FIELD GUIDE TO THE LATE TRIASSIC PORTION OF THE NEWARK BASIN SECTION IN THE DELAWARE VALLEY, NEW JERSEY

By

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with contributions by

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INTRODUCTION

Eastern North America includes the classic Atlantic-type passive continental margin formed by the breakup of the supercontinent of Pangaea. The Triassic initiation of the breakup was marked by the formation of rifted crust all along the axis of the future Atlantic, from Greenland to Mexico. In eastern North America, nine major rift basins, mostly half-graben, and several minor basins are exposed from Nova Scotia to South Carolina, with many more buried below the coastal plain and on the continental shelf (Figure 1). The exposed rift basins, which closely follow the trend of the Appalachian orogen, filled with thousands of meters of continental sediments, minor mafic volcanic rocks, and diabase plutons and dikes over a period of 45 million years. The faulted, tilted, and eroded rift strata are termed the Newark Supergroup (Van Houten, 1977; Olsen, 1977; Froelich and Olsen, 1984). The purpose of this field trip and paper is to provide a review of the geology of the Newark Basin (Figures 1, 2) division of the Newark Supergroup in the Delaware Valley.

GEOLOGICAL CONTEXT

Newark Supergroup rifts lie entirely within the Appalachian Orogen which, as presently understood, is divisible into three broad structural zones: 1) a western thin-skinned zone of allochthonous sheets lying on the essentially undeformed North American craton; 2) a central thick-skinned zone of rooted thrust slices and accreted terranes; and 3) an eastern zone transitional

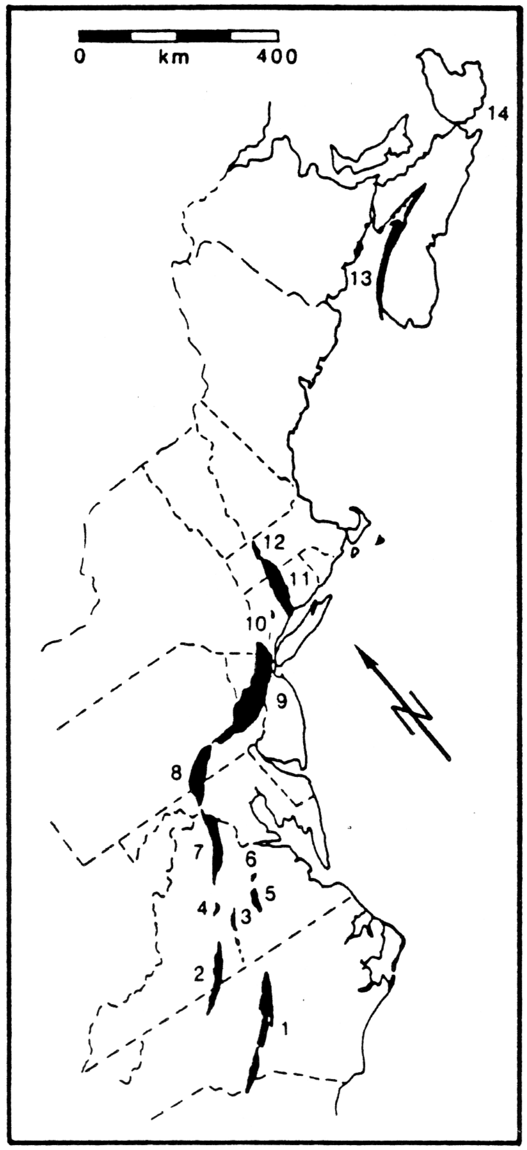

Figure 1. The Newark Supergroup of eastern North America (in black): 1) Deep River Basin; 2) Dan River Basin; 3) Farmville Basin Complex; 4) Scottsville Basin; 5) Richmond Basin; 6) Taylorsville Basin; 7) Culpeper Basin; 8) Gettysburg Basin; 9) Newark Basin; 10) Pomperaug Basin; 11) Hartford Basin; 12) Deerfield Basin; 13) Fundy Basin; 14) Chedabucto Basin (=Orpheus Graben).

to oceanic crust. The western zone consists of thin (2-10 km) allochthonous slices separated from relatively undeformed North American craton by a low angle detachment (corresponding to zone 2 of Allmendinger and others, 1987). This thin-skinned zone is separated from the thick-skinned zone by an east-dipping ramp which may extend to MOHO (zone 3 of Allmendinger and others, 1987). In proximity to the ramp (but regionally discordant to surface trends) is the Appalachian gravity gradient which is often considered to mark the edge of the Precambrian-Early Paleozoic continent. Above and immediately to the east of this ramp are rooted slices of cratonic rocks and to the east of this is the first of several apparent sutures with accreted terranes (within zone 4 of Allmendinger and others 1987). The eastern zone, transitional to oceanic crust, is as yet poorly known. It lies to the east of the basement hinge zone of the continental crust and probably consists of fragments of continental crust and Mesozoic igneous rocks (Klitgord and others, 1988).

Cook and others (1981) have plausibly argued that development of the Precambrian and earliest Paleozoic rifting and Iapetus passive margin established the configuration of the eastern edge of the North American craton. A succession of Paleozoic accretionary and collisional events reactivated the old Precambrian-Paleozoic continental margin as a ramp, with repeated emplacement of thin allochthonous slices toward the west in fold and thrust belts. The presumably thickened crust was then thinned during the formation of the present Atlantic margin in the Early

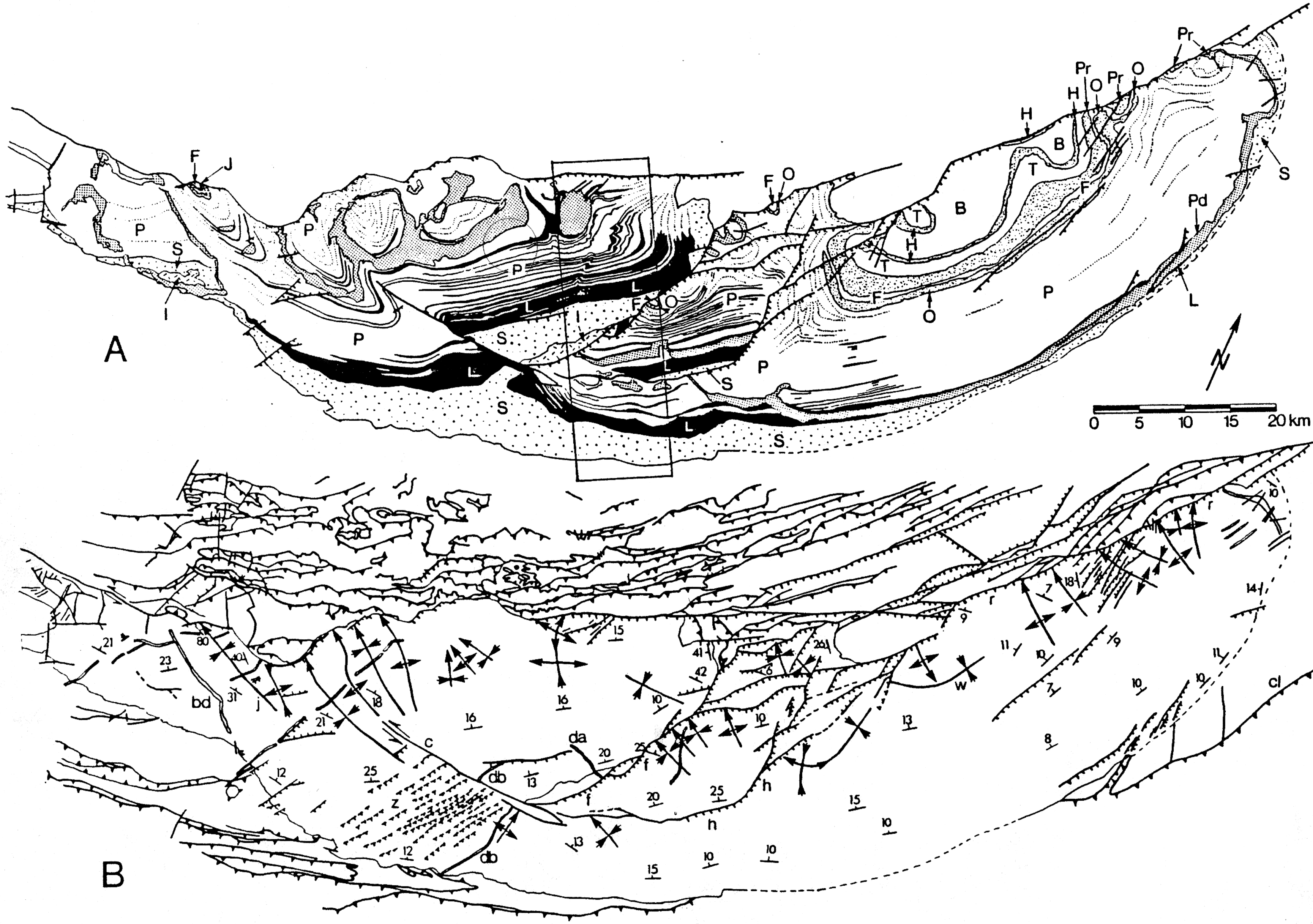

Figure 2. Geologic (**A**) and Structure (**B**) maps of the Newark Basin. Inset in (**A**) shows position of field stop key, Figure 7. Abbreviations as follows: **B**) Boonton Formation; **F**) Feltville Formation; **H**) Hook Mountain Basalt; **I**) Inlier of Paleozoic and Precambrian rocks; **J**) Jacksonwald Basalt (=Orange Mountain Basalt); **L**) Lockatong Formation; **O**) Orange Mountain Basalt; **P**) Passaic Formation (where conglomeritic called Hammer Creek Formation in Pennsylvania); **Pd**) Palisade Diabase; **Pr**) Preakness Basalt; **S**) Stockton Formation; **T**) Towaco Formation. Figure adapted from Schlische and Olsen (this volume).

Mesozoic, with the greatest thinning being manifest in the eastern zone of transitional crust, east of the basement hinge line.

The Newark basin is a block-faulted, deeply eroded, half-graben (Figures 2 and 3), very much like other Newark Supergroup basins. It seems likely it sits directly over the deep seated east-dipping ramp separating the thin skinned western zone from the thick skinned, allochthonous eastern zone. Most of the basin's northwest margin is bound by low angle (20°-65°) normal, right and left oblique faults which are reactivated thrust faults developed during the Paleozoic Taconic, Acadian, and Alleghenian Orogenies (Ratcliffe, 1980; Ratcliffe and Burton, 1985; Ratcliffe and others, 1986) (Figure 3).

The Newark Basin appears to have been a relatively simple half graben bound by these faults during most of it history (Olsen, 1985; Schlische and Olsen, this volume). However, the basin is also cut by two major intra-basin faults (Flemington-Furlong and Hopewell-Chalfont faults) which break the basin into three fault blocks, repeating most of the section three times (Figure 2). These two intra-basin faults probably post-date most basin sediments (Olsen, 1985; Schlische and Olsen, this volume; Faill, this volume). Most sediments in the basin dip 5° to 15° to the northwest toward the northwestern border faults. However, the hanging walls of most fault blocks are warped into a series of anticlines and synclines which die out toward the opposite sides of the blocks. Because of the block faulting and folds, most stratigraphic intervals can be examined at the surface in three

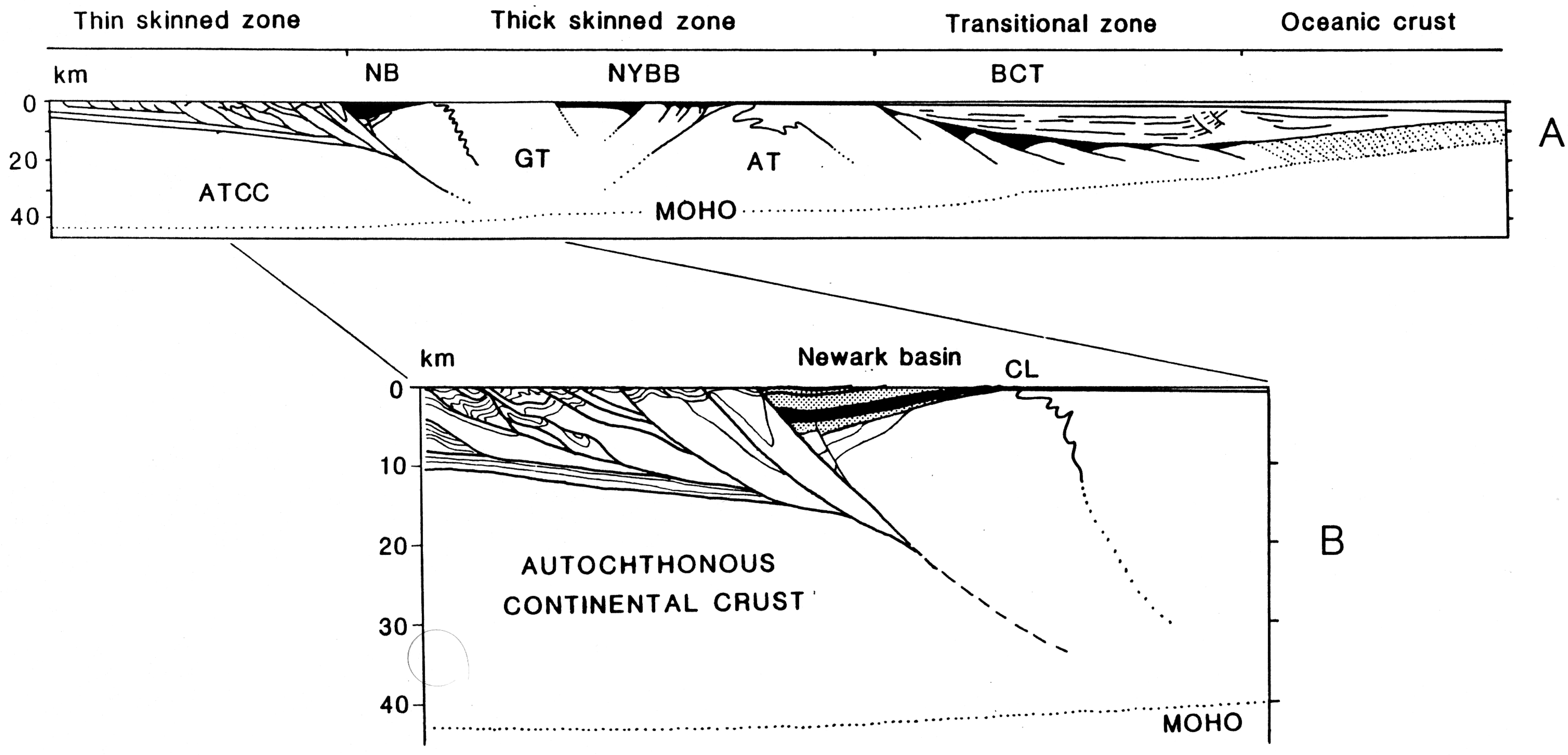

Figure 3. Generalized cross section through crust of eastern North America from New Jersey to the south east (see Figure 1) showing different crustal zones. In (**A**) rift basins are shown in black while in (**B**) The Lockatong Formation is the thick black layer in the Newark Basin while the thinner black layers higher in the section are the extrusive basalts. Abbreviations are: **AT**, Avalon Terrane; ATCC) Autochthonous continental crust **BCT**) Baltimore Canyon Trough; **CL**) Cameron's Line; **GT**) Gander Terrane; **NB**) Newark Basin; **NYBB**) New York Bight Basin. Based partly on sections in Klitgord and others (1988).

dimensions (Figure 2).

Sedimentation seems to have begun in the Middle Carnian or perhaps as early as the Ladinian of the Middle Triassic with the deposition of the predominantly fluvial Stockton Formation (Figure 4). The overlying Lockatong and Passaic formations were deposited as lacustrine ringed by fluvial sequences. Shortly after the Triassic-Jurassic boundary (preserved in the upper Passaic Formation) massive tholeiitic basalt flows covered the basin floor in three episodes, each consisting of two or more cooling units and thin sedimentary units (Orange Mountain, Preakness, and Hook Mountain basalts). These are separated by two sedimentary formations (Feltville and Towaco formations) and covered by the Boonton Formation. The syn- and post-extrusive formations were formed in similar environments to the Passaic and Lockatong formations except with a four- to six-fold increase in sedimentation rate. [The Passaic and overlying formations were included in the Brunswick Formation of Kümmel (1897) and the Watchung Basalt of Darton (1890); for a review of the stratigraphic nomenclature of the Newark Basin see Olsen (1980a and 1980b)]. Sedimentation seems to have ended by the Middle Jurassic during the period of block faulting, and this was followed by deep erosion, thermal subsidence, and coastal plain deposition along the entire Atlantic margin. On this field trip, only the Stockton, Lockatong and lower Passaic formations will be examined.

