GEOLOGY 106

Guidebook

FIELD TRIP THROUGH THE APPALACHIANS OF EASTERN PENNSYLVANIA

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INTRODUCTION

Good Morning, and Welcome to the annual GEOLOGY 106 Appalachian Field Trip. The purpose of the trip is to provide you with a first-hand look at the rocks and structures which comprise the Appalachian Mountains. A second purpose is to allow you to integrate your field observations with your classroom "book-learning" into a unified idea of the origin and evolution of an orogenic belt.

The trip will examine metamorphic, igneous and sedimentary rocks (and structures developed in them) from all major zones of the central Appalachians. The trip starts in the former eugeosynclinal area, and traverses northwest across the boundary between eugeosyncline and miogeosyncline (the Paleozoic continental shelf edge?) and terminates in miogeosynclinal rocks. Lithologies and structures characteristic of each zone are the major focus of the trip. The morning will be spent in the eugeosynclinal and boundary zones; the afternoon will be spent in the miogeosynclinal zone.

The Appalachian orogenic zone has been eroded to quite low levels during the last 200 million years, and the structures exposed in the different zones are well etched into the topography. The topography developed on different rock types is a giveaway to structure, so be prepared to see structures on a topographic basis first; every hill you see is there for a reason.

This guidebook contains much material intended to enhance your understanding of the Appalachians. A generalized geologic map and cross-section (both folded) of southeastern Pennsylvania give a general orientation, and outline the entire trip route. This map is handy for big-picture reference, especially when the smaller maps in the guidebook fail. The trip route is approximately parallel to the line of the cross-section.

A detailed explanation of the symbols and patterns used on the map is given on pages 21 to 26 . It contains descriptions of the lithologies of stratigraphic units, and thus is the basis of the entire trip; the descriptions should be read thoroughly during the course of the day.

This guidebook is divided into three parts: first, some general and introducturoy material on the general geology and evolution of the Appalachians, and the geologic map plus legend. Second, material on the Morning trip through the Piedmont and Triassic belts; this section contains descriptions of the rocks and structures at the various stops, as guides to your critical and enlightened examination of the outcrops. There will be 6 stops in the morning, and these are located on a detailed geologic maps of both northern Delaware and southeastern Pennsylvania on pages 31 and 38. Bus window guides to the geology along the trip route are included; the trip passes over much more geology than it actually examines, and it would be foolish to let it go unnoticed. The trip route is shown on the geologic maps. Third, material on the Afternoon trip through the Valley and Ridge province; this section contains route maps, descriptions and route logs for 5 more stops, making 11 in all. The Afternoon route map is on page 57. The lunch stop, Stop 6, is in rocks transitional between deformed and penetratively deformed rocks, and provides a timely tie-in from morning to afternoon.

So - enjoy yourself, learn some geology, both in general and specifically about the Appalachians, and see some nice scenery. You are encouraged to collect rock, mineral and fossil samples at all stops <u>except Stop 6</u>, as you wish or as conditions dictate. However, remember that whatever you take onto the bus, you must take off again, so be sure you really want the samples.

A WORD ABOUT SAFETY

There is a definite need on this trip to keep your wits about you, and to stay alert at all times you are off the bus. Most of the outcrops to be visited are in road cuts, and the rest are along active railroads or in mines; the need for safety at all stops is paramount, and cannot be overstressed. All the highways are busy, high-speed roads, and motorists do not take kindly to students (or anybody else) standing all over the road. In short, please observe the following guidelines:

1. Never (repeat, NEVER) step onto the active traffic lanes. Always stay on the shoulders, and preferably as far from the traffic lanes as possible.

2. As a point of general safety, always think ahead; be aware of where your next step will be placed. This will avoid tripping, stumbling and potential serious injury resulting from a fall.

A SHORT SUMMARY OF APPALACHIAN GEOLOGY AND EVOLUTION

The Appalachian Mountain System comprises a deformed mountain belt located along the eastern margin of North America. The belt, today, is perhaps 500 miles wide and extends northeast-southwest from Alabama to Newfoundland. Geologic elements of the Appalachians pass gradationally into non-Appalachian elements on the flanks, and exact lateral boundaries are difficult to locate. These problems will become evident shortly.

Geologically, the Appalachians consist of four or five distinct elements lying side by side, elongate in the general northeast-southwe trend. These elements are physiographic (geomorphic) as well as geolc division, and will be described in some detail below. However, not all elements are represented throughout the entire length of the mount belt, and the gross character of the New England and Canadian Appalach differs from that of the south-of-New-York Appalachians. These two divisions will be termed Northern and Central Appalachians, which occupy southeastern New York, New Jersey, Pennsylvania, Maryland, Virginia and West Virginia. A generalized geologic-physiographic map of this area is given in Figure 1. A more detailed geologic map of th region of the trip is given in Figure 4, as well as a cross section. Refer to this map constantly, and you will be able to see examples in the flesh (Mother Earth) of the features discussed here.

The entire Appalachian system is characterized by two distinctive features: (1) highly deformed (folded and faulted) and variably metamorphosed rocks of largely sedimentary origin, and (2) a predominantly Paleozoic age. The distinctive deformation of the rocks is a useful tool in distinguishing Appalachian from non-Appalachian rocks The styles of Appalachian deformation range from simple, upright, open folding to intense, overturned folding and large-scale thrust-faulting. In other words, Appalachian deformation was <u>compressive</u>, and tended to force existing sediments and rocks into smaller spaces (shorten the earth's crust). Many cases of extreme shortening (up to 80%-90% of the original distance) are known in the Appalachians Such intense deformation and shortening do not generally occur in cold, brittle rocks; rather, the rocks give evidence (which we will see on the trip) of being highly plastic and able to flow. This requires high temperatures, which were developed during metamorphism. Temperatures in the range of 600°-750°C. have been postulated for Appalachian deformation. Events generating high enough temperatures to permit rocks to flow were restricted to the Paleozoic era, and may have occurred more than once during that time.

As far as we know now, the sediments comprising the rocks in the Appalachian system were initially laid down on very old, Precambrian continental crust. These sialic Precambrian rocks were originally sedimentary, are now very high-grade metamorphic and igneous, and appear to have undergone a mountain-building event similar to the Appalachian events about one billion years ago. This was the Grenville orogeny of the eastern Canadian Shield, and these rocks may be considered a subsurface extension of the Canadian Shield. Grenville rocks underlie most of the Appalachians (and much of central and eastern North America also), and are not considered part of the Appalachian story, although they were passively involved in Paleozoic deformations along with Appalachian rocks. Because of their present position below Appalachian sediments and rocks, they are termed Basement. Thus, the Appalachian sediments accumulated on a Grenville-age (one billion year) basement which had been exposed to considerable erosion in the time between 1 billion years ago and the initiation of Appalachian events in the lower Cambrian.

