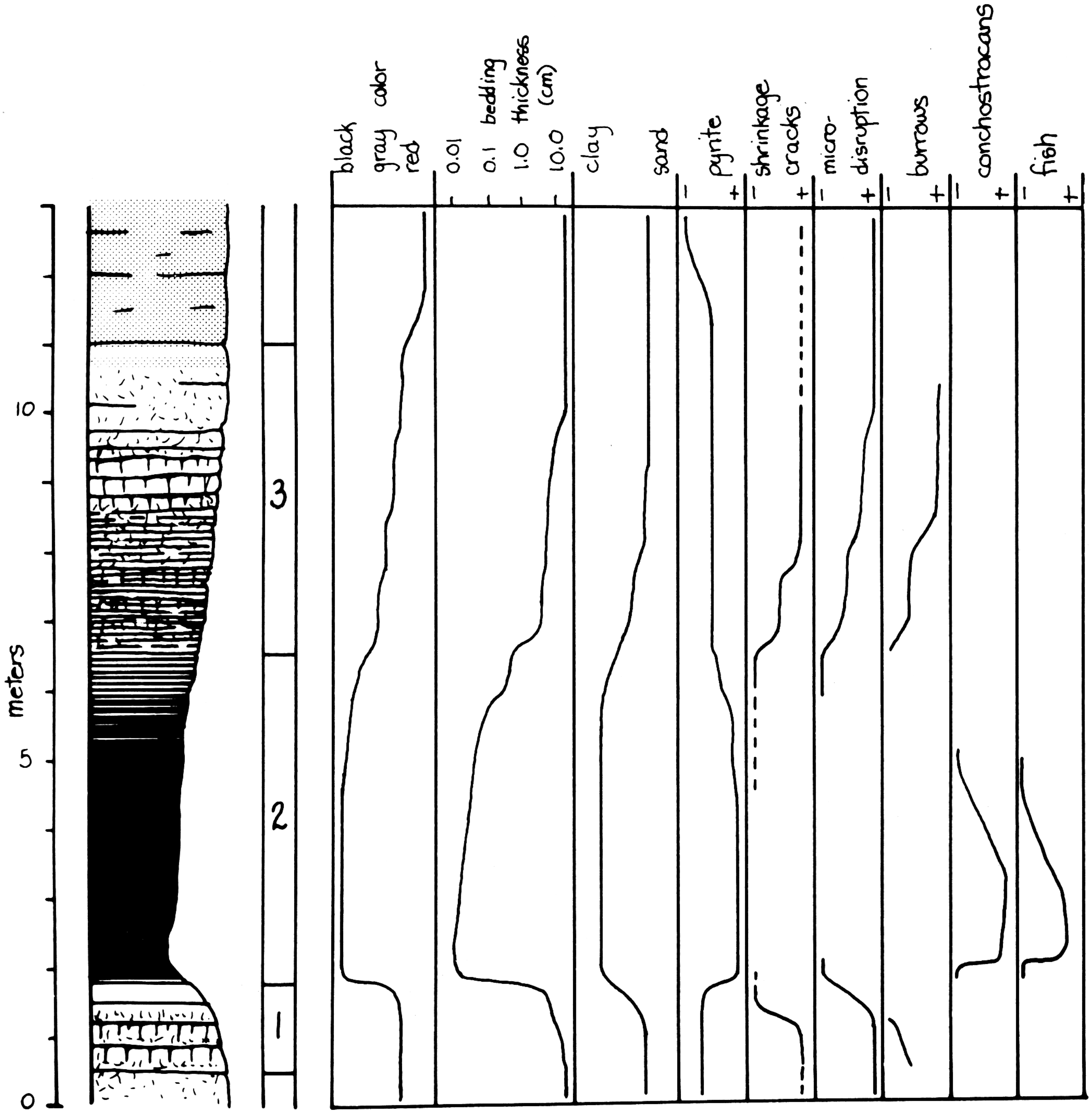


Figure 31

Short cycle comprising a part of McLaughlin's Member D of the Passaic Formation. Exposures are along Warford Creek (Stop 4).