The Lockatong and Passaic formations together make up a natural

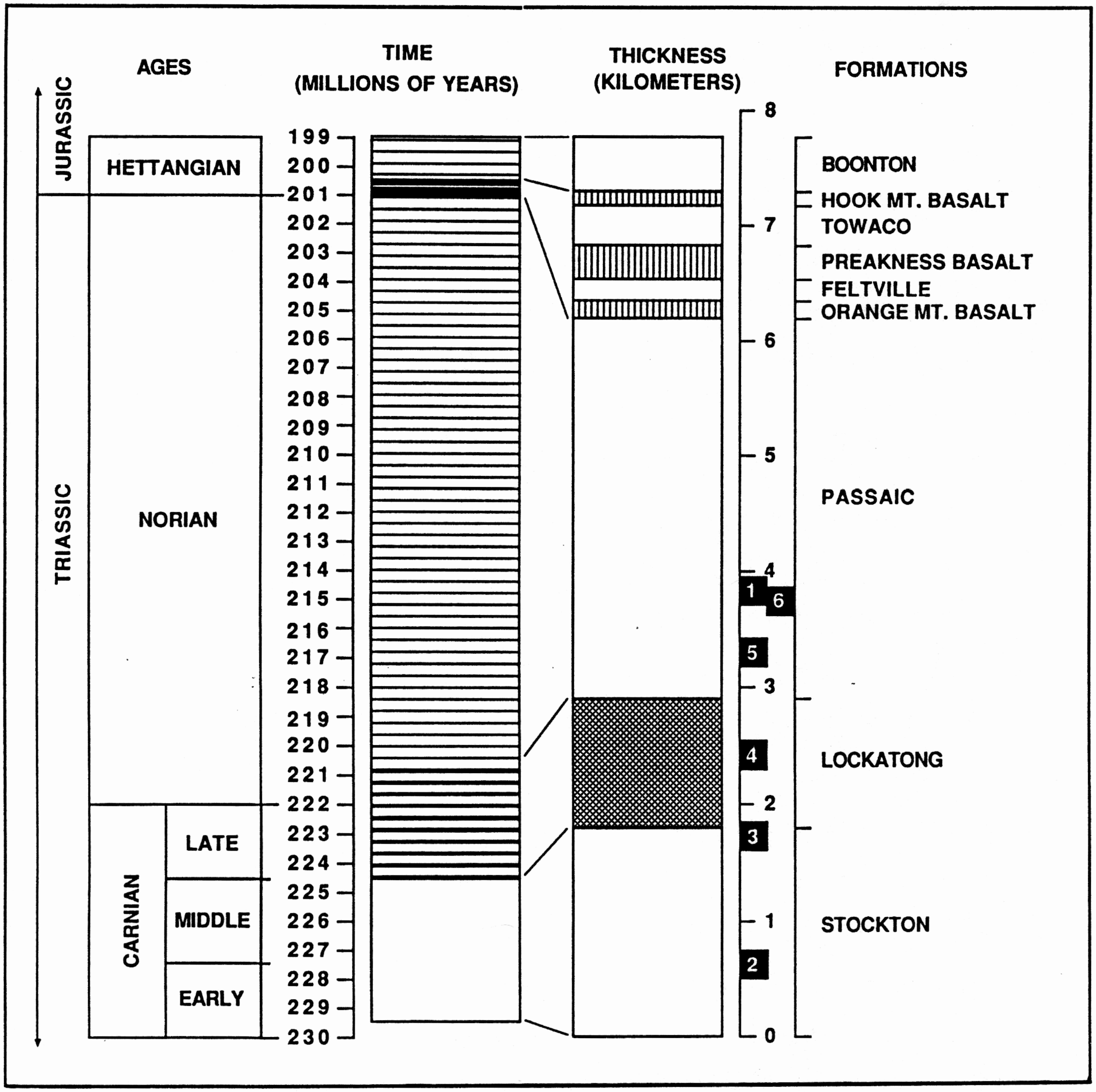

Figure 4. Stratigraphy of the Newark Basin in time based on calibration by Van Houten cycles (left) and thickness (right) showing stratigraphic position of the field stops.

facies package united by a common theme of repetitive and permeating transgressive-regressive lake level sequences called Van Houten cycles after their discoverer (Van Houten, 1964, 1969, 1980; Olsen, 1980a, 1980c, 1984, 1986). The fundamental Van Houten cycle consists of three divisions interpreted as lake transgression, high stand, and regression plus low stand facies (Figure 5).

1. Division 1 is a calcareous claystone to siltstone with pinch and swell lamination, thin bedding, occasional desiccation cracks, burrowed horizons, stromatolites, and oolites. This represents a lacustrine transgressive sequence with shoreline deposits.

2. Division 2 is a laminated to microlaminated calcareous claystone and siltstone, or limestone, with rare to absent desiccation cracks. This division has the highest organic content of the cycle and fish and other animal fossils are sometimes abundant; it represents the lake's high stand deposit.

3. Division 3 is a calcareous claystone and siltstone, with abundant desiccation cracks, burrowed and rooted horizons, vesicular and crumb fabrics, and reptile footprints. Division 3 represents the regressive and low stand deposit; the lake was at least occasionally dry with incipient soil development.

These Van Houten cycles were apparently produced by the rise and fall of very large lakes that responded to periodic climate changes controlled by variations in the earth's orbit (Van Houten, 1969; Olsen, 1984, 1986). Van Houten cycles also make up at least three orders of compound cycles (Figure 6). Fourier analysis of

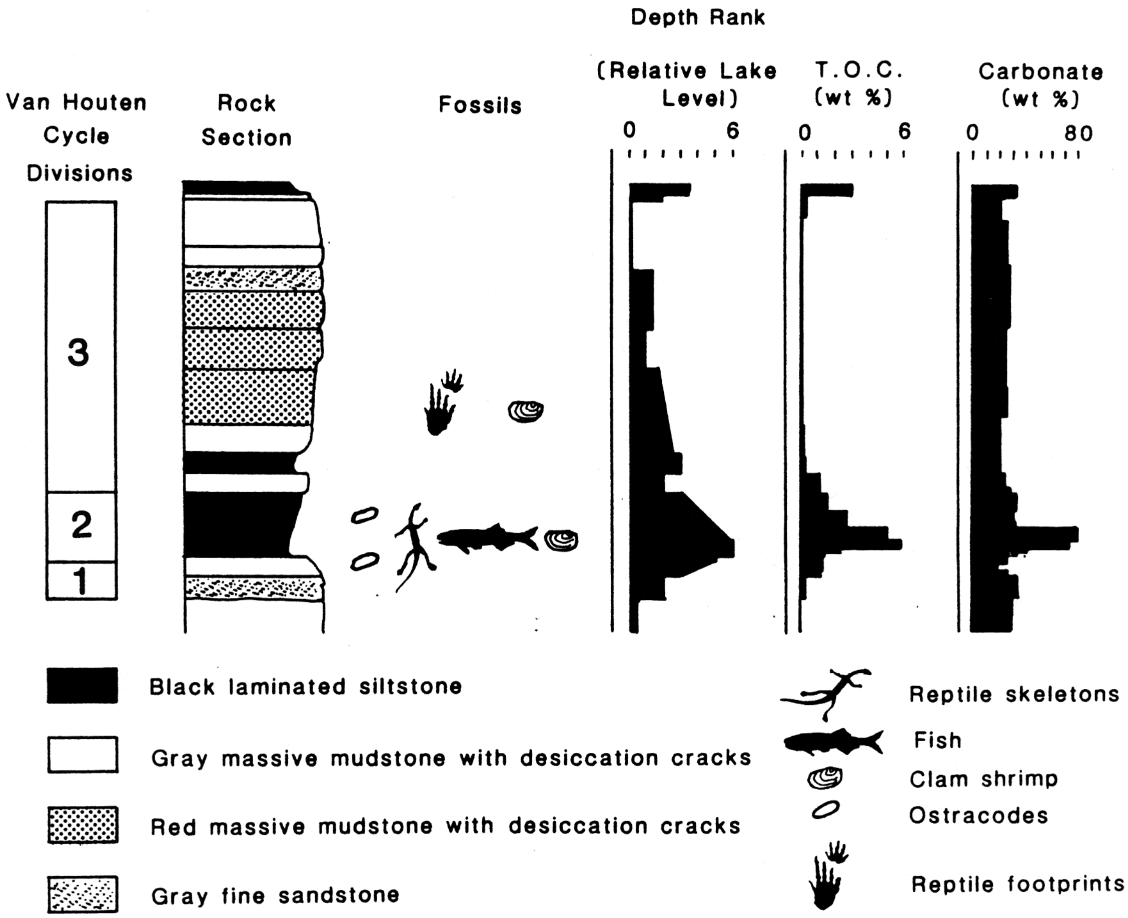

Figure 5. Generalized Van Houten cycle.

long sections of the Late Triassic Lockatong and Passaic formations show periodicities in time of roughly 21,000, 41,000, 95,000, 125,000 and 400,000 years, calibrated by radiometric time scales and varve calibrated sedimentation rates. These periodicities are in accord with the orbital theory of climate change.

The orbital theory of climate change states that celestial mechanical cycles of the earth's orbit, such as the precession of the equinoxes (21,000 years), the obliquity cycle (41,000 years), and the eccentricity cycle (95,000, 123,000, and 413,000 years), produce changes in the seasonal and geographical distribution of sunlight reaching the earth which, in turn, affects climate (Berger, 1984). The theory makes specific predictions about the periodicity of climate cycles which should be testable in the geological record. Recently, the predictions of the orbital theory have been convincingly confirmed through studies of climate-sensitive geochemical and biotic indices in deep sea sediments of Quaternary age, especially in middle and high latitudes (Hays, Imbrie, and Shakleton, 1976). The Lockatong periods are also in rather close agreement and are strong evidence for orbital forcing far into the past. Long sequences of sedimentary cycles similar to those in the Lockatong and Passaic formations occur through the Jurassic portions of the Newark basin and most of the rest of the Newark Supergroup, spanning a period of more than 40 million years. Ultimately these lacustrine cycles will allow for extremely tight controls on sedimentation rates, stratigraphy, and structural development (see Olsen, this volume).

The route of the field trip is shown in Figure 7. The trip covers the three central fault blocks of the Newark Basin, running up section though the Stockton, Lockatong, and Passaic formations. Apart from Stop 1, all the stops are in the northern (Hunterdon Plateau) fault block where the exposures are excellent.

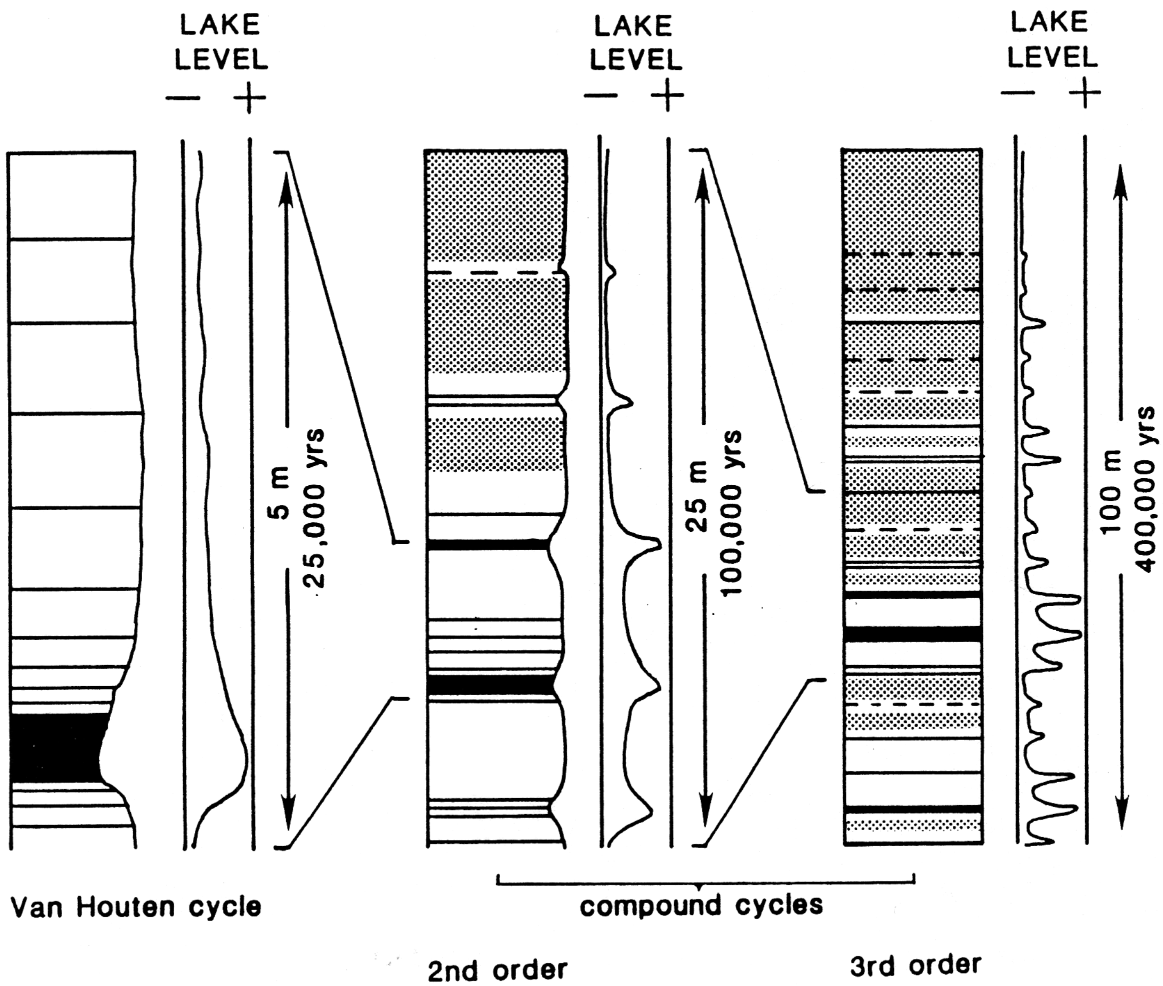

Figure 6. Compound cycles of the Newark Supergroup. Key as in Figure 5.

FIELD TRIP ROAD LOG

(Note: Mileage on left if cumulative mileage for road log; mileage on right is the increment between each mentioned mileage.)

MILEAGE FROM RIDER COLLEGE TO STARING POINT FOR FIELD TRIPS

0.0 0.0 Leave south gate of Rider College.

0.2 0.2 Leaving main entrance to Rider College.

0.7 0.5 Enter I-295 north following signs to I-95 south.

2.9 2.2 I-295 north ends, I-95 south begins.

8.1 5.2 Take exit number 1 for NJ-29 north. Mileage for field trip begins at this point.

MILEAGE FOR FIELD TRIP

0.0 0.0 Starting point - Junction I-95 - NJ-29: Scudder Falls Bridge.

West portal in Pennsylvania is in the uppermost Stockton Formation, with basal black platy mudstone of the Lockatong Formation exposed at N end of the northern access. East portal is about on the contact. Lockatong Formation in the southern fault block is about 500 m thick, about 600 m thinner than in the northern fault block (Hunterdon Plateau fault block). This thinning takes place by lateral replacement of massive gray mudstones by red mudstones in the upper Lockatong and by thinning of individual Van Houten cycles from 6.5 m in the Hunterdon Plateau fault block to 4.5 m in this area and the compound cycles they make up. This follows the typical pattern of updip thinning typical of half graben.

1.1 1.1 Analcime-rich reddish brown mudstone crosses road. Van Houten cycles well displayed in old quarry on west side of river.

1.3 0.2 Gray beds of the upper Lockatong Formation on right.

1.4 0.1 Crossing Jacob Creek. Uppermost Lockatong red mudstone beds outcrop in deep creek valley on right.

2.6 1.2 Washington Crossing State Park: thin green-gray siltstones making up bases of vague Van Houten cycles in lower Passaic Formation in low embankment on right.