The best systematic approach to understanding the Appalachians is through a description of the present structural elements, followed by an outline of the history and origin of the mountain system. The major structural provinces in the Appalachians correspond to the major physiographic provinces or divisions of the eastern United States, and are outlined in Figure 1. The shading in Figure 1 is intended to help you visually separate structural belts, and does not imply that the Piedmont and Valley and Ridge are in any way similar. From west to east, the structural belts are: The Appalachian Plateaus, the Valley and Ridge belt, the Blue Ridge and equivalent terranes to the northeast, the Triassic lowlands, the Piedmont, and the Coastal Plain. Of these only the Coastal Plain is not part of the Appalachian System, as we will see later. The field trip route runs across the general northeast strike of the system, and touches all belts but the Plateaus. It is indicated in Figure 1.

APPALACHIAN PLATEAUS

The region of western Pennsylvania, most of West Virginia, and parts of eastern Kentucky, Ohio, Tennessee and northern Alabama are underlain by dominantly clastic sedimentary rocks ranging in age from Cambrian to Permian. The region is of relatively high elevation, and contains the highest points in Pennsylvania, West Virginia and Virginia. It consists of a series of plateaus, which are deeply dissected by mature drainage networks. Structurally the region is characterized by flat-lying, essentially undeformed rocks. The greatest extent of folding is marked by a few broad warps, resembling anticlines, where limbs dip at 5° or less. The axes of three such warps are indicated in the structure map of Figure 2. Included in the horizontal sequence, however, are several major thrust faults, which are themselves horizontal, following bedding planes. Enormous displacements have been proposed for a few of these, up to 100 miles. Movements on these faults are always to the west and northwest. The faults are very rarely exposed at the surface.

The sedimentary rocks of nearly all Paleozoic periods thin to the west, so that the entire rock thickness beneath the Plateaus thins from more than 25,000 feet on the eastern margin to about 3000-4000 feet in eastern Ohio. Moreover, the flat-laying nature of the rocks causes the surface of the Pateaus to contain young, Pennsylvania and Permian rocks over most of its area. The Late Paleozoic rocks are generally coal-bearing representatives of the Cyclothem association, with minor marine limestones. Because of the coal the Plateaus are the center for the coal industry of the U. S.

VALLEY AND RIDGE PROVINCE

The Valley and Ridge Province contains sedimentary rocks of Cambrian through Pennsylvanian age, the same rocks as exist beneath the Plateaus, which have been folded into large upright anticlines and synclines. Dips of limbs reach 60°-70° and lateral shortening may reach 50% of original distances in some cases. The folds have nearly horizontal axes, and extend for long distances (up to 200 miles), without interruption. These long folds have been eroded to produce a distinctly linear topography, where resistant sandstones support parallel ridges and weak shales underlie more deeply eroded valleys; hence the name Valley and Ridge. The style of deformation, i.e. moderately tight squeezing, contrasts strongly with the very minor deformation of Plateau rocks. The folds have often been sheared off and thrust-faulted; the thrust faults dip to the east and southeast, and upper plates are displaced as much as 30 miles to the west and northwest. It is interesting that folding is the major mode of deformation in the central Appalachians, shown in Figure 2, but to both north (not shown) and south (shown) thrust faults are dominant, and take the place of folds.

The folds in most areas die out abruptly at the west edge of the Valley and Ridge belt, as if the deformation simply stopped or was turned off. Rocks standing vertically or overturned to the west at Altoona, Pa. are horizontal three miles away. The first major highland west of the Valley and Ridge underlain by the first flat-laying Late Paleozoic sandstones, is a major escarpment called the Allegheny Front; it contains the highest elevation in West Virginia.

In some areas, such as northeastern Pennsylvania, the folds die out gradually, and become more open and flatter near the Plateau boundary. In these regions the Allegheny Front is indistinct to absent. It would appear that deformation gradually dies out as the Plateaus are approached However, recent information is showing that, even if the folds cease, the Plateaus-Vallye and Ridge boundary is complexly faulted, and that several major horizontal thrusts lie at depths of up to two of three miles below the boundary. These thrusts carry over beneath the Plateaus, and it may be that the major thrusts of the western Plateaus discussed above may be western extensions of these same faults. In fact, some geologists now believe that the <u>entire</u> Valley and Ridge province, with all its folds and local thrust faults, is not now in its place of origin, but has ridden to the northwest on several super-major horizontal thrust faults.

Rocks of the Valley and Ridge province are sedimentary rocks of Cambrian through Pennsylvanian age. For a more detailed description of each of the units, see the legend to the map in Figure 4. The Cambrian and most Ordovician rocks are shallow water, algal limestones and dolomites of the orthoquartzite-carbonate association (to be seen at Stop 6). Rocks from Mid-Ordovician to Devonian constitute a graywacke (flysch) arkose (molasse) couple (Stop 7). A thin orthoquartzite-carbonate-association unit occupies the lower Devonian (Stop 8); this is followed by Devonian flysch and molasse, and by Late Paleozoic molasse and cyclothem association deposits (Stops 9,10 & 11). In all, the Valley and Ridge section reaches 30,000-35,000 feet thick; perhaps 15,000 feet of this is Cambrian-Ordovician carbonates. These lowest carbonates are generally exposed in the southeastern parts of the Valley and Ridge, along the boundary with Blue Ridge and Triassic belts; the valley eroded in these carbonates and overlying flysch shales is called the Great Valley (or Shenandoah, Cumberland, Lehigh, etc.). This valley contains Allentwon and Harrisburg in Figure 4. This valley is actually the first, farthest-southwest valley of the Valley and Ridge. The first ridge occurs slightly to the nrothwest, and is marked by the first exposeure of Silurain conglomerate and hard sandstone of the earlier molasse sequence (Stop 7).

Nearly all rocks of the Valley and Ridge (and those of the Plateau as well) contain evidence of deposition and formation in shallow, wave-agitated water, no deeper than, say, 300 feet. Current bedding, cross-bedding, mud-crack, algal structures, generally good sorint, and the universal presence of shallow-water organisms are some lines of evidence for pointing to a shallow-water to subaerial origin. Rocks of all but flysch associations are included here. Moreover, the thick sections of molasse contain evidence of continental, non-marine fluvial deposition. Directional data indicate sediment derivation from lands to the east. Thus, to accumulate a pile of shallow-water sediments nearly 7 miles thick, the basin of accumulation must have been slowly but continuously subsiding, during the Paleozoic so that the depth of water above the already accumulated sediment always remained shallow.

However, there were occasional interuptions of the general subsiding, and these are marked by two major unconformities in the section. The lower of these separates Silurian rocks above from deformed Mid-Ordovician rocks below (Stop 7). The younger separates Mississippian above from deformed Devonian below. Both these uncomformities are confined to easternmost Pennsylvania, New Jersey and New York; they disappear to the west, in central Pennsylvania and western Virgina. This implies that subsidence was continuous in these western areas, and that orogenic uplift and erosion generating the unconformities were confined to areas gnerally east of the Valley and Ridge. This location will be borne out shortly by other evidence.

BLUE RIDGE

Southeast of the Valley and Ridge lies a belt of metamorphic and volcanic rocks which make up the Blue Ridge province. Many of the rocks here are meta-volcanic rocks and quartzites, and these form a considerable ridge extending from southern Pennsylvania to Georgia and Alabama. The Blue Ridge in North Carolina contains the highest peak in the Appalachian system (Mount Mitchell).

