NAGT EASTERN SECTION - 1996

FIELD TRIP

METAMORPHISM AND LITHOLOGY, CENTRAL APPALACHIAN PIEDMONT, PENNSYLVANIA - MARYLAND - DELAWARE

MAY 25, 1996

LEADER:

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UNIVERSITY OF DELAWARE

INTRODUCTION TO THE FIELD TRIP:

WELCOME to this NAGT field trip on the nature of metamorphism in the central Appalachian Piedmont. Actually, the trip will focus on both metamorphic and igneous rocks/ Nearly all rocks of the Piedmont province have undergone at least some metamorphism, and it is difficult to separate the metamorphic story from other stories in the rocks. In addition, nearly all the metamorphic rocks have been affected by deformation, and hence the structural story is a theme today also.

Figure 1 shows a map indicating the route of the trip. The trip contains nine stops, from southeastern Pennsylvania through northeastern Maryland and into northern Delaware. We will make as many of these stops as we can, and I don't guarantee we'll cover them all. We will take mid-morning, noon and mid-afternoon pit stops, and will alter the route or the timetable to accommodate group demands and mandates. This is your day, not mine.

GEOLOGIC FRAMEWORK OF THE PIEDMONT PROVINCE:

The Piedmont province contains the "core" zone of the old Appalachian mountain belt. It consists of a number of geologic "belts", striking ENE to E through this area, each of which is internally fairly consistent in both rock type, structure and degree of metamorphism. Across strike, however, adjacent belts may be strikingly different, and may represent considerably different geologic settings and histories.

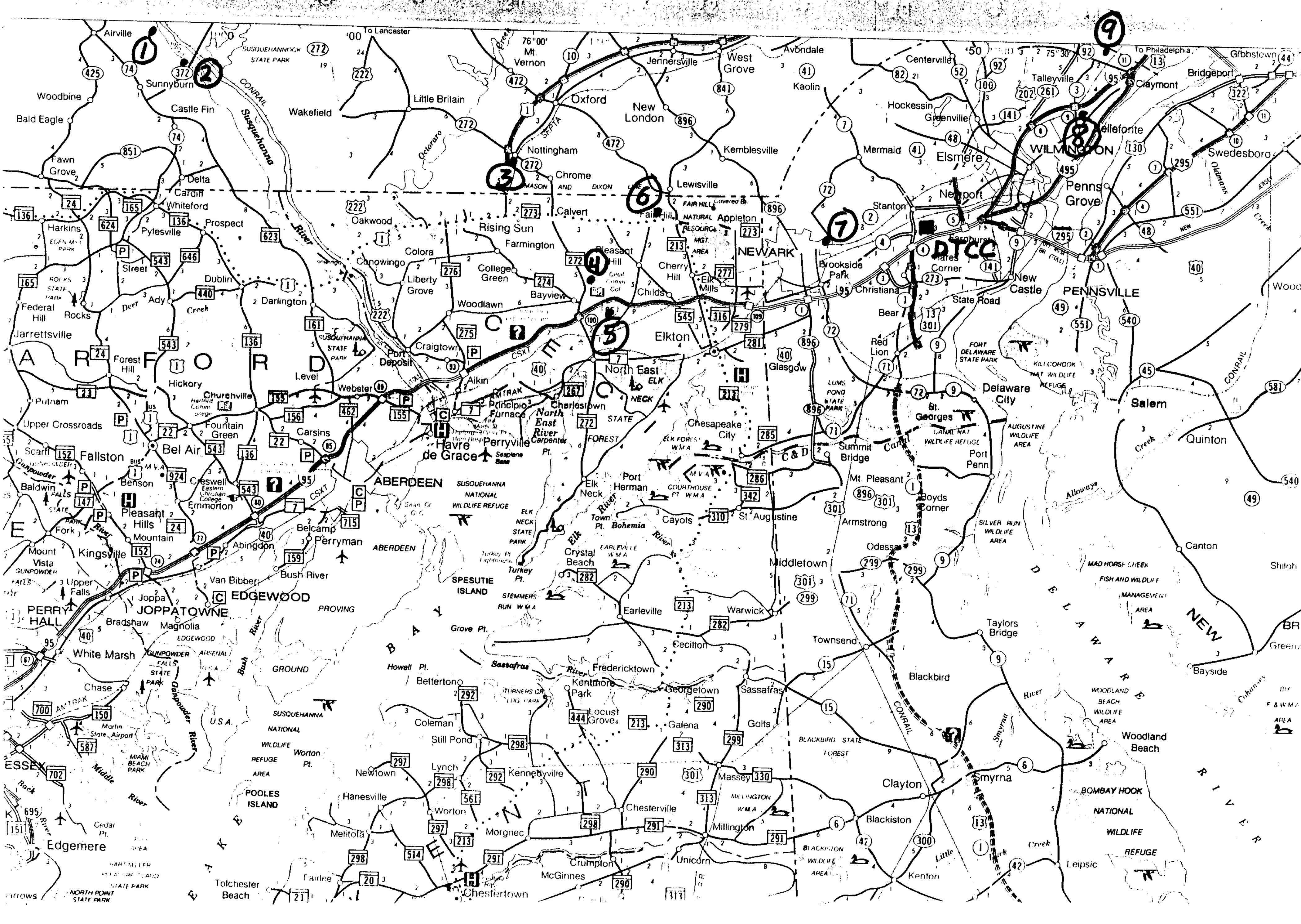
The northwestern belts (stops 1 and 2), in Pennsylvania, contain originally sedimentary rocks, of probably deep-marine origin in the late Precambrian and early Cambrian Iapetus Ocean. The metamorphic grade is low, but deformation is high. The rocks have been thrust-faulted westward over older rocks.

Belts in the central area of the trip (stops 3, 4, 5 and 6), mainly in Maryland, contain originally sedimentary and igneous rocks, which probably originated in a magmatic arc setting. The igneous rocks are both plutonic and volcanic, and the sedimentary rocks contain volcanic contributions. These central belts contain the suture zone along which the Iapetus ocean was closed by subduction during the Taconian orogeny in late Cambrian and Ordovician times. Metamorphic grade here is low to moderate, and deformation is low to high.

The eastern belts (Stops 7, 8 and 9), in Delaware, contain originally sedimentary and igneous rocks of uniformly high metamorphic grade and extreme deformation. They are probably part of a suspect terrane, that did not originate in its present location but was brought to this location by subduction of oceanic lithosphere.

The trip will cross the Piedmont belts from WNW to ESE.

Figure 1



1
2
3
4
5
6
7
8
9
DTCC
WILMINGTON
NEWARK
PENNSVILLE
ABERDEEN
EDGEWOOD
JOPPATOWNE
PERRY HALL
Elkton
North East
Havre de Grace
Perryville
Bel Air
Fallston
Chestertown
Middletown
Smyrna
Clayton
Salem
Penns Grove
New Castle
Delaware City
Oxford
Rising Sun
Port Deposit
Aikin
Charlestown
Elsmere
Newport
Stanton
Christiana
Bear
Red Lion
Glasgow
Chesapeake City
St. Augustine
Odessa
Townsend
Blackbird
Claymont
Bellefonte
Swedesboro
Bridgeport
Gibbstown
Quinton
Canton
Hockessin
Greenville
Centerville
Mermaid
Kaolin
Avondale
West Grove
Jennersville
New London
Kemblesville
Lewisville
Nottingham
Chrome
Calvert
Little Britain
Wakefield
Delta
Cardiff
Whiteford
Pylesville
Airville
Sunnyburn
Castle Fin
Woodbine
Bald Eagle
Fawn Grove
Harkins
Jarrettsville
Forest Hill
Hickory
Churchville
Fountain Green
Creswell
Emmorton
Abingdon
Belcamp
Perryman
Joppa
Magnolia
White Marsh
Kingsville
Bradshaw
Edgemere
Chase
Conowingo
Colora
Liberty Grove
Craigtown
Woodlawn
College Green
Farmington
Bayview
Pleasant Hill
Childs
Cherry Hill
Elk Mills
Appleton
Brookside Park
Hares Corner
State Road
Summit Bridge
Mt. Pleasant
Boyds Corner
Armstrong
Port Penn
St. Georges
Warwick
Earleville
Cecilton
Fredericktown
Georgetown
Galena
Sassafras
Golts
Massey
Millington
Chesterville
Kennedyville
Morgnec
Crumpton
McGinnes
Worton
Hanesville
Melitola
Still Pond
Coleman
Betterton
Tolchester Beach
Lynch
Newtown
Fairlee
Kenton
Blackiston
Leipsic
Woodland Beach
Taylors Bridge
Bayside
Shiloh
Unicorn
Elk Neck
Port Herman
Cayots
Crystal Beach
Turkey Pt.
SPESUTIE ISLAND
POOLES ISLAND
DELAWARE RIVER
NEW
SUSQUEHANNA NATIONAL WILDLIFE REFUGE
BOMBAY HOOK NATIONAL WILDLIFE REFUGE
FORT DELAWARE STATE PARK
SUSQUEHANNOCK STATE PARK
BLACKBIRD STATE FOREST
FAIR HILL NATURAL RESOURCE MGT. AREA
CONRAIL
AMTRAK
CSXT
C & D Canal
Susquehanna River
Sassafras River
Bohemia River
Elk River
Gunpowder River
Bush River
Middle River
Octoraro
76°00'
75°30'
To Lancaster
To Philadelphia
MASON AND DIXON LINE

STOP 1: OTTER CREEK PARK
Red Lion, PA .

The rocks here on the banks of the Susquehanna River are **mica schists** and **phyllites** of the Prettyboy Formation. Minor layers of **sandy schist** and impure **quartzite** are interbedded with the schists. Major minerals in the schists include **muscovite, chlorite, quartz**, and small **plagioclase feldspar** (albite) porphyroblasts. These rocks probably had sedimentary shales, mudstones and impure sandstones as parents. The presence of chlorite and muscovite indicate low grades of metamorphism, consistent with the **greenschist facies** of regional metamorphism.

Despite the low metamorphic grade, these rocks have been intensely deformed, and at least **three episodes of deformation** are visible here. (1) The major **foliation** (layering) is of structural rather than sedimentary origin, and is defined by thin stringers and lensoid eyes of quartz. Look for small- (cm to mm-) scale folding of the quartz stringers. The rock shows good examples of **boudinage**, which is a separation of lenses of layers, and has undergone considerable **extension** parallel to layering, primarily by **stretching**. (2) After the extension, the layering was strongly **folded**, and you can see decimeter- and meter-scale tightly pressed, nearly isoclinal folds lying parallel to the foliation. (3) superimposed on all earlier structures are very fine, mm-scale **crenulation folds**, which give foliation surfaces a ruled, lineated appearance. Look at these folds closely, and you'll see micas/chlorite folded around the hinges. This is well shown on the large outcrop near the river.

NOTES:

STOP 2: HOLTWOOD DAM, SUSQUEHANNA RIVER

If the water's low enough to allow us out on the spillway, this location displays good examples of **greenschists** as well as mica schists and phyllites. In the spillway are masses of greenish rock containing large amounts of the mineral **epidote**. **Chlorite** and **plagioclase** are also common here. The parent rocks of these mineral assemblages were probably **igneous rocks**, such as **basalt**. The presence of epidote plus quartz suggests that these rocks represent **low-grade metamorphism**, consistent with the **greenschist facies**.

The rocks of basalt composition, the epidote-bearing, greenish rocks, appear to be discontinuous on all sides, and to be surrounded by mica schist and phyllite. The logical interpretation of these relationships is that these masses represent **blocks** of basalt included tectonically in a **breccia**-like rock termed **melange** (= blocks in a matrix). Such melanges commonly form along the leading edges of subduction zones, just above the subducting plate. If this is true, this rock may represent part of the closing and elimination of the early Paleozoic **IAPETUS** ocean, to whose evolution the Appalachians are tied. The blocks of basalt may represent torn-off pieces of oceanic crust torn off the subducting plate and incorporated into the thrust-faulted belt at the edge of the overriding plate.

NOTES:

STOP 3: **NOTTINGHAM PARK**
Nottingham, PA

This location exposes the rock **serpentinite**, a greenish-gray, rather grungy-looking rock made up mostly of the mineral **serpentine**, variety **antigorite**. Antigorite is the massive variety of serpentine, and comprises most of the occurrences of serpentine. The fibrous variety, **chrysotile**, is more rare, and may be seen in small veins that cut through the serpentinite.

Serpentine forms as the result of low-grade metamorphism and hydration of the mineral **olivine**. The serpentine reaction is known from laboratory experiments to take place at low temperatures; serpentinite thus reflects **low-grade metamorphism**, consistent with the **greenschist facies** of regional metamorphism.

The serpentine reaction entails a 47% volume increase over the original olivine, and as a result serpentine and serpentinite are relatively light, low-density materials. Heft a few samples and check that out. Most serpentinite is thought to represent olivine rich rocks, primarily **peridotite** and **dunite**, which are in turn thought to represent pieces of the earth's **mantle**.

Examine these serpentinites with a hand lens. Note the black, metallic mineral; probably **chromite**. Note the "box-work" or "lattice-work" textures of the serpentine: massive pale green-gray serpentine surrounding rounded cores (looking like sand grains) of other minerals. Could these cores be grains of the original olivine? Check it out.

Note the lack of foliation, the well-developed sets of brittle fractures (**joints**), and the several parallel **veins** of whitish mineral. Are these veins generated by the metamorphism? Or could those be metamorphosed igneous **dikes**?

NOTES:

STOP 4: **GILPINS FALLS**
Northeast, MD

This is private land; ask permission at the house before examining the rocks. WATCH OUT FOR POISON IVY HERE!

The rocks here in central Cecil county, MD, are **pillow basalt** lavas belonging to the James Run Formation. The pillow forms are well displayed on the vertical facies of the outcrops. Note the dark, black, dense-looking outer rims of the pillows, followed inward by very small, round masses of white mineral (plagioclase feldspar), followed by central zones which look fairly coarse-grained. This internal zonation is a relic from the original cooling of the magma against cold ocean water. The black outer rind represents a glassy sleeve/skin quenched against the cold ocean water that insulated the interior of the pillow and permitted slower cooling and larger grain sizes. The small round grains represent filling of originally open gas-bubble cavities, or **vesicles**, that formed when dissolved gas came out of solution as the magma cooled. Note the rock material between pillows; this represents oceanic sediment that filled the inter-pillow space. Like pouring dirt on a pile of potatoes.

The original basalt has been transformed to **greenschist** by the metamorphism. The major minerals here are **epidote, chlorite,** and **actinolite**, all green to green-black minerals, and collectively responsible for the name "greenschist". The minerals are consistent with metamorphism in the **greenschist facies** of regional metamorphism.

INTERIM SUMMARY: To this point in the trip, we have seen three **different original rock types** (shale/Maidstone, basalt (twice), peridotite) metamorphosed under the **same set of conditions** (low temperature, low pressure, water present), that is, greenschist facies, produce **different metamorphic rocks** and **different mineral assemblages**. This is one of the most basic principles in metamorphic petrology.

NOTES:

STOP 5: MARYLAND MATERIALS QUARRY
Northeast, MD

Ask permission at the quarry office of scale house before entering quarry. Access easy on weekends, difficult during week. Hardhats preferred.

This quarry is the major supplier of crushed stone in northeastern Maryland and all of Delaware. Most of I-95 in those two states came out of this pit.

The rocks here consist of silicic, felsic, intrusive **granodiorite** and **quartz diorite** of a small batholith (stock?) that intrudes a series of volcanic rocks, including **rhyolite, basalt** and probably some **pyroclastic ash flows**. All rocks have undergone low-grade, probably greenschist-facies metamorphism.

The basalt is dark-colored, and the rhyolite looks brown-gray. Both are massive, dense rocks, but you may be able to see some internal structure in them. They contain occasional **pyrite, chlorite** and quartz crystals.

The intrusive contact of the plutonic rocks into the volcanic rocks is in the NE corner of the quarry, but is not well shown or accessible.

The silicic intrusives are medium-grained, and contain **quartz, plagioclase feldspar** (albite), **biotite,** and **amphibole**. The effects of metamorphism are not clearly shown in these rocks. The rock is massive, with no flow layering or xenoliths.

The batholith has been affected by strong brittle deformation, and is fractures and faulted. Several **faults** are visible on the north wall. Offset layers are absent, and the faults are detected by the presence of fault **gouge**, which is dark, shiny, slippery, powdered rock material ground down by the crushing action of the two walls of the fault. The minerals in the gouge are **chlorite, actinolite, pyrite** and **tourmaline**. Smaller fractures, defined by dark gouge streaks, pervade the rocks.

Although not clearly shown, the metamorphic grade here is established as **low-grade, greenschist facies** by the presence of pyrite, actinolite, chlorite and tourmaline.

NOTES:

STOP 6: **ROCK CHURCH**
Elton, MD

The rocks in this outcrop in the front year of Rock Presbyterian Church belong to the same pillow basalt unit we saw at Stop 4. And the metamorphic grade here is about the same as at Stop 4, that is, low temperatures and pressures of the greenschist facies. Here, however, the metamorphic mineralogy is dominated by the amphibole **actinolite** and by **plagioclase feldspar** rather than by epidote. The rock here is an **amphibolite**, of the greenschist facies, and not of the amphibolite facies.

The parent rocks of these amphibolites were pillow basalts, and it is possible to make out the faint outlines of deformed pillows low on the front face of the outcrop. Rounded to stretched-out (pencil-shaped) mm-scale masses of feldspar represent filled gas-bubble **vesicles** in the original lavas.

The effects of deformation, particularly folding, are strongly developed in these rocks. At least **four** or five **generations of folds** have affected the rocks, and some examples of multiple folding and refolding will be pointed out.

NOTES:

STOP 7: **WINDY HILLS BRIDGE**
Newark, DE

Under the DE 2 highway bridge over White Clay Creek are outcrops of light-colored **quartz-feldspar gneiss,** dark-colored **amphibolite,** and **granite** that belong to the James Run Formation. The gneisses contain **quartz, plagioclase feldspar, K feldspar,** and **biotite** in various proportions. The amphibolites contain **hornblende amphibole** (not actinolite), **pyroxene, biotite**, plagioclase and quartz. These minerals are consistent with experimental data that support origin at **high temperatures, high pressures,** and relatively **low water pressures**. The mineral assemblages are consistent with metamorphism in the **amphibolite facies** of regional metamorphism.

This assessment of temperature and pressure conditions is supported by the presence of bodies of **granite** that show no chilling at their contacts with metamorphic rocks, and by streaks of enfiladed, coarser-grained granitic material within gneiss layers. These streaks have resulted from partial melting of the metamorphic rocks. This collectively points to the existence of high temperatures.

This rock has enjoyed intense deformation. Extreme shearing has taken place within the amphibolite layers, as shown by strung-out and flattened folds. Many folds are nearly isoclinal, and have been flattened. Some late, larger Z-folds have been sheared off and intruded by granite masses. Most of the folds have grown in connection with right-lateral, horizontal faulting. At least four stages of faulting can be recognized with a good imagination and a few beers.

NOTES:

STOP 8: **BRINGHURST WOODS PARK**
Wilmington, DE

This is a county park; no hammers please.

This location displays one of the best examples of igneous crystallization textures in the US. The rock here is a **gabbro**. The gabbro now contains **plagioclase feldspar** (labradorite), a little **pyroxene**, and a very little **olivine**. As we walk through the park, we will see that proportions of those minerals change considerably over short distances, leading to compositional **variation** and the use of different rock names to express that variation. At one end of the compositional spectrum is **anorthosite**, a rock composed mostly of plagioclase; at the other end is **melanogabbro**, a rock rich in dark minerals. We will see these and all grades in between.

The rocks in this batholith are particularly **coarse-grained**. Some crystals reach 15 to 20 cm long. The crystal size occasionally truly approaches that of a **pegmatite**.

It is possible to establish the **sequence of crystallization** of the minerals on the lightly weathered faces. Go for it. The early-formed crystals have rectangular outlines and straight sides; the later-forming crystals fill in the left-over space, and often have pointed and scalene-triangular outlines.

On appropriate surfaces, look for grains of mafic minerals that show orange-brown cores. Those orange-brown cores are olivine, and the rims around the cores are double rims of pyroxene next to olivine and hornblende next to plagioclase. These rims are called **coronas**, and they represent a partial, uncompleted, metamorphic reaction between olivine and plagioclase. Look around, and I'll bet you never find olivine and plagioclase touching each other. They're chemically unstable together, and reacted to form the hornblende and pyroxene, with which both are stable. Laboratory experiments on this reaction allow us to fix the conditions under which this reaction took place as between 6 and 7 kilobars and 600-650 degrees C. This qualifies as **high-grade metamorphism**, under conditions of the **granulite** facies of regional metamorphism.

However, the rock is structurally **pristine, undeformed**. The best igneous rock you'll ever see. There has been **no deformation** of this rock. It has escaped all tectonic deformation. How did it get metamorphosed and yet stay undeformed? If you have ideas, I'm listening... The metamorphism must have been a local event, related to the particulars of the cooling history of this particular batholith, and not part of a regional metamorphism.

As we walk up the creek, we will come to the contact between gabbro and the country rocks. Watch the proportions of minerals change, watch both the average grain size and the size range change, watch xenoliths and inclusions appear, and try to tell if and when (and whether) you've cross the contact. It's clear, but it isn't all that obvious.