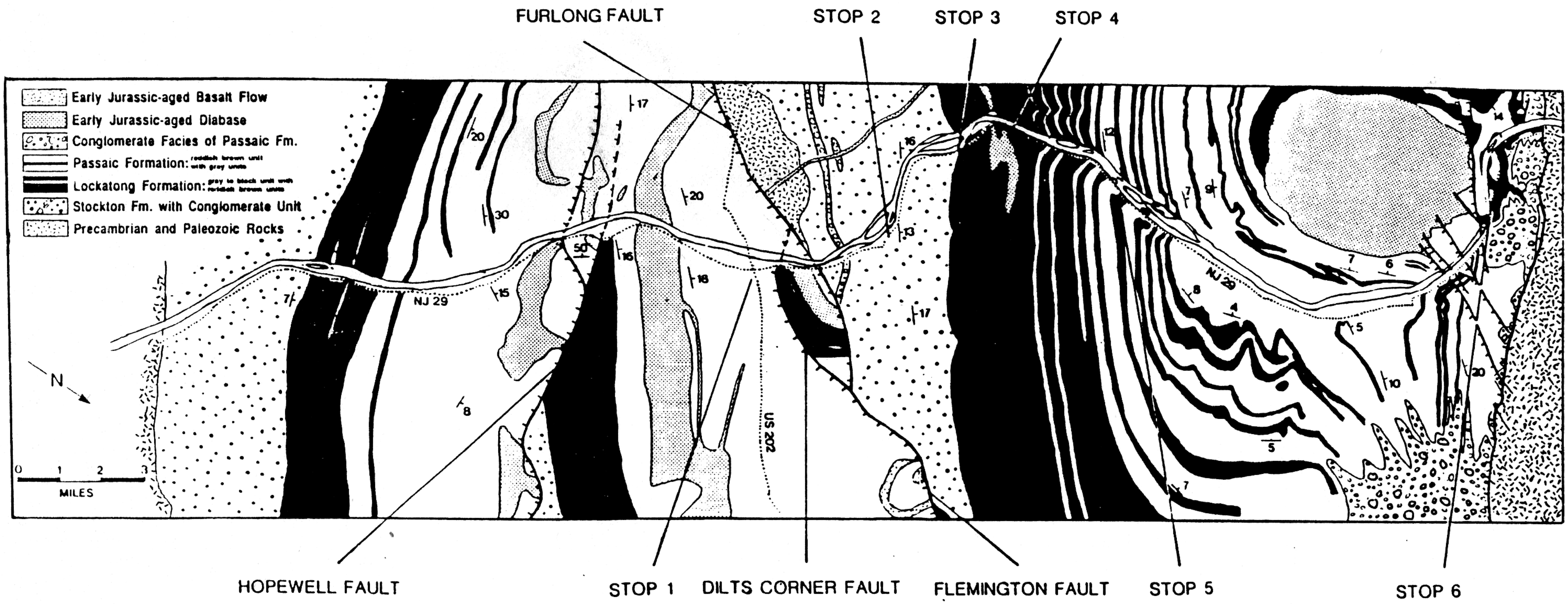

Figure 7: Geologic map of the Delaware River region of the Newark basin, showing the field trip stops (after Van Houten, 1969, and Ratcliffe *et al.*, 1986).

3.4 0.8 Van Houten cycles of lower Passaic Formation with a grey and black division 2 in back of lunch stand. These are unnamed and uncorrelated to sequences in other fault blocks.

5.6 2.2 Moore Station quarry in Baldpate Mountain diabase and metamorphosed Passaic Formation.

6.0 0.4 Moore Creek. Southern branch of Hopewell fault crosses river and continues west as the Buchmanville fault.

6.5 0.5 Mercer County Correctional Center Quarry in small Belle Mt. diabase body. Across the river this sheet forms Bowman Hill and has cross-cutting contacts (for additional details see Stop 1 of Husch and Hozik, this volume).

7.0 0.5 Crossing Hopewell Fault and entering Stockton Formation of middle (Sourland Mountain) fault block which is about 6.5-8 km wide along the river; section previously passed through is now repeated.

7.8 0.8 Lower Lockatong Formation poorly exposed in back of Flea Market.

8.9 1.2 Exposures of Lambertville Sill on right.

9.1 0.2 Crossing approximate top of Lambertville Sill (550 m thick)

9.4 0.3 NW-dipping hornfels of lower Passaic Formation on right.

9.7 1.0 Left onto Bridge Street in Lambertville and then right at first traffic light onto Main St. (NJ-29).

10.7 1.0 Right To US-202

10.9 0.2 Right onto US-202 N ramp. First of a series of four large outcrops of Passaic Formation stratigraphically close to the Perkasie Member of early Norian Age. These exposures show a number of Van Houten cycles which are extensively faulted at several scales, with considerable duplication of section. Division 2 of the most prominent Van Houten cycle at this outcrop is highly uraniferous as are several outcrops of what may be the same unit at mileage 11.3 and 12.1. M. J. Hozik has contributed the data presented in Figure 8 and this outcrop corresponds to Station 1 in that figure.

11.3 0.4 Section seemingly a duplication of that seen at previous outcrop. This is Station 2 of Figure 8.

12.1 0.8 Pull off on right next to large outcrops.

STOP 1
FAULTED PASSAIC FORMATION ADJACENT TO DILTS CORNER FAULT: IMPLICATIONS OF STRUCTURES

Largest road cut of hornfels along US-202, again apparently duplicating the previous exposures, stratigraphically. This is Station 3 of Figure 8.

The following discussion of the structures visible at this outcrop was contributed by R.T. Faill:

Two statements can be made about the mesoscopic deformational structures seen in outcrops along the Delaware River: 1) the structures do not seem to reflect the megascopic basin tectonics; and 2) they appear only sporadically.

It is a geologic truism that large-scale megastructures that characterize a geologic terrane often appear in smaller form in the mesostructures that can be seen in the outcrops throughout the terrane. The Mesozoic basins of eastern North America apparently lack this characteristic. True, the rocks are not greatly metamorphosed or deformed, nor on the other hand are they undeformed and flat lying. This itself reveals a great deal about the basin history. Steeply dipping faults are locally common, but often they are in orientations quite different from the presumed orientation of the major faults; and those kinematic indicators, the slickenlines, occur in a multiplicity of orientations.

A good example of this apparent inconsistency occurs at the northwest margin at Monroe, on the west side of the Delaware River. (It is not one of the stops on this field trip.). The Mesozoic/Pre-Mesozoic contact is mapped as a fault (Drake and others, 1967). Recent drilling data (Ratcliffe and Burton, 1985; Ratcliffe and others, 1986) clearly demonstrate the presence of two Paleozoic thrusts at and just below the Mesozoic margin. These faults dip only moderately to the southeast, at 27 and 34 degrees respectively. Cataclastic structures associated with these faults suggest that they were apparently reactivated late in the basin history (Early Jurassic?), perhaps as listric faults. Cataclastic zones in the pre-Mesozoic rocks dip on the average 30 degrees to the southeast, and slickenlines trend northeast and northwest on southeast dipping faults and northwest dipping antithetic faults (Ratcliffe and Burton, 1985).

In the outcrop along PA-611, within 200 meters of

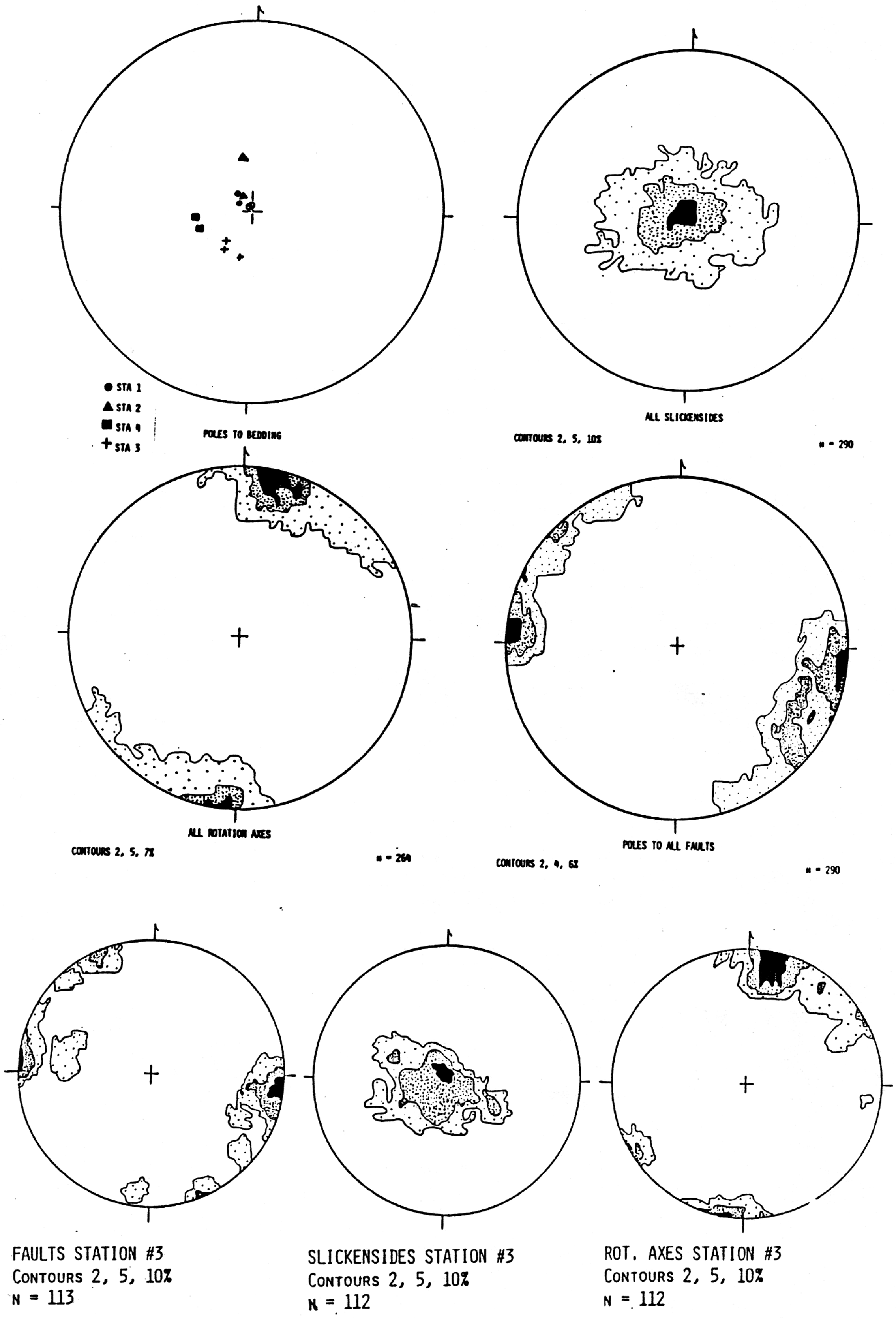

Figure 8. Equal area stereograms for bedding and fault data from exposures of lower Passaic along NJ-202. Upper four diagrams based on data from all exposures (stations 1-5). Lower 3 diagrams for station 3, Stop 1. Figure contributed by M.J. Hozik.

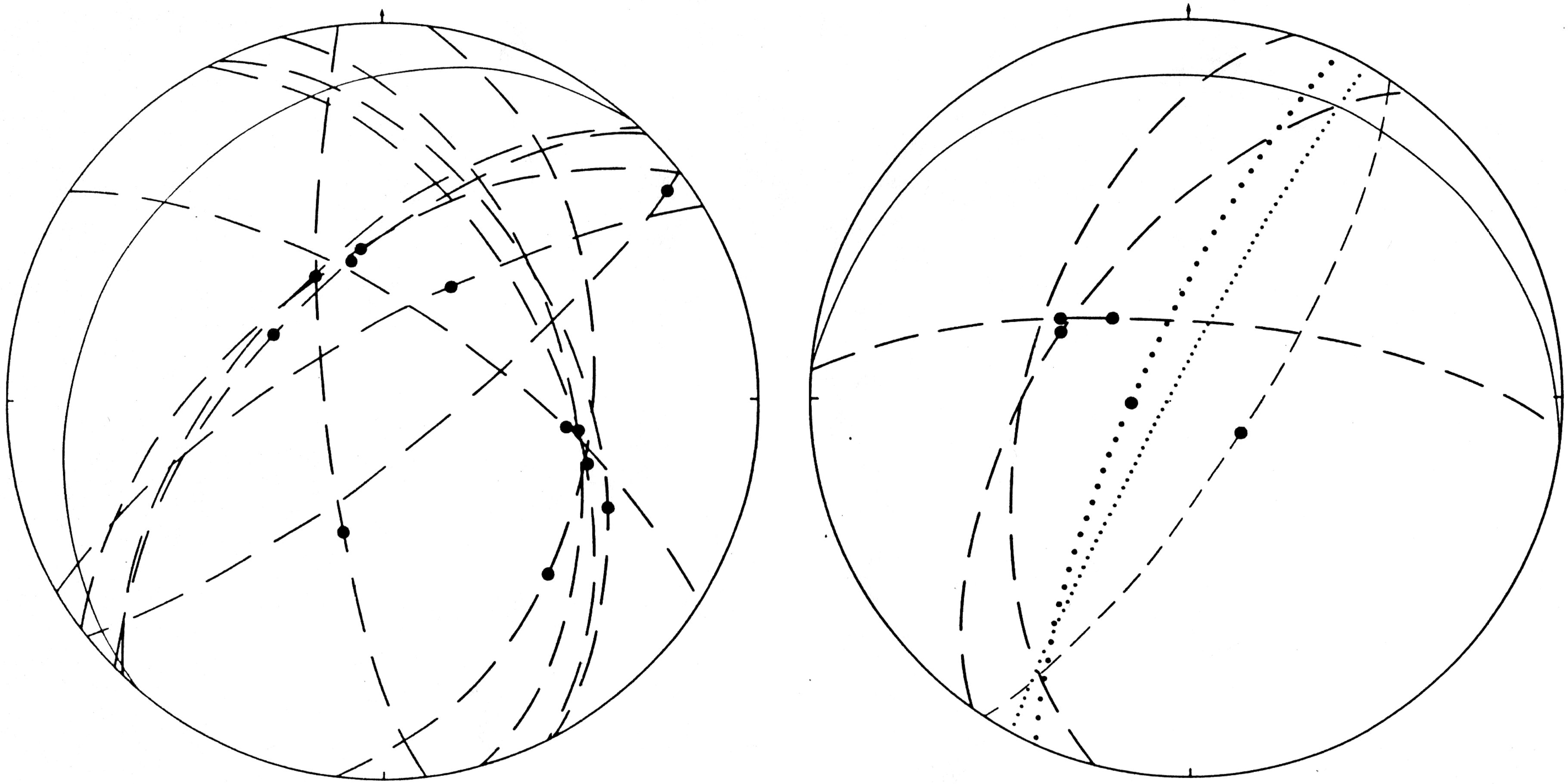

Figure 9. Data for Stop 1 contributed by R.T. Faill. Left, Equal-area stereogram (lower hemisphere), showing traces of bedding (solid line) and the slickensided fractures (dashed lines) at the basin margin, south of Riegelsville. Right, Equal-area stereogram (lower hemisphere), showing traces of bedding (solid line), faults, and slickensided fractures along U.S. Route 202, east of Delaware River. Light dot, fracture with plumose structure; heavy dot, sigmoidal fracture; light dash, east end fault; heavy dash; cleft faults; bullets, slickenline orientations.

the fault contact, interbedded carbonate-clast fanglomerates, siltstones, and argillaceous siltstones dip to the northwest at 22 degrees. (Relative to dip in the surrounding few kilometers, this dip is anomalously steep). One might expect that structures reflecting the basin margin tectonics would also be present here. Faults are present, but they do not dip moderately to the southeast as the margin faults do. Instead, they dip moderately to the east and northeast, and steeply to the northwest (Figure 9). In addition, the slickenlines plunge to the east and northwest. There is nothing in the outcrop that is consistent with the cataclastic extensional structures in the pre-Mesozoic rocks. In other words, the mesoscopic structures give little clue here to the overall basin tectonics.

This characteristic applies to the outcrops along US-202 at Stop 1 as well. Here, we are in the southern part of the Newark basin, separated from the northern part by the Chalfont-Furlong-Flemington fault complex and the Buckingham window. The Dilts Corner fault, a subordinate part of the complex, lies a few hundred meters north of this Stop. The structures seen in these road cuts may reflect the movements on the Dilts Corner fault rather than the basin as a whole, but this is not known.

In the third long road cut east from the river (on the south side of the road), bedding dips northward at 15 degrees. Subvertical fractures with a persistent north-northeast trend carry prominent plumose structures. And faults are common. Near the center of the cut, a pair of steep faults, one north dipping, the other west dipping, have formed a prominent cleft in the face of the road cut. Slickensides on both plunge steeply to the northwest, down their mutual intersection (Figure 9). To the east along the exposure is a set of steeply west-northwest dipping fractures that pass through a subhorizontal, meter-wide zone halfway up the face. Within this zone, the dip of the fractures decreases markedly, giving the fractures a sigmoidal form. Many of the fractures are covered with a dark green chlorite sheen, and slickensides indicate a dip slip movement. Even farther to the east, bedding is offset by tens of cm (down on west) by several steeply west dipping faults, again with subvertical slickensides.

Just what relationship these numerous structures have with the nearby Dilts Corner fault is unknown. And what role they and the steeply northwest plunging slickensides have with the overall basin tectonics is similarly not known.