The Blue Ridge is probably the most difficult part of the Appalachian to understand. Lithologically, the Blue Ridge is unique; it contains distinctive volcanic flows and thick quartzites which found nowhere else in the Appalachians. All rocks are metamorphic, and include a metasedimentary sequence laid atop very old, basement gneisses and granites of the Grenville orogeny. The Blue Ridge is the locus of most exposures of Precambrian rocks in the Appalachians.

Structurally, the Blue Ridge has been deformed along with the Piedmont and Valley and Ridge, and is difficult to distinguish from them. In the central Appalachians of Maryland and Pennsylvania, the Blue Ridge has the form of a very large, asymmetric, anticlinal fold, which is overturned to the north west (see Figure 2); both limbs dip east and southeast, but the western limb is upside down. The highest, youngest rocks on the west limb are barely metamorphosed at all.

As the Blue Ridge continues to the southwest, the compression was greater, and the fold was pushed farther to the northwest, so far that the bottom limb eventually sheared off and the entire upper limb moved westward as a thrust fault. The beginnings of the Blue Ridge Thrust may be seen in the lower part of Figure 2. The Blue Ridge thrust continues into Georgia, and has a maximum westward displacement of 75 miles in North Carolina and Tennessee. Again, the direction of movement of the upper plate was to the northwest.

In eastern Pennsylvania, in the same relative position as the Blue Ridge, there occurs a narrow zone of deformed Precambrian gneisses and quartzites which connect to similar rocks in southeastern New York and New England (Figure 2). This area is called the Reading Prong, and will be seen as we pass around its southwestern end near Reading (see Figure 4). It is tempting to call the Reading Prong an extension of the Blue Ridge. However, the rocks are not at all like Blue Ridge rocks; they lack the extrusive volcanic, and consist of basement gneisses, thin quartzites and overlying carbonates of Valley and Ridge affinities. Moreover, structural styles are different; the Blue Ridge in southern Pennsylvania is an anticlinal fold, while Reading Prong rocks are multiply thrust-faulted and folded into thin, flat nappes. It appears as if plastic deformation was much more extensive here than in the Blue Ridge. So perhaps they are not equivalent tectonic divisions.

We will treat the next belt, the Triassic lowlands , after a discussion of the Piedmont.

PIEDMONT

In many places, such as at the bottom of Figures 1 and 2, rocks of the Blue Ridge grade imperceptibly eastward into metamorphic and deformed rocks fo the Piedmont Province. Geologic relations in the Piedmont are very poorly known because of low relief, considerable soil development, general lack of exposure, and extremely complex geology. However, the following generalizations can be made.

The Piedmont is a region of low, gently rolling country characterized by mature drainage. Rocks of the Piedmont range from low-grade metamorphic (phyllites, slates) to ultra-high-grade metamorphic (gneisses, schists and others) and igneous. A great variety of premetamorphic, parent rock types is represented in the Piedmont. Shales and graded sandstone-shale sequences are by far the most abundant original rock type, and several major shale (now phyllite and schists) units are present. Stops 1 and 2 will examine variations in the largest such phyllite-schist body, the Wissahickon Formation. Very rarely in small areas of low-grade rocks, fossils of Cambrian and early Ordovician age are present. Volcanic rocks are frequently represented parent rocks: simatic volcanic rocks (basalts) sialic volcanics (rhyolites), and orogenic volcanics (andesites) are all present (see Figure 4). Large masses of serpentine rock, gabbro, olivine rock (dunite) and pyroxene rock (pyroxenite) occur throughout the Piedmont (stop 1). It is hard to tell the effects of metamorphism on these rocks, because the mineral contents are already stable at high temperatures and pressures. These simatic rocks are possibly the most interesting and significant rocks in the entire Appalachians.

The degree of metamorphism increases in a general way from the western margin to the eastern margin. Phyllites and shales are found in western sones, schists and gneisses in eastern zones. Rocks at Stop 1 are higher grade than those at Stop 2. There are numerous exceptions to this general rule, however.

Structurally, the Piedmont is characterized by very tight, over, turned, recumbent fold structures which formed by extreme plastic flow and ductitlity in response to intense lateral and vertical compression. Major thrust faults are relatively rare in the Piedmont; and almost all deformation has occurred by flowage. At least two periods of deformation have affected the Piedmont; folds of the first deformation have been refolded about axes corresponding to the second deformation. Many major refold structures occur in the Piedmont, generating incredibly complex rock distributions and histories. The anticlinal and synclinal axes shown in the Piedmont in Figure 2 are second-fold structures, and contain bent and refolded foliations from the first deformation. These deformations affected the Blue Ridge and possibly some of the Valley and Ridge as well as the Piedmont.

The multiple deformations are of Paleozoic age, and can be dated by radiometric methods. The metamorphic rocks themselves give ages of ranging from 600 million years to about 350 million years; some of these may be ages of formation of the original rocks rather than dates of metamorphism. Radiometric dates on intrusive granites generated by the deformations cluster at about 450 m.y. and at about 350 m.y.; these correspond to Mid-Ordovician and Mid-Devonian, respectively; It will be shown that these times correspond to periods just prior to extensive molasse development in the Valley and Ridge, and that there is a close connection between these two events.

The eastern margin of the Piedmont, today, lies at the position of overlap by much later Coastal Plain sediments. It is not known how far east and southeast the Piedmont rocks extend beneath the Coastal Plain cover; several geologists talk in terms of 200-300 miles. In any cases, the present east edge of the Piedmont is <u>not</u> the east boundary of the original Paleozoic Appalachians.

Each of the above belts is defined primarily by structure and style of deformation. The structures within each belt, whether folds or faults, are nearly always parallel to the elongate trend of the belt itself; this is evident in Figure 2. Anticlinal and synclinal axes in the Valley and Ridge and other provinces are parallel to the boundaries of the provinces, and bend from nroth-northeast to east-northeast in crossing Pennsylvania, in harmony with the major structural belts. The Blue Ridge fold axis parallels the boundaries of the Blue Ridge province. In the Piedmont, axes of large recumbent folds and nappes, where currently known are generally parallel to the general northeast trend of the Piedmont belt; both first- and second generation folds strike in this direction. The net result of all this is a distinct linearity, or elongation, of the entire Appalachian system. The remarkable parallelism of structural trends, and the sameness of those trends in different belts,strongly suggest that all the structures (and the belts as well) are of a common, closely related origin. Nearly all the structures are compressional, i.e. generated by compression and shortening of the earth's crust. Thus the common origin was compressional in nature.

TRIASSIC LOWLANDS

Lying across the compressional structural belts, at small to large angles to the structural trends, is a discontinuous zone of Triassic-age sedimentary rocks. The weak nature of these poorly consolidated rocks promotes considerable erosion, and the rocks underlie broad, low valleys. The rocks occur in narrow, elongate basins which are not necessarily related to the general Appalachian trend. Several isolated basins occur in the Appalachians; one is shown in Figures 1 and 2, and in more detail in Figure 4. Others occur in Nova Scotia, Connecticut-Massachusetts, and North Carolina. They generally lie along the Piedmont-Blue Ridge boundary, and none is located wholly within Valley and Ridge terranes. Many (but not all) basins are bounded on one side by normal faults of considerable displacement (estimates of 25,000-30,000 feet), as shown in Figure 2. The entire Triassic period in the Appalachians is characterized by tensional, rifting tectonics rather than orogenic compression.