NOTES:

STOP 9: **THE TIMBERS**
north Wilmington, DE

The rocks here are coarse-grained, porphyritic, intrusive igneous rocks composed of **plagioclase feldspar, K feldspar, quartz,** and a little **pyroxene**. The rock is **anorthosite**. It is essentially undeformed, and to my knowledge is unmetamorphosed.

The rock contains abundant feldspar grains that are distinctly coarser than the surrounding groundmass; these are **phenocrysts**. Examine the phenocrysts for **twinning** (lengthwise down the grain; Carlsbad twins), for **preferred shape orientation** (due to magmatic flow), and internal **compositional zoning** (concentric layering of different compositions) in plagioclase.

Note several small inclusions of other kinds rock. The general name for these masses is **enclaves**. If enclaves are of the country rock, they are **xenoliths**; if of any other origin, they are simply enclaves. Examine these enclaves for igneous textures, for minerals, for foliation or structure. See if you can make a case for an igneous origin for these enclaves. Do they contain more light-colored minerals than the anorthosite? More dark-colored minerals? Do you think they represent the same magma as the anorthosite magma?

Although these rocks are probably Lower Paleozoic and are related to events of Appalachian evolution, they look exactly like Precambrian anorthosites in upstate new York and Quebec, and it is tantalizing (if a bit unscientific) to speculate on how the story of the Appalachian evolution would have to change if they actually are of Precambrian age.

NOTES:

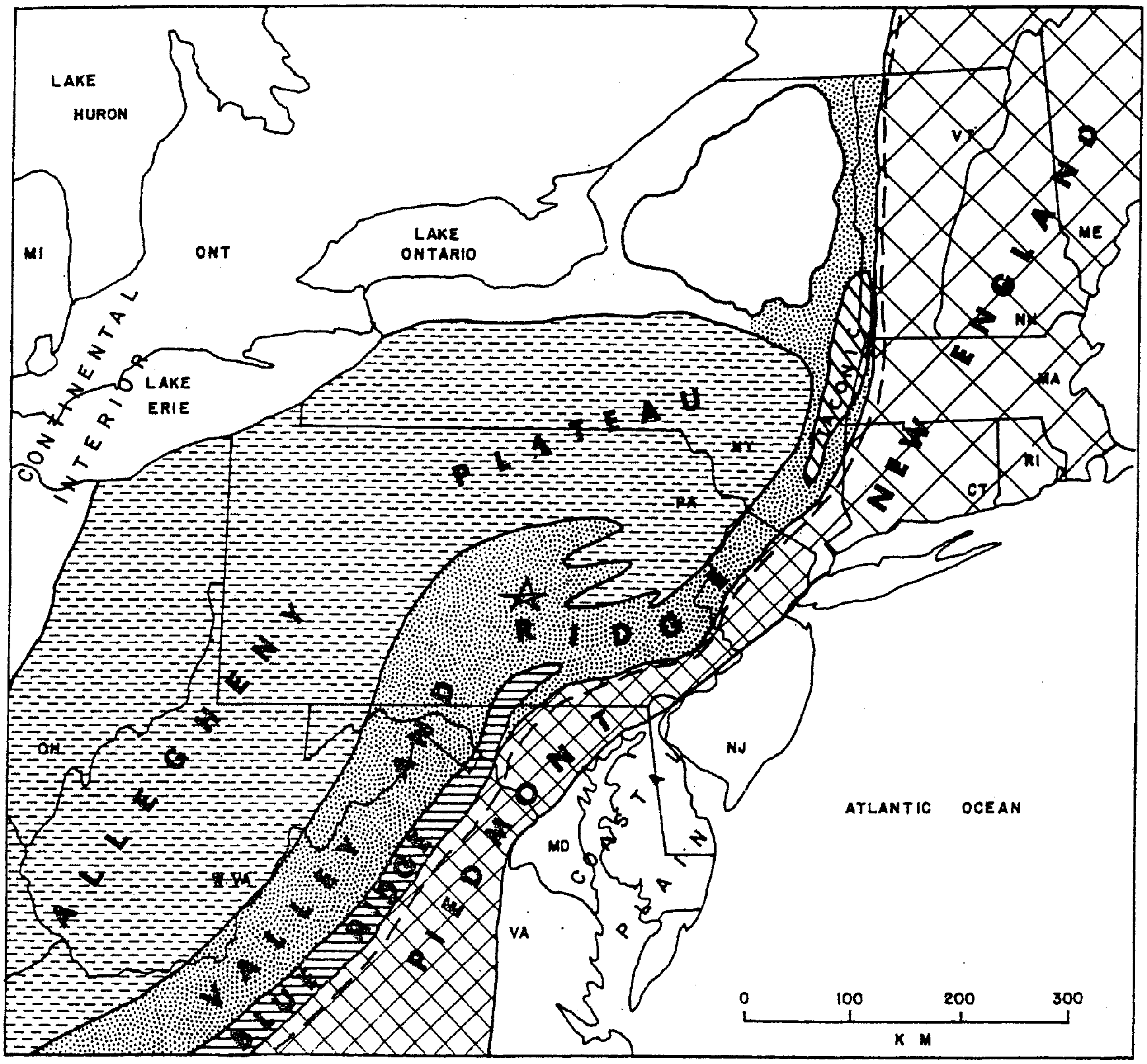


FIGURE 3. MAJOR PHYSIOGRAPHIC-GEOLOGIC PROVINCES OF CENTRAL APPALACHIAN OROGENIC BELT (PATTERNED AREAS). DASHED LINE INDICATES INFERRED EASTERN EDGE OF EARLY PALEOZOIC NORTH AMERICAN CRATON.

☆ = Reedsville, PA.

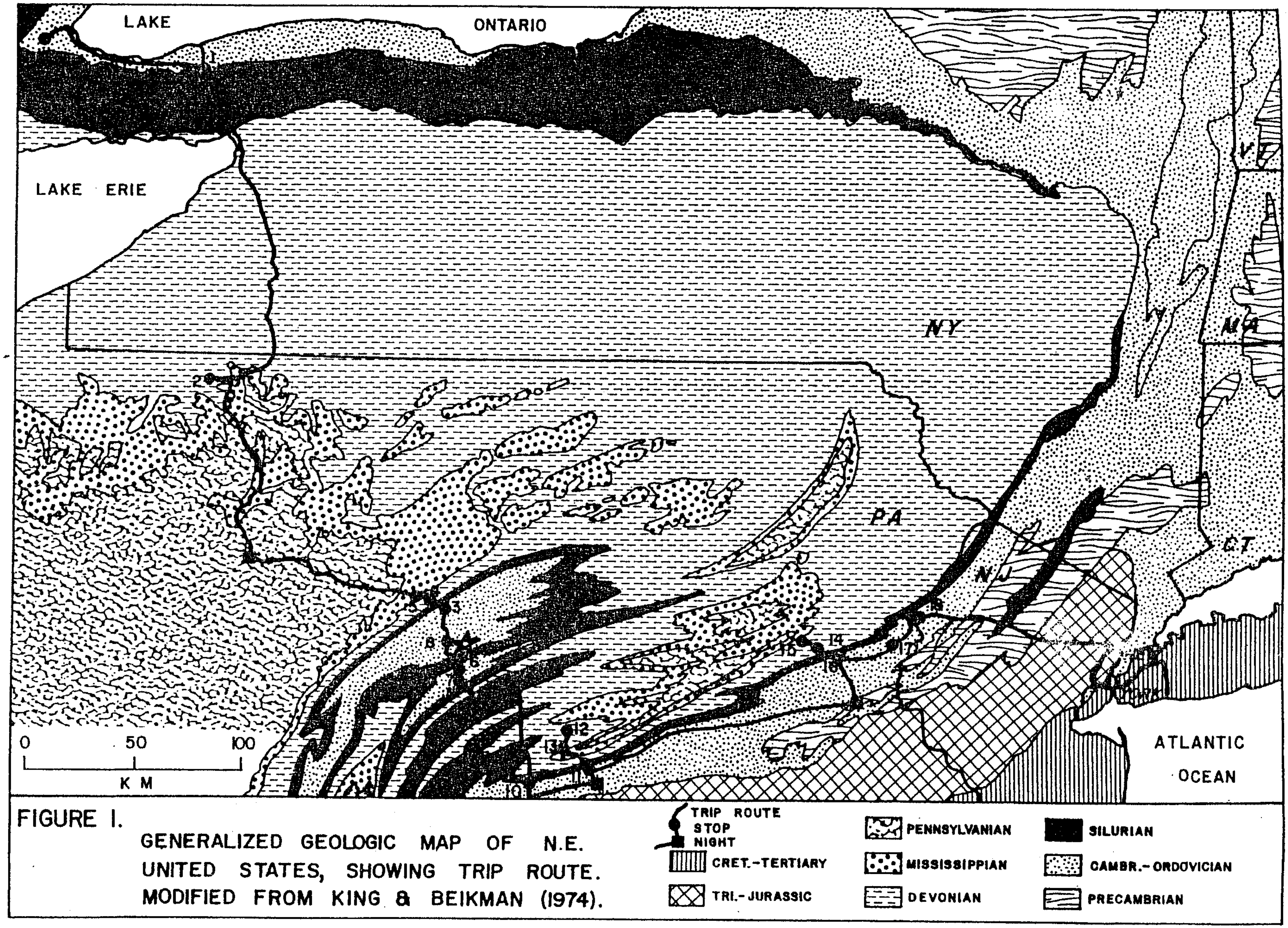


FIGURE I. GENERALIZED GEOLOGIC MAP OF N.E. UNITED STATES, SHOWING TRIP ROUTE. MODIFIED FROM KING & BEIKMAN (1974).

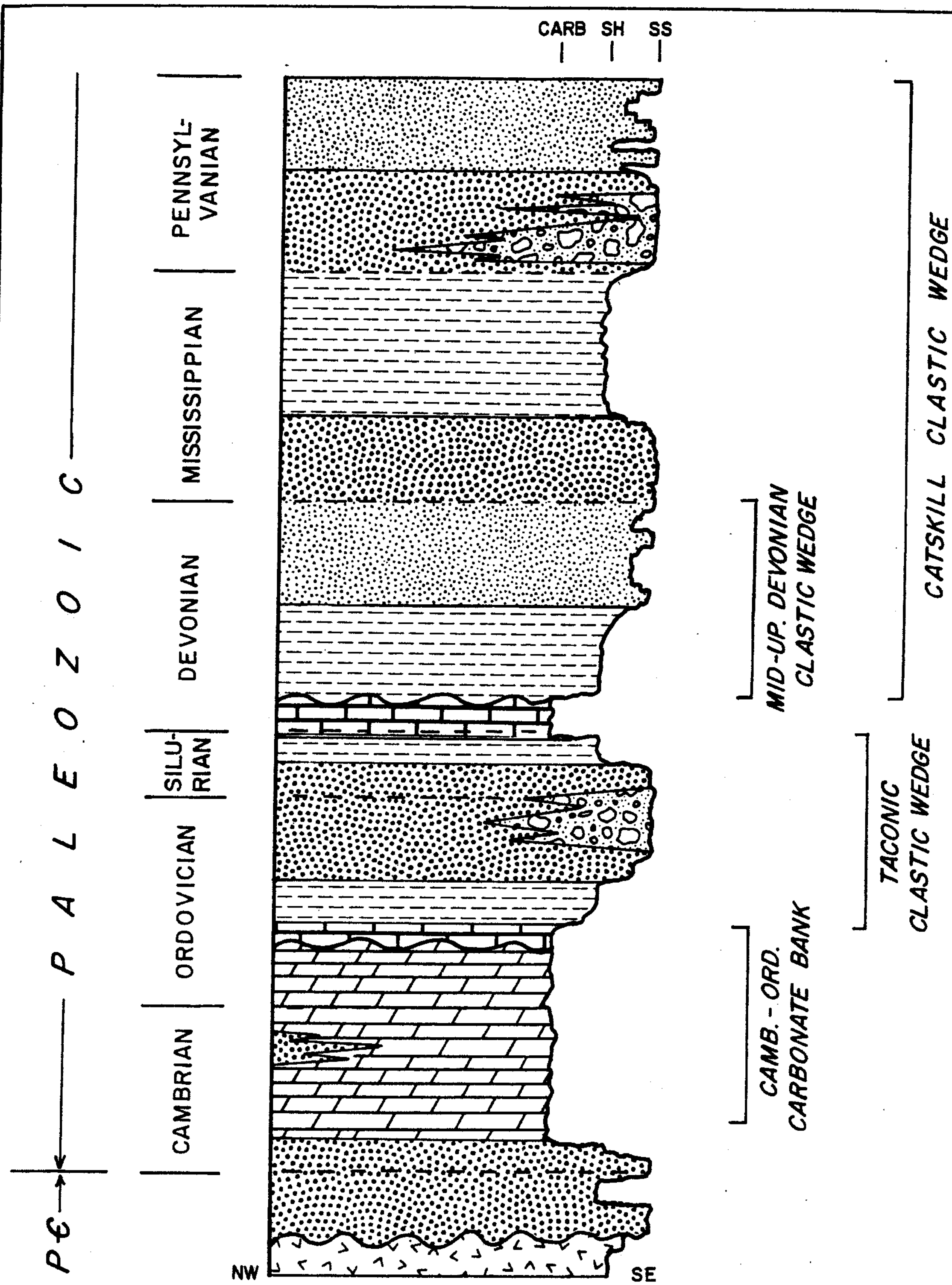
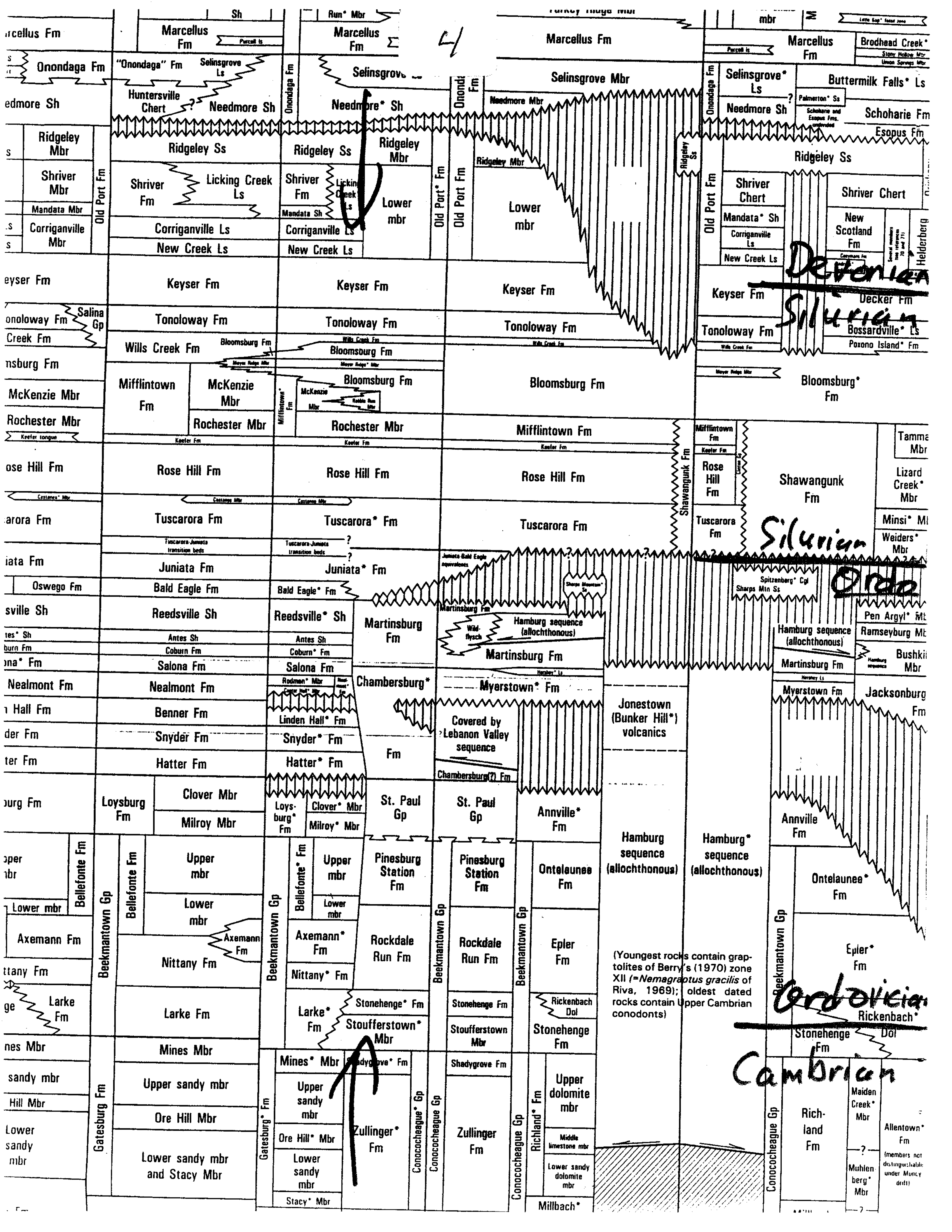


FIGURE 5. GENERALIZED STRATIGRAPHY OF THE NORTHEASTERN APPALACHIAN BASIN IN CENTRAL AND EASTERN PENNSYLVANIA.


4
Marcellus Fm
Onondaga Fm
Needmore Sh
Ridgeley Mbr
Shriver Mbr
Mandata Mbr
Corriganville Mbr
Old Port Fm
Keyser Fm
Tonoloway Fm
Salina Gp
McKenzie Mbr
Rochester Mbr
Keefer tongue
Castanea Mbr
Oswego Fm
Nealmont Fm
Axemann Fm
Larke Fm
Lower mbr
Bellefonte Fm
Beekmantown Gp
Gatesburg Fm
Marcellus Fm
Purcell Ls
"Onondaga" Fm
Selinsgrove Ls
Huntersville Chert
Needmore Sh
Ridgeley Ss
Shriver Fm
Licking Creek Ls
Corriganville Ls
New Creek Ls
Keyser Fm
Tonoloway Fm
Wills Creek Fm
Bloomsburg Fm
Mifflintown Fm
McKenzie Mbr
Rochester Mbr
Keefer Fm
Rose Hill Fm
Tuscarora Fm
Tuscarora-Juniata transition beds
Juniata Fm
Bald Eagle Fm
Reedsville Sh
Antes Sh
Coburn Fm
Salona Fm
Nealmont Fm
Benner Fm
Snyder Fm
Hatter Fm
Loysburg Fm
Clover Mbr
Milroy Mbr
Upper mbr
Lower mbr
Axemann Fm
Nittany Fm
Larke Fm
Mines Mbr
Upper sandy mbr
Ore Hill Mbr
Lower sandy mbr and Stacy Mbr
Marcellus Fm
Onondaga Fm
Selinsgrove
Needmore* Sh
Ridgeley Ss
Ridgeley Mbr
Shriver Fm
Licking Creek Ls
Mandata Sh
Lower mbr
Corriganville Ls
New Creek Ls
Keyser Fm
Tonoloway Fm
Wills Creek Fm
Bloomsburg Fm
Bloomsburg Fm
McKenzie Mbr
Rochester Mbr
Mifflintown* Fm
Keefer Fm
Rose Hill Fm
Castanea Mbr
Tuscarora* Fm
Tuscarora-Juniata transition beds
Juniata* Fm
Bald Eagle* Fm
Reedsville* Sh
Antes Sh
Coburn* Fm
Salona Fm
Linden Hall* Fm
Snyder* Fm
Hatter* Fm
Loysburg* Fm
Clover* Mbr
Milroy* Mbr
Bellefonte* Fm
Upper mbr
Lower mbr
Axemann* Fm
Nittany* Fm
Larke* Fm
Stonehenge* Fm
Stoufferstown* Mbr
Mines* Mbr
Shadygrove* Fm
Upper sandy mbr
Ore Hill* Mbr
Lower sandy mbr
Stacy* Mbr
Gatesburg* Fm
Zullinger* Fm
Conococheague* Gp
Martinsburg Fm
Chambersburg*
Fm
St. Paul Gp
Pinesburg Station Fm
Rockdale Run Fm
Old Port* Fm
Old Port Fm
Onondaga Fm
Marcellus Fm
Selinsgrove Mbr
Needmore Mbr
Ridgeley Mbr
Lower mbr
Keyser Fm
Tonoloway Fm
Bloomsburg Fm
Mifflintown Fm
Keefer Fm
Rose Hill Fm
Tuscarora Fm
Juniata-Bald Eagle equivalents
Sharps Mountain* Ss
Martinsburg Fm
Wild-flysch
Hamburg sequence (allochthonous)
Martinsburg Fm
Myerstown* Fm
Covered by Lebanon Valley sequence
Chambersburg(?) Fm
St. Paul Gp
Pinesburg Station Fm
Rockdale Run Fm
Stonehenge Fm
Stoufferstown Mbr
Shadygrove Fm
Zullinger Fm
Conococheague Gp
Beekmantown Gp
Annville* Fm
Ontelaunee Fm
Epler Fm
Rickenbach Dol
Stonehenge Fm
Upper dolomite mbr
Middle limestone mbr
Lower sandy dolomite mbr
Richland* Fm
Millbach*
Jonestown (Bunker Hill*) volcanics
Hamburg sequence (allochthonous)
Hamburg* sequence (allochthonous)
(Youngest rocks contain graptolites of Berry's (1970) zone XII (=Nemagraptus gracilis of Riva, 1969); oldest dated rocks contain Upper Cambrian conodonts)
Ridgeley Ss
Shawangunk Fm
Marcellus Fm
Purcell Ls
Brodhead Creek*
Selinsgrove* Ls
Buttermilk Falls* Ls
Needmore Sh
Palmerton* Ss
Schoharie and Esopus Fms, undivided
Schoharie Fm
Esopus Fm
Ridgeley Ss
Shriver Chert
Shriver Chert
Mandata* Sh
Corriganville Ls
New Creek Ls
New Scotland Fm
Helderberg
Old Port Fm
Onondaga Fm
Devonian
Keyser Fm
Decker Fm
Silurian
Tonoloway Fm
Bossardville* Ls
Wills Creek Fm
Poxono Island* Fm
Bloomsburg* Fm
Mifflintown Fm
Keefer Fm
Rose Hill Fm
Tuscarora Fm
Shawangunk Fm
Tamma Mbr
Lizard Creek* Mbr
Minsi* Mbr
Weiders* Mbr
Silurian
Ordo
Spitzenberg* Cgl
Sharps Mtn Ss
Pen Argyl* Mbr
Ramseyburg Mbr
Hamburg sequence (allochthonous)
Martinsburg Fm
Bushkill Mbr
Hershey Ls
Myerstown Fm
Jacksonburg Fm
Annville Fm
Ontelaunee* Fm
Epler* Fm
Beekmantown Gp
Ordovician
Rickenbach* Dol
Stonehenge Fm
Cambrian
Richland Fm
Maiden Creek* Mbr
Allentown* Fm
(members not distinguishable under Muncy drift)
Muhlenberg* Mbr
Conococheague Gp

Late Ordovician Deposition

STRATIGRAPHIC FRAMEWORK

The unmetamorphosed sedimentary sequence contained in the Plateau, Valley and Ridge and westernmost Piedmont provinces accumulated in a long-lived trough termed the Appalachian Basin. Figure 5 shows a generalized stratigraphic column of the Basin rocks. A good account of its stratigraphy is given by Colton (1970).