Hozik (1985) offers a different interpretation of the same outcrops. According to Hozik, these outcrops provide ample evidence of normal faulting specifically associated with movement on the Flemington-Dilts Corner fault system. Fewer than 10 out of 150 of the small faults measured by Hozik (Figure 8) show a significant strike-slip component of movement (based on slickenlines. He notes that most of the faults strike northeasterly and dip steeply either to the northwest or to the southeast. Faults that strike N40°E and dip 70° to the northwest or southeast appear to define a conjugate set which would require σ_1 to be nearly vertical, σ_2 to be nearly horizontal and trending N40°E, and σ_3 to be horizontal and trending S50°E.

As pointed out by Hozik (1985) both Sanders (1962) and Manspeizer (1980) have argued that the intrabasin faulting was essentially strike slip in origin and specifically that Flemington fault should be a right lateral fault (Figure 8). Hozik's data suggest dominantly normal motion on the Flemington-Dilts corner system which is much more in line with the predictions of the Ratcliffe-Burton (1985) and Schlische and Olsen (this volume) models regional northeast-southwest extension (Figure 8). Of course, the Flemington fault is not exposed in the vicinity of these outcrops and the structures visible might, as Faill (above) argues, have nothing to do with the regional picture. However, the type of intense brittle fracturing seen at these outcrops is limited to the vicinity of the major faults and thus should be related to movement during some part of the history of the basin.

12.8 0.7 Section on both sides of roads expose faulted red beds of the Passaic Formation from a stratigraphic position somewhat above the previous outcrops. This outcrop corresponds to Station 4 of Figure 8.

13.0 0.2 Exit right for Mt. Airy - Dilts Corner

13.4 0.4 Left onto Queen Road and pass under US-202.

13.6 0.2 Left onto ramp for US-202 south and enter highway.

15.6 2.0 Exit right for NJ-29.

15.8 0.2 Left on Alexauken Creek Rd.

16.1 0.3 Right onto NJ-29 N.

16.8 0.7 Crossing Dilts Corner fault.

17.0 0.2 Quarry in Mount Gilboa Diabase, gabbro, and metamorphosed Lockatong Formation.

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17.0 0.2 Quarry in Mount Gilboa Diabase, gabbro, and metamorphosed Lockatong Formation.

17.6 0.6 Lockatong nepheline-cancrinite hornfels above diabase intrusion. Nepheline and analcime syenites crop out along small creek to east (Van Houten, 1969). Barker and Long (1968, 1969) proposed that these syenites formed by reaction of Lockatong Formation mudstones with a granophyric differentiate of diabase (see also Husch and Hozik, this volume).

17.9 0.3 Crossing Flemington Fault. Entering northern or Hunterdon Plateau Fault Block. Across river in Pennsylvania is uplifted basement consisting of Precambrian metamorphic rocks, Cambro-Ordovician limestones and phyllite, all overlain by basal Stockton Formation.

18.0 0.1 Entering Stockton, New Jersey - type area of the Stockton Formation (Kümmel, 1897; McLaughlin, 1945). Exposures of conglomeratic Solebury Member of Stockton Formation (McLaughlin, 1960) on right.

18.4 0.4 School yard with exposures of Solebury Member

19.3 0.9 Crossing Wickecheoke Creek at junction with N.J. Rt. 515 in Prallsville, New Jersey, with extensive exposures of Stockton and Lockatong formations upstream. Lower Lockatong well exposed and typically fossiliferous. Old quarries along road and canal in vicinity are in Prallsville Member of Stockton Formation.

19.6 0.3 Turn right onto open dirt area and park.

STOP 2
QUARRY IN PRALLSVILLE MEMBER OF STOCKTON FORMATION, MIDDLE CARNIAN AGE.

Recently active quarry in upper part of the Prallsville Member of the Stockton Formation exposes about 60 m of section and begins about 760 m above the base of the formation (Van Houten, 1969, 1980).

Four main sediment types are obvious at these outcrops: 1) massive, well sorted medium gray to buff arkose with faint to prominent large scale cross bedding; 2) massive to crudely crossbedded (2 m) arkosic conglomerate units some of which are kaolinized and have small to large rip up clasts; 3) well bedded red coarse siltstone with small dune scale cross bedding, ripple cross lamination, and parallel lamination; 4) blocky, massive red mudstone intensely bioturbated by *Scoyenia* and roots. Scoyenia is the most common Newark burrow-type and it may have been made by crayfish-like crustaceans in environments with perennially high fresh water tables. The sediment types seen here make up thick

17.6 0.6 Lockatong nepheline-cancrinite hornfels above diabase intrusion. Nepheline and analcime syenites crop out along small creek to east (Van Houten, 1969). Barker and Long (1968, 1969) proposed that these syenites formed by reaction of Lockatong Formation mudstones with a granophyric differentiate of diabase (see also Husch and Hozik, this volume).

17.9 0.3 Crossing Flemington Fault. Entering northern or Hunterdon Plateau Fault Block. Across river in Pennsylvania is uplifted basement consisting of Precambrian metamorphic rocks, Cambro-Ordovician limestones and phyllite, all overlain by basal Stockton Formation.

18.0 0.1 Entering Stockton, New Jersey - type area of the Stockton Formation (Kümmel, 1897; McLaughlin, 1945). Exposures of conglomeratic Solebury Member of Stockton Formation (McLaughlin, 1960) on right.

18.4 0.4 School yard with exposures of Solebury Member

19.3 0.9 Crossing Wickecheoke Creek at junction with N.J. Rt. 515 in Prallsville, New Jersey, with extensive exposures of Stockton and Lockatong formations upstream. Lower Lockatong well exposed and typically fossiliferous. Old quarries along road and canal in vicinity are in Prallsville Member of Stockton Formation.

19.6 0.3 Turn right onto open dirt area and park.

STOP 2
QUARRY IN PRALLSVILLE MEMBER OF STOCKTON FORMATION, MIDDLE CARNIAN AGE.

Recently active quarry in upper part of the Prallsville Member of the Stockton Formation exposes about 60 m of section and begins about 760 m above the base of the formation (Van Houten, 1969, 1980).

Four main sediment types are obvious at these outcrops: 1) massive, well sorted medium gray to buff arkose with faint to prominent large scale cross bedding; 2) massive to crudely crossbedded (2 m) arkosic conglomerate units some of which are kaolinized and have small to large rip up clasts; 3) well bedded red coarse siltstone with small dune scale cross bedding, ripple cross lamination, and parallel lamination; 4) blocky, massive red mudstone intensely bioturbated by *Scoyenia* and roots. Scoyenia is the most common Newark burrow-type and it may have been made by crayfish-like crustaceans in environments with perennially high fresh water tables. The sediment types seen here make up thick

(+ 10 m), poorly defined upward fining cycles possibly deposited by large, perennial meandering rivers (J. Smoot, pers. comm.).

The large river systems implied by these outcrops are incompatible with a closed basin model for the Newark Basin and indicate an open basin for this part of the basin's history. This is in accord with the predictions of the basin filling model outlined by Olsen (this volume) and Olsen and Schlische (1988).

Other items:

1. Na-feldspar to K-feldspar ratio is commonly 2:1.
2. This interval is part of a large magnetically reversed interval (Witte and Kent, 1987).
3. Micro-placers of specular hematite (after magnetite) grains locally outline thin bedding. Probable implications for detrital remnant magnetism.
4. Small to large root mottles and goethite stained weathered vertical trains of nodules, probably following roots.

Stockton Vertebrates

The Stockton Formation remains almost entirely unprospected for fossils. Nonetheless, important reptile remains have been found. Sinclair (1917) described the lower jaw of a very large labyrinthodont amphibian from the basal Stockton near Holicong, Pennsylvania. This jaw, still not described in detail, may belong to a large capitosaur, rather than a metoposaur as usually thought (W. Seldon, pers. comm.). The age of the basal Stockton is unknown and it could be as old as Middle Triassic. Early Middle Triassic capitosaurs are known from fragments from the oldest parts of the Fundy basin sequence (Olsen and Sues, 1986).

All the rest of the Stockton vertebrates come from the upper beds of the formation of Late Carnian Age. These include a large headless phytosaur skeleton referred to *Rutiodon manhattanensis* (Von Huene, 1913) from Fort Lee, New Jersey, an impression of the fragment of a metoposaur interclavicle (Baird, 1986) from Princeton, New Jersey, phytosaur teeth from Assinetcong Creek in Flemington, New Jersey (Olsen and Flynn, in press), and a few small assemblages of footprints and very scrappy bones from Rockland County (Olsen and Flynn, in press). The following ichnotaxa occur: *Rhynchosauroides* cf. *hyperbates*, *Apatopus lineatus*, *Brachychirotherium eyermani*, and ?*Atreipus* sp. This assemblage does not differ appreciably from that of the Lockatong Formation and it is in fact possible that the fossiliferous portions of the Stockton of Rockland County may be a shoreward facies of the Lockatong.

The uppermost Stockton (Raven Rock Member) at Carversville, Pennsylvania has produced a rich assemblage of plants dominated by cycadeoides, especially *Żamites powelli* (Bock, 1969, Ash, 1980). Another upper Stockton assemblage, this time dominated by the conifer *Pagiophyllum simpsoni* has more recently been described by Axsmith (in press) from Phoenixville, Pennsylvania. Silicified wood is common in the middle and lower Stockton Formation and plant foliage and stem compressions have been found including *Zamites* cf. *powelli*, and *Neocalamites* sp. Again, there has been no systematic attempt to prospect for plants, although what has been found so far is obviously promising.

Return to vehicle and turn right onto NJ-29 north.

20.8 1.2 Crossing Lockatong Creek - extensive exposures of middle and upper Stockton Formation and type section of Lockatong Formation are exposed upstream (McLaughlin, 1945).

22.0 0.2 Old quarry in woods on right in Raven Rock Member of Stockton Formation. Lower parts of quarry expose gray uraniferous sandstones and siltstones which were the site of a uranium prospect during the 1950's (Turner-Peterson, 1980). This radon producing unit has been traced from central Bucks County, Pennsylvania to Wickecheoke Creek to the east (Turner-Peterson and others, 1985).

22.3 0.3 Cliffs of red mudstones and sandstones of upper Stockton Formation on right.

22.7 0.4 Crossing approximate Stockton-Lockatong transition. Turn right onto small rest area.

STOP 3
STOCKTON-LOCKATONG TRANSITION

Several good exposures of uppermost Stockton Formation transitional into Lockatong Formation occur on slopes above small rest area. Measured section of portion of the sequence is shown on Figure 10 Sequence resembles single Van Houten cycle. (Figure 10 and comments below contributed by K. W. Muessig and H.F. Houghton).

Notable at this outcrop are:

1. Well-bedded purplish-brown sandy mudstone.
2. Thin, interbedded units of indistinctly laminated, gray mudstones and sandstones with calcareous cements.

3. Uranium concentrated in grey mudstones and locally, possibly secondarily, in calcareous sandstones.
4. Elevated radon levels in homes built on this unit throughout the southern portion of the Newark basin.

23.1 0.4 Stumphs Tavern Road.

Stream along north side of road exposes gray and red beds of the ?Weehawken Member of the lower Lockatong Formation. The Weehawken and succeeding Gwynedd Member of the lower Lockatong are the most fossiliferous portions of the Lockatong. Precisely equivalent cycles are exposed in creeks which cut down cliffs on opposite side of river at Lumberville, Pa. Here a microlaminated and strongly metamorphosed limestone (by overlying Byram Sill) of division 2 of a Van Houten cycle produces complete Turseodus and abundant conchostracans. Presumably equivalent beds produce copious fossils in the Princeton, Weehawken, and North Bergen areas of New Jersey to the north east. Unfortunately exposures of this part of the Lockatong are very poor in this part of the Newark Basin.

Note on Lockatong Formation Nomenclature.

McLaughlin (1943, 1945) mapped the distribution of the red portions of the 400,000 year cycles in the Hunterdon Plateau fault block and gave most of them informal member names. These names consist of a mixture of descriptive terms (First Thin Red Member), letter designations (member B), and place names (Smith Corner Red). The gray portions of the cycles in the Lockatong were not named with the exception of members A_1, A_2, and B. Because of the intense interest in many of the gray portions of these same cycles, it makes sense to apply some kind of informal, consistently applied name to each. Rather than add a new set of names for the gray portions of the cycles and retain McLaughlin's informal names for the red parts of the cycles, it would be more useful to revise the nomenclature of the Lockatong so that each member consisted of a lower gray portion and an upper red portion making up a single 400,000 year cycle, and receiving the same member name (Figure 11). Where McLaughlin used place names for a unit, the names are conserved. However, new names are needed both where he used letter or descriptive designations and for the units he never named (in accordance with the American Code of Stratigraphic Nomenclature 1961, 1983). Most of these names have already been used informally in previous works (Olsen, 1984, 1986). In the central Newark Basin, the Lockatong Formation is 1100 meters thick and is thus divided into 11, 400,000 year cycles, each about 100 m thick (Figure 11).

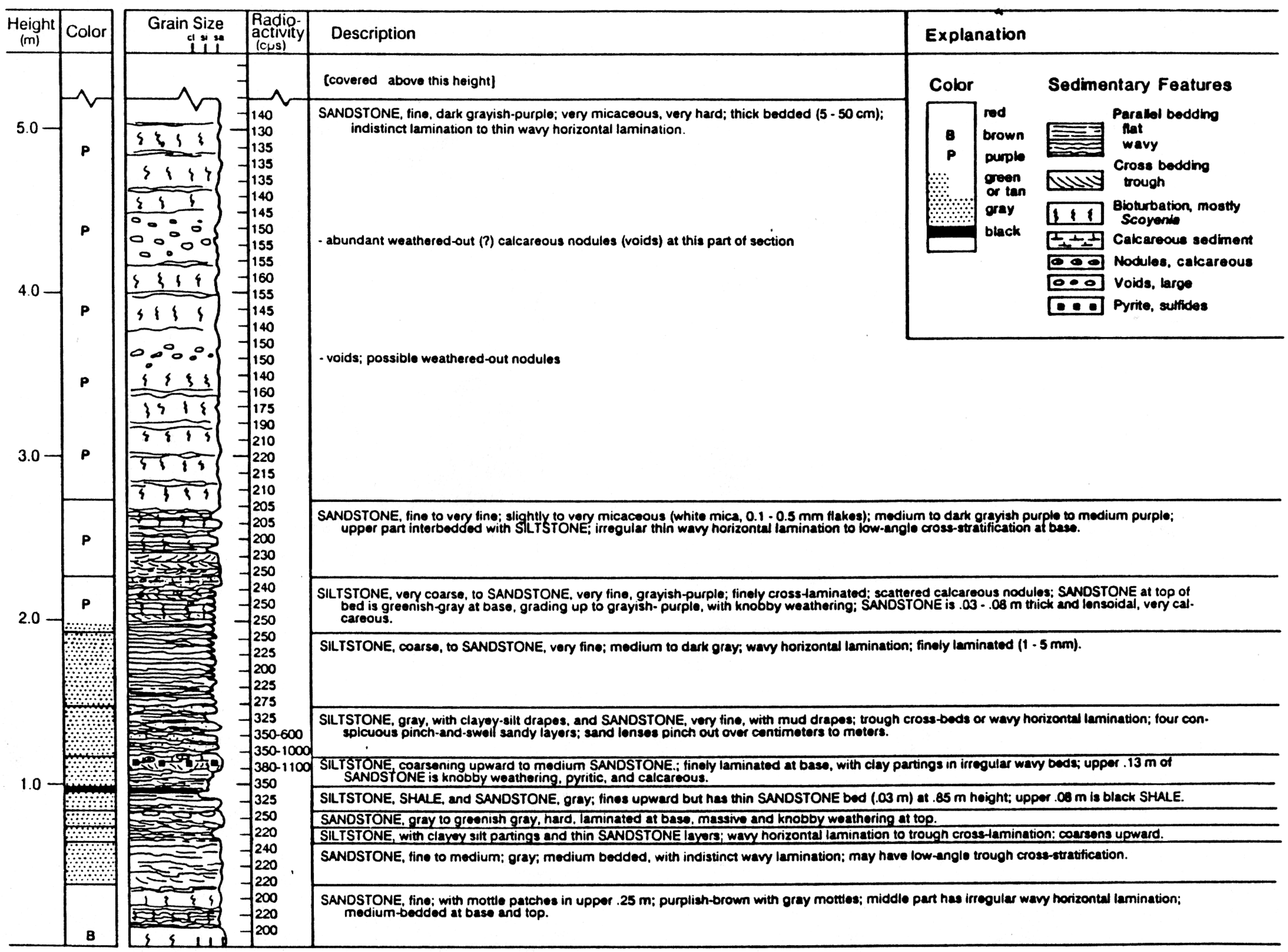


Figure 10. Measured section of upper Stockton (or basal Lockatong) north of Raven Rock, N.J., Stop 3 (Lumberville PA-NJ 7 1/2' quadrangle). Radioactivity measured by hand held scintillometer and given in units of counts per second. Figure contributed by K. W. Muessig. and H.F. Houghton.