The Triassic rocks are mainly red shales and sandstones of the Molasses association which contain many features indicative of fluvial deposition. These rocks will be seen at Stops 4 and 5. Less common gray shales containing salt crystals and minerals, as well as fish remains, indicate deposition in saline lakes. Mountain valley deposition is a reasonably good model for sedimentation of the rocks. The Triassic rocks in Figure 4 dip uniformly to the northwest, toward the northwest margin; they also coarsen in that direction and are conglomeratic near the borders. This suggests that the source of Triassic sediments was in the Blue-Ridge-Reading Prong-Valley and Ridge area just beyond the Triassic belt.

The Triassic rocks are intruded by numerous dikes and sills of diabase (a coarse-grained basalt or gabbro) to be seen at Stop 3, which form conspicuous hills in the lowlands. Magma of this sort is commonly associated with tension and rifting in the crust, and supports the postulated reversal of stress direction in the Triassic.

COASTAL PLAIN

To the east of the Piedmont-Triassic belts lies the Atlantic Coastal Plain province. This zone conatins dominantly clastic sedimentary rocks of Cretaceous and younger ages, which are essentially unconsolidated and totally undeformed. The Coastal Plain province is unrelated to the structures or evolution of the Appalachians, and represents a much later "cover" put over the eastern parts of the old Appalachian system. The Piedmont-Coastal Plain contact is unconformable. Rocks of the Coastal Plain will be seen on the way to Stop 1. The Coastal Plain is actually the exposed, landward extension of the present Continental Shelf deposits.

ORIGIN OF APPALACHIAN SYSTEM

The foregoing descriptions of the rocks and structural provinces provide the basis for interpreting the origin and history of the Appalachian mountain system. Several questions should be in your minds already, such as Why are there different structual belts? What caused the different structures? What do the rock types have to do with mountain origin? How can you get high mountains from submarine, or at least sea-level subaqueous, sea floors? How can an area go from compressional to tensional tectonics? To answer these and other questions in a coherent manner, the best place to start is to try to abstract out of the above descriptions significant points relating to the genesis of the rocks and structures.

SUMMARIZED DATA

First, the present structural belts are superimposed on an already existing, largely independent stratigraphic sequence of sedimentary rocks; in most cases structural belts do not coincide with fundamental differneces in original depositional environments or lithologic associations. The Paleozoic section thickens progressively eastward, right across the boudary between Plateaus and Valley and Ridge and independently of it. The rocks of the Blue Ridge have lateral equivalents to west (Valley and Ridge) and to east (Piedmont). The western edge of the Piedmont is not marked by changes in rock types or associations but by metamorphic and structural feautres; rocks of Valley-and-Ridge affinities and origins continue southeastward into the Piedmont for some distance. The Triassic fault valleys are laid on and cross all other belts, regardless of rock type.

It appears, then, that the structural belts are post-depositional rearrangements laid on an already existing pile of strata which can be traced through the various types of deformation, and which present a unified, coherent pattern of sedimentary evolution. There has probably been no large-scale displacements of the structural belts themselves;they are today in the relative positions in which they formed. The deformation, while widespread, was confined to rearrangements of rocks within belts.

Second, crystalline rocks of the Piedmont and Blue Ridge reveal two periods of intense plastic deformation,and both are Paleozoic. One is Mid-Ordovician, 450 m.y. ago and is called the Taconic Orogeny; the other Mid-Devonian, 360 m.y. ago, and is termed the Acadian Orogeny. A very few areas show evidence of a third deformation, in the late Pennsylvanian at 275 m.y. ago.

Third, sedimentary rocks of the Valley and Ridge reveal only one period of deformation, in the latest Paleozoic(Permian). This orogeny involved elastic, brittle deformation, and is called the Allegheny Orogeny. Pennsylvanian rocks are caught in the folds, and are older.

Fourth, the overall intensity of metamorphism increases eastward, The Piedmont is the principal deformed belt. Moreover, within the Piedmont, metamorphism and deformation were more intense in the eastern than in western parts. Along the Blue Ridge-Piedmont margin metamorphic grade is fairly low (slates and phyllites), while on the Coastal Plain boundary the grade is very high (gneisses and schists). Igneous intrusives are much more common in eastern than in western Piedmont, suggesting a possible genetic relationship with high grade metamorphism.

Fifth, in zones of intense deformation, the folds are overturned to the northwest; that is axial planes dip to the southeast. Also, thrust faults have displacements to the northwest. These features suggest that the compressive forces generating the Appalachian mountains were directed from southeast to northwest.

Sixth, although metamorphism is confined to Blue Ridge and Piedmont zones, pervasive, wide-ranging shearing deformation generated by folding carries well into the Valley and Ridge province. This pervasive deformation, often called "penetrative" because it shears through all types of rocks regardless of lithology, generated closely spaced fractures,cleavages and other types of fractures including thrust faults. The southeastern third of the Valley and Ridge contains pervasive, penetrative deformation, but without metamorphism. The distribution of penetrative deformation is shown in Figure 3. We will see penetrative deformation at Stop 6, in unmetamorphosed limestones. In the big picture, then, penetrative deformation, and the intensity of deformationin general, decreases to the northwest across the entire Appalachian belt.

Seventh, sedimentary features and primary structures (cross-bedding, grain-size decrease) which record directions of current flow show that Valley-and-Ridge sediments were derived from two differing directions, but that only one direction was dominant at a time. Late Precambrian-Cambrian-lower Ordovician Orthoquartzite-carbonate-Association rocks were derived both locally and from the west (the craton),and are on the whole mature sediments. Post-Mid-Ordovician sediments of the Valley and Ridge and Plateaus were derived from the east and southeast (from the Piedmont area), and are terrigenous and generally immature. This means that the Piedmont, with its marine shales and turbidites, must have undergone active subaerial erosion above sea level to generate the terrigenous sediment.

THE APPALACHIAN GEOSYNCLINE

It should be apparent by now that there is a very fundamental difference in the nature of Plateau-Valley and Ridge rocks and Piedmont rocks (before metamorphism). Valley-and-Ridge rocks span the entire Paleozoic, are relatively thin and continuous over long distances, and are almost wholly made up of current-bedded rocks of shallow-water origin. Both marine and continental enviornments are represented, in orthoquartzite-carbonate, molasse and cyclothem associations. Nearly all marine rocks are of shallow-shelf origin. Volcanic rocks are singularly absent. On the other hand, the original rocks of the Piedmont are predominantly of Lower Paleozoic (possibly even late Precambrian) age, and consist largely of very thick shales and minor sandstones deposited in mildly localized basins. The evidence in these rocks points to a deep-water origin, below the limits of wave and current agitation; the rocks are of the flysch association, and originated by turbidity-current resedimentation of original shallow-water sediments. Volcanic rocks are commonly present; they are basalts and andesites, and probably represent old lava flows as many contain pillow structures.

Moreover, styles of deformation differ between Piedmont and Valley and Ridge provinces. Rocks of the Valley and Ridge are unmetamorphosed and relatively mildly deformed; the major structures are upright folds and thrust faults, which originated by bending and breaking of elastic, essentially brittle rocks. Brittle deformation occurs at relatively low temperatures and pressures, i.e. high in the earth's crust.