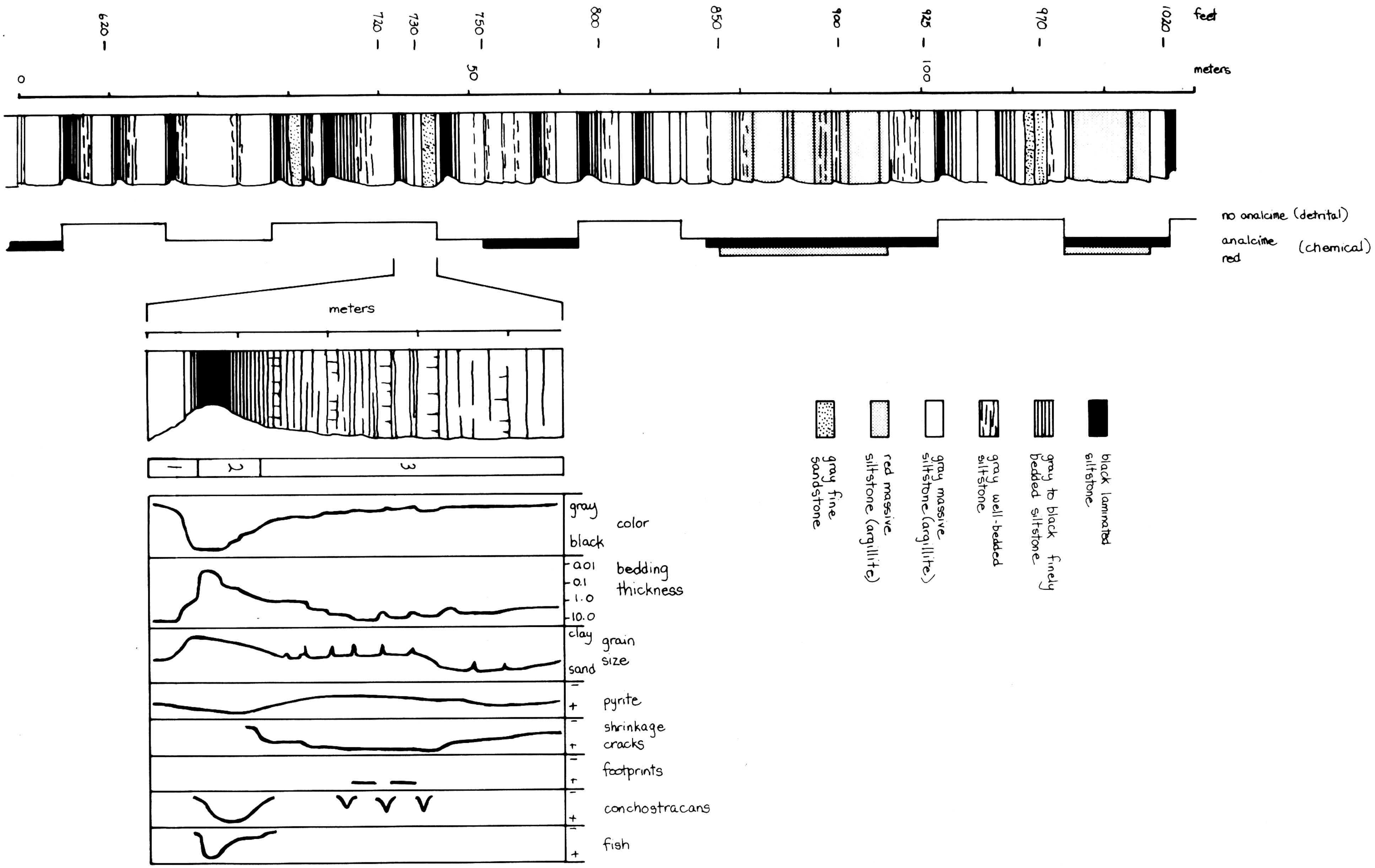


Figure 32

Detailed section above Van Houten's (1969) 600 foot mark (Stop 5 of this guide book) and detail of a single detrital cycle. Note that this detrital cycle is the only one in the section known to have whole fish and a well developed microlaminated unit.

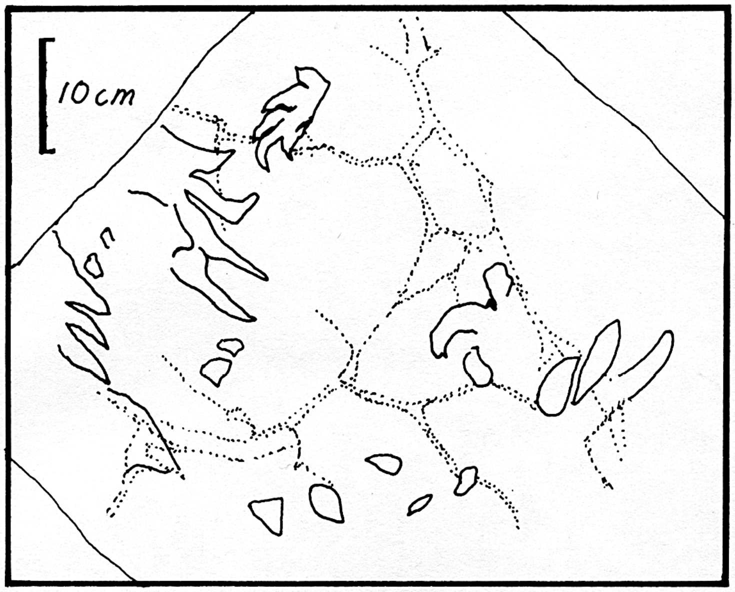


Figure 33

Footprints from division 3 of the single detrital cycle detailed in Figure 32. These are very poor footprints apparently belonging to the footprint-genus Apatopus and were probably produced by a swimming phytosaur in shallow water. About 10 cm above this bedding surface is a unit with irregular parting planes covered with small conchostracans.

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