23.5 0.4 Poor exposures on right of upper part of lower Lockatong Formation (upper ?Gwynedd Member).

23.8 0.3 Pull over on right next to culvert.

STOP 4
BYRAM SILL AND MIDDLE LOCKATONG FORMATION

This outcrop is one of the largest in the Newark Supergroup covering a stratigraphic thickness of over 500 m of section along a distance of 1.2 mi. Begin at the Byram sill and walk to the north.

Byram Sill on right (Figure 12) intruding zone between lower and middle Lockatong Formation.

Items:

1. Vague cyclic pattern of major ledges of albite-biotite hornfels; Nepheline occurs about 30 m below sill.
2. Lower contact of chilled border of diabase with sheared, weathered Lockatong pelitic hornfels.
3. Coarse-grained diabase, extensively fractured. Joint minerals have no apparent relation of compositional layering in the diabase.
4. Complex upper contact (Figure 12) on north, is a fault, probably post-intrusion as is common for cross-cutting intrusions. On the south is a welded curved contact. Nepheline, cancrinite, pyroxene and amphibole present in both blocks of Lockatong albite-biotite hornfels.
5. Relations of 21 m sequence from faulted diabase contact to outcrops north of creek obscure because of intervening faults.
6. The Byram Sill does not seem to extend down dip in this area as revealed by proprietary seismic reflection studies in Pennsylvania and a magnetic traverse along the railroad grade parallel to NJ-29 by R. Colombo (M.J. Hozik, pers. comm.

Walk to west.

23.9 0.1 Begin 410 m almost continuous section of middle Lockatong.

A "0" painted on outcrop marks beginning of undisturbed continuous sequence of middle Lockatong Formation (Figure 12). Measured section shown in Figure 13 is in meters but marks on outcrop are in feet with the correspondence shown in the figure. About 95 % (401

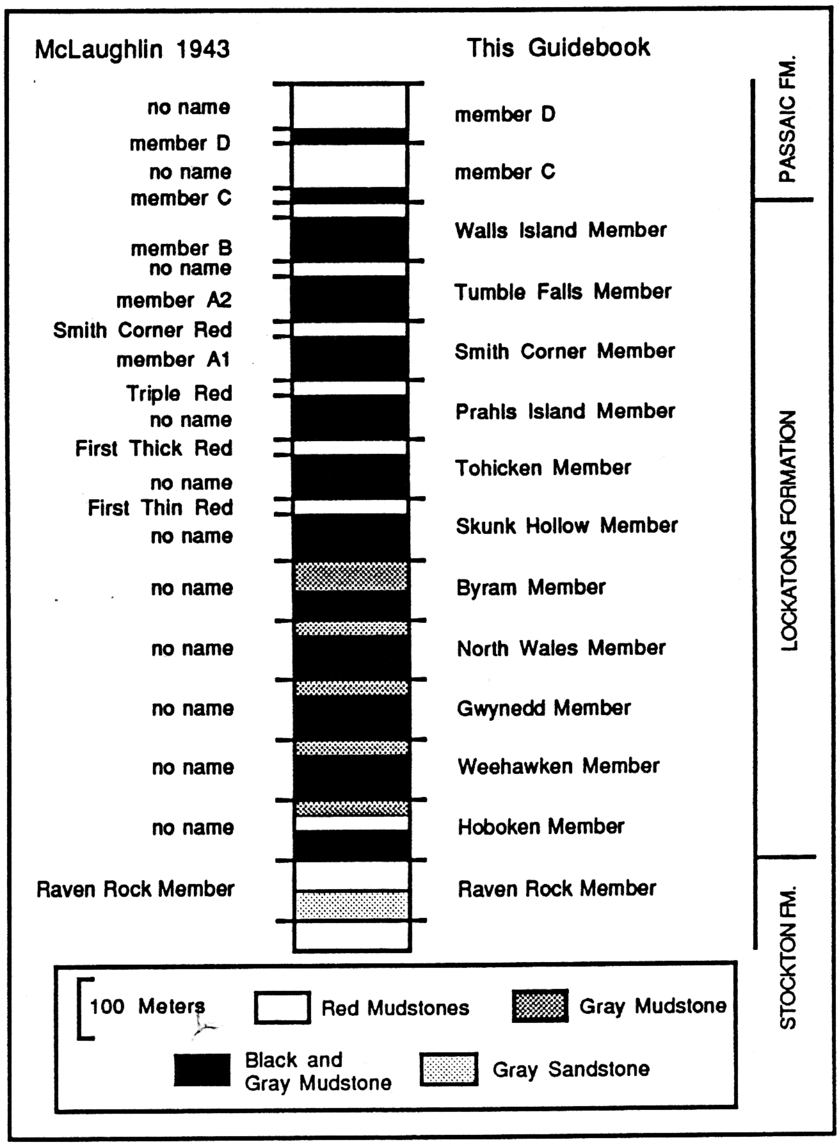


Figure 11. Subdivisions of the upper Stockton, Lockatong, and basal Passaic formations.

m) of this section consists of fine calcareous mudstone and claystone with the rest 5 % (5 m) consisting of very fine sandstone. In the terminology outlined above, these exposures include North Wales, Byram, Skunk Hollow, and Tohicken members. McLaughlin's (1944) "First Thin Red" makes up the upper part of the Skunk Hollow Member and the "First Thick Red" makes up the upper part of the Tohichen member.

This section shows the cyclic pattern typical of the Lockatong and Passaic formations perhaps better than any other section in the Newark Supergroup. Fourier analysis of sediment fabrics in this section (Figures 14, 15) and calibrated by varve sedimentation rates and radiometric time scales show the main thickness and time periodicities typical of both the Lockatong and Passaic formations in this part of the basin. At these outcrops there are prominent periods in thickness at 5.5 m, 6.1 m, 24.0 m, 32.0 m, and 96.0 m. The 5.5 and 6.1 m cycles are Van Houten' chemical and detrital cycles, respectively [*i.e.*, Olsen's (1986) Van Houten cycles], the 24.0 and 32.0 m cycles are the "25 m" long cycle, and the 96.0 m cycle corresponds to the "100 m" long cycle of Van Houten. In terms of time, these five thicknesses of cycles were evidently controlled by the precession cycle of 19,000 and 23,000 years, and the eccentricity cycles of roughly 95,000, 123,000 and 413,000 years.

The interval from the 115 to the 300 foot mark (35-91 m) is exposed in old quarry in upper part of North Wales and lowermost part of Byram members about 0.3 mi north of the 0 mark in this traverse (Figures 12, 13). Thomsonite is a common joint mineral along with analcime, calcite, and rarer ilmenite. Scapolite in the hornfels and laumontite on joints reported by Lewis (1909) have not been confirmed. This dark gray hornfels produces crushed stone megascopically almost indistinguishable from fine grained diabase. A quarry in this interval, across the river at Point Pleasant, has produced slab of large but sloppy *Apatopus* (D. Baird, pers. comm.).

The pattern of short and longer cycles can be best seen in the interval from the 550 ft mark to the northern end of the main outcrop (Figure 13).In order to facilitate comparisons with the succeeding stops and in order to illustrate the wide range of variation exhibited by the Van Houten cycles at this outcrop, we will compare two end-members of the range of sequences of sedimentary fabrics present in this section (Figure 16). These two end-members correspond, in part, to Van Houten's (1962, 1964, 1969) detrital and chemical short cycles.

A single Van Houten cycle is shown in Figure 16a (cycle SH2 - Figure 13) between the 620 and 815 marks

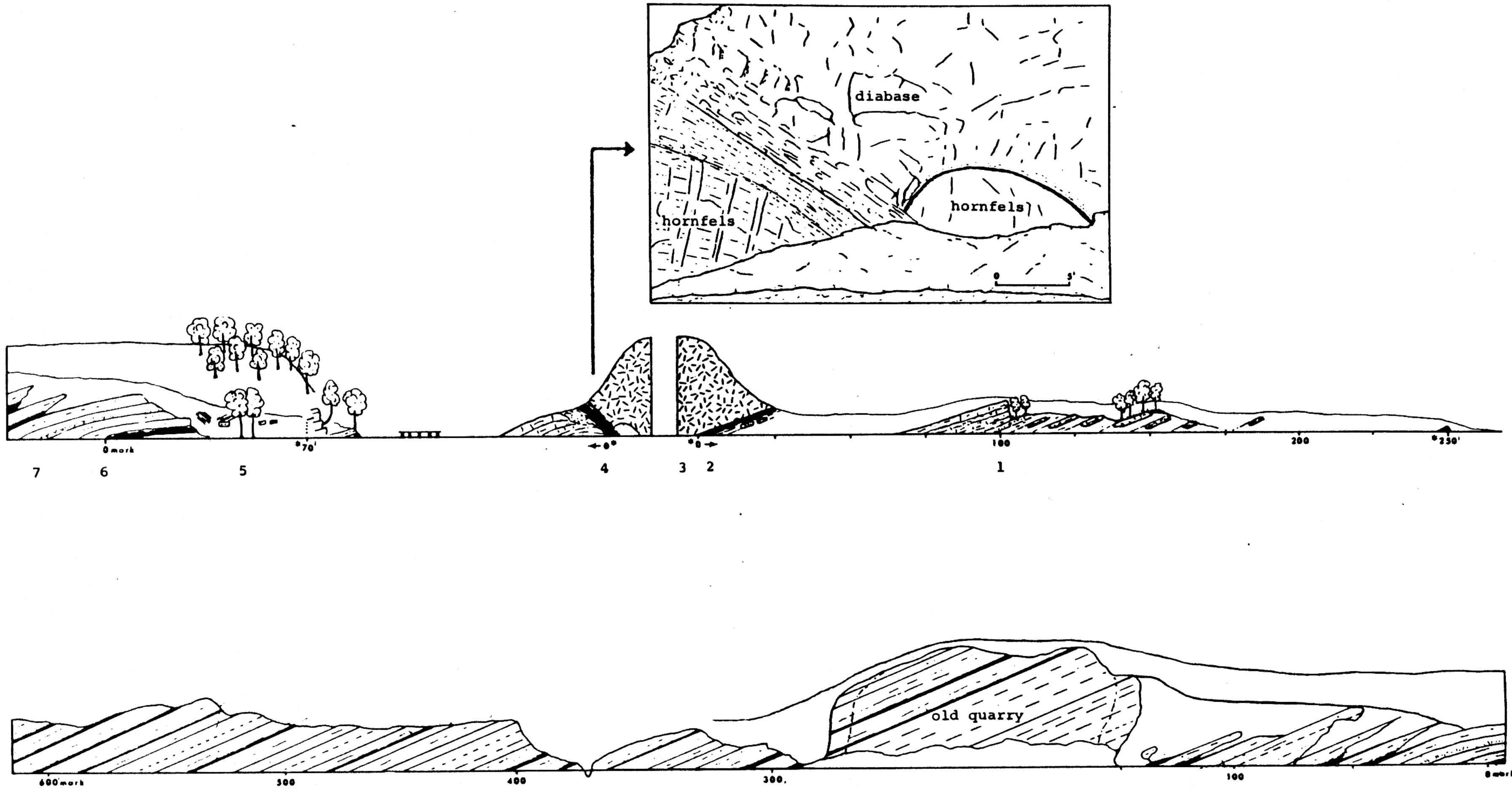


Figure 12. Sketch of road cut through middle part of the Lockatong Formation and Byram diabase sheet, NJ-29, Byram, N.J., Stop 4 (adapted from Van Houten, 1969).

Upper profile: Lockatong hornfels 76 m stratigraphically below and 21 m stratigraphically above diabase. Enlargement is of upper contact; 1-7, items mentioned in text; 0 mark, probablely about 21 m above diabase; base of continuous section measured in feet above base (0 mark).

Lower profile: Lockatong Formation 21 to 218 m above 0 mark (70 to 715 ft). Well displayed analcime rich Van Houten cycles (chemical cycles of Van Houten, 1969) between 137 and 168 m (450 - 550 ft marks).

(about 750 ft, 227 m) in the lower part of the Skunk Hollow Member. This is the most fossiliferous cycle exposed in this outcrop. Division 1 is a thin sand overlain by thin bedded mudstone with an upward increase in total organic carbon (T.O.C.). This represents the beginning of lake transgression over the mostly dry playa flat of the preceding cycle and this is followed by deposition under increasing water depth.

The transition into division 2 is abrupt and is marked by the development of microlaminated calcareous claystone consisting of carbonate rich and carbonate-poor couplets, an average of 0.2-3 mm thick. The basal few couplets of this interval contains articulated skeletons of the aquatic reptile *Tanytrachelos* (Figure 16a) and infrequent clam shrimp and articulated fossil fish (*Turseodus* and ?*Synorichthys*) and abundant conchostracans occur in the middle portions of the unit. In its upper part, the microlaminae are very discontinuous, perhaps due to microbioturbation. No longer microlaminated, the succeeding portions of division 2 become less organic-rich and less calcareous upward, and there is an upward increase in pinch and swell lamination. Deep, widely spaced, and sinuous desiccation cracks propagate down from the top of the unit. The average T.O.C. of division 2 (83 cm thick) of this cycle is 2.5 % which is a rather common value for black siltstones and limestones of the Lockatong.

The absence of syndepositional desiccation cracks, and the presence of extremely fine microlamination and articulated aquatic vertebrates, suggest that division 2 is the high stand deposit of lake which formed this Van Houten Cycle. Studies of similar microlaminated units in other parts of the Lockatong suggest deposition in water in excess of 100 m deep, below wave base, and in perennially anoxic water (Manspeizer and Olsen, 1981; Olsen, 1984).

As noted by Turner-Peterson and others (1985) microlaminated and adjacent units such as this one are often uraniferous and radioactive. According to K. W. Muessig and H.F. Houghton (pers. comm.) homes in the southern portion of the Newark Basin built on similar units are notably elevated in radon.

The presence of the articulated reptiles at the base of the microlaminated unit may represent the transgression of the chemocline of the chemically stratified lake as the lake expanded. It is common for articulated reptiles to occur right at the base of the microlaminated portions of division 2 in many other cycles of the Lockatong (Olsen, 1980c) and in other Triassic formations as well (Olsen *et al.*, 1978). This pattern is of considerable use in prospecting for these little reptiles. The decrease in microlamination toward the top of division 2 suggests the action of

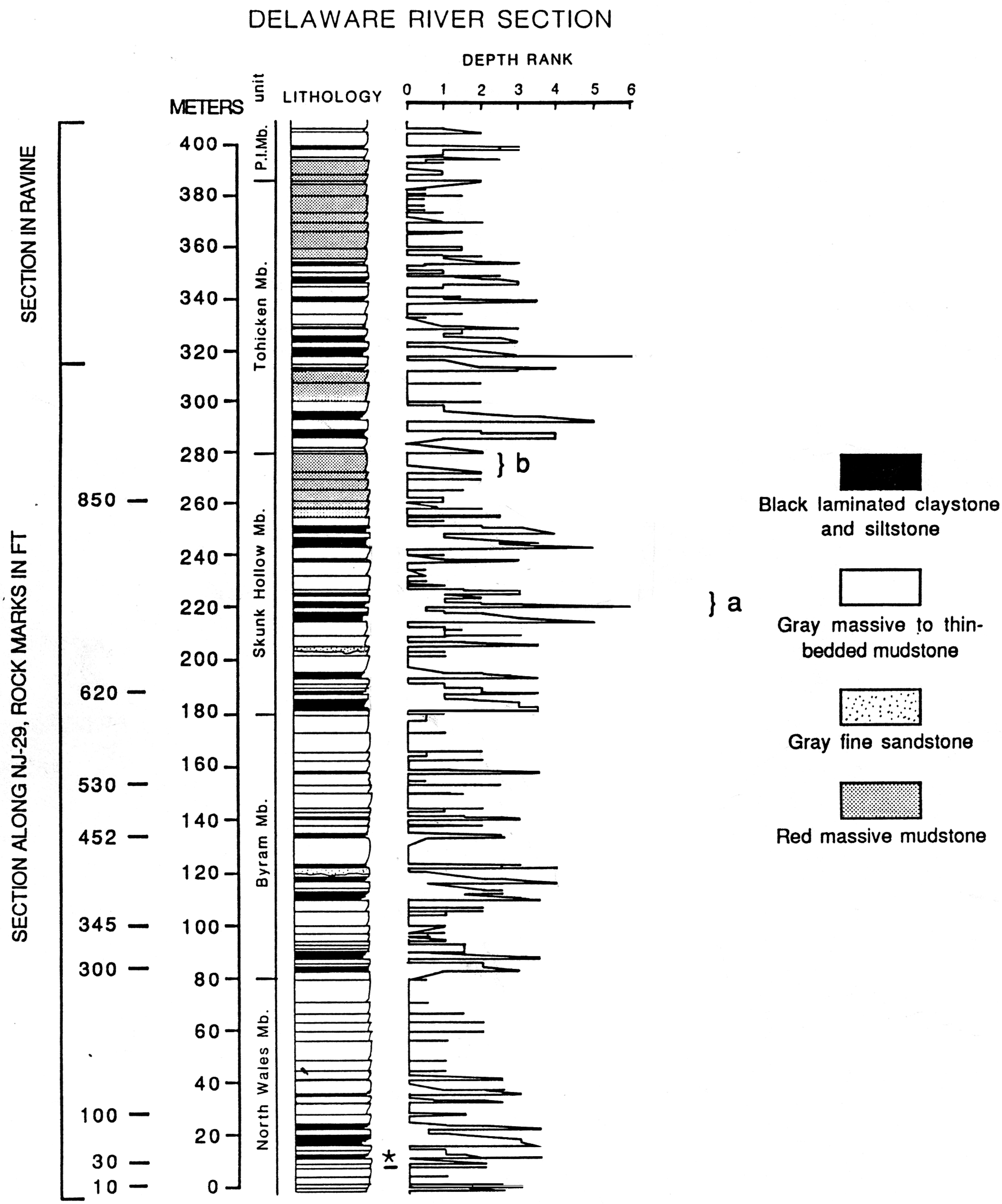


Figure 13. Measured section through the middle Lockatong Formation along NJ-29 at Byram (Stop 4) showing depth rank and positions of detailed measured sections shown in Figure 16. (**a**) Corresponds to Van Houten cycle in Figure 16a, and (**b**) corresponds to cycle in Figure 16b.