Piedmont rocks are highly metamorphosed, often beyond recognition as originally sedimentary. Moreover, they have been deformed intensely at least twice. Each deformation was plastic in character, and involved extensive solid-state flow of plastic, essentially ductile rock material. In many cases the orogenic heat and pressure were so great that rocks melted partially to generate magma; the magma was intruded upward from low levels to higher levels of the crust as igneous rocks, usually granites. These igneous rocks represent the culmination of orogenic deformation, and granites are diagnostic of orogenic zones. The Piedmont was thus the center of orogenic activity in the Appalachians.

These differences in lithology and deformation have long been recognized, and have formed the basis for the development of the concept of a <u>geosyncline</u>. The geosyncline was more or less "invented", as a mental crutch to help explain and understand the very complex relationships seen in folded mountain belts. Historically, the geosyncline concept was originated with the Appalachians as the prime example, so we can be relatively safe in using the crutch here.

Basically, a geosyncline is a very large, elongate, tectonically mobile downwarping of the earth's crust which continuously subsides to receive many thousands of feet of sediment. It is a sedimentary model, invented to explain the accumulation of certain types of sediment in particular places: geosynclines localize tremendous thicknesses of sediment along the margins of cratonic masses (continents), which then undergo subsequent deformation. The geosyncline pre-dates the deformation, which is localized in parts of the sediment pile. Although essentially a sedimentary feature, geosynclines are very closely related to compressive tectonics, and it is more than coincidence that geosynclinal piles are compressively deformed.

In recent years there has been general agreement that geosynclines are divisible into two parts, or troughs, lying side by side and both elongate in the same direction on a very large scale. The belt lying nearest the craton is termed the <u>miogeosyncline</u> ; the one lying nearest the ocean basin is the <u>eugeosyncline</u>. Thus, in many cases in earth history eugeosyncline-miogeosyncline couples have constituted buffer zones between cratons and ocean basins; geosynclines are the forerunners of the <u>mobile belts</u> we discussed in class.

According to Dietz and other workers, the miogeosynclinal zone corresponds to the continental shelf, and the eugeosynclinal zone to the continental rise and adjacent deep-ocean floor. The dividing zone may be equated with the continental slope and shelf edge.

The eugeosynclinal areas of deep-ocean sediments, for reasons best explained by plate tectonics, eventually become the locus for intense compression, deformation and metamorphism collectively termed mountain-building or <u>orogeny</u>. As a result, great masses of crumpled and deformed ocean crust and overlying thick eugeosynclinal sediments are shoved up and transported both toward the craton (landward) and upward (vertically), as rocks are forced to occupy smaller spaces. This deformation and uplift may affect adjacent tectonic elements, such as the miogeosyncline, or may leave them unaffected. The compression is generated probably by sea-floor spreading, and subduction of ocean crust ben eath the continental rise; thus compression and deformation are localized in that zone.

Applied to the Appalachian system, the miogeosyncline-eugeosyncline couple, and the geosynclinal nature of the entire system, are easily recognized. The miogeosyncline is represented by the Plateau and Valley-and-Ridge rocks, and by unmetamorphosed rocks in the western Piedmont (see Figure 3). These rocks are continuous, are of essentially similar origins (wave-agitated, shallow-water), and are adjacent to the North American craton. The miogeosyncline was a zone of deeply subsiding (sediment thickness = 25,000 feet) but tectonically stable continental crust, built continuously close to sea level; it contains sedimentary but few textonic reflections of intense tectonic events in the eugeosyncline. The eugeosyncline is represented by the eastern and central Piedmont. It was a zone of deeply subsiding (sediment thickness more than 40,000 feet), tectonically very active and unstable crust which may have been either continental or oceanic. Water depths in the eugeosyncline were great, and the eugeosyncline contained deep-water depositional environments which received turbidites and submarine lavas.

OUTLINE OF APPALACHIAN HISTORY

With the miogeosyncline-eugeosyncline framework as a reference, we can chronicle the major events of Appalachian evolution. The history is mainly Paleozoic, and may be divided into three Acts.

ACT 1 - The Lower Paleozoic.

The Lower Paleozoic (Cambrian, Ordovician and lower Silurian) were characterized by a classic miogeosyncline-eugeosyncline couple off the then east coast of North America. The distribution of the two belts is shown in Figure 3. The miogeosyncline was characterized by a continental-shelf sequence of mainly shallow-water, algal, tide-dominated carbonates (seen at Stop 6) which built eastward and shallowed through Cambrian and lower Orodvician time. The eugeosyncline, to the east, was a deeper-water environment, and received shale and turbidite deposits (Stops 1 and 2). The margin between the two contains interbeds of each lithology (Stop 2), and also large blocks of carbonate which presumably slid down the continental slope.

These relations were maintained for at least 150 million years, until the Middle Ordovician. In lower Ordovician time, a subduction zone was initiated beneath the eugeosyncline, and the turbidite and other sediments were subjected to heating, compression and orogeny. The first evidence of this orogeny appeared in Middle Ordovician, in the form of narrow, deep, short-lived flysch basins along what used to be the continental shelf margin. The sediments in the flysch basins (Stop 7) were supplied from newly risen, orogenic land masses to the east which were built up along the subduction zone on the site of the former eugeosyncline. As more sediment was supplied from the rising orogenic lands, the flysch basins filled up and became molasse basins. Molasse sediment (Stop 7) spread westward across the entire miogeosyncline in the Late Ordovician. Deep within the eugeosyncline, extensive metamorphism, deformation and local melting took place (Stop 1), and numerous granites were intruded to higher levels of the orogenic zone. This Middle to Late Ordovician orogeny was the Taconic orogeny. It lasted for only a short time, say 25 m.y., but affected the entire Appalachian geosyncline from Canada to Alabama; subduction was thus probably occurring all along the geosyncline. The Taconic orogeny also marked the end of the eugeosyncline as a depositional site, and terminated the eugeosyncline-miogeosyncline couple; for the rest of Appalachian history, some orogenic land mass occupied the site of the former eugeosyncline. It would seem that miogeosyncline-eugeosyncline pairs are developed only along subduction zones.

Molasse sedimentation in the miogeosyncline continued into the Late Silurian, with accumulation of several unusual rock types (e.g. iron ores). Most deposition was continental and marginal marine). The Taconic mountain range was eroded away and uplifted again at least twice during the Silurian.

ACT 2 - The Middle Paleozoic.

In Late Silurian time the miogeosynclinal area subsided, and the sea again inundated large areas. Quiet deposition of orthoquartzite-carbonate-association rocks accompanied this transgression, and continued through Lower Devonian into Middle Devonian time. There was no active eugeosyncline, and that zone was occupied by Taconic highlands.