The Appalachian Basin is a polygenetic feature. From latest Precambrian to Middle Ordovician time, the basin possessed the aspects of a miogeosynclinal, craton-margin basin which contained predominantly eastward-prograding carbonate platform and bank facies. The lowest clastic sequence and the Cambro-Ordovician carbonate sequence represent deposition on this broad, shallow bank. The carbonates are intertidal and shallow subtidal, and are composed mainly of biogenic, in situ sediment. The bank terminated eastward at a continental slope, as indicated by carbonate megabreccias and channelized deposits overlying laminated, black deep-water carbonate. Little terrigenous sediment existed on the bank from Middle Cambrian to Middle Ordovician time. That sediment, and the underlying clastic sequence, show derivation from the craton to the west.

The miogeosynclinal bank extended and thickened eastward from what is now the Allegheny Plateau into the western Piedmont (Fig. 3), and may extend much farther east beneath the allochthonous Piedmont crystalline rocks in the southern Appalachians (Cook and Oliver, 1981). The carbonate bank and its facies define the Appalachian miogeosyncline (Champlain belt of Kay, 1951), and constitite the evidence for a passive margin and proto-Atlantic ocean (Fig. 4-B).

With the onset of Taconian deformation in Middle Ordovician time, the Appalachian Basin changed from miogeosynclinal carbonate platform to exogeosynclinal, foreland molasse basin, and maintained that status (except for Upper Silurian and Lower Devonian) to the close of the Paleozoic. The foreland basin axis lay near the present eastern margin, and lay within sediments of the earlier bank. There is evidence that the position of the eastern basin margin varied with time, and may have lain considerably farther east than it presently does. The western basin margin lay in western Pennsylvania and Ohio; the boundary between Valley and Ridge and Allegheny Plateau provinces is not a facies boundary.

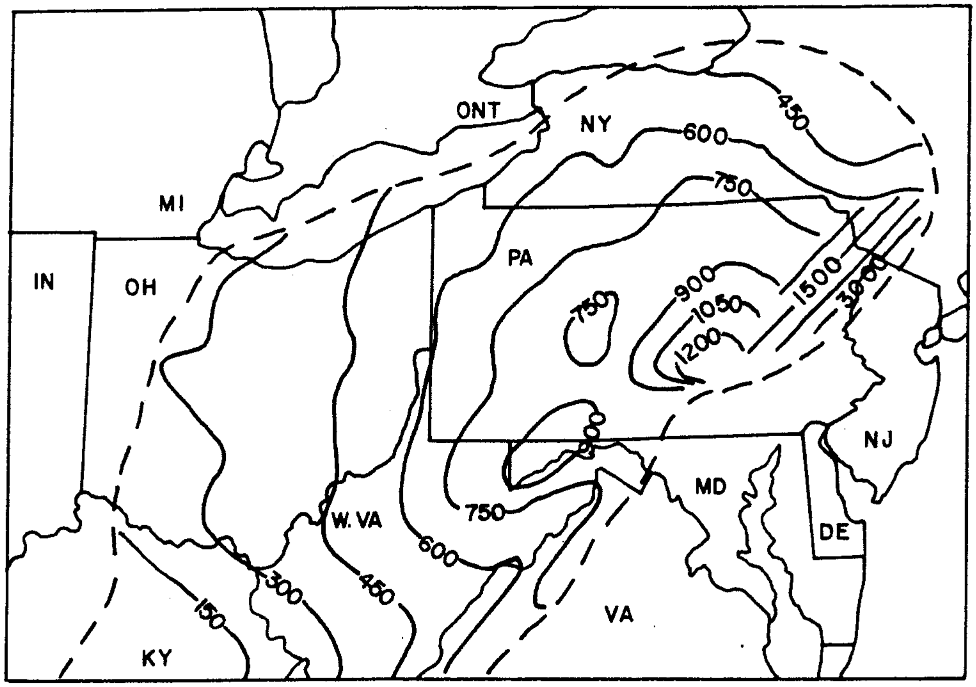
These post-Lower Ordovician deposits are characterized by east-derived, terrigenous clastic sediments which generally coarsen and thicken eastward (Fig. 5). Both Taconic and Catskill clastic wedges contain lower flysch sequences overlain by thicker, largely red molasse successions. The Catskill wedge contains Carboniferous coal sequences in its upper parts. Additional clastic wedges occur in the southern parts of the Basin (King, 1959).

Local tectonic activity contemporaneous with sedimentation in the Appalachian basin has been identified primarily in the Allegheny Plateau, but also occur farther east. The presence of deep-seated faults along which recurrent movement occured during Paleozoic sedimentation is discussed by Bradley and Pepper (1938), Woodward (1963), Kelley and others (1970), Harris (1975), Wagner (1976), and Root (1981). Growth of folds and their effect on coal deposition in western Pennsylvania during the Carboniferous is discussed by Kent and Gomez (1971), Williams and Bragonier (1974), and McCulloch and others (1975). Growth of folds during Devonian sedimentation in eastern Pennsylvania and New York has been suggested by Fletcher (1964) and Fletcher and Woodrow (1970), and in north-central Pennsylvania by Woodrow (1968). A large basin in northeastern Pennsylvania was tectonically active during the Mississippian and may have been active during the Late Devonian (Woodrow and Fletcher, 1967; Glaeser, 1974).

THE TACONIC CLASTIC WEDGE

The Taconic clastic wedge comprises a thick succession of terrigenous clastic rocks preserved today along the western margin of the Appalachian orogen. The rocks are exposed in the Valley and Ridge province and in western New York and Ontario (Fig. 1), beneath the Allegheny Plateau. The present eastern margin of the wecge probably marks the westernmost extent of Taconian uplift, and also the first well-defined eastern margin of the Appalachian Basin. The wedge is thickest in the area of east-central Pennsylvania and New Jersey (Fig. 6), reaching approximately 4000 m there. Total thickness decreases rapidly to the east and southeast by both erosion and nondeposition, and less rapidly in other directions.

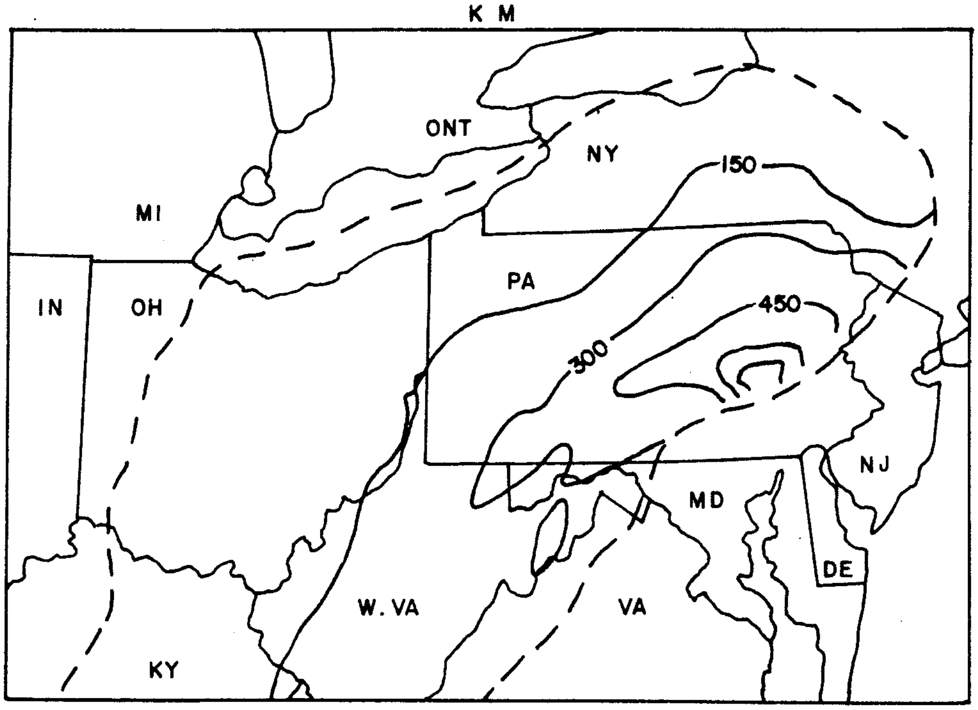
The term Taconic is used here in the broad sense to include all east-derived terrigenous rocks from Middle Ordovician (Caradocian) to Upper Silurian (Wenlockian) age. The term Queenston Delta has been applied by many workers (e.g. Dennison, 1974) to the Upper Ordovician, coarse clastic portion of the



MIDDLE AND UPPER ORDOVICIAN

CONTOUR INTERVAL 150 m

0 100 200 400
KM



LOWER AND MIDDLE SILURIAN

FIGURE 6. GENERALIZED THICKNESS OF TACONIC CLASTIC WEDGE SEDIMENTS. ADAPTED AND MODIFIED FROM COLTON (1970). BLOOMSBURG FORMATION THICKNESS NOT INCLUDED ON LOWER DIAGRAM.

wedge. The wedge comprises two regressive phases, Middle to Late Ordovician and Middle to Late Silurian, and an intervening Lower and Middle Silurian transgressive phase.

STRATIGRAPHY

Figure 7 shows the generalized stratigraphy within the Taconic clastic wedge. Figure 8 gives a schematic cross-section through the wedge in the area of the trip. The initial clastic phase, marine shales and sandstones, are termed the Martinsburg Formation in the eastern Valley and Ridge province (Great Valley) and Reedsville Formation west of the Great Balley. Marginal-marine and continental sandstones and conglomerates above the Reedsville are Bald Eagle (Oswego) Formation if gray to greenish gray, and Juniata (Queenston) Formation if red. The red-gray color boundary fluctuates stratigraphically by as much as 300 m, and obscures a continuous sequence of six distinct Late Ordovician lithofacies (labelled A to F in Fig. 8) which show consistent regional variations in thickness and composition. Recognition of this lithofacies sequence (Thompson, 1970a) has enhanced the understanding of the early phases of wedge sedimentation.

The Juniata Formation comprises red wackes, occasional conglomerates, shales and minor arenites above the Bald Eagle. The Bald Eagle and Juniata thin rapidly to the southeast against uplifted Martinsburg, and are largely responsible for the wedge shape of the Taconic sequence.

Above the Juniata lie quartz arenites of the Tuscarora Formation. Although devoid of datable body fossils, the Tuscarora is usually assigned an early Silurian (Llandoverian) age. The Tuscarora thickens and coarsens eastward into the Shawangunk (pronounced Shawngum) Conglomerate, which is cut out by erosion farther east (Fig. 8). The Shawangunk rests unconformably on deformed Martinsburg east of the Bald Eagle-Juniata pinchout, and the Tuscarora-Shawangunk is probably transgressive eastward across this erosion surface. Significant quantities of Bald Eagle and Juniata may have been eroded below the unconformity.

The Tuscarora is overlain by paralic and shallow-marine shales and minor sandstones of the Clinton Group and McKenzie Formation. The upper Clinton is regressive, and is overlain by Late Silurian red beds of the Bloomsburg Formation. The Bloomsburg interfingers westward with marine facies, and is bounded above by platform carbonates marking the end of Taconic-clastic-wedge deposition.

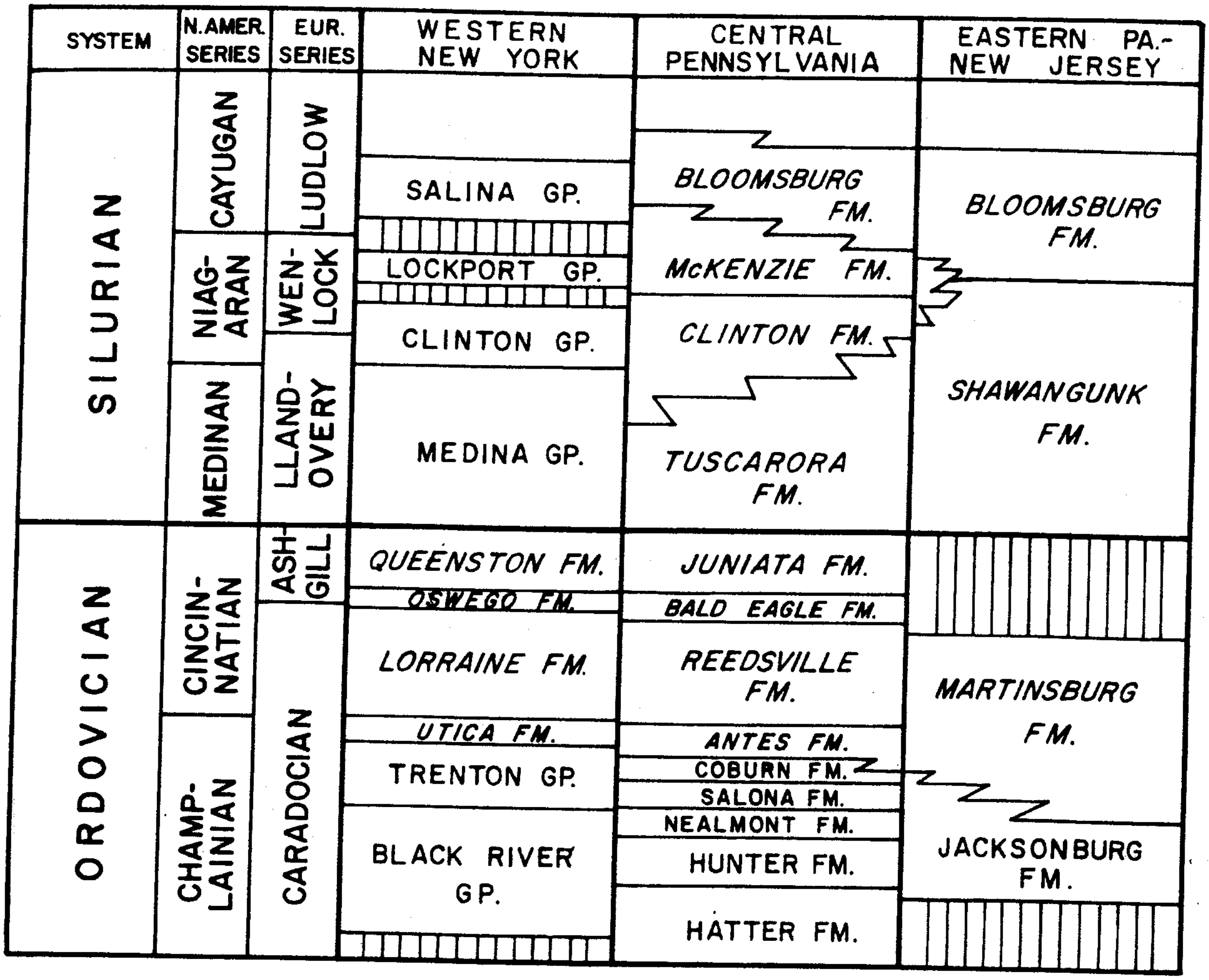


FIGURE 7. CORRELATION OF ORDOVICIAN AND SILURIAN STRATIGRAPHIC UNITS IN AREA OF FIELD TRIP. UNITS COMPRISING TACONIC CLASTIC WEDGE SHOWN IN *ITALICS*. MODIFIED FROM SWARTZ et al. (1942), TWENHOFEL et al. (1954) AND RONES (1969).

INPUT CENTERS

Most paleocurrents in the terrigenous rocks indicate west- and northwest-dipping paleoslopes and paleocurrent flow throughout the history of the wedge. Progradation was to the west and northwest.

The early marine phases (Martinsburg) show consistently northwest-oriented paleocurrent flow from Virginia to New York, and suggest derivation from a long-ranging source area fronting the basin for a considerable distance (Fig. 6). Thicknesses and grain sizes decrease away from that site, and paleocurrents spread from it (Yeakel, 1962).

Centers of Silurian sediment input were located farther east than Ordovician centers. Individual, smaller-scale sediment supply centers cannot be iden-

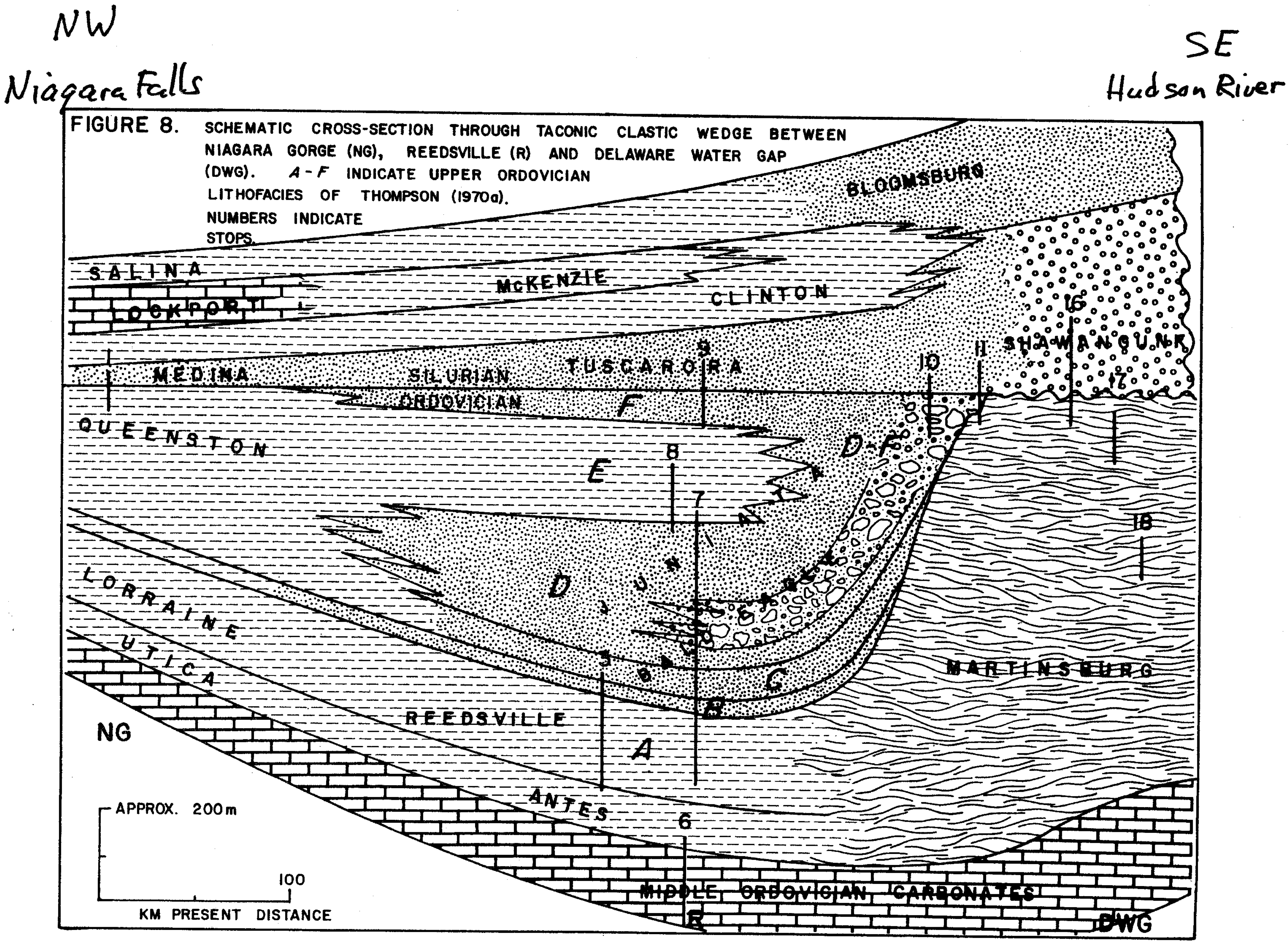


FIGURE 8. SCHEMATIC CROSS-SECTION THROUGH TACONIC CLASTIC WEDGE BETWEEN NIAGARA GORGE (NG), REEDSVILLE (R) AND DELAWARE WATER GAP (DWG). *A-F* INDICATE UPPER ORDOVICIAN LITHOFACIES OF THOMPSON (1970a). NUMBERS INDICATE STOPS.