Table 1.
Key to units in Figure 16.

Figure 16A

N +30 cm black laminated claystone (2.9% TOC).
M 10 cm gray mudstone with widely spaced desiccation cracks.
L 96 cm massive seemingly structureless monosulfide-bearing gray mudstone (0.6% TOC).
K 30 cm gray fine oscillatory rippled sandstone.
J 240 cm gray decimeter-scale siltstone and fine sandstone beds with abundant contorted desiccation cracks, soft sediment deformation, reptile footprints (*Apatopus*), and rare clam shrimp (*Cyzicus*)(,0.5% TOC).
I 30 cm dark dray laminated mudstone with rare fish bones (0.1% TOC).
H 30 cm dark gray centimeter-scale mudstone beds with widely spaced, deep, contorted desiccation cracks (1.3 % TOC).
G 83 cm black, laminated organic-rich (5.0% TOC) black limestone (77% carbonate) grading up into less calcareous (34% carbonate) and less organic rich (1.6% TOC) siltstone with deep, widely spaced, and sinuous desiccation cracks originating in the overlying beds. Abundant pinch and swell laminae present. Clam shrimp (*Cyzicus*) and ostracodes (*Darwinula*) abundant at the base but absent at top.
F 3 cm black, laminated, organic-rich (6.6% TOC) blebby limestone (76% carbonate) with occasional microlaminae. Abundant ostracodes (*Darwinula*) and clam shrimp (*Cyzicus*) present.
E 8 cm black, microlaminated limestone with even microlamination and some pronounced stylolites passing up into limestones with very discontinuous blebby microlaminae. Clam shrimp (*Cyzicus*), ostracodes (*Darwinula*), fish (*Turseodus* and *Synorichthyes*) , and coprolites present.
D 3 cm black, microlaminated blebby calcareous siltstone with extremely abundant clam shrimp (*Cyzicus*), articulated fish (*Turseodus),* and coprolites.
C 4 cm black, microlaminated calcareous claystone (1.4% TOC, 33% carbonate). Basal few couplets with articulated reptiles (*Tanytrachelos*) and rare clam shrimp (*Cyzicus*).
B 12 cm black well bedded mudstone showing an upward increase in thin-bedding and total organic content. Rare fish bones (?*Diplurus*) and clam shrimp (*Palaeolimnadia* and *Cyzicus*).
A 39 cm gray, climbing ripple-bedded fine sandstone (0.3% TOC), Desiccation cracks are absent in contrast to underlying division 3 of the preceding cycle.

Figure 16B

F +20 cm gray massive mudstone with crumb fabric.
E 491 cm consisting of 7 massive mudstone sequences, each 150 to 20 cm thick, showing upwards transition from thin-bedded claystone to breccia fabric to crumb fabric.
D 31 cm red and green laminated to thin-bedded claystone with widely spaced desiccation cracks projecting down from overlying unit,
C 8 cm gray claystone becoming laminated upwards with widely spaced desiccation cracks at top.
B 82 cm gray massive mudstone with well developed crumb fabric with analcime filled vesicles.

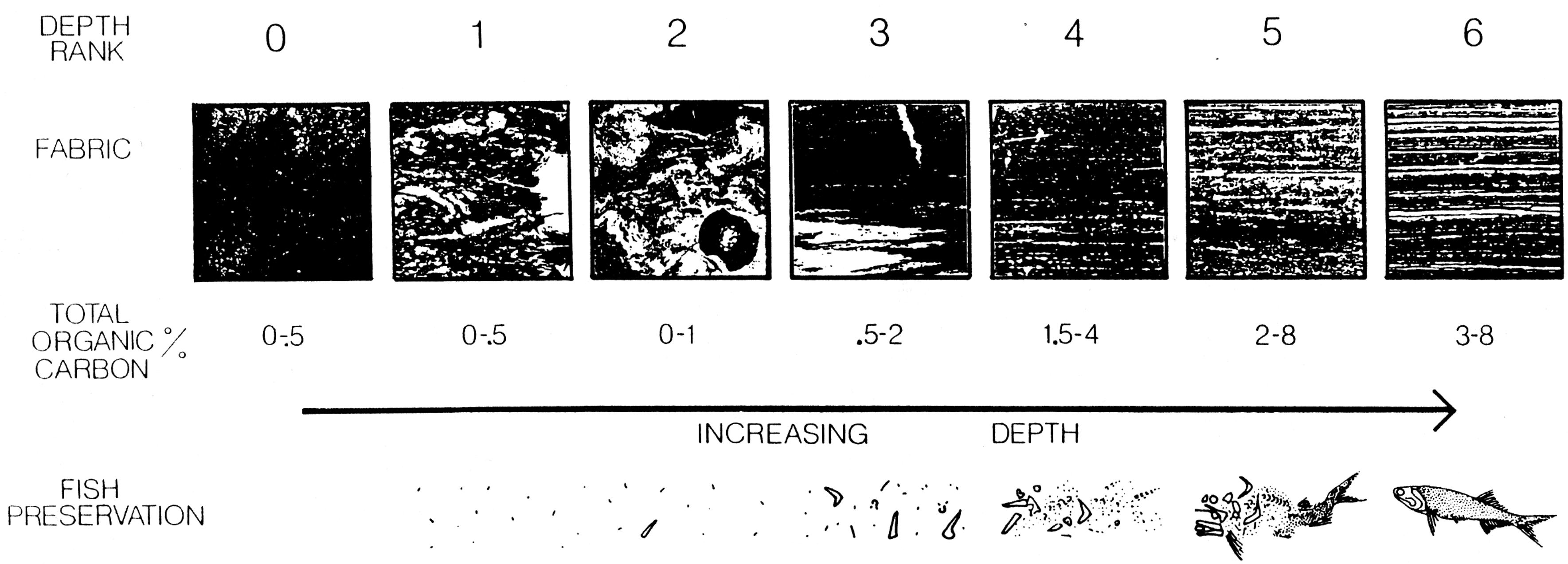


Figure 14, Sedimentary fabrics characteristic of "depth ranks" showing a range from massive, intensely desiccated breccia and crumb fabrics (depth rank 0) to completely undisturbed, microlaminated calcareous siltstone and claystone (depth rank 0). Complete descriptions of these depth ranks are in Olsen (1986).

microbioturbation and increased water column ventilation which we attribute to slowly decreasing water depth (Olsen, 1982, 1985a).

Division 3 is characterized an overall upward increase in the frequency and density of desiccation cracked beds and an decrease in thin bedding. Reptile footprints (?*Apatopus*) occur near the middle of the sequence (Figure 16). Organic carbon content drops through division 3 is low (1.3 % - 0.5 %). This interval shows the greatest evidence of exposure in the cycle and represents the low stand of the lake. However, as evidenced by the relatively low frequency of desiccation cracked intervals and the generally wide spacing of the cracks themselves, submergence was much more frequent than emergence during the deposition.

The cycle below SH2 (SH1, Figure 13) also contains a division 2 with a microlaminated base, fish and clam shrimp. The total thickness of division 2 of this cycle is much thicker than the succeeding cycle.

Division 2 in other cycles at this outcrop are not as organic rich or as well laminated as SH2 and SH1, and the other cycles also show greater degrees of desiccation of division 3. The only fossils present tend to be rare clam shrimp and indeterminate fish bones and plant scraps.

Figure 16b shows a Van Houten cycle in McLaughlin's "First Thin Red" about 40 m above the cycle shown in Figure 16a (top of cycle about 1.5 m below the 900 ft mark, 274 m). This cycle contrasts dramatically with the Upper Skunk Hollow Fish Bed in consisting of 75 % red massive mudstone and completely lacking a black organic-rich division 2. Division 3 of the previous cycle (also mostly red) consists of red massive almost homogeneous appearing mudstone with a faint but highly vesicular crumb fabric which according to Smoot (1985) formed by breaking up, by desiccation, of aggrading mud in a playa lake with the vesicles representing cement-filled voids (now dolomite and analcime) formed during aggradation and cemented shortly after deposition. The vesicles do not seem to be related to an evaporitic texture as suggested by Van Houten (1969).

The overlying massive mudstone of division 1 is gray and contains a better developed crumb fabric. This unit was probably deposited under much the same conditions as the unit underlying it; its iron was reduced, however, by the interstitial waters from the lake which deposited the next unit. The transition from an aggrading playa to a short lived perennial lake is marked by an upward increase in lamination, a disappearance of the crumb fabric and a decrease in the density of desiccation cracks.

Division 2 of this cycle consists of red and green laminated to thin-bedded claystone lacking

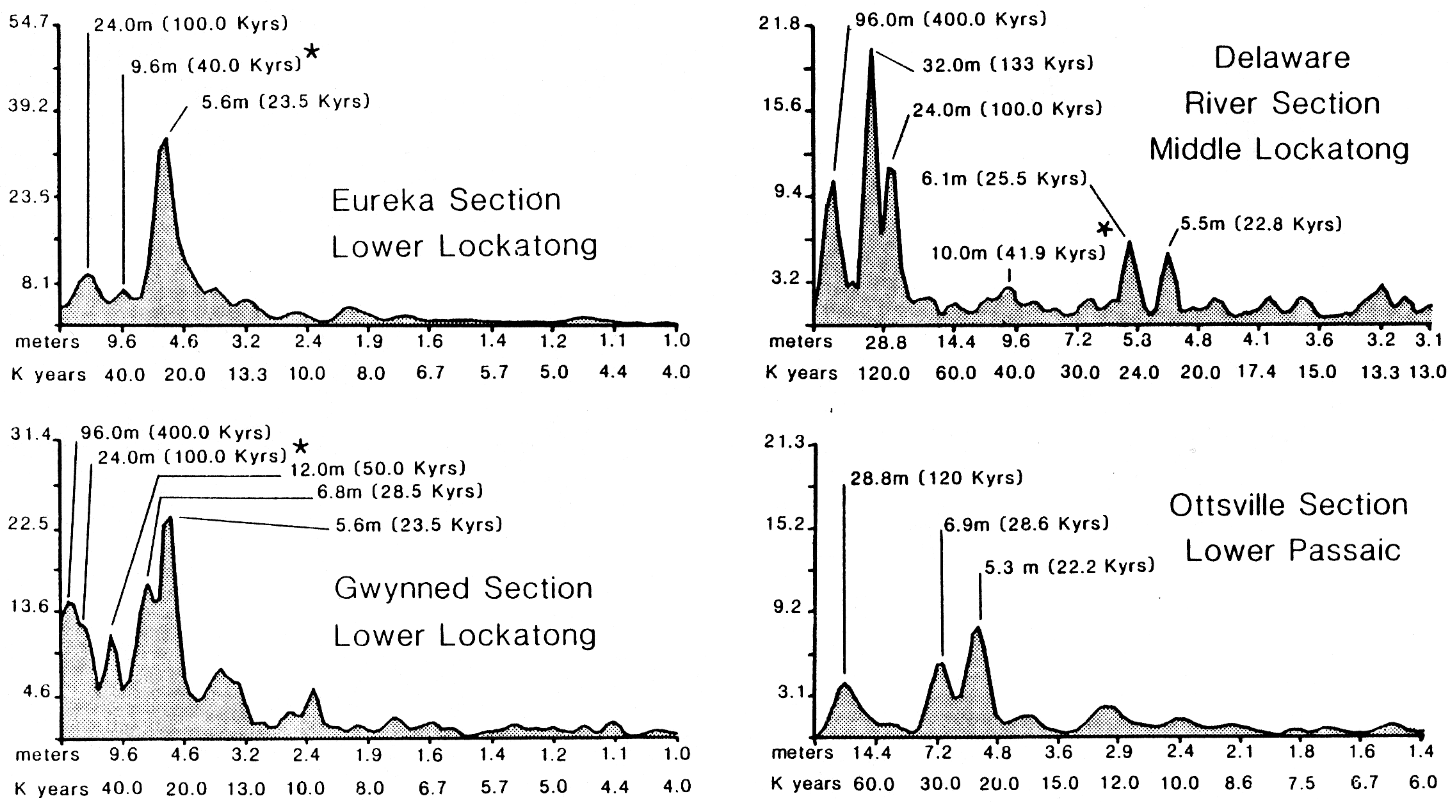


Figure 15. Power spectra of sections in the Lockatong and Passaic formations (from Olsen, 1986). The power spectrum for Stop 4 is the "Delaware River Section" on the upper right. Section is calibrated to time using varve counts yielding a sedimentation rate of 0.24 mm/yr.

syndepositional desiccation cracks. This is the high stand deposit of this cycle and is most comparable to the fabric seen in the lower part of division 3 of the cycle shown in Figure 16a.

Division 3 consists of massive mudstone (argillite) sequences consisting of a basal green-gray mudstone passing into a very well developed breccia fabric (Smoot, 1985) and then upwards into a well developed crumb fabric. Breccia fabrics consist of densely spaced anastomosing cracks separating non-rotated lumps of mudstone showing some remnant internal lamination. They are very common in the Lockatong Formation and are directly comparable to fabrics produced by short periods of aggradation separated by longer periods of desiccation and non-deposition (Smoot and Katz, 1982). The breccia fabric passes upward into a well developed vesicular crumb fabric. The transition into the overlying similar sequence is abrupt. These thin sequences, several of which here make up division 3 of a Van Houten Cycle, are very common in the fine grained facies of the Newark Supergroup (Smoot in Olsen and Gore, in press).

The upper half of these thin sequences are cut by dish-shaped, upward concave clay-lined surfaces with radial slikensides. These "dish structures" were described by Van Houten (1964, 1969) and interpreted as a possible gilgai-type soil feature (Van Houten, 1980). A mechanical analysis of these structures suggests they are coulomb fractures produced in relatively rigid, but not lithified, mud by more or less isotropic expansion in a three dimensional analogue of Davis, and others' (1983) "bulldozer" model for the development of thrust faults in accretionary wedges. The volume increase was probably due to eolian deposition of mud in desiccation cracks followed by rewetting. Because the bed was confined laterally, it fractured along listric, dish-shaped faults and compensated for increased volume by increasing in thickness. As a mechanical consequence of volume increase, the dish-structures are probably not specific to any particular environment in larger sense, but could be indicative of a limited range of environments in a particular basin setting such as the Lockatong (J. Smoot, pers. comm).

Clearly, this particular Van Houten cycle represents the transgression and regression of a lake which never became as deep as the cycle shown in Figure 16a and when lake level dropped the lake desiccated for longer intervals. Unfossiliferous here, cycles of this type contain clam shrimp in division 2 and sometimes abundant reptile bones in division 3 in coarser facies (see Stop 4). Most of the cycles at this stop fall somewhere between these two extremes.

At the north end of the outcrop is a creek with excellent exposures of addition 100 m of section of the upper Tohicken and lower Prahls Island Member (Figure 13).

Return to vehicle and head north on NJ-29.

25.0 1.1 Upper part of Tohicken Member (McLaughlin's "First Thick Red" exposed on right.

25.2 0.2 Old Busik Quarry on right is in the upper part of Prahls Island Member (McLaughlin's "Triple Red"). Section in quarry has been described by Van Houten (1969, Stop 3).

25.5 0.3 Ravine on left exposes lower parts of Smith Corner Member with well developed black and gray Van Houten cycles. The lowest exposed produces *Cyzicus* and indeterminate fish scraps.