In Middle Devonian, terrigenous, clastic sediments appeared from the east and southeast. Small in quantity at first, these sediments were deposited in shallow marine environments of orthoquartzite association, and supported some of the most prolific invertebrate faunas of the entire Paleozoic (Stop 8). In late Middle Devonian the clastic supply dramatically increased and coarsened, indicating more abundant sediment and closer source areas. Compressive deformation and metamorphism again affected the old eugeosynclinal area, but this time took place without extensive volcanism and submarine deposition; ocean-floor subduction was apparently not the cause of this orogeny (termed the Acadian orogeny). The effects of the Acadian orogeny are limited to the central and northern Appalachians, and are strongest in central New England. This orogeny was caused by colliding continents: continental drift in reverse, the end product of a closing Atlantic Ocean. The Acadian orogeny lasted only a short time, 20 m.y., and involved collision of the northern Appalachians with the northwest African coast, in the region of the present Atlas Mountains.

Again, as with the Taconic orogeny, the miogeosyncline was suddenly and temporarily downwarped into flysch basins early in the orogeny, then uplifted and flooded with Acadian molasse eroded off the newly risen mountains. Most of the molasse was continental red beds of the Late Devonian Catskill Formation. Some molasse was probably shed off to the east, into what is now North Africa.

ACT 3 - The Late Paleozoic.

The Late Paleozoic (Mississippian, Pennsylvanian and Permian) was a time of mainly continental deposition in the miogeosynclinal zone. The Mississippian, although universally represented by limestones elsewhere, here consists of coarse sandstones and shales of continental fluvial origin (Stop 9). The Pennsylvanian contains similar fluvial sandstones and conglomerates, and great thicknesses of cyclothem-association, fluvial coal sequences (Stop 10). Permian rocks are cyclothemic also, but are confined to western Pennsylvania and West Virginia. The rocks of all three periods are terrigenous, continental and derived from eastern, Acadian mountain sources.

The Allegheny orogeny occurred after deposition of latest Pennsylvanian strata, and threw the miogeosyncline into large, broad to tight, upright folds and thrust faults (Stop 7; Stop 11). This deformation did not affect the former eugeosynclinal zone; only scattered small granite plutons of Pennsylvanian or Permian age are known from the Piedmont. The cause of the Allegheny orogeny is not known. It was certainly compressive, but was not orogenic in the Taconic or Acadian sense. It may represent the final crumpling by a last burst of Acadian-orogeny compression. At any rate, the Allegheny deformation was the last compressive episode in Appalachian history, and its termination marked the complete transformation of the initial, Appalachian eugeosynclinal-miogeosynclinal continental margin. into deformed, stabilized, cratonic continental crust. This new continental crust would in the future serve as Basement on which a new pile of potentially geosynclinal sediments (the present Coastal Plain sediments) might accumulate.

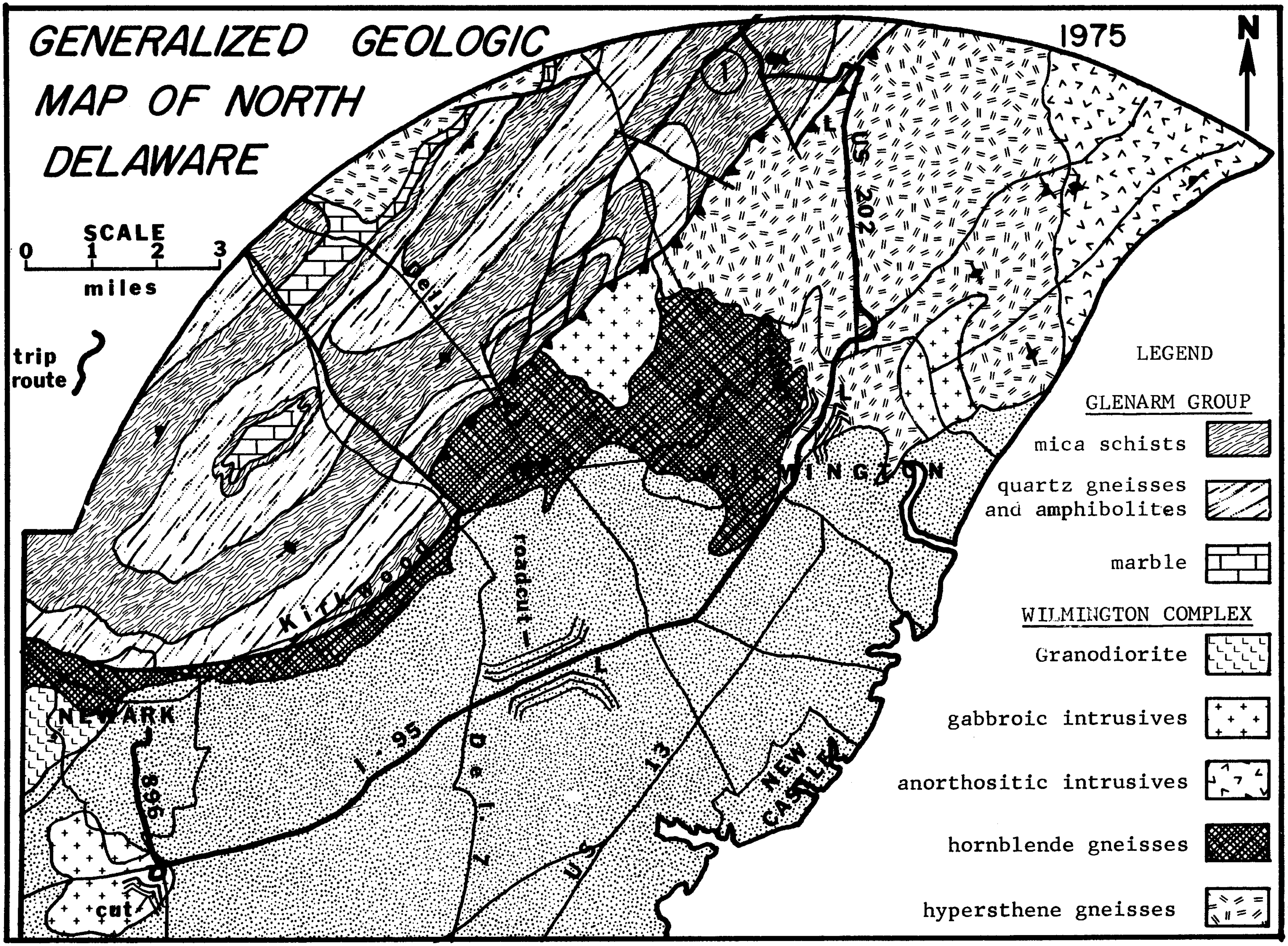
EPILOG

In the Triassic, the former compressional zone was rifted apart by tensional tectonics, and restricted molasse deposition took place in elongate, separated, often fault bounded mountain valleys. Great thicknesses of red beds (Stops 4 and 5) accumulated in the valleys, and generous amounts of basaltic magma formed during rifting were intruded into the sediments (Stop 3); locally they produced contact metamorphism of the sediments along their borders (Stop 4).

The rifting can be directly related to the tensional tectonics generated by the opening of the Atlantic Ocean (initial breakup of Pangaea) in the Triassic, and the "pulling" of the Americas westward from the Mid-Atlantic Ridge. In the Triassic, the Appalachians marked the trailing edge of the newly rifted American plate, and were mildly pulled apart by the generated tension.