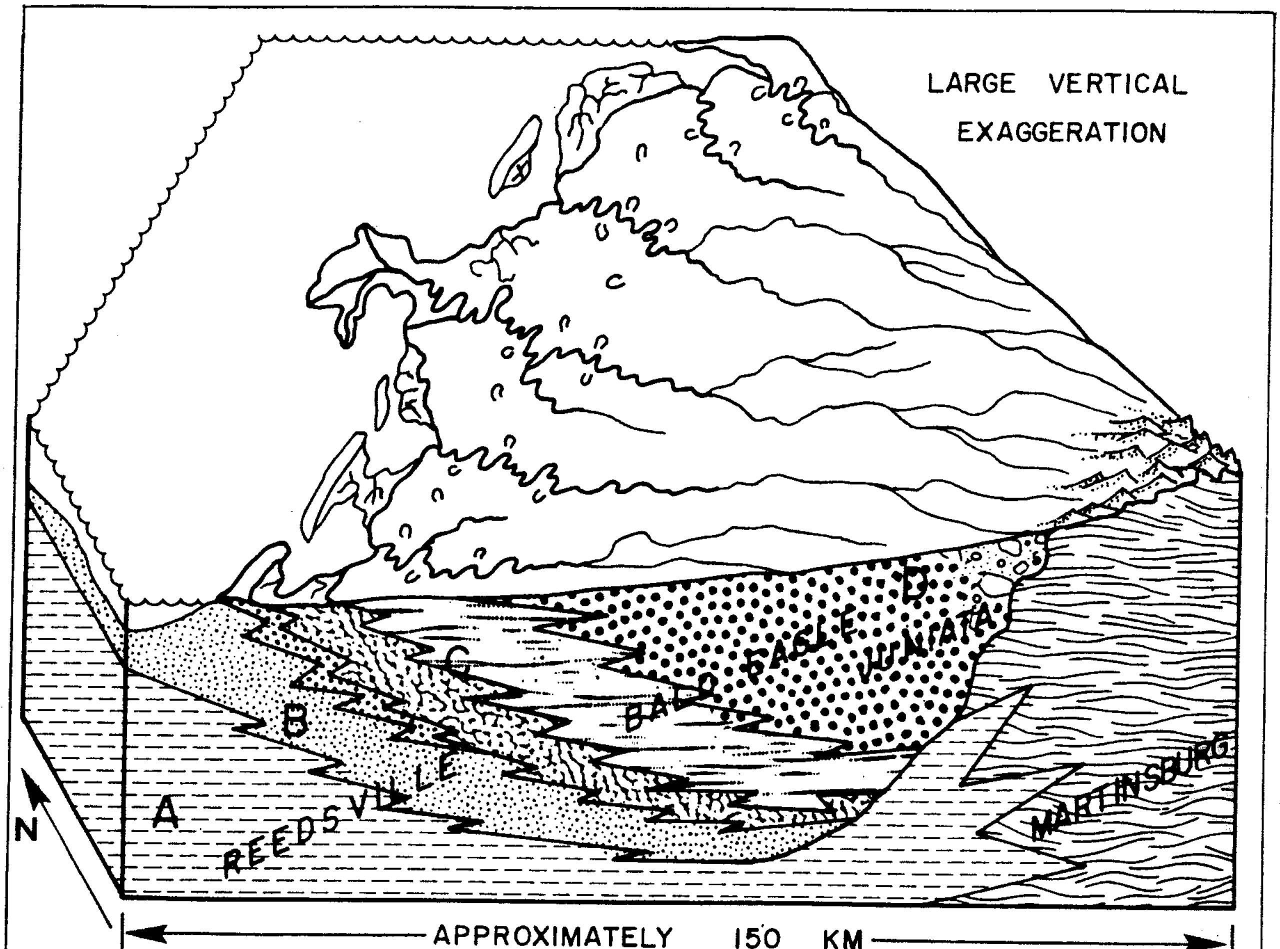


FIGURE 9. INFERRED UPPER ORDOVICIAN REGRESSIVE FACIES ARRAY IN CENTRAL PENNSYLVANIA, SHOWING ALTERNATIVE MODELS OF MARGINAL-MARINE FACIES ASSOCIATIONS.

tified due to limitations of outcrop.

CONSTRAINTS ON ORDOVICIAN DEPOSITION

Two time-dependent factors, which may have influenced the nature of sedimentation in the Taconic wedge, should be pointed out. First, the land surface was probably largely bare. According to present estimates of the age of terrestrial plant evolution, land plants were not present in sufficient quantities in Ordovician time to colonize the land surface and prevent accelerated runoff and erosion. This absence had a considerable influence on continental sedimentology, because the presence of macerated plant material, acting as a binding agent, strongly affects the erodability and resistance of silt- and clay-size sediments (Schumm, 1963). Lower-sinuosity channel forms and shallower channels resulted from the increased erodibility of bank materials in the absence of terrestrial plants.

Second, Late Ordovician (Ashgillian) glaciation of possibly continental dimensions has been documented in Africa and elsewhere (Doré and LeGall, 1972; Fairbridge, 1971). While no direct evidence for glaciation has been found in the Appalachians, some indirect evidence does exist. Sheehan (1973) has documented the abrupt changes in the character of marine invertebrate faunas across the Ordovician-Silurian boundary, at the time of the glaciation. A regional unconformity (the Taconic unconformity) along the eastern edge of the Appalachian Basin above known Ordovician deposits is largely of tectonic origin, but some of the hiatus could be due to glacial sea-level lowering (Dennison, 1974). Sedimentary-facies evidence for lowering of sea level is best documented in the southern Appalachians (Dennison, 1974), but is not strong in the central Appalachians. The best evidence in the area of the field trip is the far westward progradation of lower delta-plain mudstones of the Queenston Formation (Dennison, 1974). However, the considerable thickness of Queenston argues against an origin by simple eustatic sea-level change.

DEPOSITIONAL MODEL

The following is a brief summary of the major depositional facies and tentative interpretations. Please refer to Figure 8.

Platform Carbonate

Rocks immediately beneath the Taconic clastic wedge are marine limestones of Middle Ordovician age (to be seen at Stop 6). The carbonate succession contians basal stromatolitic, algal-laminated and mud-cracked lime mudstones just above the horizon of a regional disconformity (see Fig. 5). Oolitic, cross-bedded grainstones overlie the algal rocks, and are in turn overlain by burrow-mottled, thick-bedded fossiliferous mudstones which become more homogenous and less current-bedded upward. Black siliciclastic clay first appears in these quiet-water mudstones. Cyclic facies repetitions suggest shoaling buildups on a steadily deepening and/or more offshore basin floor. The facies suggest a position on the downflexing hinge of a nascent foreland basin; the clay signals initiation of the Taconic clastic sequence.

Marine Shale and Flysch

Above the carbonates lie several hundred meters of silty shale and minor siltstone and sandstone of the Martinsburg and Reedsville Formations. The thickness of the Martinsburg is probably thousands of meters, while that of the Reedsville is less than 300 m. The gross internal stratigraphic organization of the two formations is similar, and facies thicknesses vary in similar ways. The two formations are not physically continuous. McBride (1962) has interpreted the Reedsville as the distal, basin-center facies equivalent of the Martinsburg.

The basal lithofacies (Stops 3, 6, 7) in both formations comprises gray to black, graptolitic silty shale with millimeter-scale laminated to micro-cross-laminated siltstone and sandstone. This shale in central Pennsylvania was termed the Antes Shale by Kay (1944). Graded bedding is common in the Martinsburg, and is less common in the Antes. Features of soft-sediment deformation and sole markings indicate sporadic sediment transport and rapid deposition. These data suggest deposition on distal, lower-fan to toe portions of submarine fans.

Above the lower shales of the Martinsburg lie several hundred meters of interbedded shale and fine-grained sandstone in nearly equal proportions (Stops 17, 18). Graded bedding is common, as are sole marks and flute casts. The sandstones also show evidence of locally sustained bottom traction currents. These data collectively suggest flysch deposition on the medial to more proximal portions of submarine fans.

Sandstones in the upper 200-300 m (Facies A) of the Reedsville Formation

(Stops 3, 7) are less often graded than Martinsburg sandstones, and contain evidence of deposition of relatively shallow water above wave base. Channeling and rapid lateral pinchouts are common, as are hummocky cross-stratification and symmetrical ripple marks. Sandstones and occasional limestones contain disarticulated but generally unabraded skeletal remains of delicate shallow-water, photic-zone organisms. Bedding-plane paleocurrent indicators frequently show southeast transport directions.

Based on these criteria, McBride's (1962) deep water, basin-center interpretation of the Reedsville may be debated (e.g. Thompson, 1972). Both formations indicate regressive, possibly deltaic sedimentation, but the sedimentologic relations between them may be more complex than presently thought.

Marginal-Marine Rocks

Rocks above the fan/slope complex of the Martinsburg have been lost by erosion along the eastern basin margin. Directly above the Reedsville in the west lie 10-30 m of fine-grained, well-sorted quartz wacke and interbedded poorly sorted burrowed wackes (Facies B of Thompson, 1970a; Stops 3, 7). The well-sorted sandstones are parallel-laminated to ripple-bedded, and show parting lineations and shallow scours. The unbedded, burrowed and homogenized fossiliferous wackes contain lenticular and disrupted brachiopod-pelecypod-*Lingula* coquinas. The bedded rocks probably represent subaqueous bars, and the burrowed rocks quieter, interbar areas (bays?), in which storms or other extreme events caused frequent scouring and redeposition. The bars could be shoreface bars/shoals, governed by longshore transport, or could be subaqueous rivermouth bar-finger sandstones of a delta front.

Above the highest coquinas lie 20-80 m of interbedded well-sorted arenites and minor siltstones and shale, all of which are unfossiliferous (Facies C of Thompson, 1970a; Stop 7). Several types of sedimentologic organization exist in these rocks: (1) light-colored, parallel-laminated quartz arenites, (2) trough cross-bedded and channeled quartz arenites with occasional mud-chip conglomerates, and (3) thinly interbedded cross-bedded wackes and ripple-bedded wackes and silty shales. These thin wackes show reactivation surfaces and basal grazing ichnofossil assemblages. The lithologies, primary structures and bed organization suggest deposition in a tide-dominated marginal-marine sand-flat complex. These flats may have fronted a prograding coastline between mouths of distributary river channels, or characterized emergent shoals and tidal flats seaward of the river mouths.

The upper parts of this facies at several localities (not Stop 7) contain fining-upward sequences typical of high-sinuosity channel-floodplain deposits. This suggests that rivers were flowing across a lower delta plain behind the sand flats.

Sandstone-Conglomerate

The major Ordovician lithofacies comprises up to 400 m of medium and coarse-grained and conglomeratic lithic arenite and wacke of the Bald Eagle and Juniata Formations (Facies D of Thompson, 1970a; Fig.8; Stops 7, 10 and 11). The rocks contain abundant large-scale trough and planar cross-bedding, channeling and scour structures, mud-chip conglomerate, mud cracks and other evidence of intermittent exposure in an environment of episodic, high-velocity current flow. Lithic conglomerate is confined to a tongue in the lower and middle parts. Shale and siltstone are virtually absent, and where present are thin (centimeters) and mud-cracked. The sedimentology suggests a low-sinuosity, braided, proximal alluvial-plain to coalescing-fan complex.

This lithosome contains the red-gray color boundary separating Juniata from underlying Bald Eagle Formations. The position of the boundary has been shown to be of diagenetic origin (Thompson, 1970b).

This proximal alluvial-fan facies is present in the eastern portions of the lower Silurian parts of the wedge. The Shawangunk Conglomerate (Stop 16, possibly Stop 11) comprises pure quartz arenites with planar and trough cross bedding, thick bedding and abundant scour-and-fill structures. It has been interpreted by Smith(1970) to represent braided-stream deposition on a proximal alluvial apron fronting the Taconic highland.

Nonmarine Shale

Rocks of this facies comprise interbedded wackes, siltstones and shales. The scale of interbedding ranges from 10 cm to 10 m, and averages 1 to 2 m. Lithologies are organized in fining-upward sequences; each progresses from coarse, cross-bedded wacke with mud chips above a marked erosion surface upward through small-scale cross-bedded and burrowed wackes and siltstone to laminated and ripple-bedded siltstone and shale. The lithologic sequences, lack of body fossils, and primary structures suggest deposition in channel/point bar arrays on the low-gradient, high-sinuosity, distal portions of an alluvial plain (middelta plain).

The distal alluvial plain facies is present in three parts of the Taconic clastic wedge. First, it is often developed at the top of the marginal marine complex in the Bald Eagle Formation (Facies B, Fig. 8). Second, it characterizes much of the Juniata Formation (Facies E; Stop 8), where it reaches 300 m thick. There, it overlies the proximal alluvial-plain facies and indicates lessening of the regional gradient as the initial Taconic highland was denuded. It probably represents the continental expression of a minor late Ordovician marine transgression. Third, the facies occurs in the eastern portions of the Bloomsburg Formation (Fig. 8; no stop). Here it indicates a general mid- to lower-delta-plain environment and marks a general marine regression. The Bloomsburg grades westward into marine facies (Hoskins, 1961).

Quartz Arenite

Above the Juniata shales in central Pennsylvania lie several hundred meters of sandstones of uncertain origin. The lowest 50-100 m often contain red, gray and green quartz wacke and quartz arenite with interbedded thin red, gray and black shales. These sandstones (lithofacies F; Fig. 8; Stops 9 and 10) are included in the Juniata Formation on the basis of color. They are cross-bedded channeled, load-casted, and contain a Skolithos ichnofauna. Modes of sedimentologic organization are capable of several interpretations.

The overlying white quartz arenites are included in the Silurian Tuscarora Formation (Fig. 8; Stops 9, 10 and 11). These rocks are cross-bedded and parallel-laminated, with thin shale drapes. Skolithos and Arthrophycus trace assemblages are present, but skeletal fossils have never been recorded. This facies grades eastward into the Shawangunk conglomerates (Stop 16). Paleoenvironmental interpretations of the Tuscarora range from braided fluvial (Smith, 1970) to shallow marine (Folk, 1960). Cotter (1982) has interpreted a coastal sand-flat to shallow-marine shelf model for the Tuscarora.

General Model for Basin Evolution

Based on the above, the following emerges as a tentative, generalized evolutionary history of the Taconic clastic wedge.

The Taconic basin was initiated as a foredeep flysch basin in Middle Ordovician time by downflexing of a preexisting continental-margin carbonate platform. Downflexing progressed from east to west, involving successively more internal portions of the platform. Transgressive carbonate deposition on the western basin margin gave way to pelagic siliciclastic deposition and then to regressive flysch deposition on submarine fans along the eastern margin. Tectonism of the eastern margin progressed westward, and cannabilized earlier basin deposits. As the flysch basin filled, shallow-marine and continental molasse facies prograded westward. Figure 9 shows a schematic model of this phase of the regression and presents alternative interpretations of the marginal marine complex facies: deltaic with sand-flat, and sand-flat only. This regressive phase marked the climax of Taconian deformation and uplift in the central Appalachians.

The regression was followed by a general lowering of base level and deposition of finer-grained fluvial sediments. This was caused either by lowering of the sediment source area due to continued erosion, or by sea level rise, which may have been related to Late Ordovician glaciation.

Models of Silurian depositional history depend on how the paleoenvironments of the Tuscarora are interpreted. If marine or coastal, then the transgression initiated during Juniata fluvial deposition continued, bringing high-energy shoreline environments eastward over the fluvial facies. The shoreline sands were followed seaward by marine shales and ironstones of the Clinton Formation. This transgression reached its easternmost extent east of Lehigh Gap (Stop 16) and west of Delaware Water Gap (Stop 18). Regional regression followed, generating the Bloomsburg deltaic rocks.

If the Tuscarora is continental and fluvial, then a regressive phase followed the Juniata shale deposition, as either source-area uplift was renewed or sea level dropped eustatically (or glacially). The Clinton transgression then did not witness substantial development of sandy shoreline facies.

Blue Mountain

STOP 11. Blue Mountain.

Setting: This stop exposes the eastern, proximal, thinned equivalents of Ordovician clastic-wedge rocks, the complete thickness of the Tuscarora Formation, and part of the overlying Clinton Formation (Fig. 30). The Bald Eagle and Juniata Formations probably total less than 15 m in thickness, although exact thicknesses cannot be determined; the Tuscarora is unusually thin here.

Although the exposure is structurally complex, sedimentologic analysis can be carried out on all rocks above the Martinsburg. The section dips south, and is overturned; tops face north. The Bald Eagle-Martinsburg contact may be a decollement zone, the Blue Mountain decollement, and is structurally highly disturbed; if not a thrust, it is a disconformity with significant amounts of Martinsburg missing.

Procedure: Examine the outcrop of Martinsburg northward into the Clinton. Do Not Climb Up The Slope.

Martinsburg Formation: This first look at the Martinsburg only hints at its sedimentologic features, which will be seen in more detail at later stops. A strong southeast-dipping transposition cleavage has obliterated most bed continuity; only the thicker sands persist through the outcrop. Centimeter-scale, very-fine-grained sandstones and siltstones are interbedded with black, graptolitic shale. The sandstones display parallel lamination and minor small-scale ripple-bedding, and show features suggestive of graded bedding.

Bald Eagle Formation: Above the Martinsburg lie approximately 10 m of greenish-gray, mature conglomerate. The sand matrix is coarse- to very-coarse-grained, and contains some clay matrix. The pebble suite contains vein quartz, green and black chert, and metavolcanics; pebbles reach 15-20 cm in length, and are well rounded. Compare the pebble composition with that seen at Reedsville. The matrix is not visibly bedded or cross-

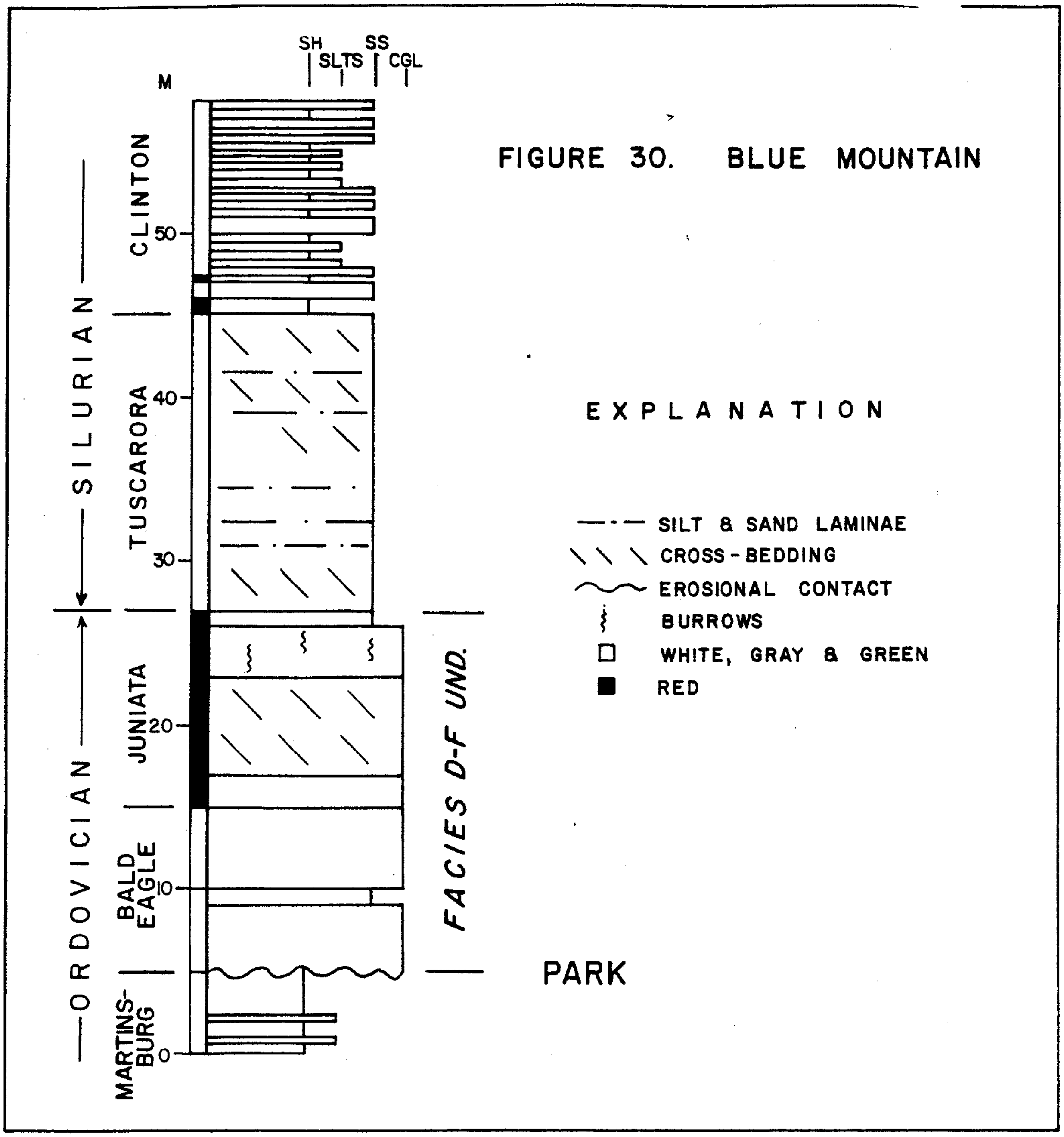


FIGURE 30. BLUE MOUNTAIN
SH
SLTS
SS
CGL
M
SILURIAN
ORDOVICIAN
CLINTON
TUSCARORA
JUNIATA
BALD EAGLE
MARTINS-BURG
50
40
30
20
10
0
FACIES D-F UND.
PARK
EXPLANATION
SILT & SAND LAMINAE
CROSS-BEDDING
EROSIONAL CONTACT
BURROWS
WHITE, GRAY & GREEN
RED

bedded, and could be characterized as thick-bedded.