25.6 0.1 Red and Gray Van Houten cycles comprising the upper parts of the Smith Corner Member

25.9 0.3 Tumble Falls Road. Stream on right exposes most of Tumble Falls Member of upper Lockatong Formation, the upper the red parts of which correspond to McLaughlin's member B. Minor transgressive interval in middle of division 3 of a gray Van Houten cycle exposed in stream at road level contains abundant and well preserved *Rhynchosauroides* sp.

26.2 0.3 Upper red beds of Walls Island Member (member B plus High Rocks member of McLaughlin). These red beds have usually been considered the basal beds of the Passaic Formation (Van Houten, 1969) even though they are mineralogically more similar to the Lockatong (Van Houten, 1969). They are regarded here as the uppermost beds of the Lockatong and the base of the Passaic Formation is defined at the base of the gray beds of member C.

26.3 0.1 Exposures of gray and red Van Houten Cycles of McLaughlin's member C. Section described by Van Houten (1969, 1980).

McLaughlin (1944, 1946) split the Passaic Formation into members differently than the Lockatong and named the gray portions of the 400,000 year cycles, not the red. Thus, this gray interval is named C of the Passaic Formation (Brunswick of Kümmel, 1897), while the underlying red interval of the Lockatong was named B. Pending detailed revision, we use McLaughlin's member names for the Passaic, but include the overlying red half of each 400,000 year cycle in the named unit.

26.5 0.2 Large exposures of upper parts of Member C of Passaic

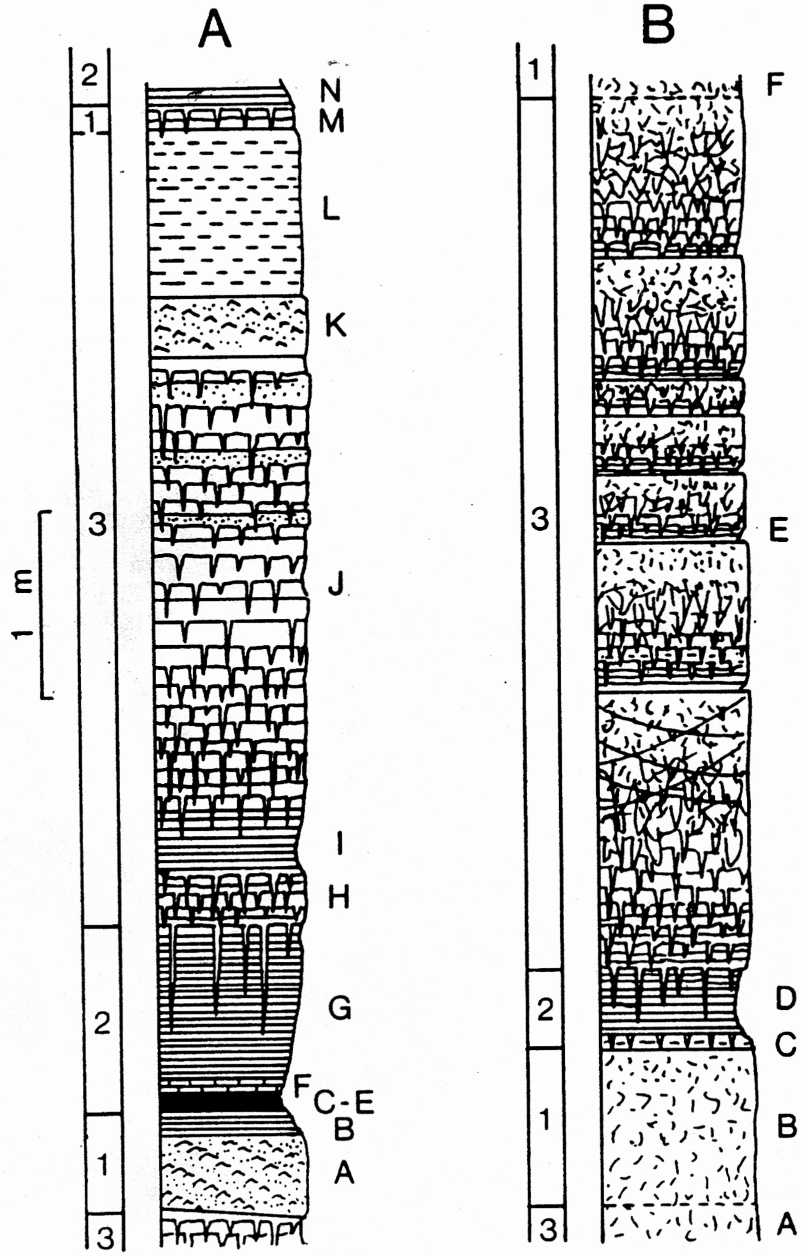


Figure 16. Two end members of the cycle types seen at Stop 4 along NJ-29. (A) corresponds to Van Houten's detrital cycle type while (B) corresponds to Van Houten's chemical cycle type (Van Houten, 1964). Key to units in Table 1.

Formation showing continuation of pattern of Van Houten cycles expressed as variations in red mudstone fabric resembling the red mudstone cycle described in detail at Stop 2. *Rhynchosauroides* sp. occurs in some of the red laminated mudstones of division 2 of these cycles.

27.2 0.7 Pull off on right just in front of culvert for Warford Creek.

STOP 5
MEMBER D OF PASSAIC FORMATION - WARFORD CREEK

Extensive exposures of a single Van Houten cycle in the lower part of Member — of Passaic Formation extend for over 0.5 mi. upstream (Figure 17). The lower part of division 2 of this cycle is microlaminated and contains articulated and disarticulated *Semionotus* cf. *braunii* and *Paleolomadia*-type clam shrimp. Division 3 contain *Scoyenia*, abundant tool marks, and possibly poor *Rhynchosauroides*. This same cycle outcrops 6 mi. to northeast along east branch of Nishisackawick Creek where it still contains fish, although they are disarticulated (Olsen and Gore, in press). Although mapping is as yet incomplete, member D evidently is traceable more than 30 mi to the south west to Linfield, Pennsylvania, near the Limerick nuclear power plant. At a small exposure along Longview Road the lower part of division 2 of the same cycle exposed along Warford Creek consists of black siltstone with well developed oscillatory ripples. Articulated and disarticulated *Semionotus* cf. *braunii* are common in calcareous nodules in the black claystone laminae. Oscillatory ripples adjacent to the fish are also carbonate cemented and much less compacted than other ripples showing the nodules to be of early diagenetic origin.

The uranium concentration is unusually high in sandstone beds of division 1 of this Van Houten cycle at Warford Brook, and moderately high in part of the thinly laminated black siltstone. No radon problem has been identified at this time in association with this unit, although, this may be due to the small number of houses located on it.(Paragraph contributed by K. W. Muessig and H.F. Houghton).

27.8 0.6 Excellent exposures of members E and F in creek to right. In this case, McLaughlin (1944) named two the gray parts of two successive 100,000 year cycles in the lower part of a 400,000 year cycle members E and F.

30.7 2.9 Members G and H of McLaughlin are poorly exposed in hills on right. G and H are two 100,000 years cycles

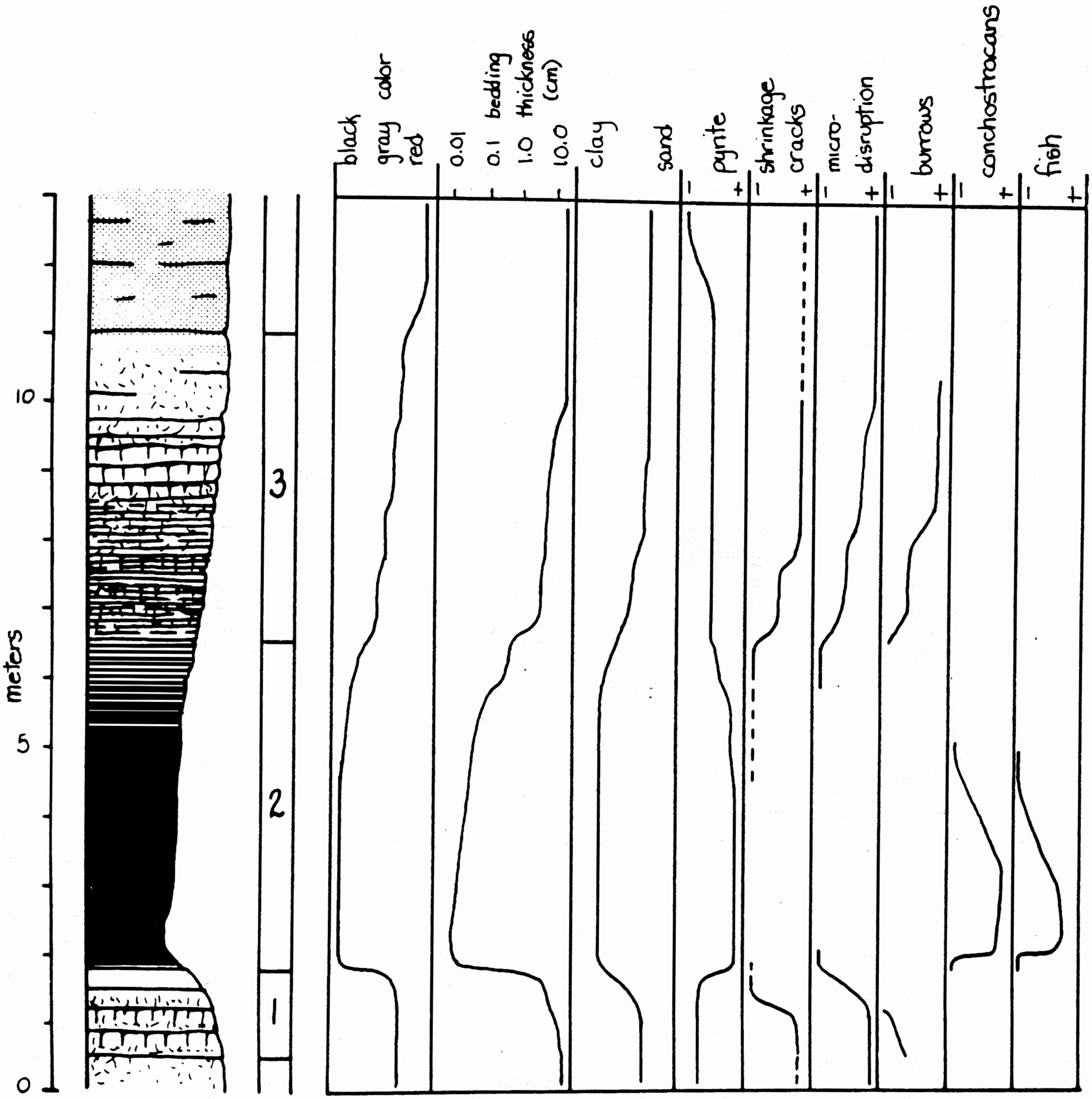


Figure 17. Van Houten cycle in member D of the lower Passaic Formation, Stop 5 (from Manspeizer and Olsen, 1981).

named in the same way as E and F; however, McLaughlin (1933) provided an alternate name, the Graters Member. McLaughlin (1943, 1944, 1946) mapped the Graters and its constituents over much of the basin.

30.9 0.2 Crossing Nishisakawick Creek.

31.0 0.1 Turn left (west) onto Main St. and then right (N) onto Hunterdon County Road 615 (Harrison Street) and head north.

32.6 1.6 Small quarry on right in Passaic Formation. Much burrowing by *Scoyenia* and some very poor footprints are present (*Brachychirotherium*). Outcrop described by Van Houten (1980, Stop 3).

34.6 2.0 Turn left at intersection with County Road 515 at traffic light, Milford center.

About 0.8 mi north of here are several good exposures of the Perkasie Member of the Passaic Formation and adjacent beds (Olsen and Flynn, in press). A road cut on the east side of Water Street (see Olsen and Flynn, in press) exposes gray and red claystones of division 2 of a Van Houten cycle about 5 m above the base of member O containing *Semionotus*, the clam shrimp *Cyzicus* sp. and cf. *Ellipsograpta* sp. and non-darwinulid as well as darwinulid ostracodes. These and a succeeding Van Houten cycle make up Cornet's (1977) pollen and spore localities M-3 and M-4. About 100 m above the Perkasie further north up the road are outcrops of another gray member.

McIntosh *et al.* (1984) have identified the boundary between a lower thick normally magnetized zone and an upper thick reversed zone in this same outcrop. Here the base of the Perkasie lies about 20 m above boundary between magnetozones. This boundary has been identified at several outcrops to the southwest in the Hunterdon Fault Block and in the Watchung Syncline 60 km to east (Olsen and Gore, in press).

The Smith Clark Quarry is located on the east side of the large hill to the east of Water Street (Olsen and Flynn, in press). It is the locality for much of the type material of reptile footprints characteristic of the Triassic parts of the Newark Supergroup. The types of *Atreipus milfordensis*, *A. sulcatus* (Baird, 1957; Olsen and Baird, 1986), *Brachychirotherium parvum* (C.H. Hitchcock, 1889), *B. eyermani* (Baird, 1957), *Apatopus lineatus* (Bock, 1952), and *Rhynchosauroides hyperbates* (Baird, 1957) were collected from this site. Examples of Grallator (*Anchisauripus*) *parallelus* (Baird, 1957), *Rhynchosauroides brunswickii* (Baird, 1957). *Coelurosaurichnus* sp. (Olsen and Baird, 1986), and an uncertain tridactyl form (Baird, 1957) have also been found along with abundant plants. The stratigraphy and detailed paleontology of this site have been described in Olsen and Flynn (in press).

McLaughlin's members L and M are exposed about 100 m below the Perkasie Member on west side of York Street, at the base of the hill below and to the south of the the Smith Clark Quarry (Olsen and Flynn, in press). Outcrops of these gray members contain clam shrimp and constitute Cornet's localities M-1 plus M-2 and M-6, respectively. Pollen and spores form these beds indicate an early Norian age (Cornet, 1977; Cornet and Olsen, 1985) for the Perkasie Member and members L and M.

34.7 0.1 Right onto Church Street and then left on continuation of Church Street.

34.8 0.1 Right onto Spring Glen Rd. (Hunterdon Co. 627).

THIS ROAD IS VERY NARROW AND HAZARDOUS; BEWARE OF ONCOMING VEHICLES.

35.1 0.3 Culvert on right and adjacent exposure of member M, described by Turner-Peterson (1980). Gray shale at base of division 2 of Van Houten cycle at this outcrop has produced disarticulated *Semionotus* and *Cyzicus*.

35.7 0.6 First of a series small faults which are down to the east.

35.9 0.2 Estimated position of second fault.

36.0 0.1 Cyclical mudstone beds of Passaic Formation below members L and M.

Cycles are obvious at several scales. Picard and High (1963) report that this exposure show an alternation of massive ledge forming units of poorly sorted siltstone with less resistant and finer-grained units, with the couplets ranging from 1.1 to 4.8 m and averaging 2.6 m thick. Most units show intense bioturbation and common desiccation cracks merging into breccia fabrics. The thinner of these alternations seem to us to be grouped into larger cycles averaging 5 to 7 m thick. We hypothesize that these larger cycles are probably homologous to the Van Houten cycles in the more arid portions of the 400,000 year cycles as seen at Stop 4, while the shorter alternations correspond to the "aggradational cycles" also seen in the Lockatong at Stop 4. This hypothesis needs testing by careful measurement of this section combined with Fourier analysis. This section is also described in Van Houten (1969, Stop 5).