Some Late Cretaceous igneous intrusions occur in New Hampshire (the White Mountains) and Quebec (the Monteregian Hills); these are directly related to rifting and spreading of the American Plate. Other than these and the unending slight uplift and erosion, the Appalachian mountains have been a quiet, stable zone since the Triassic (in spite of the Wilmington earthquake), and are likely to remain so for some time.

Figure 4 is a large, relatively detailed geologic map and cross-section of the region of eastern Pennsylvania; it contains real-world examples of all that has been said here. It is on the next page, and thelegend for it follows. USE IT CONSTANTLY.



GENERALIZED GEOLOGIC
MAP OF NORTH
DELAWARE
1975
N
SCALE
0 1 2 3
miles
trip
route
LEGEND
GLENARM GROUP
mica schists
quartz gneisses
and amphibolites
marble
WILMINGTON COMPLEX
Granodiorite
gabbroic intrusives
anorthositic intrusives
hornblende gneisses
hypersthene gneisses
US 202
Del.
Kirkwood
WILMINGTON
roadcut
I 95
Del. 7
US 13
NEW CASTLE
NEWARK
896
cut

ROUTE TO STOP 1 (23 miles)

-Leave Penny Hall. Proceed south on Del. 896, South College Avenue. Route travels on thin Coastal Plain sediments, the Lower Cretaceous Potomac Group. See Delaware Route Map. The Coastal Plain sediments are not part of the Appalachians; and southeast at very gentle angles.

- Enter Interstate 95, eastbound. Iron Hill, at entrance, is an isolated part of the Piedmont surrounded by Coastal Plain sediments (see Delaware Route Map). It consists of lower Paleozoic coarse-grained gabbro (pyroxene-plagioclase igneous rock) intruding dark, metamorphic gneisses of about the same composition. Some of the gneiss is exposed in the cut for the on-ramp at the toll booth.

-De. 7 (Churchmans Road) exit.

- LOOK STOP. In the half mile beyond Churchmans Road exit, the highway cuts through a low hill (see Delaware Route Map) exposing Cretaceous- and Pleistocene- age sediments of the Coastal Plain. Entering the cut, near the bridge, orange-buff coarse sands and gravels are exposed; these sediments are part of a Pleistocene braided river channel. This channel is cut down into red, white and black clays and sands of the Potomac Group, which are exposed beyond the bridge at road level. The Potomac rocks are flat-lying, so the lateral change from Potomac to Pleistocene sands must indicate that a channel-type erosion surface separates the two. Red clays dominate the Potomac on the north side of the road, white and black rocks on the south side. There must then be pronounced facies changes in short distances within the Potomac rocks.

Of particular note are the large slump blocks of red clay which are sliding down the north face to road level. Wet clay is a good lubricant, and provides slippage planes for the slump blocks.

- LOOK STOP. Just east of the same road cut- To right rear is an example of engineering and environmental geology, and of some hazards typical of this area. The bare hill and slope is exposed Potomac Group clays; it has been graded off (smooth) and prepared for apartment construction. But the Potomac, as we have seen, is highly unstable, and has been gullied deeply in less than 8 months (since September 1972). The gullying will undoubtedly continue, and will endanger whatever is built on the soft clay. The easy erodibility, plus the proven ability of the clay to slump in coherent large blocks, makes one wonder about the permanence of the coming apartments, and about the need for detailed geology and soils studies prior to urban expansion.

- Highway crosses Churchmans Marsh, a tidal backup pool and marsh developed at the confluence of White Clay Creek and the Christina River. Highway is built on a causeway across the marsh, and the south half has been drained.

- Bear left on I-95 to Wilmington and Philadelphia. Road bed and bridge abutments lie on artificial, filled land, built up from sea level during construction.

- Cross bridge over Christina River. Here and for the next 1/2 mile, the land to the right is tidal marsh, alternately flooded and drained by each tidal cycle. These tidal flats have been partially stabilized by permanent vegetation growing on the flats, so that the rate of change of tidal creek positions, and the rate of accretion of the flats, is low. These sediments are Modern, of essentially zero age, and are representatives of the Recent, or Holocene, sediments which are forming in response to rising sea level and consequent drowning of the river and creek valleys.

- Fourth Street Exit. Skyline to left marks the southeastern edge of the Piedmont. The surface of the beveled Piedmont slopes steeply down toward us, and passes beneath the first sediments of the Coastal Plain about at our present position. See the Delaware Route Map. The hill on the right, containing the downtown area, is developed on Coastal Plain sediments.

- Del. 52 (Delaware Avenue) exit.

- LOOK STOP. Just beyond Del. 52 exit are excellent exposures of Piedmont rocks, the Wilmington Complex of the Delaware Route Map. We will be able to examine samples of these rocks at Stop 1. The rocks are dark, high-grade metamorphic gneisses, and are typical of a broad association of such gneisses widely developed in the eastern Piedmont of Delaware, Pennsylvania and Maryland. The rocks in this cut appear homogeneous, but are actually faintly layered and intensely folded and compressed; small isoclinal folds are occasionally visible in this outcrop. The present layering is probably generated by the folding, and is not a primary feature that survived the deformation.

  The original, pre-metamorphic nature of the Wilmington Complex rocks is not known. It is possible that they represent a slab of old ocean crust, thrust up into the Appalachian eugeosynclinal orogenic belt during sea-floor spreading in the lower Paleozoic subduction zone. Alternatively, they may be metamorphosed lava flows. Features establishing a volcanic origin are seen in at least some rocks, particularly those along the Kirkwood Highway near Newark. In any event, it is probable that the original rocks were not terrigenous or carbonate platform sediments.

Rocks similar to these, and of similarly suspected sea-floor-spreading and thrusting origin, characterize many parts of the Piedmont throughout its extent, especially in eastern zones. This reinforces the conclusion that, whether or not the rocks were actually slabe of ocean crust, the Piedmont zone was the site of Paleozoic crustal plate interaction and resulting deformation and metamorphism. Although not mountainous now, the Piedmont was the orogenic center of the Appalachian mountain belt.

- Exit I-95 onto U.S. 202, northbound. Proceed north on 202.
- Turn left onto Naamans Road (Del. 92), westbound.
- One-half mile west of U.S. 202, turn left, following Del. 92.
- About 1/2 mile farther - bear right off Del. 92, and descend into valley of Brandywine River. Turn right at T-intersection in front of river, and proceed past outcrop to parking lot on left.

STOP 1.

BRANDYWINE VALLEY

STOP 1.

High-Grade Metamorphic Rocks
Folds
Floodplain

This stop is along a narrow road, with little clearance, so be careful of traffic. Also, make sure that you don't slip or fall while climbing the slope. Avoid broken glass also.

This stop is in very high-grade metamorphic rocks of the eastern, or Inner, Piedmont, and provides a fine example of metamorphic and tectonic features in the central, core zone of an orogenic belt. These rocks will be contrasted with those at Stop 2, which are less metamorphosed equivalents of these and constitute the western, or Outer, Piedmont.