Juniata Formation: Juniata comprises about 10 m of coarse- to very-coarse-grained, red, lithic and quartz wacke. Pebbles are rare, and conglomerate occurs only near the base. Red mud-chip conglomerates are present, although red shale drapes are lacking. The sandstones are frequently trough cross-bedded and channeled; channel fills are generally coarser than the rocks below them. Grain-size decreases somewhat higher in the Juniata, and the finer sandstones are often burrowed.

There is apparently a correlation between lithology (proportion of conglomerate) and rock color, which suggests that Bald Eagle and Juniata sediments represent different depositional environments, and that the color difference is environmentally controlled. However, evidence hinting otherwise is shown by the pebble suites: chert, sandstone, and shale-chip pebbles in green conglomerates are green and black, and in red conglomerates are red and reddish black. This suggests that present rock color may be a secondary feature, and may not necessarily be dependent upon depositional environment.

The top of the Juniata is conglomeratic, with 20 cm of green conglomerate (with green and black pebbles) just below the boundary. Above a 2-cm weathered zone lie white quartz arenites of the Tuscarora. The Ordovician-Silurian boundary here is not demonstrably erosional.

The Bald Eagle and Juniata here represent lithofacies D-F undivided (Fig. 8), and are equivalent to the entire sandy Ordovician section at Reedsville, and to the 100 m section at Waggoner's Gap. These units thin markedly over the visible distance. On the west side of the Susquehanna River the Bald Eagle and Juniata total 54 m thick; at the railroad cut just west of this highway they are 44 m thick; in this cut they are no more than 18 m thick. This area probably lies on the feathering-out proximal edge of the Taconic clastic wedge. Thirty kilometers to the east, the Tuscarora lies disconformably on the Martinsburg.

Tuscarora Formation: The Tuscarora is 15 m thick or less here; the cause of this anomalous thinness may be structural or genuinely stratigraphic. The Tuscarora comprises medium- to coarse-grained, nonconglomeratic quartz arenite, with rare paper shale drapes. Most bedding is trough cross-bedding, in 15-40-cm-thick sets and cosets. Low-angle cut-and-fill structures are abundant, and lateral impersistence is the rule. The lower 2 m of Tuscarora are sparsely conglomeratic with white quartz and black chert granules. Compare the bedding and facies development seen here with those at Waggoner's Gap and Jacks Mountain.

Waggoners Gap

top. STOP 10. WAGGONER'S GAP.

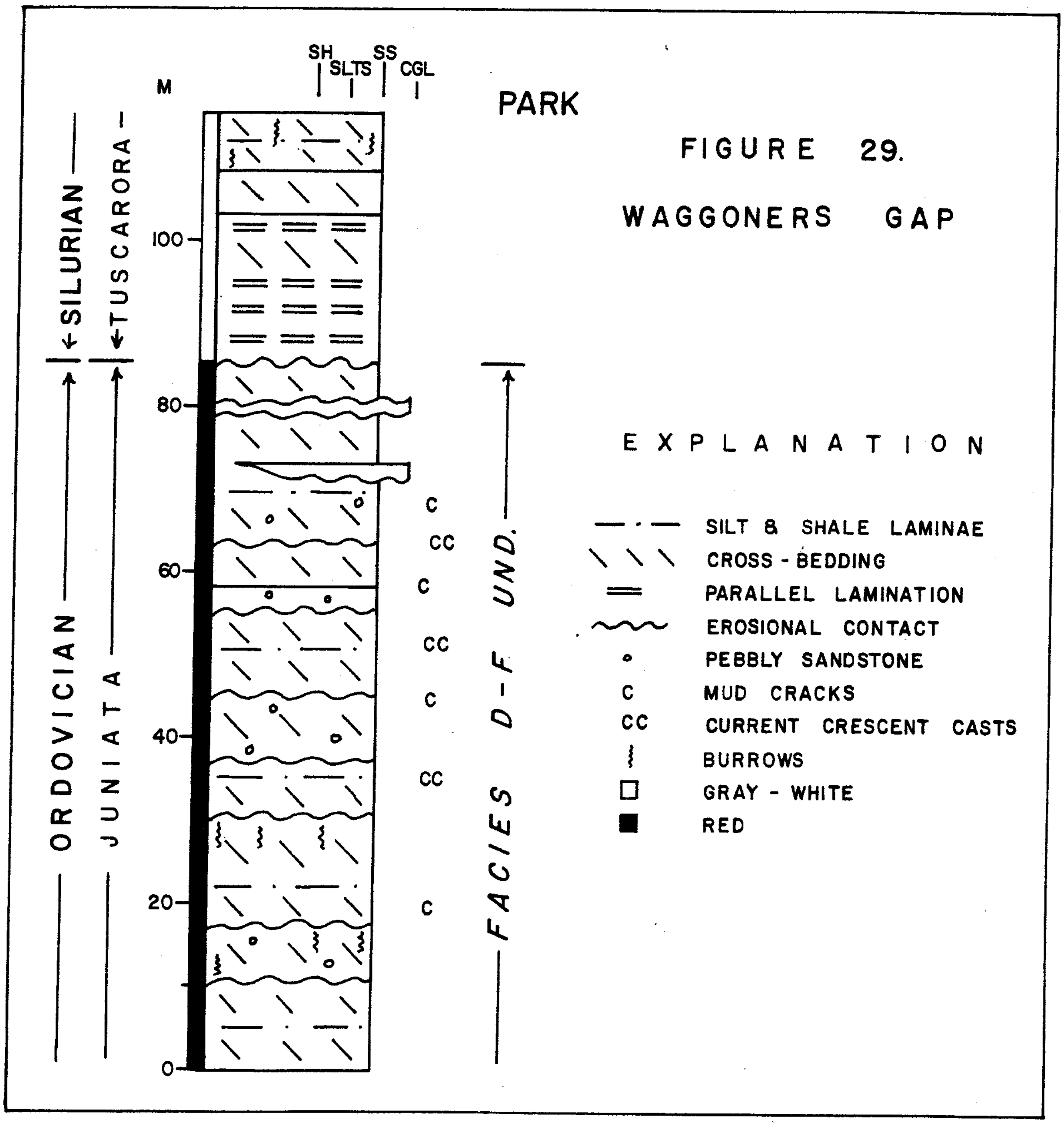
Setting: This outcrop is of the Silurian Tuscarora and Ordovician Juniata Formations on Blue Mountain (Fig. 29), and is the first of three stops on this ridge. The Ordovician rocks belong to lithofacies D-F undivided (Thompson, 1970a, and occur in the proximal, up-fan portions of the Taconic clastic wedge (see Fig. 8). Lithofacies B and C are presumably absent here, and facies D-F rests disconformably on the Middle Ordovician Martinsburg Formation less than 25 m below the base of the exposure.

Procedure: Examine this section from the top down, starting with the highest outcrops of Tuscarora.

Silurian Rocks: The exposed Tuscarora comprises 18 m of medium-grained quartz arenite, with occasional gray shale clasts. Above the shoulder pullout bedding is relatively consistent 50- to 100-cm-thick cosets of trough cross-strata, separated by paper shale drapes with Arthrophycus trace fossils. Lithic conglomerate is absent, and the maturity of the sand is notable.

Below the pullout the Tuscarora shows cm-scale parallel-bedding in several thick "sets" reaching 3 m thick. When examined in detail, the "parallel" bedding is actually flatly lenticular, low-amplitude ripple-bedding, suggesting very shallow water. Rippled bottom surfaces support this interpretation. Look for scour-and-fill structures, lateral persistence vs. impersistence of bedding, hummocky cross-strata, and truncation of low-angle foresets.

Just above the Juniata boundary the sandstones become conglomeratic with fine-grained, well-sorted quartz granules to pebbles. The pebble layers resemble lag concentrates, and are confined to the basal 2 m of the Tuscarora. Mud-chip conglomerates containing red shale clasts occur just above the boundary, suggesting an erosional contact. The lowest white sandstone fills a scour surface o the highest red sandstone; the Ordovician-Silurian boundary is thus, here, a local scour surface of questionable regional or temporal significance.


SH
SLTS
SS
CGL
M
PARK
FIGURE 29.
WAGGONERS GAP
100
80
60
40
20
0
ORDOVICIAN
SILURIAN
JUNIATA
TUSCARORA
FACIES D-F UND.
C
CC
C
CC
C
CC
C
EXPLANATION
SILT & SHALE LAMINAE
CROSS - BEDDING
PARALLEL LAMINATION
EROSIONAL CONTACT
PEBBLY SANDSTONE
C MUD CRACKS
CC CURRENT CRESCENT CASTS
BURROWS
GRAY - WHITE
RED

Ordovician Rocks: Below the Tuscarora are exposed 85 m of coarse-grained, dusky red lithic wacke, and minor lithic and quartz arenite. Red shale partings are occasionally present, and mud-chip conglomerate is abundant. The sandstones are sparsely pebbly (granule grade) throughout, but conglomeratic only in the upper few meters. Trough cross-bedding is abundant, in sets reaching 70 cm in thickness. Well-defined parallel lamination is rare, and several intervals show little obvious bedding. Paleocurrent directions are generally to the northwest. The shale drapes pinch out laterally, and much scour-and-fill is present. The finer sandstones and shales show burrow structures.

The exposed bedding planes show an abundance of primary structures, including current crescent casts, rill marks, load casts, mud cracks, ripples, trace fossils and others. These argue for very shallow, intermittent water flow during deposition, with much lateral bar migration and occasional dessiccation. These features, combined with bedding characteristics, indicate a relatively high energy, high-gradient, probably braided alluvial complex.

Summary: The sedimentologic features of the Ordovician rocks contrast with those of the overlying Silurian rocks, and suggest that the Ordovician-Silurian boundary here marks a change in depositional environment. The thick, ripple-bedded sequences in the Tuscarora are capable of several interpretations; one possible model is of a beach complex.

Comparisons between the proximal facies exposed here and the more distal facies at Reedsville and beyond may be made for both the Ordovician rocks and the Tuscarora. The Ordovician rocks here are equivalent to facies B, C, D, E and F at Reedsville, are significantly thinner, and are of less diverse facies. There is little evidence for substantial pre-Silurian erosion of Ordovician rocks below the Tuscarora. The base of Tuscarora shows different bedding types and bedding sequences here.

Evaluate similarities or differences in grain size, sorting, matrix content, type and scale of bedding and cross-bedding, bedding sequences, evidence for current energy and velocity, and evidence for paleogradients.

25

Millerstown

STOP 1. TUSCARORA MOUNTAIN NORTH OF MILLERSTOWN

Eastern cross-laminated lithofacies; distal braided fluvial.

The 82 m (270 ft.) of Tuscarora exposed here is approximately the upper half of the formation. A detailed measured section of this outcrop was published by Faill and Wells (1974, p. 240-244); some of their unit numbers are still visible on the outcrop. The transition into the overlying Rose Hill Shale is not presently well exposed, but when Faill and Wells described it during the period of highway construction, it was exposed on upper benches at the north end of the cut.

This entire succession of Tuscarora is part of the eastern cross-laminated lithofacies and was deposited in the distal reaches of a braided fluvial system. This interpretation is supported by features of the composition and texture, bed geometries, sedimentary structures, and vertical sequences.

Composition and Texture

As shown in Figures 23D,E the sandstone composition is sublitharenite and litharenite. Average grain size is coarse, and generally ranges from medium to very coarse. Gravel lags can be found at the bases of beds. Grains are subangular and poorly sorted. Matrix is present at least some of which is primary. In a general way, the maximum grain size present in a bed is directly related to the thickness of the bed. Shale intraclasts are common in numerous beds, and they are in places abundant near the base of channel scours (Fig.23C). Many beds are graded with sharp bases and transitional tops.

Shale is interbedded with sandstone beds with great frequency. Some shale beds wedge out into sandstone zones. There is some tendency for cyclicity in the abundance of shale (see below - sequences). Toward higher parts of the succession the proposition of shale increases to amounts approximately 20 to 25% of the section

Bed Geometry

There is a remarkable lateral continuity to individual sandstone beds and groups of beds. These high width/thickness ratios of the genetic units were described as being of "sheetbraided" fluvial style by Cotter (1978). Part of the great lateral extent at this outcrop results from the orientation of the outcrop face with respect to the ancient paleoslope (flow was generally from right to left and parallel with the outcrop.

The limited thickening and thinning of the beds resulted from shallow scour into underlying deposits. This has produced channel forms (Figs. 23A, C) and laterally contiguous shallow swales along bed bases (Fig.24). The tops of sandstone beds and zones show no pronounced waviness. Bed thickness varies as a result of basal scour.

Toward the lower part of the section, sandstone units can average about a meter in thickness, whereas higher in the section, sandstone zones are grouped with thin shales in possible cycles from 2 to 3 m thick (see below - vertical sequences).

Sedimentary Structures

Most of the sandstone beds are thin- to thick-bedded, and the shales are very thin- to thin-bedded. Some sandstone beds contain a single set of cross laminae, but most of the sandstones have composite sets. The orientation of the outcrop face with respect to paleocurrents is not helpful in determining the type of cross lamination in each bed. It appears that most beds are planar cross laminated in sets that range from 10 to 50 cm, with an average of about 20 cm. A minority of the beds contain trough cross lamination. Many of the thinner beds intercalated with shale are current-ripple laminated.

As mentioned above, sandstone beds are commonly graded, and basal contacts are sharper than upper contacts. No examples of reverse grading were found. On the bases of some thin sandstone beds overlying shale are poorly developed examples of the biogenic structure Arthrophycus.

The inclination of the cross laminae throughout this section is toward the northwest. No reverse directions of inclination were found. Paleocurrents, therefore, appear to be unimodal and to be oriented down the regional paleoslope to the northwest.

Vertical Sequences

Much of this succession, particularly the lower part, shows little evidence of grouping of features into vertical patterns (Fig.23A). However, where shale is more abundant higher in the section, there are indications of cycles of thinning-upward and fining-upward nature. These repeated cycles are about 2 to 3 m thick. Beds near the base are about 0.5 m thick and gradually thin upward to less than 15 cm, where there is roughly equal proportion of sandstone and shale at the top of the cycle (Fig. 23B). The beds in the lower, sandstone-dominated parts of some cycles show low-angle lateral inclination, and there are some cases of lateral changes of lithology from all sandstone to heterolithic sandstone and shale. Examples of these cycles and lateral changes may be seen in the vicinity of telephone pole number 299, five telephone poles north of the starting point near highway marker 7/45.

Discussion

The features of this outcrop indicate deposition in a distal braided fluvial system. Flow was flashy, and the unstable, vegetationless banks were not able to confine the flow during floods. Scour during the floods produced some broad channel forms at the bases of sandstone zones, and toward the upper part there is some indication of lateral channel migration. The change vertically from sandstone zones about 1 m thick to cycles of sandstone and shale about 2 to 3 m thick suggests that there might have been a tendency toward somewhat deeper, more confined channels through time.

Figure 23. Features of eastern cross-laminated lithofacies along U.S. Route 22-322 north of Millerstown, Pa. (Stop 1).

23A. General nature of beds. Note shallow basal scour and laterally extensive beds.

23B. Fining-upward sequence. Scale is clipboard 30 cm long.

23C. Channelform scour at base of sandstone. Contains shale intraclasts.

23D. Photomicrograph (plane light); narrow dimension of photo =3.7 mm.

23E. Photomicrograph (cross-polarized light); same field as D.

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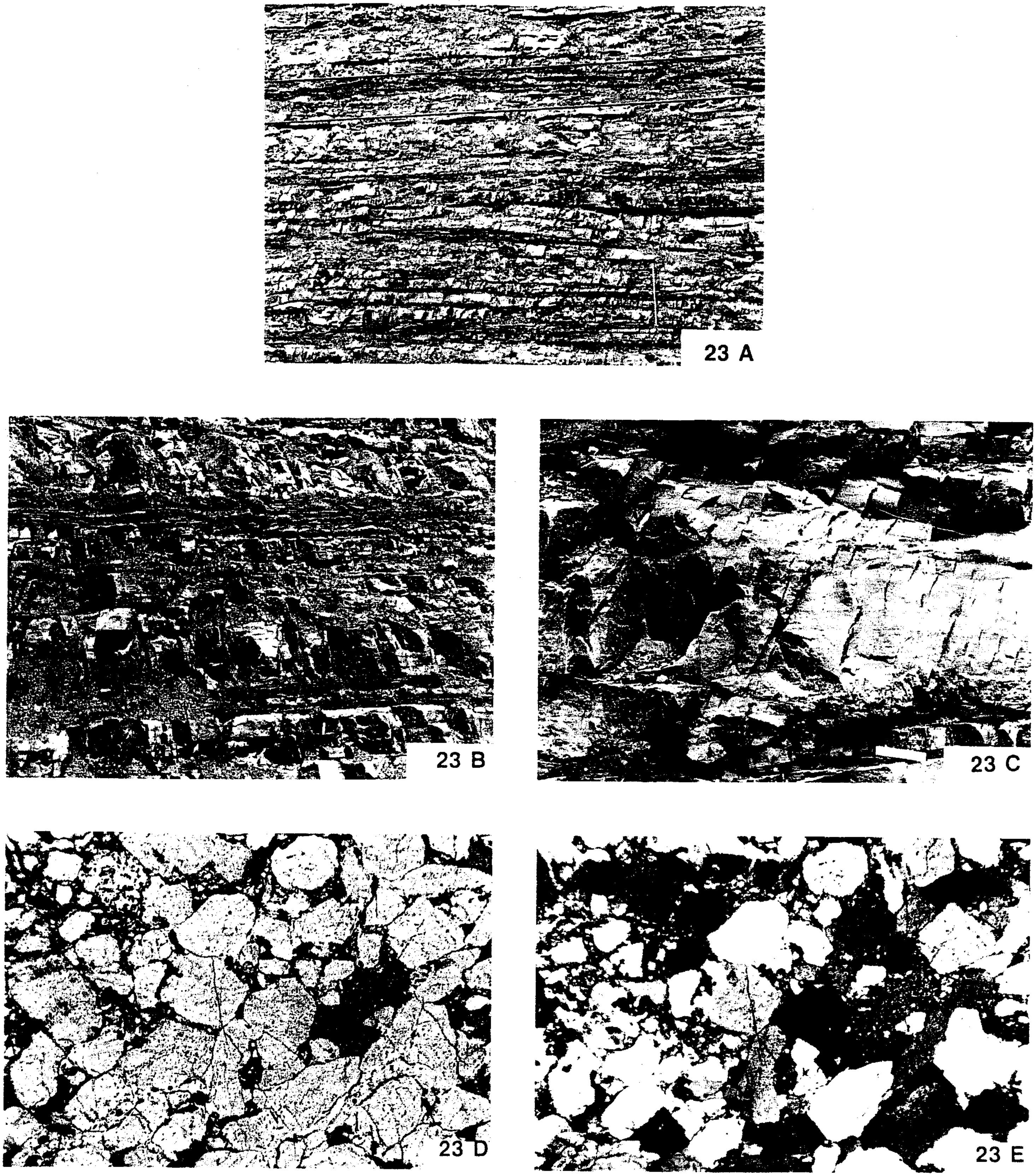
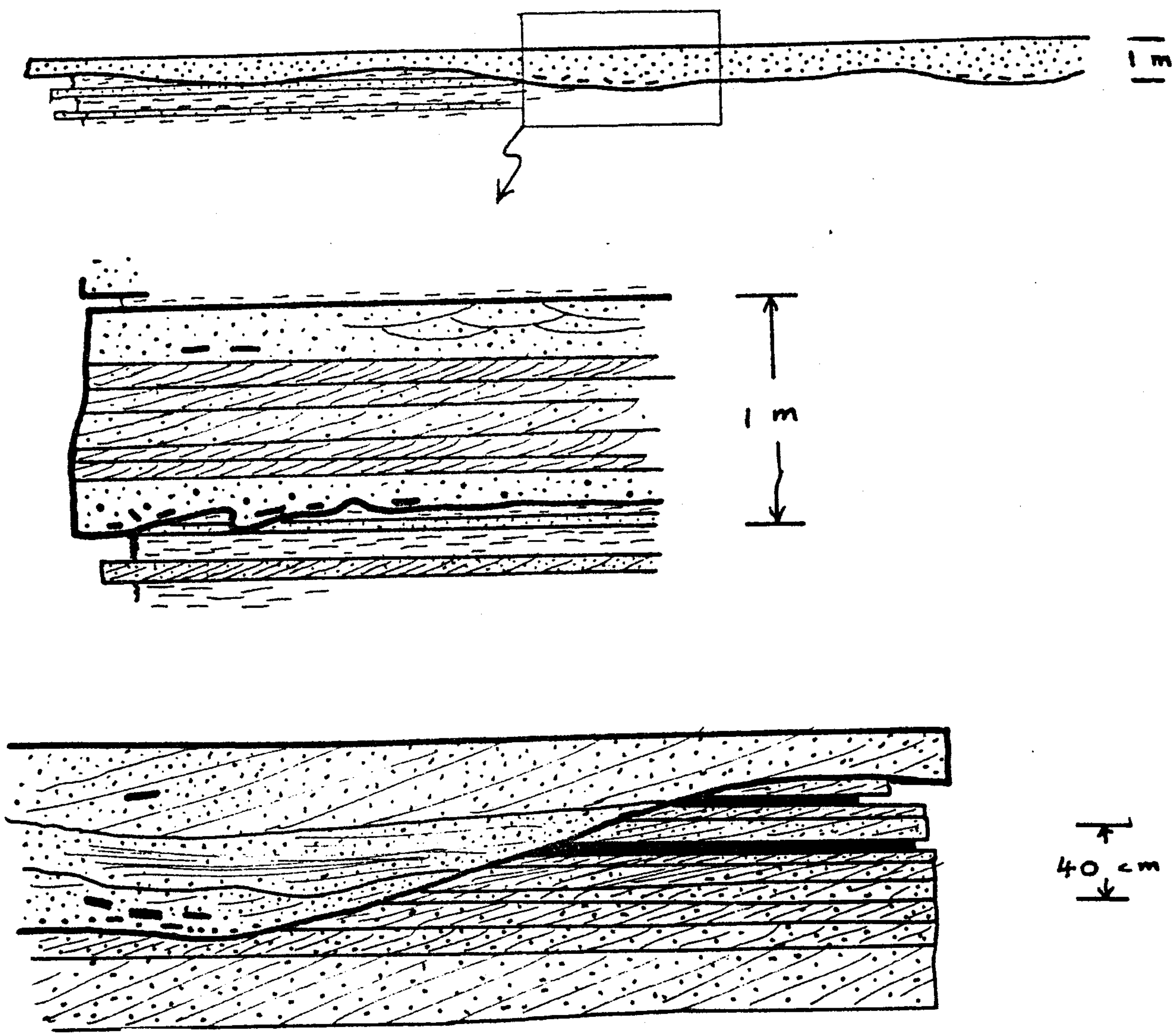