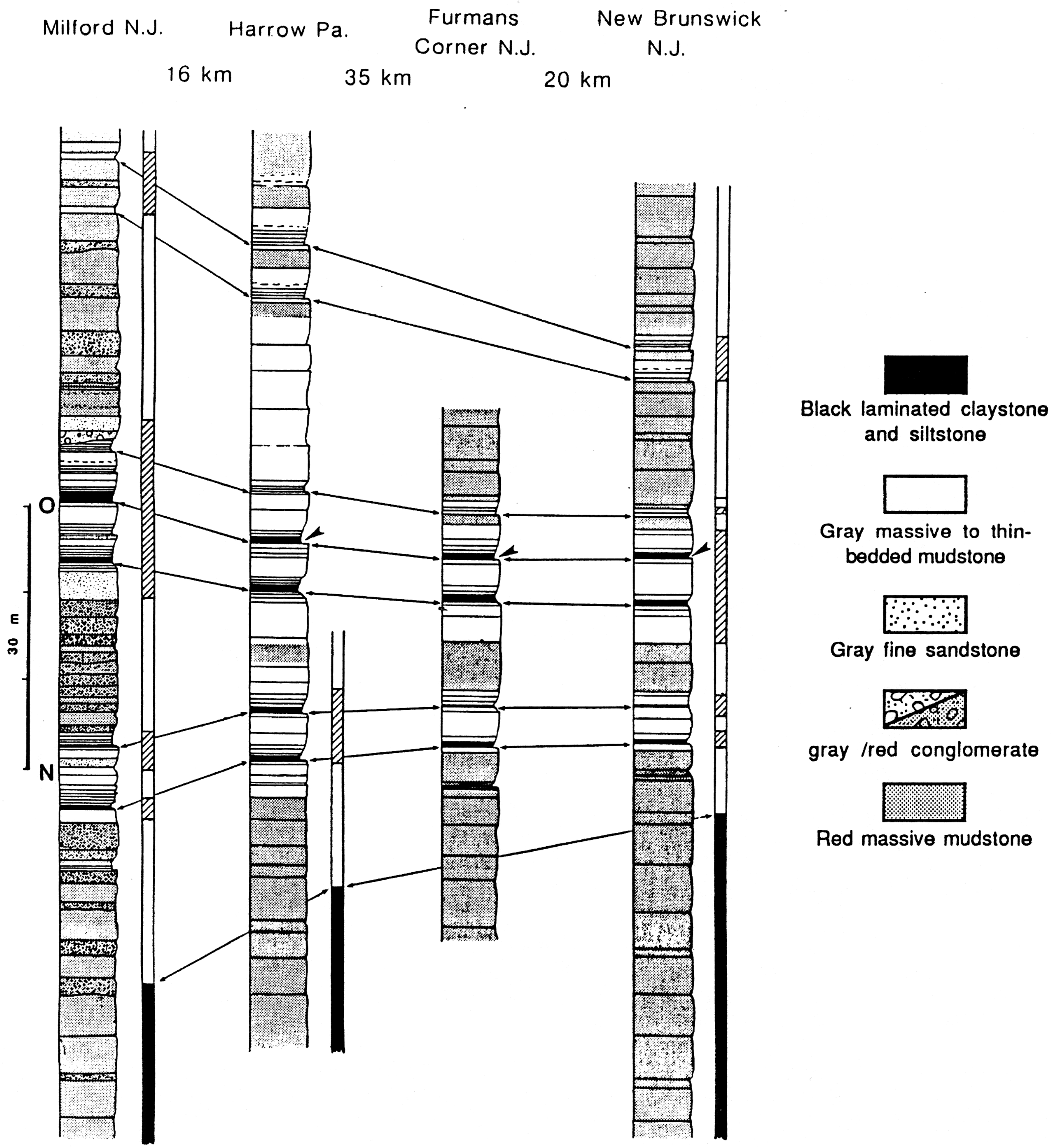


Figure 18. Stratigraphy and lateral correlation of the Perkasie Member from New Brunswick (on right) to Milford on left (from Olsen, in press). Vertical black, white, and diagonal ruled bars represent normal, reversed, and uncertain polarity zones, respectively. Large chevrons denote intervals enriched in uranium.

36.3 0.3 Park in dirt area off road to right at railroad milepost 37 (adjacent to tracks and road).

STOP 6
PEBBLE BLUFF EXPOSURES OF CONGLOMERATE AND LACUSTRINE BEDS AT EDGE OF NEWARK BASIN

These outcrops [also described by Van Houten (1969, Stop 6; 1980, Stop 1) and Arguden and Rodolpho (1987)] consist of extensive exposures of thick sequences (+20 m) of red conglomerate and sandstones alternating with cyclical black, gray, and red mudstone, sandstones. Dip averages 10-15° NW and there several faults between the largest outcrops which drop down to the east. The largest gray beds (see Figures 18, 19) appear to be the Perkasie Member.

The Perkasie Member consists of Van Houten cycles and compound cycles showing the same pattern as the Lockatong (Figure 18) (Olsen, in press; Olsen and Baird, 1986). It consists of two sequential 100,000 year cycles, each containing two well developed Van Houten cycles and one weakly developed red and purple Van Houten cycle, succeeded upwards by red clastics (Figure 20). McLaughlin named the lower set of gray beds member N and the upper member O.

Once thought to be the youngest strata in the Basin, it is now clear that the Perkasie Member and surrounding strata actually lie in the lower Passaic Formation roughly 2,800 m below the top of the formation. All of the overlying strata have been eroded in this area. Correlation of the Milford area with other fault blocks of the Newark basin where these younger beds are still preserved is afforded by magnetostratigraphy, lithological matching, and a palynological correlation web.

Most striking at these outcrops of the Perkasie and adjacent units are the large amounts of conglomerate present (Figure 19). According to Van Houten (1969, 1980), most of the conglomerates are made up of fining-upward sequences averaging about 7-9 m thick. Each sequence consists of poorly sorted conglomerate passing upward into poorly sorted sandstone with carbonate nodules (arranged in vertical columns or streaks) which become more dense upward. Most clasts are less than 8 cm in diameter, but some are as large as 23 cm (Figure 20). According to Van Houten (1969) these sequences resemble those of alluvial fans and the calcareous horizons are probably caliches. Some of the mudstones and sandstones show cross bedding at the more eastern outcrops, but elsewhere, they appear massive (Van Houten, 1969). We

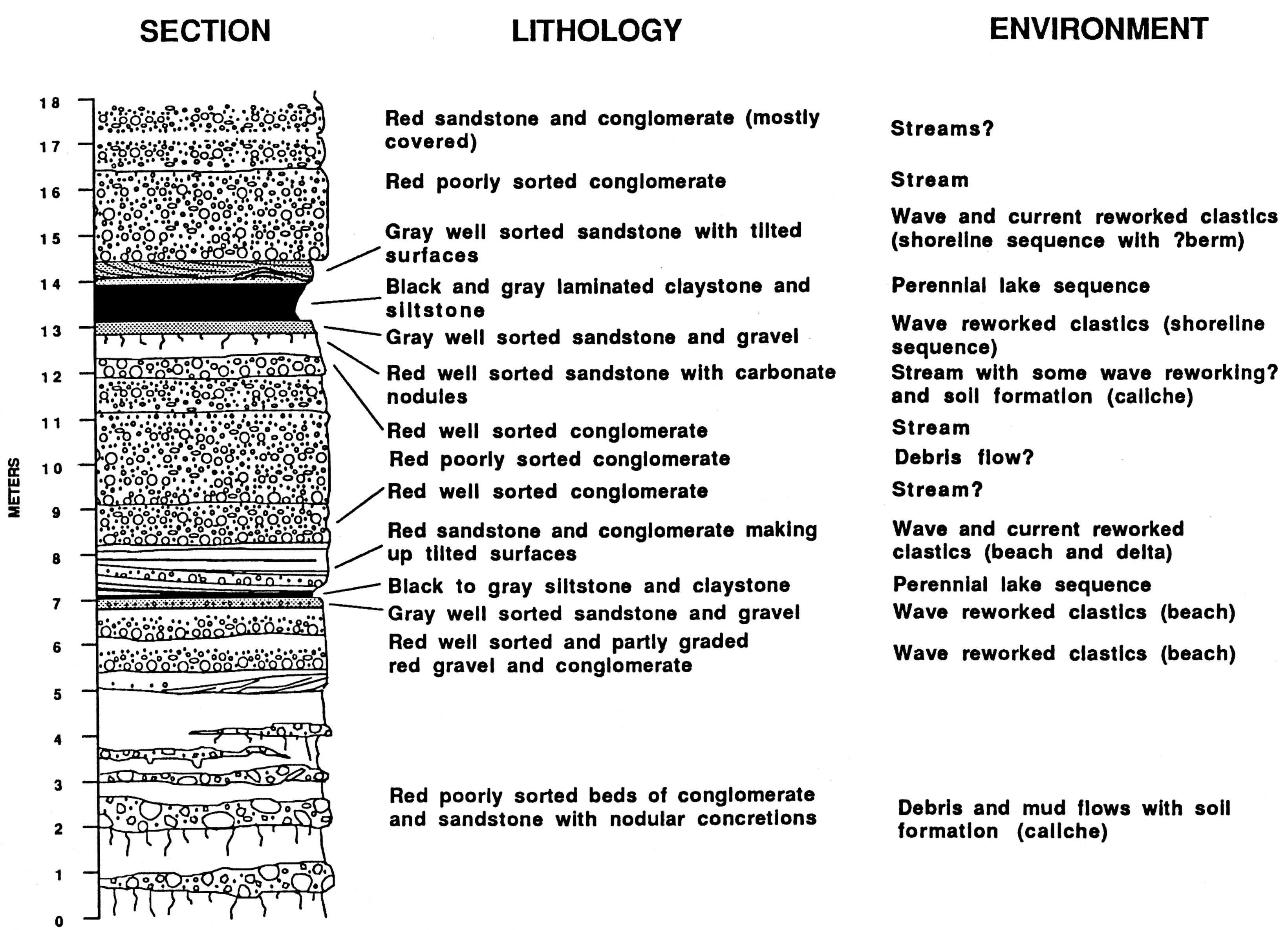
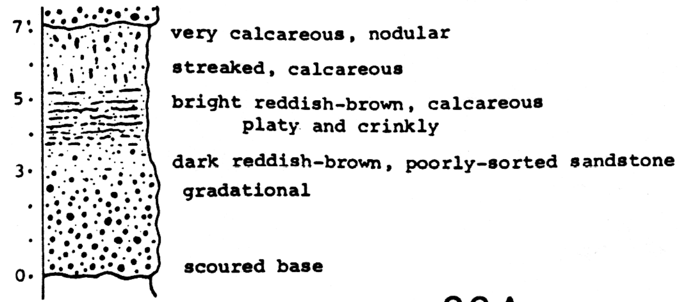
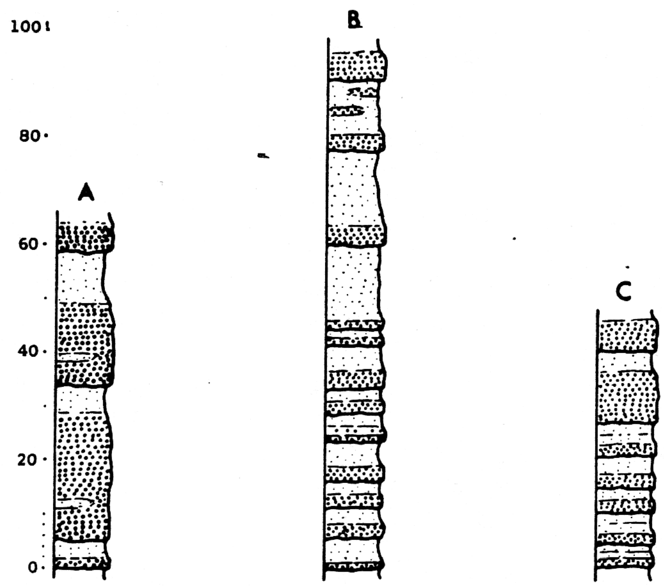


Figure 19. Section through small part of section at Stop 6 showing interfingering between perennial lake sequences, shoreline deposits, and alluvial fan sequences.



20A



20B

Figure 20. Conglomerate and caliche from Pebble Bluff area, Stop 6: 20A, Model of fining-upwards conglomerate-sandstone unit, showing sequence of elements commonly present (from Van Houten, 1969); 20B, Vertical sections of lenticular fining-upwards conglomerate-sandstone units [A is 0.5 mi northwest of C, maximum clast size is about 33 cm for (A) and about 23 cm for (B)](from Van Houten, 1969).

wonder if these sequences might not be related in some way to the smaller scale cycles seen at mileage 36.0.

Arguden and Rudolpho (1987) recognize three types of conglomerates at these outcrops: 1) matrix supported, poorly sorted conglomerate often showing reverse grading, which they interpret as debris flow deposits; 2) poorly sorted clast supported conglomerate, which they interpret as a hyperconcentrated stream facies; and 3) better sorted clast supported conglomerates which they interpret as short-lived braided stream deposits. They interpret all three conglomerate types as the products of alluvial fans. At least some beds which fit the criteria of their last type of conglomerate, however, are very closely packed, tabular beds with crude normal grading, and are intimately associated with black and gray Van Houten cycles of the Perkasie; these closely resemble wave reworked fluvially supplied gravels as described by Bourgeois and Leithold (1984) and LeTourneau (1984). Within these conglomerates J. Smoot (pers. comm.) recognizes the presence of patches of oscillatory ripples, preferential sorting of larger particles adjacent to pebbles, interbedded sets of internally well sorted thin beds of different clast size.

Laterally continuous black and gray siltstones and claystones within division 2 of Van Houten cycles (Figure 18) contain pinch and swell laminae abundant burrows and rare conchostracans and are definitely lacustrine deposits, almost certainly marginal to the finer grained facies more centrally located in the basin. These lacustrine sequences mark transgressions of perennial lakes over the toes of alluvial fans, much as LeTourneau (1984) has described in marginal facies of the Portland Formation in Connecticut. Division 2 of cycles comprising the Perkasie member were produced by lakes which were almost certainly shallower than those which produced the microlaminated, whole fish- and reptile-bearing units in other parts of the Newark basin section. They evidently were deep enough, however, to transgress over at least the relief caused by the toes of alluvial fans. To what degree have more subtle transgressions of shallower lakes modified clastic fabrics elsewhere in this section? A number of researchers (Van Houten, pers. comm.; Smoot, pers. comm., Manspeizer, pers. comm.) have commented how many of the conglomerate clasts in many of the debris flow units are relatively well rounded, and mixed with angular clasts. We suggest that it is possible that these debris flows originated by degradation of shoreline deposits formed high above the basin floor during high stands of the great Perkasie Member lakes.

In this reagion individual Van Houten cycles of unit O are an average of 7 m thick, as compared with a mean of 6.5 for the same two cycles to the southeast and 4.5 for the cycles at New Brunswick (Figure 20). The large, comound cycles show the same trend as well. This thickening toward the border fault is typical of most of the Newark Supergroup. The trend to greater fossil richness is evident at this outcrop as is typical for more marginal facies of the Passaic Formation, and the conchostracans present in the upper parts of division 2 are absent in the more basinward exposures.

The border fault is less than 2.4 km (1.5 mi.) to the northwest of this series of outcrops. As mapped by Ratcliffe and others (1986) on the basis of surface geology, drill cores, and Vibroseis profile the border fault in this area is a reactivated imbricate thrust fault zone dipping 32° SE. Core and field data reveal Paleozoic mylonitic fabrics of ductile thrust faults in Precambrian gneiss and early Paleozoic dolostone overprinted by brittle cataclastic zones of normal Mesozoic faults which form the border fault system of this part of the Newark basin. According to Ratcliffe and others (1986, p. 770), "Field evidence indicates reactivation of the imbricate thrust faults in an extensional mode, a dominant extension direction being S40° to S50°E. These data suggest strongly (1) that reactivation of Paleozoic thrusts controlled the formations of the border fault in eastern Pennsylvania and (2) that fault patterns may have formed by passive response to extension rather than by active wrench fault tectonics as proposed by Manspeizer (1980). This differs from the interpretation of Drake and others (1967) who proposed that the border fault of the Newark basin is a relatively high-angle reactivated, overturned thrust fault of the Musconetcong nappe. Ratcliffe and others' model is in agreement with proprietary seismic lines and drill hole records in this area and to the southwest.

A series of very gentle but rather complex folds are present in this area close to the border fault (Figure 7). They are the most northeast folds in the hanging wall along this part of the border fault system. On the New Jersey side of the Delaware River their axes are parallel to the fault but the folds have axes which switch to high angles with the border fault on the Pennsylvania side of the river. What might this transition have to do, if anything, with the formation of folds in the basin?

Additional Comments on Structure (contributed by R.T. Faill)

The northward dip of bedding, and the various fractures dominate the structure here. One set of fractures is noteworthy. These fractures dip southward, and are quite common and persistent. The distinctive aspect is that some of these bend sharply into the bedding planes. No offsets are apparent, but at least one of them has subhorizontal slickenlines, parallel to the strike (northeast). This suggests that these fractures are strike slip faults, and therefore the absence of bed offsets is not surprising.

Spring Garden Road is 600 m south of the nearby railroad milepost 37. The Passaic Formation crops out for 450 m south of Spring Garden Road, with beds dipping northward at approximately 10 degrees. As another illustration of the sporadic distribution of structures, cleavage and numerous faults occur near the south end of that outcrop, a distinct contrast to here, at Stop 5. There, the most common features are steeply northeast to east dipping fractures, some of which offset bedding by several centimeters each, down on the east. Slickensides are steeply to moderately northwest plunging, an orientation also seen at Stop 1.

In addition, a few of the argillaceous siltstone beds have developed a spaced cleavage in them that dips steeply to the east, subparallel to the faults. Spacing of this fracture cleavage is 1 to 5 cm, and a lineation on the cleavage plunges steeply to the north. This lineation is more a crenulation than slickenlines. The cleavage is not present in the more argillaceous beds, which themselves possess a fair fissility.

Many of the outcrops along the Delaware River do not exhibit much structure. But they do support the two contentions: 1) the mesostructures that are present show little direct relevance to the overall extensional tectonics of the basin; and 2) the occurrence of specific structures is sporadic.

END OF FIELD TRIP

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