Figure 23



from Cotter,
Eastern Section
SEPM guidebook,
1982

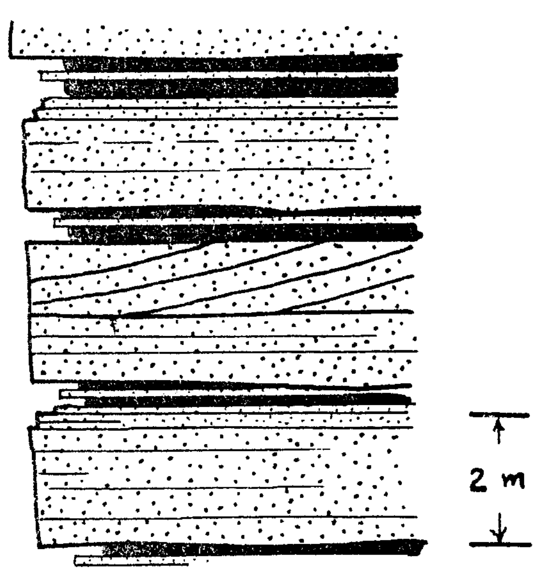


Figure 24. Sketches of outcrop relations at Millerstown (Stop 1).

Buffalo Mountain

120.1 STOP V. BUFFALO-BERRY SYNCLINE: THE UPPER DEVONIAN CATSKILL FORMATION, DUNCANNON MEMBER. Estimated time: 4:25 P.M. Allotted time: 60 minutes.

DISCUSSANTS: Richard Wells, Rodger Faill

The exposures at STOP V consist of three separate outcrops on the southbound (lower) lane, and one long continuous outcrop on the northbound lane. The main part of STOP V is the middle outcrop on the southbound lane (at Milepost 5-10). After discussion of the geology, the road may be crossed to examine the outcrops along the southbound lane. If time permits, we will climb to the top of the median strip for a spectacular view of the exposures on the east side of the northbound lane. (The ascent can be made between the middle and northern outcrops, or below (to the north of) the northern outcrop.) Do not approach the base of the cliff on the east side of the northbound lane, because of meta-stable slope conditions and danger from falling loose rock.

STRATIGRAPHY

The Catskill Formation is divisible into three members in the lower Juniata and Susquehanna valleys. The basal Irish Valley Member consists of gray sandstones and siltstones, grayish-red siltstones and silty claystones and includes the marine-non-marine transitional beds ("motifs") that will be seen at STOP VI. Above this is a sequence of interbedded red siltstones and very fine-grained sandstones, the medial Sherman Creek Member. The upper Duncannon Member, consists of light olive gray sandstones, reddish-gray silty sandstone, red siltstone and red silty claystone arranged in upward-fining cycles (Fig. V-A). This pattern of upward-fining cyclicity is characteristic through the entire Catskill Formation: they are present in the Irish Valley Member, they are thicker and better organized in the Duncannon Member.

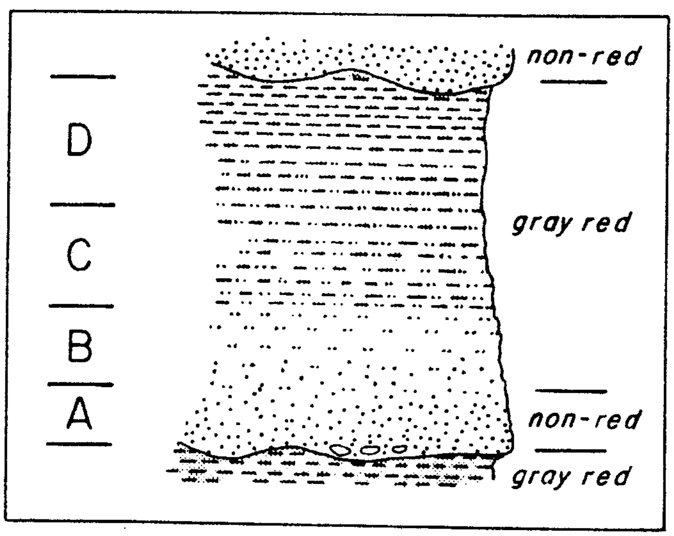


Figure V-A. Idealized Duncannon Member fining-upward cycle, as seen in the exposures in Buffalo-Berry Mountain syncline.

The ideal cycle consists of a basal light olive gray, fine and very fine grained, micaceous, cross-bedded sandstone which generally occupies a channel or irregular erosional surface cut into the top of the underlying cycle. Lenses of carbonate nodules, shale chips, fish teeth, and occasional plant fragments commonly occur lying directly upon this erosional surface, and can be seen at the north end of the southernmost outcrop on the south-bound lane. Part A, the gray sandstone, is overlain by B, reddish gray, very fine-grained silty sandstone, part C, grayish red silt-stone, and part D, grayish red silty claystone. The boundaries between segments of the cycles may be sharp or gradational and indistinct; boundaries between cycles are generally distinct.

The 11 fining-upward cycles exposed here at STOP V are near the middle of the Duncannon Member, and have an aggregate thickness of more than 200 feet. In most of these cycles, the four basic elements A-B-C-D are preserved. The upward-fining cycles represent fluvial deposition in natural levees, flood plains and flood basins in the upper (subaerial) portion of the regional Catskill delta. The scoured bases and the upward decrease in grain size from element A to D is evidence of a regular decrease in available energy and fluid velocity during a single depositional pulse. Gradation from one element to another occurs laterally as well as vertically. The laterally finer beds were deposited near the edges of the flood deposit. Lateral migration of the main flood channels has resulted in continued erosion of previously deposited cycles, with preservation of only a few cycles during a period of fairly continuous subsidence.

A number of clastic dikes (Wells, 1969) occur in the siltstone of at least one of the cycles in the Buffalo Mountain West Section. These dikes are composed of dark to light grayish red and greenish gray, medium to coarse silt which locally grades into very fine-grained sandstone. The dike material is argillaceous, micaceous, slightly hematitic, poorly sorted and has little porosity or permea-bility. The host rock is a fine grained, argillaceous siltstone, which is grayish red to dark grayish red. The dikes penetrate downward into the host rock from an overlying bed of sandy siltstone usually two to three inches thick, of the same color and lithology as the dikes themselves. These beds are minor interruptions of the fining-upward pattern, and are of limited lateral extent. The dikes are connected to the overlying beds and apparently formed from the same sediment. Angular fragments of the host rock sometimes occur in the upper parts of the dikes, and in the associated overlying beds.

The geometric form of these dikes is usually that of a slightly tapering sub-vertical wedge, and the dike walls are sharp. The dikes are straight, slightly irregular or have a zig-zag cross section.

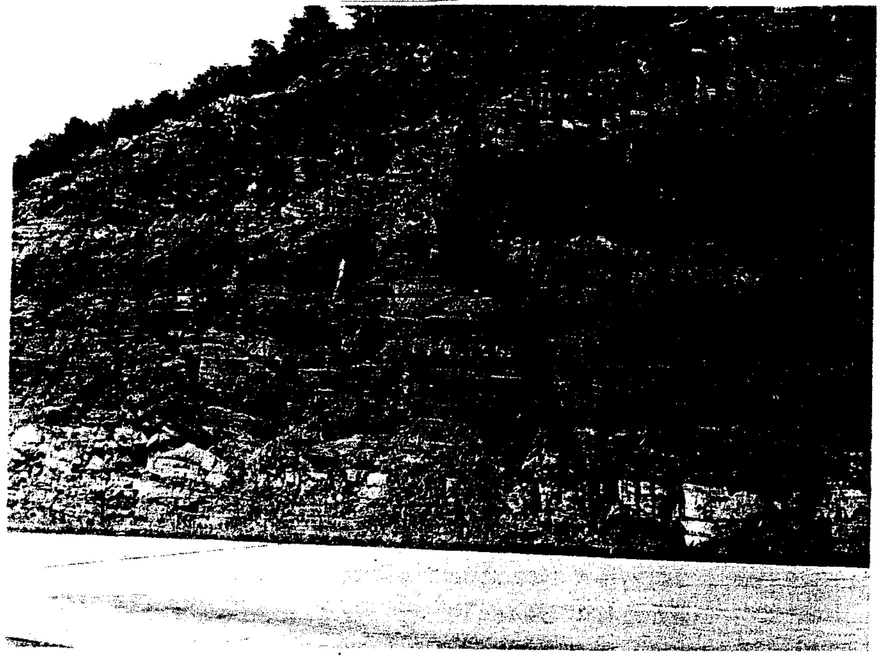
Six of these dikes were measured in detail, and range in height from four to twelve inches, and taper from a width of 3/8 to one inch at the top to a width of 1/2 to 1/16 inch or less at the base. The four dikes on which a strike could be determined trend from 115° to 150°, and dip from 50° southwest, through vertical to 67° northeast. The dikes are restricted to a lateral distance of thirty-five feet, at two stratigraphic levels three feet apart.

These dikes can be seen near the center of the middle outcrop on the southbound lane; however; good exposures such as this are rare so please do not hammer on them!

STRUCTURAL GEOLOGY

Although the spectacular aspects of this exposure are the sedimentologic cycles of the Duncannon Member, there are some deformational structures worth noting. Perhaps the most noticeable is the wedge fault which rises out of the base of the middle outcrop (southbound lane), crosses the sandstone base of the cycle, and passes upward through the section (to the left). The displacement of this fault is only two or three feet. Yet near the top of the gray sandstone in this cycle, the displacement appears to be much greater, on the order of 15 to 20 feet. This is purely illusory. The fault happens to parallel the edge of a sandstone channel, and the apparent offset of the gray sandstone represents the feather edge of a channel and not a duplication of the underlying sandstone beds. A few other similar wedges can be observed throughout these outcrops.

Another structure present in this outcrop are two sets of slickensided fractures that dip steeply (one to the north, the other to the south) at a large angle (60 degrees or more) to the bedding (Fig. V-B). Fractures of one set offset fractures of the other set (they are mutually offset), they intersect each other at approximately 60 degrees (they possess a conjugate geometry), and thus they are conjugate (the movements on them were contemporaneous with each other). These movements have resulted in a lateral extension of these beds (i.e., they are extension faults, Norris, 1958), in direct contradiction with the lateral contraction, or shortening, represented by the wedging on the beds. But the extension faults offset the wedge (contraction) faults, and are not offset by them. This indicates that in this outcrop a period of bed-parallel shortening was followed by bed-parallel extension. A possible explanation derives from the fact that this exposure lies in the hinge of the Buffalo-Berry synclinorium. As the fold developed, the (relatively) sharp bending of beds in this fold hinge produced a local reorientation of stress within the hinge. That is, after an initial bed-parallel shortening (by wedging), the beds in the fold hinge were extended in response to the bending of the beds. This explanation differs from the one given for the conjugate extension faults at Laurel Creek (STOP III). However, the position in the fold is different--there was no reorientation of stress in the fold limb as there was here in the fold hinge.



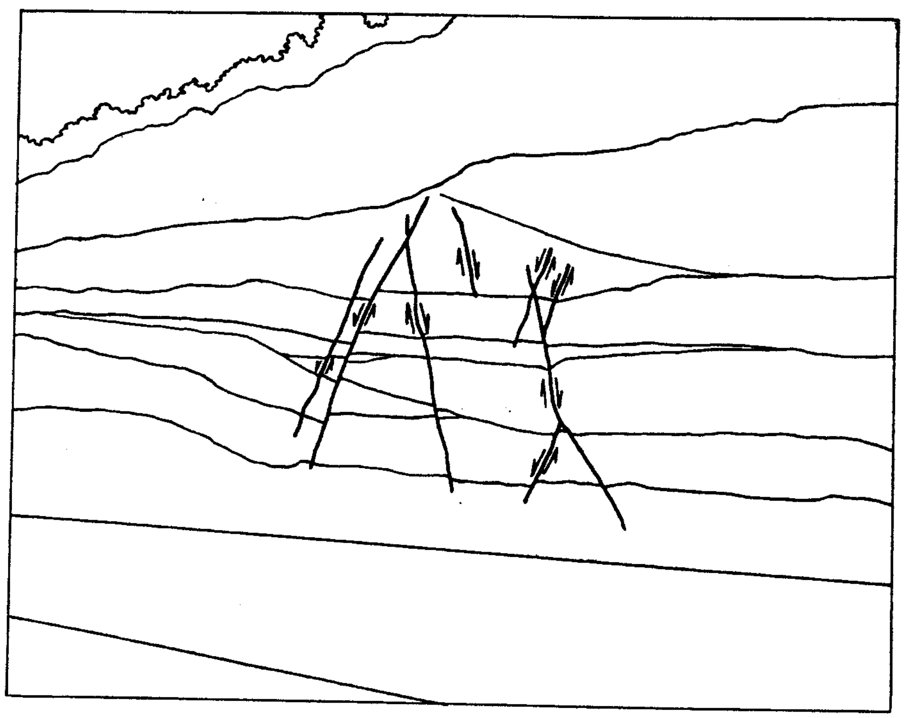


Figure V-B. Conjugate extension faults in the Duncannon Member of the Catskill Formation at the hinge of the Buffalo-Berry syncline. U.S. Routes 22-322, southbound lane, middle outcrop, 1 mile north of Newport.

from Faill et al., FCPG 38, 1973.

PA 655

Setting: The next four stops are all close to the town of Reedsville, and provide a nearly complete cross-section of the Ordovician portion of the Taconic clastic wedge, from pre-wedge carbonates into Silurian sandstones, at a point intermediate between distal alluvial plain and proximal mountain front. The wedge attains its maximum thickness and facies diversity in this medial position.

This first stop is in sub-wedge, mid-Ordovician carbonates of the Trenton Group (see Figs. 7 and 8), and shows the progression of carbonate environments associated with the evolution of the eastern edge of the cratonic platform in response to the onset of the Taconic orogenic movements to the east (Fig. 25). It also reveals details of the onset of siliciclastic deposition into the nascent Taconic flysch/molasse basin.

Procedure: Cross PA 655 and walk north up the onramp to US 322. Begin examination of the carbonates beneath the power line. Proceed south around the corner to the correlation bed, marked "O". Then recross PA 655, pick up bed "O", and proceed south up the offramp and onto PA 322 to south end of outcrop. BE CAREFUL OF TRAFFIC.

The Rocks: This outcrop exposes a complete marine transgression, recorded in carbonates, from supratidal conditions to offshore basin floor. As this transition was occurring, the evolving basin began to receive pelagic clay, and siliciclastic clay appears independent of the carbonates in the sequence. It is important to separate these two histories. A third independent event recorded in the rocks is volcanic ash-falls, represented by yellow-weathering bentonites.

The carbonate rocks are predominantly fossiliferous lime mudstones (micrites), with lesser amounts of oolitic grainstone, skeletal grainstone and packstone, peloidal packstone and wackestone. The stratigraphic nomenclature is detailed, complex, and the rocks are best subdivided on a lithofacies basis.

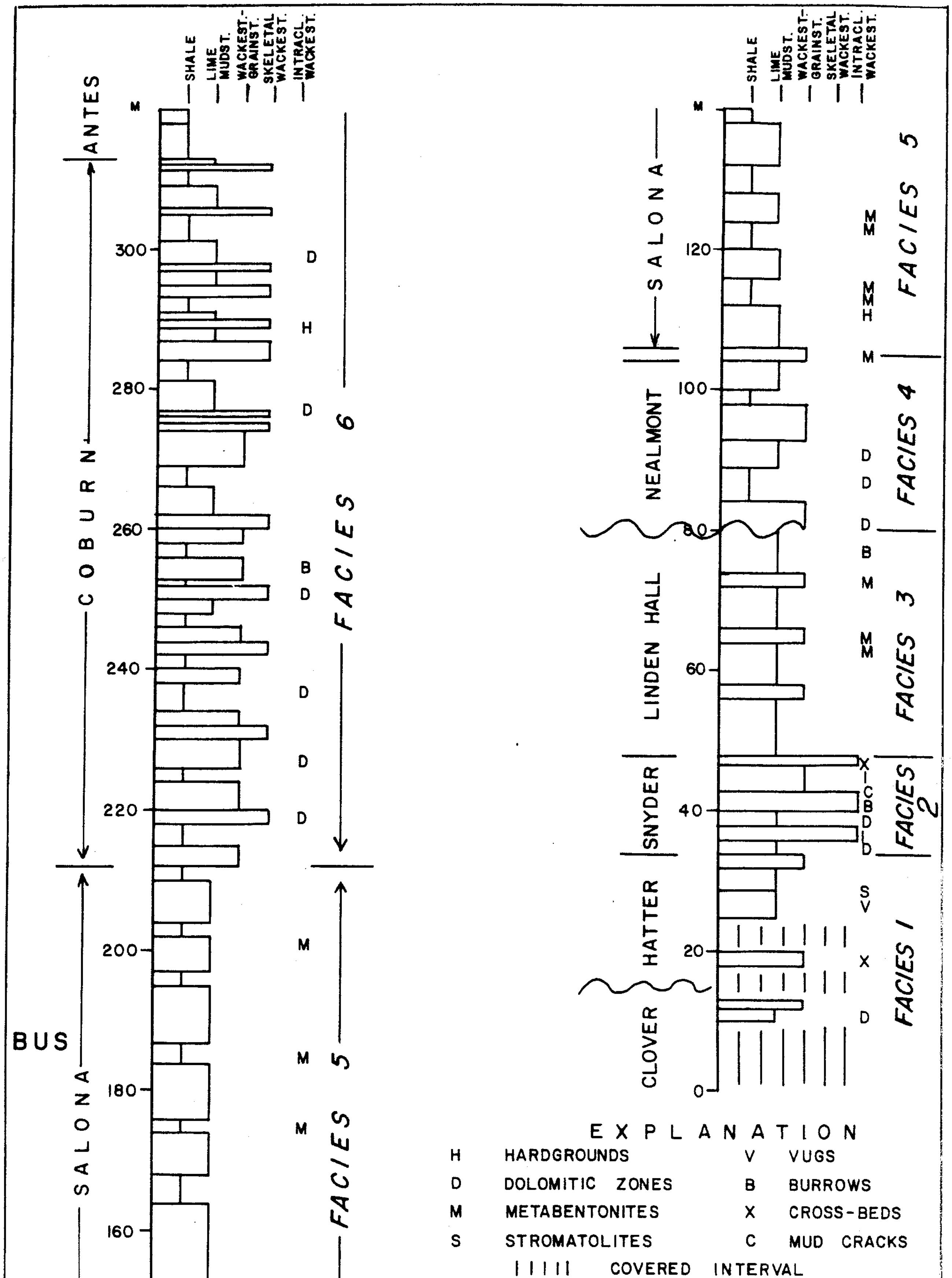


FIGURE 25. PA ROUTE 655

layers and mud-cracks place the depositional environment at intertidal to supratidal. Most lithologies show evidence of burrowing by infaunal, mining and grazing populations. Current-bedded skeletal concentrates become more abundant higher in the facies. Look for evidence of traction-current bedding, deposition from suspension, and organic fixation of sediments.

Facies 2: Peloidal/Oolitic grainstone. At the base of the onramp are exposed 5 m of well-sorted, medium-grained peloidal and oolitic grainstone. These rocks are cross-bedded in planar-base sets and cosets, and often show approximately bipolar cross-stratification. Layers of mud-chip conglomerate are common, and scour-and-fill structures are abundant. These beds may represent a tidal channel dominated by reversing traction currents, or, considering the contrasting facies they separate, a submerged to emergent bar fronting a lagoonal intertidal complex.

Facies 3: Mottled Mudstone. Above the grainstone, and carrying across to the south side of PA 655 and the offramp, there occur 30 m of thick-bedded to unbedded, burrow-mottled, fossiliferous lime mudstones. Bedding has been largely destroyed by an abundant infaunal population. The presence of traction currents is indicated by occasional lenticular, cross-bedded skeletal grainstone lenses, and by frequent skeletal packstone layers with erosional contacts. Brachiopods, gastropods and trilobites dominate the body fauna; they are generally thin-shelled and frequently articulated. Look for hardgrounds and other evidence of penecontemperanous cementation. Siliciclastic clay appears as a major sediment type near the top of this facies.

Upward in this facies, the skeletal sands are progressively replaced by peloid grainstones and packstones, the abundance of sand decreases, fossil abundance and diversity increase, and size and activity of burrowing increases. These changes are consistent with a marine environment progressively farther offshore, but still above wave base.

Facies 4: Crinoidal Grainstone. Low on the offramp are exposed 5 m of sandy, skeletal and crinoidal grainstone and packstone which may include oolites and peloids. Clay and mud are absent from this facies, and the rocks are current-bedded and lenticular. Look for cross-bedding and evidence for scour-and-fill. These traction-current deposits could represent an offshore bar or subtidal channel complex.

Facies 5: Carbonate and Shale. Above the grainstones, along the offramp and onto US 322 itself, there occur 100 m interbedded gray carbonate and black calcareous siliciclastic shale. Much carbonate is in mudstone beds 10-30 cm thick, that show internal parallel lamination, wavy bedding, and ripple-drift cross-lamination. They erosionally overlie shales, and grade up into shales, and resemble T_{C-E} and T_{B-E} sequences. Skeletal sand is conspicuously absent; the fossils are less robust, smaller and less abundant than below.

Repetitive, cyclic sedimentation on several scales is apparent in this facies. On the smallest scale, repeating hardground layers up to 30 cm thick are visible. Larger-scale cyclicity occurs low in the unit, and grades from thick-bedded mudstone to thin-bedded mudstone and shale. Still larger repetitive bedding (10-20 m) begins with thinly interbedded graded carbonate/shale sequences, and becomes thicker-bedded, more fossiliferous, burrowed, more current-bedded, more dolomitic, less shaly and less graded upward. These large cycles resemble shoaling, coarsening-upward sequences seen in modern environments.

Facies 6: Carbonate and Shale with Skeletal Grainstones. The top facies comprises interbedded graded lime mudstone and siliciclastic shale, as below, and in addition conspicuous erosionally bound, lenticular coquinoid skeletal packstones and grainstones. The graded sequences show frequent T_{A-E} sequences, with size-graded skeletal hash in the basal parts of the beds. Skeletal grainstones reach 50 cm thick, and are erosionally bound; some are cross-bedded. Many limestones are burrowed.

Midway up in this facies the proportion of siliciclastic shale increases abruptly. Walk south past some excellent small examples of concentric folding to the south end of the outcrop. Here Antes Shale, without carbonate, is in abrupt, thrust-fault contact with the carbonate section.

Summary: The facies encountered on this traverse record a major marine transgression from supratidal shoreline to offshore basin floor. This transgression took place as the American cratonic margin began to downwarp into the Taconic flysch/molasse basin. The bentonites signal volcanic activity in the region, and the initiation of shale deposition indicates the appearance of terrigenous clay in the basin water. Paleocurrent data indicate the source of clay was to the east and southeast, off a rising tectonic welt (McBride, 1962; Golike, 1980).

Reedsville

Setting: This outcrop is the best single exposure of Upper Ordovician strata in central Appalachians. Rocks from the middle Reedsville to the Tuscarora are exposed (Fig. 26). All or parts of Ordovician lithofacies A through E are exposed (Fig. 8); lithofacies F and the Tuscarora are exposed across the highway. They afford a detailed look at the maximum development and diversity of facies in the Taconic clastic wedge.

The outcrop is reasonably free of structural complications. A vertical fault surface is visible along the road, and some small flexural folds appear in lithofacies C. A reentrant in lithofacies D may represent erosion along a fault. Rocks are right-side-up, and dip southeast.

Procedure: Walk north to the access road and begin examination at outcrop of lithofacies A. Work your way south, up-section, part-way up the slope behind the scrub growth. At the covered interval return to road level, and continue up-section through facies B, C and D and into facies E. The section ends at the east end of continuous exposure, west of the driveway.

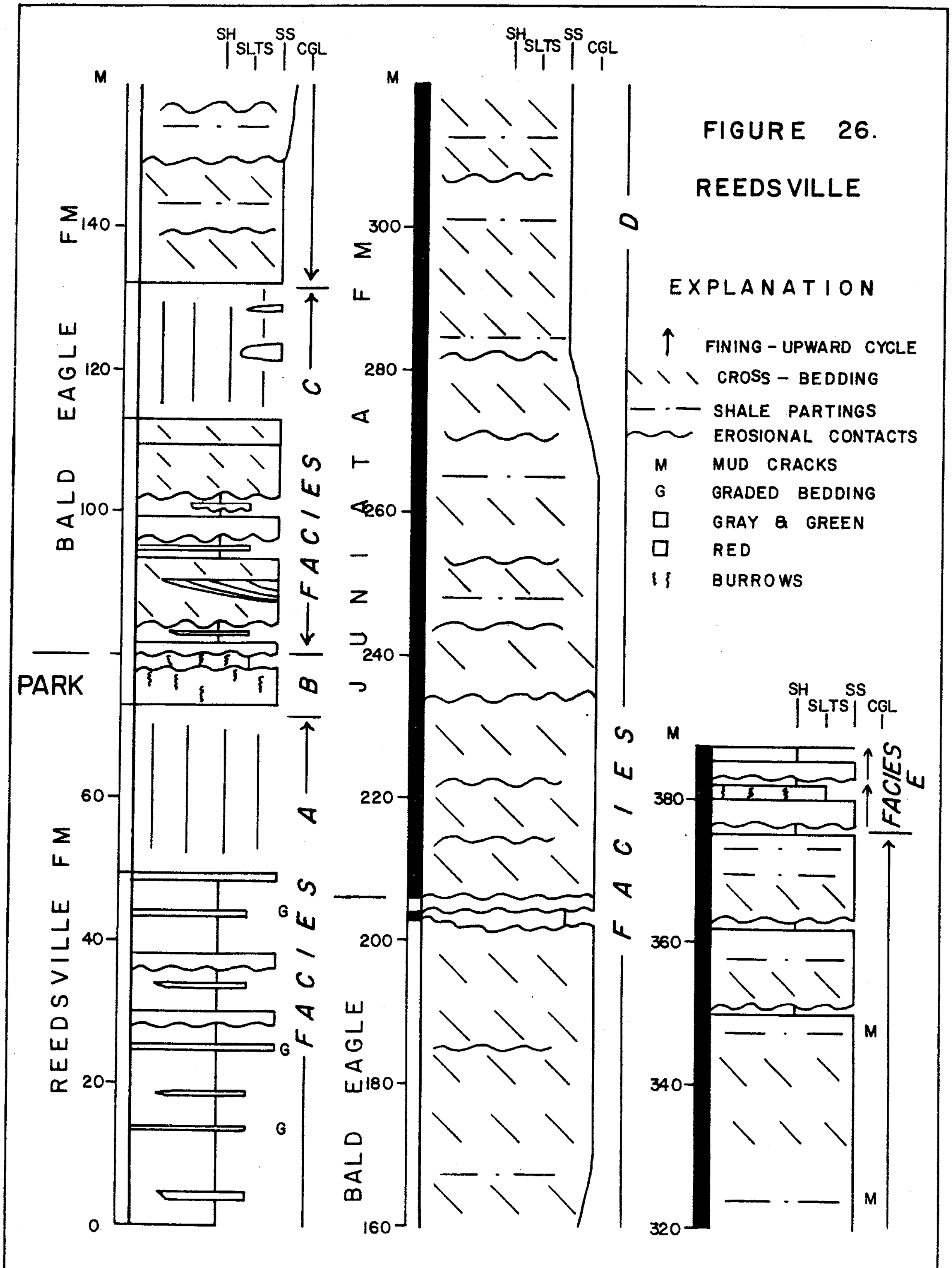


FIGURE 26.
REEDSVILLE
EXPLANATION
FINING - UPWARD CYCLE
CROSS - BEDDING
SHALE PARTINGS
EROSIONAL CONTACTS
M MUD CRACKS
G GRADED BEDDING
GRAY & GREEN
RED
BURROWS
SH SLTS SS CGL
M
REEDSVILLE FM
PARK
BALD EAGLE FM
JUNIATA FM
BALD EAGLE
FACIES A
FACIES B
FACIES C
FACIES D
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Facies A: Facies A contains thinly interbedded, gray to black shale, fine-grained sandstone and bioclastic, coquinoid sandstone. Genuine limestones such as were present at Curt Gap are rare to absent. The sandstones are frequently graded above and below, and parallel-laminated to hummocky-cross-stratified and ripple-laminated internally. Look for rippled upper surfaces of sandstones, 10-20 cm-long rounded shale rip-up clasts in sandstones, and undulatory basal surfaces of sandstones. The sandstones are impersistent, and show considerable pinch and swell in outcrop; the upper surfaces are often scoured out. Look for evidence in the sandstones favoring traction-current or suspension-current deposition. Lenticular bedding and starved ripples are occasionally seen in the shales. Sole marks suggest northeast-southwest sediment movement.

Facies B: Above the covered interval, Facies B consists of about 15 m of dark gray, fine-grained sandstone, with lenticular coquinas and essentially no shale. Two sandstone facies are distinguishable: well-sorted, clean sparsely fossiliferous sandstones lacking coquinas, mottled, cross-bedded and burrowed, blocky sandstones with a brachiopod (Orthorhynchula sp., Lingula sp.)-pelecypod fauna. These same taxa are often concentrated into lenticular, burrowed coquinas that may constitute storm-lag concentrates. Look for parallel lamination, cross-bedding and pinching bed thicknesses in the sandstones, and skeletal lag concentrates in the clean sandstones.

Facies C: Rocks of facies C are unfossiliferous, and consist of two contrasting lithologic associations: clean, quarzitic, fine-grained sandstone, and thinly (cm-scale) interlayered sandstone and siltstone to mudstone. The clean quartzitic sandstone intervals are recognized by prevalent thin parallel laminations, with less abundant trough cross-stratification. Sedimentation units are impersistent laterally, and scouring and channeling are common. Shale drapes over sandstones are often cut out along strike. The sandstones are not visibly size-graded, and do not contain basal lag gravels or skeletal debris. Look for grazing burrow structures, current-crescent casts, parting lineations (oriented northeast), and skeletal debris at the bases of sandstones. Note the abundance of parallel lamination, and its relation to cross-bedding. Look for bipolar cross-strata, reactivation surfaces and other distinctly intertidal features.

The intervals of siltstone and mudstone are of variable thickness (up to 2 m), but contain individual beds usually less than 10 cm thick. Many sandstone layers are single sets of small-scale cross-strata, with erosional lower boundaries and rippled tops; others are parallel-laminated. The siltstones are ripple-bedded and wavy-bedded, with rippled upper surfaces. They are probably burrowed, but the organisms were confined to the siltstones.

Note vertical changes in Facies C as you walk south. Clean, quartzitic sandstone becomes less abundant; sand-grain size generally increases; parallel lamination is replaced by trough cross-bedding as the dominant bedding type; and cosets come to predominate over sets. In the upper parts of Facies C in other outcrops (e.g. Loysburg, 85 km to the southwest), the lithologic associations described above give way to 2- to 10-m-thick, size-graded sandstone/red shale sequences resembling channel/over-bank fining-upward sequences.

An acceptable paleoenvironmental model should account for the contrasting lithologic associations, the prevalence of parallel lamination and of single, isolated sets of cross-strata, the absence of fossils, the localized sites of sand and mud deposition, and the upward appearance of channel/overbank facies.

<u>Facies D</u>: Above a covered interval are exposed 250 m of medium- to coarse-grained sandstone, which is locally conglomeratic. The sandstones are lithic arenites and lithic wackes, with both depositional and authigenic clay matrix. The lower parts are gray (Bald Eagle Formation), the upper parts red (Juniata Formation); the color boundary is gradational over 10 m (more elsewhere), and its present position is of diagenetic origin (Thompson, 1970b) and does not conform to lithofacies boundaries.

Throughout the facies shale and siltstone are virtually absent; they are restricted to widely scattered irregular, centimeter- and millimeter-scale layers. Look for erosional, scoured tops of thin beds, and strong lateral impersistence. However, the former, temporary existence of many such mud beds is attested to by the abundance of intraformational shale clasts and shale-clast conglomerates.

The sandstones coarsen upward from the base of the facies, to a maximum of very coarse sand just above the color boundary, then fine upward to medium sand at the top. Lithic-pebble conglomerate characterizes the coarsest sandstone; pebble size, abundance and diversity all increase upward to the grain-size maximum, then decrease above it. Look for quartz, chert, meta-volcanic and other pebble types, for comparison with suites to be seen at Stop 11 tomorrow. The conglomerate fines and dies out to the northwest, and marks the climax of the Taconic Orogeny in the central Appalachians.

Bedding in the sandstones and conglomerates is predominantly large-scale trough cross-bedding. Paleocurrents are predominantly northwest (Yeakel, 1962), with fairly low variability. Thick-bedded and unbedded rocks are present in the conglomeratic zone. Low-angle channel fills are visible on the high face. Many beds are single sets of trough and planar cross-strata, which reach 2 m thick and overlie thin shales. Above the conglomerates bedding scale decreases somewhat; rippled surfaces and cosets become more abundant near the top. Mud-cracks are apparent above the conglomeratic interval. Look for evidence of water velocity, water depth, persistence or impersistence of flow, and evidence for exposure.

An acceptable paleoenvironmental model for this facies should account for the great predominance of sand deposition over clay deposition, rapid fluctuations of current velocity, frequent exposure, and the abundant thick sand bars.

<u>Facies E</u>: Near the top of facies D shale becomes more abundant and the sandstones become finer-grained, and at the mark the

section contains more than 33% shale. Shale layers come persistent laterally, and just above the facies boundary are burrowed in the lower parts. The sandstones are trough cross-bedded, and erosionally overlie shales. Look for erosional or gradational contacts between shale and sandstone. Evidence for repetitive bedding here is poor, and will be better seen at the next stop.

Broad Mountain

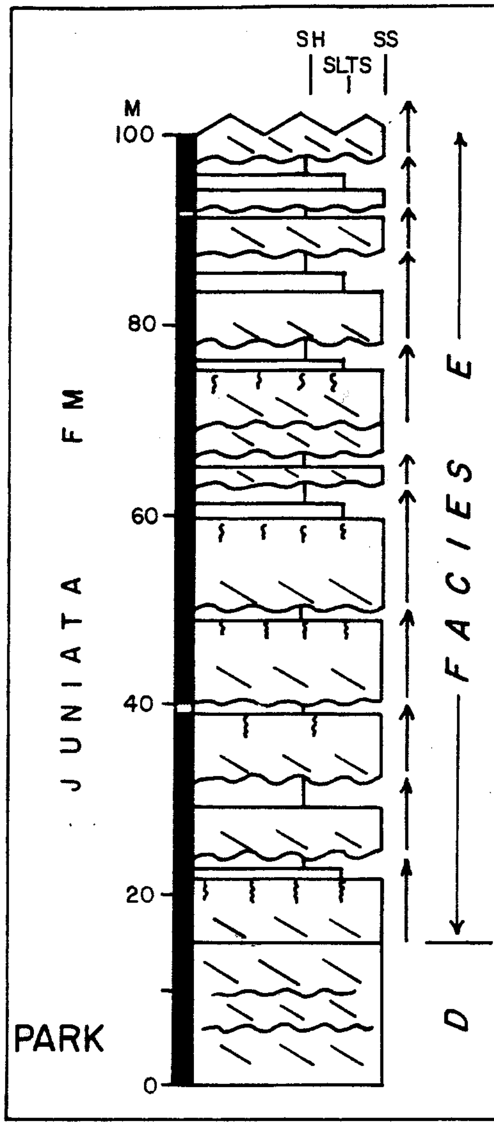


FIGURE 27. BROAD MOUNTAIN

EXPLANATION

Union Furnace

INTRODUCTION

About 850 feet of Middle to Upper Ordovician-age (Black Riverian-Trentonian) carbonates are exposed in this roadcut (lat. 40°37'78" N, long. 78°10'25" W) which was completed in 1962 (A. Sternagle, personal communication, 1986). Exposed are the Loysburg, Hatter, Snyder, Linden Hall, Nealmont, Salona, and Coburn Formations, or what Rogers (1856) called the Auroral and Matinal Limestones (see p. 7-11).

Historically, this part of the Paleozoic section has been economically significant. In view of this, 32 units of varying thicknesses, within the stratigraphic section from the Loysburg through Nealmont Formations, were sampled here and analyzed for $CaCO_3$, $MgCO_3$, and insoluble residues (Figure 49). These analyses combined with the excellence of the exposure provide an opportunity to examine the physical and chemical characteristics of this carbonate sequence and to speculate about the origin of these rocks for the amusement of geologists over the next 150 years.

The upper half of the Snyder Formation and the entire Linden Hall Formation average about 90 percent $CaCO_3$ and 4 percent insoluble residue. These values indicate that this 210-foot-thick interval has a good potential in the acid-mitigation markets. This interval appears to have been deposited in a subtidal or lagoonal environment of deposition. Generally, however, the entire carbonate section exposed here reflects an overall gentle deepening of a storm-dominated environment from the tidal flats of the Loysburg Formation through the shallow (less than 100 feet) ramp and basin setting of the uppermost Coburn Formation. The Loysburg through Snyder Formations appear to reflect a series of small-scale, episodic (?), fining-upward (shoaling-upwards) cycles within the tidal and intertidal zones while the Linden Hall through Coburn Formations were apparently deposited below sea level in more open-marine settings.

Twenty bentonite and 5 possibly bentonitic layers have been identified here (Table 6) in the Hatter through Coburn Formations. The trace-element geochemistry and the significance of these bentonites are discussed on pages 13-19. Bentonites have been used for more than 50 years in attempts to unravel stratigraphic complexities in the Valley and Ridge Physiographic Province of Pennsyl-

Figure 49. Columnar section showing the lithology, bentonites, chemistry, and environments of deposition for the Loysburg through Coburn Formations. Explanation for figure below. Figure-opposite page.

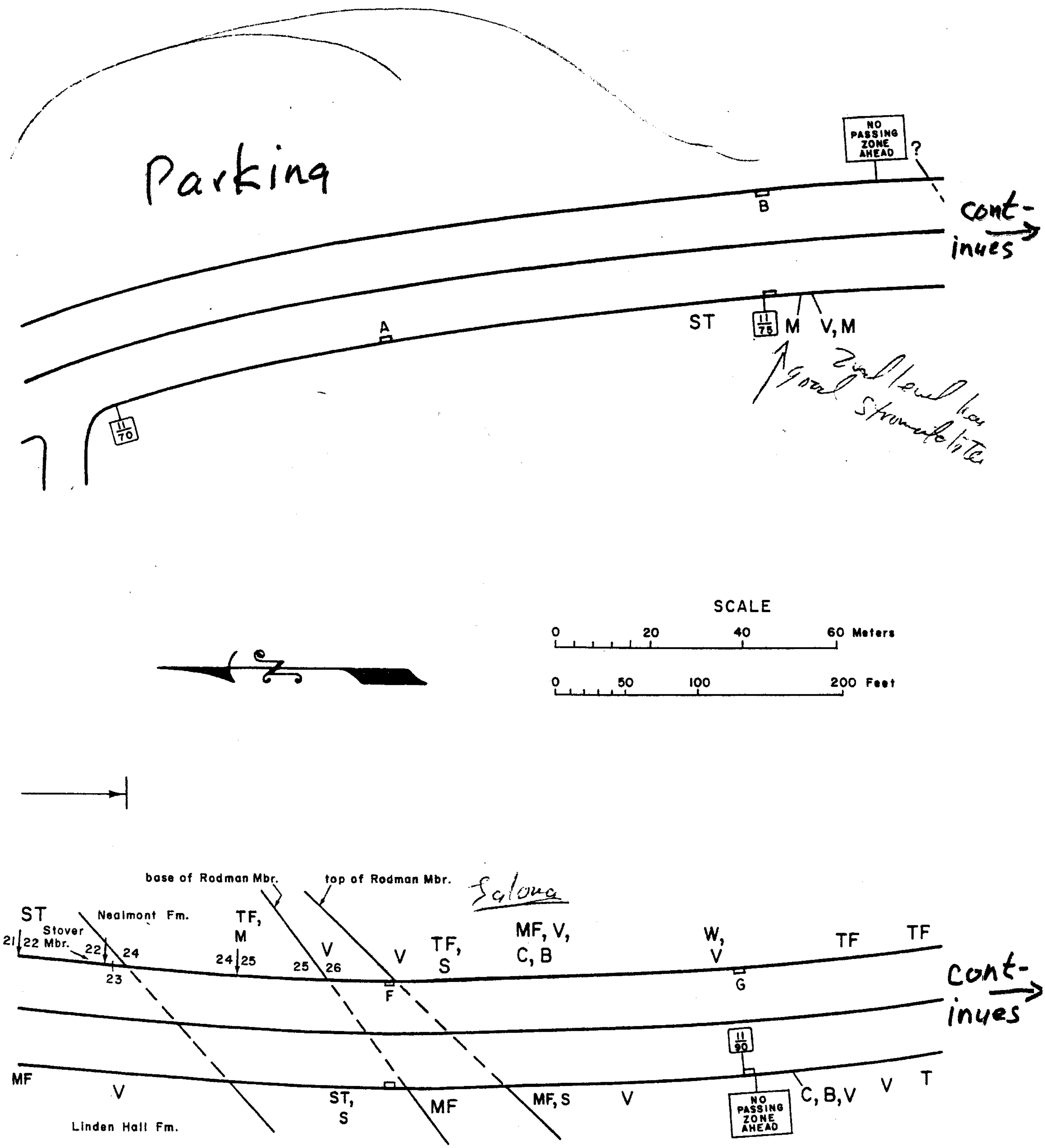
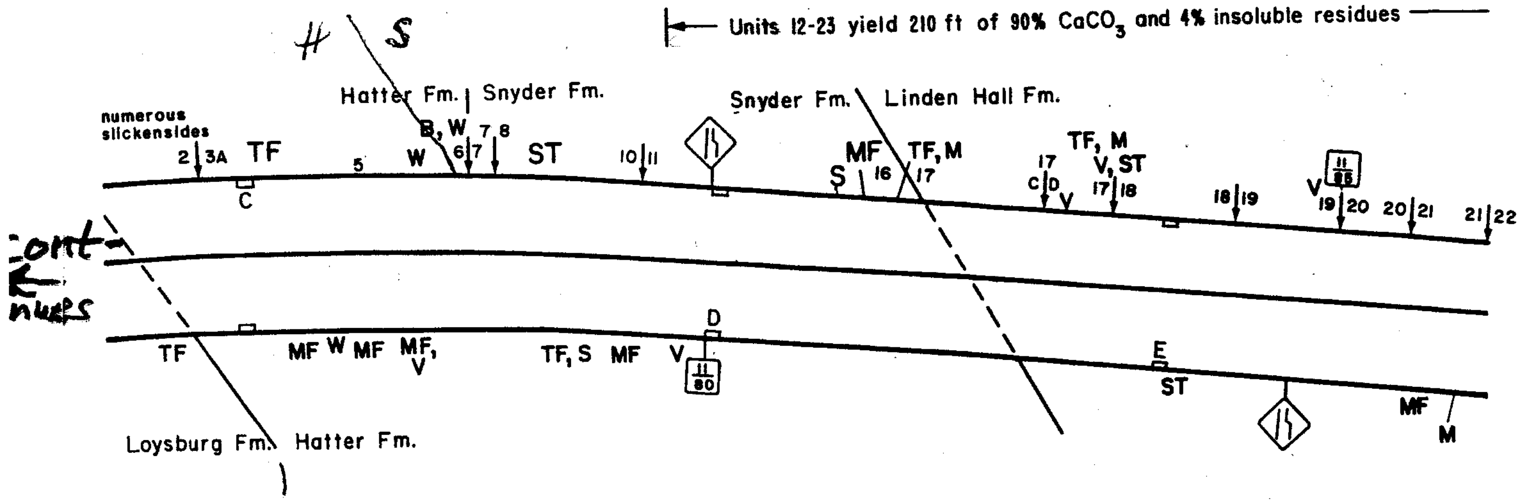
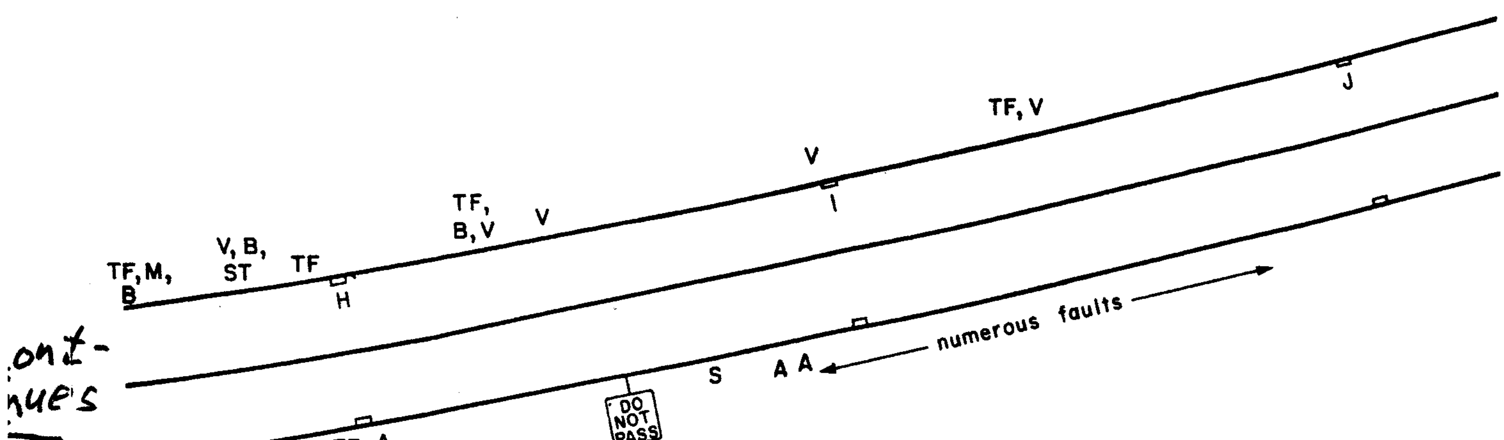


Figure 50. Geologic map of the Union Furnace outcrop along PA Route 453, showing locations of formation boundaries, chemical sample units, and some of the mesostructures. Also shown are the locations of the various highway signs, and the drainage culverts, which are labeled from the north end, A through J.



EXPLANATION

TF - Transverse fault
MF - Master fracture
WF - Wedge fault
V - Array of veins
T - Thrust fault
A - Anticline
ST - Stylolite
C - Cleavage
M - Mullion
B - Breccia
S - Solution



vania and with refined "geochemical fingerprinting" they have the potential of being even more useful. Furthermore, the acid-volcanic events that produced these bentonitic units appear to have signaled impending doom to the "carbonate factory." Relative subsidence (drowning) of this platform occurred contemporaneously or shortly after these events.

Faill (p. 119-126) discusses the effects of Alleghanian deformation present at this exposure. No structural evidence of the "stupendous" Taconian orogeny of Rogers (1858) are found here due to the early foreland setting (pericratonic or cratonic shelf). The only significant Taconian influence to be observed here, and only as a prelude to orogensis, is the change from a passive margin carbonate platform or shelf to a gradually deepening basinal depocenter. Evidence for this can be found in the character and thickness of the 100-million-year-long Cambro-Ordovician carbonate sequence, the thickness of the overlying Reedsville Shale, and in the observations of Kay (1951), Rogers (1971), Read (1980), Hardie and others (1981), Diecchio (1985), and others.

Appendix 1 contains a measured section of the Loysburg through Nealmont Formations. Thompson (1963) provides a detailed stratigraphic section of the Salona and Coburn Formations 0.75 mile north of Union Furnace between Warner Company's Quarry 1 and Quarry 2. Combined, these descriptions provide a composite section of the Loysburg through Coburn Formations.

BELLEFONTE FORMATION. Working upward through the stratigraphic section at Stop 1, the upper part of the Bellefonte Formation (Beekmantown Group) is the lowest unit encountered. Although not a focus of this stop, it is exposed in the northern portion of the roadcut across from the debarkation area on the west side of the road. The Bellefonte comprises dark-gray to light-olive-gray, magnesium-rich mudstones, and finely recrystallized dolomites. Within this unit, the presence of cryptalgal laminae, birds-eye or fenestral textures, mudcracks, horizontal burrowing, and possible relict anhydrite pseudomorphs suggest cyclic carbonate sediment accumulation on a tidal flat and supratidal platform. Chemical data for this part of the section are limited; about 53 percent $CaCO_3$, 41 percent $MgCO_3$, and 5.5 percent SiO_2 are average (Miller, 1934). This dolomite-rich formation is a source of railroad ballast and aggregate, generally having a skid resistance level (SRL) of G (Berkheiser and others, 1985). The Pennsylvania Department of Transportation evaluates the desirability of a material for use on road surfaces based on the degree to which a high coefficient of friction can be maintained over time. SRL designations, from best to worst, are E, H, G, M, and L.

LOYSBURG FORMATION. The Loysburg Formation is the lowermost carbonate unit we will examine in detail. It is exposed in the northern part of the roadcut on the west side of the highway and comprises about 56 feet of olive-gray to olive-black, cryptalgal dolomite and limestone (mudstone). It contains thin intraclastic zones (mostly as rip-up algal mats), horizontal worm burrows and burrow-mottling, mudcracks, minor thin skeletal wackstones, and occasional convex-up stromatolites (Unit 2 on Figure 49). These features have been interpreted to suggest a tidal to supratidal environment of deposition. The presumed reduced salinity of supratidal brines (therefore more limestone) of the Loysburg Formation versus the Bellefonte Formation may indicate a change from an arid climate to a wet and rainy climate as postulated by Hardie and others (1981). Chemical analyses reveal a weighted average of 79.5 percent $CaCO_3$, 11.4 percent $MgCO_3$, and 5.1 percent insoluble residue for this exposure of the entire formation (See

Figure 49 for detailed chemical analyses). This formation is a source of aggregate, generally having the lowest possible SRL or L designation (Berkheiser and others, 1985).

HATTER FORMATION. The almost 100-foot-thick Hatter Formation is an argillaceous dark-gray to olive-black sequence of laminated carbonate mudstones and minor skeletal wackstones and packstones. Locally, it contains greater than 35 percent insoluble residue composed predominantly of clay and silica silt. Physical characteristics include undulatory, discontinuous laminations, planar laminations, brachiopod fragments and other skeletal debris, thin intraclast zones, minor fenestral textures (Unit 3), horizontal burrows and burrow-mottling, rare hardgrounds, lensoidal and pod-like forms of skeletal packstones and wackstones, and cross-bedded siliclastic-rich intervals. These features suggest shallow subtidal (probably lagoonal) to intertidal environments of deposition. The upper 37 feet of the formation averages about 22 percent insolubles (clay, silt, and silica sand), which suggests a possible intertidal or tidal-channel affinity. Recently, Gardiner (1985) recognized cyclic patterns for these rocks. She characterized both the Loysburg and the Hatter Formations as comprising thin (generally less than 6 inches) storm-deposited, fining-upward cycles (shoaling-upward), having scoured basal contacts and a basal intraclastic skeletal wackstone-packstone interval. The Hatter Formation may contain some previously unrecognized bentonitic partings, especially toward the base where a relatively low energy lagoonal environment is postulated (Figure 49).

Chemically the Hatter Formation averages about 80.8 percent $CaCO_3$, 5.4 percent $MgCO_3$ and 11.8 percent insoluble residue on a weighted average basis. Hypersaline environments apparently were not significant and dolomitization is minimal. During quarrying, the Hatter Formation is usually combined with the entire section producing an aggregate with a SRL rating of L. However, if it were selectively mined, it might have a higher SRL due to its siliclastic nature.

SNYDER FORMATION. The Snyder Formation consists of about 95 feet of grayish-black to olive-black, faintly laminated, burrow-mottled mudstones and skeletal wackstones and packstones. Horizontal and vertical burrows, ooliths, intraclastic zones typically less than 0.5-foot-thick, flat pebble conglomerates, mudcracks, cross-bedding, and fragments of bryozoa, brachiopods, gastropods, crinoids, and possible corals are common. Fining-upward cycles with basal intraclastic lag zones are conspicuous. Gardiner (1985) recognized these as thin, storm-deposited cycles comprising a basal intraclastic lag conglomerate, which is missing at times, overlain by a crossbedded pelletal wackstone-packstone which then grades into an uppermost burrowed mudstone. These features appear to be characteristic of shallow-water intertidal to subtidal shoals or washover islands, perhaps seaward of a lagoonal facies. The Snyder Formation contains the stratigraphically lowest observed definite bentonite beds (Table 6). Assuming an ash-to-bentonite compaction ratio of about 2:1 and ash injection into the stratosphere, from the observed thickness it can be postulated that these volcanic layers probably had climatic influence.

The Snyder Formation here consists of 84.2 percent $CaCO_3$, 7.2 percent $MgCO_3$, and 6 percent insoluble residue. The upper 60 feet averages about 89 percent $CaCO_3$, 4 percent $MgCO_3$, and 5 percent insoluble residue. This formation is a source of SRL L aggregate and in places is mined for agricultural limestone (Berkheiser and others, 1985). The upper portion of the unit has the potential to be used in the manufacturing of coal mine rock dust (pulverized carbonate rock which is sprayed on the interior of underground coal mines to reduce combustibility), cement raw materials, acid neutralization materials, mineral fillers, and feeds.

LINDEN HALL FORMATION. The Linden Hall Formation consists of approximately 151 feet of relatively pure, olive-black to brownish-black, burrow-mottled mudstones with undulatory laminae and thin discontinuous intraclastic wackstones and packstones. The mudstones characteristically average about 0.5 foot thick and commonly contain discontinuous and anastomosing laminae. The intraclastic wackstones and packstones are commonly about 0.2 foot thick and occur as discontinuous concave-upward lenses. Hardgrounds, irregular chert nodules, possible hummocky cross-stratification, brachiopods, gastropods, corals, crinoid fragments, and possible echinoderm fragments are present. These features may be interpreted to suggest an open-marine, subtidal depositional environment. The occurrence of possible hummocky cross-stratification and intraclastic wackstone-packstone lenses suggest that storms still influenced sedimentation, albeit below normal wave base. Here, the rate of subsidence apparently was greater than the rate of sedimentation. Numerous preserved bentonites are found thoughout the formation, some over 3 inches thick (Table 6). Logically, as the wave energy and sedimentation rates decreased, the possibility of preserving ash falls increased. However, this may be more than coincidental. The decrease in wave energy may have been caused by global climatic changes and relative subsidence brought about by these same volcanic eruptions. Possibly, these eruptions are related to an ensialic back-arc basin in Trenton Group rocks now located in North Wales (Orton, 1986).

Weighted chemical averages for the entire 150.5 feet of the Linden Hall Formation reveal 90.3 percent $CaCO_3$, 2.8 percent $MgCO_3$, and 3.8 percent insoluble residue. At this location, the basal ~40 feet is the purest in terms of $CaCO_3$, whereas toward Bellefonte, PA, the upper ~90 feet of the formation is the purest ("Valentine Member" or "Bellefonte Ledge"). This formation produces the same products as the Snyder and has the same economic potential as the upper 60 feet of that formation. If combined into a mining interval, the two would yield 210 feet of relatively pure limestone with about 4 percent insoluble residue.

NEALMONT FORMATION. This formation comprises about 76 feet of olive-black to grayish-black, laminated and nodular mudstones with minor (less than 0.2 foot thick) discontinuous skeletal wackstone lenses. Most argillaceous laminae and bands are undulatory and anastomosing, and gradually become nodular in the upper 18 feet of the formation (Rodman Member). Burrow-mottling, horizontal and minor vertical worm burrows, articulate and disarticulate brachiopods, gastropods, corals, and echinoderm fragments also are common. These features occur in rocks that appear to represent a transition between subtidal and deep ramp or basin margin settings. Anoxic black shales are present and represent quiet-water reducing conditions. The carbonate nodules may be due to pressure solution, compaction, and/or patchy sea-floor cementation. Most of the sediment has been washed in from the nearby subtidal "carbonate factory" and the skeletal wackstone lenses probably record storm events. Energy levels at the time of deposition of these rocks were less than those of the subjacent rocks. Bentonite beds up to 1.6 inches thick are present.

The Nealmont Formation consists of 85.3 percent $CaCO_3$, 2.9 percent $MgCO_3$, and 8.1 percent insoluble residue, which reflects a lower-energy subtidal depositional regime and more clayey nature of the sequence. This formation is also a source of SRL L aggregate and is usually combined with the previously described formations to yield a thicker mining interval.

SALONA AND COBURN FORMATIONS. These formations, 390 feet of "rhythmites," comprise fining-upward, alternating beds of dark carbonaceous mudstone to wackstone and black calcareous shale. Fossils are sparce in the Salona, and increase in abundance in the Coburn. Low-angle crossbedding and hummocky cross-stratification occur in both. Skeletal wackstone-packstone lags with scoured bases are present in the Coburn and commonly contain fragments of brachiopods, trilobites, gastropods, and bryozoa. These fine upwards into crossbedded wackstones, which usually grade vertically into hemipelagic shales. This sequence of rock appears to be a classical storm deposited deep ramp or slope setting. The lack of fossils in the Salona Formation might be attributed to the abundance of preserved volcanic ash we see here (see Smith and Way, 1983 for a discussion of chemical changes and variables related to ash preservation). Bentonite layers nearly 10 inches thick occur here (Table 6). About 200 feet of Salona section contains approximately 29 composite-inches of bentonite, or about 1 inch of preserved volcanic rock for every 7 feet of carbonate rock. Volcanic activity indicated here appears to be about 3 times greater on a sediment-to-ash ratio than in the underlying and overlying formations.

? & Bull

REMARKS

What type, or "model," of carbonate platform are we looking at here? One obvious conclusion should be that one outcrop does not a model make. It does not appear that organic build-ups are significant. It does appear, however, that we may be looking at some sort of carbonate that became drowned.

ACKNOWLEDGEMENTS

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from Berkheiser + Cullen-Lollis, FCPG 51, 1986

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Loysburg

STOP 4. LOYSBURG. LITHOFACIES B, C, E. Two hours.

Pull off highway onto wide parking area on south side of highway opposite road cut. This is a heavily traveled road, with narrow shoulders and a large population of high-speed logging and other trucks. Please keep away from the road surface at all times.

This stop examines exposures of lithofacies B, C and E. Stratigraphic tops are to the east. About 20 meters of lithofacies B are exposed at the west end of the road cut. Most of this thickness consists of burrowed and bioturbated, fossiliferous sandstones with abundant lenticular coquinoid beds reaching 30 cm. thick. A chert nodule showing contorted bedding, interpreted by Horowitz (1965) to represent hydroplastic slumping, occurs two meters above the base. At 13 meters above the base there are two meters of clean, fine-grained sandstone which are parallel-laminated, low-angle trough cross-bedded and unfossiliferous. A similar unit just above it contains well-developed ripple trains observable on weathered surfaces. Scour features are abundant in this lithofacies; local channel fills up to 30 cm. thick truncate preexisting rocks. The top of the lithofacies is defined by the last coquinoid bed, and is marked by a yellow paint stripe.

Lithofacies C is characterized by pronounced heterogeneity and angular relationships of rock units. It is unfossiliferous, and consists of 80 meters of sandstone and shale, interbedded on widely differing scales. The basal three meters consist of fine-grained, parallel-laminated sandstone containing parting lineations and small shale clasts oriented in the plane of the bedding. Scour features are common in this unit. Above this zone lie 10 meters of thinly (1-5 cm.) interbedded, small-scale trough cross-bedded and micro-cross-laminated sandstones and laminated to cross-laminated siltstones and shales. All lithologic boundaries are erosional, and bedding planes show many kinds of sedimentary structures, including current and linguloid ripples, mud cracks, load casts, groove casts, current crescent casts, parting lineations, worm trails and others. Medium-grained sandstones occupy common local and steep-walled scours. One planar cross-bed set is visible; its well-developed torrential foresets are inclined at 30-35^{o} to the basal surface. The shales are occasionally burrowed.

The upper parts of the lithofacies contain at least six large-scale lithologic repetitions, ranging from 0.4 to 11 meters thick. These consist of highly sandy lower portions and highly silty and shaly upper portions; grain size progressively decreases upward within a sequence. The bedding types become smaller in scale upward. The sandstones are large-scale trough cross-bedded and thin-bedded in portions close to the base, and are micro-cross-laminated and small-scale cross-bedded near the top. The overlying siltstones are micro-cross-laminated to parallel-laminated, and become shaly in their upper parts. The siltstones and shales are burrowed; the sandstones generally are not. The silty and shaly top of one sequence is scoured out be the sandy base of the overlying sequence.

Lithofacies D is partially exposed on the natural hillside above the road, and less well at road level; most of these rocks are considerably weathered. Some shearing has affected the red lithofacies-D rocks exposed 245 meters east of the end of the major cut.

The lower 100 meters of lithofacies E are exposed in the road cut at the curve in the highway, 0.25 mile east of the parking shoulder. <u>BEWARE HIGH-SPEED TRAFFIC HERE</u>. The rocks are sandstones and shales, and show a large-scale repetitive interbedding resembling that in the upper parts of lithofacies C: sandstones pass irregularly upward into siltstones and shales. The sandstone-shale sequences average three to four meters in thickness. Sandstones are large-scale trough cross-bedded near the base, and in middle portions frequently are parallel-laminated. Upper parts of sandstones are generally micro-cross-laminated. The siltstones and shales are laminated to micro-cross-laminated, and occasionally contain mud-cracked bedding planes. Both sandstones and siltstones are often vertically burrowed; different types of burrow structures in the two rock types imply different faunal elements. The sequences contain abundant evidence of internal scour and erosion; individual sandstone beds often pinch out in short distances. Each sequence is externally scoured downward into the underlying shales.