The two major rock types making up the Inner Piedmont of Pennsylvania, Maryland and Delaware are both present at this stop. The massive outcrop in the rock cut consists of gneisses and schists of the Wissahickon Formation, the major lithologic unit in the Piedmont. These gneisses are composed of plagioclase feldspar, quartz, garnet and biotite mica, and are generally light-colored (if you allow for the weathering). These rocks are quite coarse-grained, with crystals reaching 1/10 to 1/5 inch in length. The biotite and garnet are particularly large and observable (biotite is black and very shiny; garnet is dark red). The mineralogy and coarse grain size together indicate that these rocks were metamorphosed at very high-grade conditions, i.e. temperatures and pressures in the range of maybe 600-650°C. and 4000-5000 atmospheres, respectively. These conditions are not achieved anywhere near the earth's surface, but only at considerabl depths (maybe 5-10 miles). so that these rocks are exposed only because there has been extensive erosion.

Compositionally, these schists and gneisses contain minerals with large amounts of aluminum (Al_2O_3; also sodium and potassium) in their lattices. Metamorphic rocks of this chemical type are termed <u>pelitic</u>. The most probable parent rock for these pelitic gneisses is a pelitic sedimentary rock; silicate-mineral mudstone and shale are the best bets. Other than composition, almost all evidence of, and any resemblance to, original shales have been wiped out by the metamorphism and deformation. In eastern Maryland, however, the Wissahickon does contain recognizable depositional structures (graded bedding), proving a sedimentary parent rock.

During the metamorphism the rocks were severely deformed, and you can see evidence of this deformation in nearly all faces of the outcrop. A distinct layering, or foliation, is visible in the rocks; it is defined by closely spaced fractures, and is now standing nearly vertically. It was probably generated by the metamorphism, and it is not known whether it parallels any original sedimentary layering. You might see if you can trace an individual foliation completely through the outcrop. Structures more dramatic than the foliation include abundant folds, both open and isoclinal. These folds are on scales of inches to feet, and are outlined by folded foliation layers. Where you can see folds, you should note that individual layers do not remain of the same thickness in all parts of a fold, The thinning on limbs and thickening in crests is an example of plastic deformation; the rock material flowed in a solid state.

The second major rock type visible here is represented by the large blocks bordering the road and parking lot, and is gray to dary gray gneisses. The blocks are not native to this place, but were brought here from quarries probably in Wilmington. The rocks are part of the Wilmington Complex, probably the "gabbroic gneiss" facies of the Delaware Route Map. We have seen these rocks in outcrop already, in the I-95 cut in Wilmington.

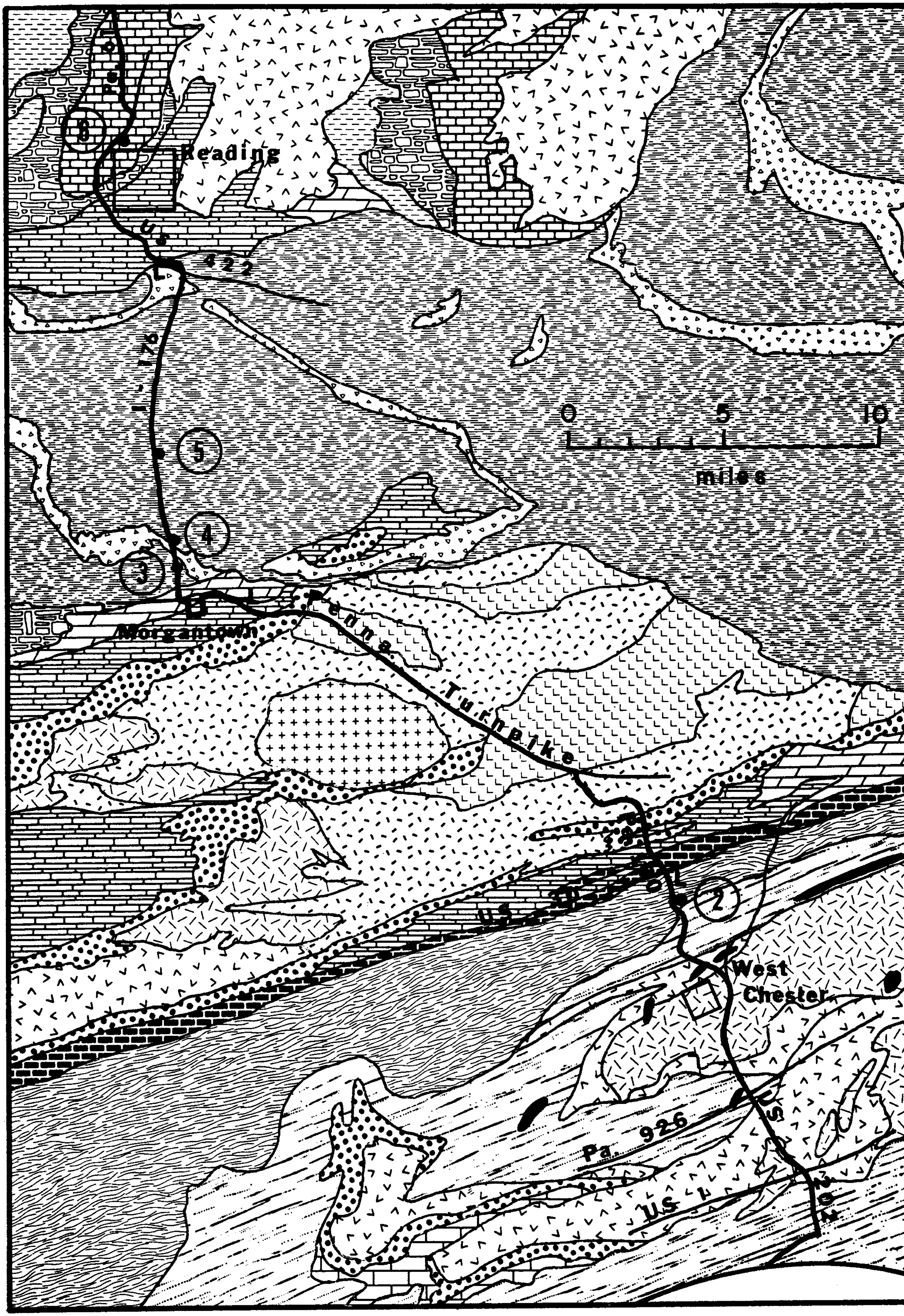
The gneisses are composed of plagioclase, pyroxene of two types, and minor quartz. Minerals typical of the Wissahickon, i.e. garnet and biotite, are lacking here. Chemically these rocks are not pelitic (i.e. contain few to no Al-rich minerals), but instead are Magnesium and Iron rich, and therefore were probably derived from magnesium- and iron-rich parent rocks. The rocks appear uniform and massive on fresh surfaces, and contain very little visible structure or foliation. The orange-weathering faces, however, show delicate differences in weathering rate, and reveal subtle mineral and grain-size differences between well-defined layers. An extra Food Service Box Lunch to anyone who finds folds in these rocks.

Although probably metamorphosed, these rocks are of the right mineral and chemical composition to compare with modern ocean crust rocks. One interpretation of the origin of the Wilmington Complex, already mentioned, is that it represents Paleozoic mid-ocean ridge rocks, old ocean crust, thrust-faulted up into the Appalachian orogenic belt during the Ordovician, Taconic subduction event. Other interpretations are possible, however.

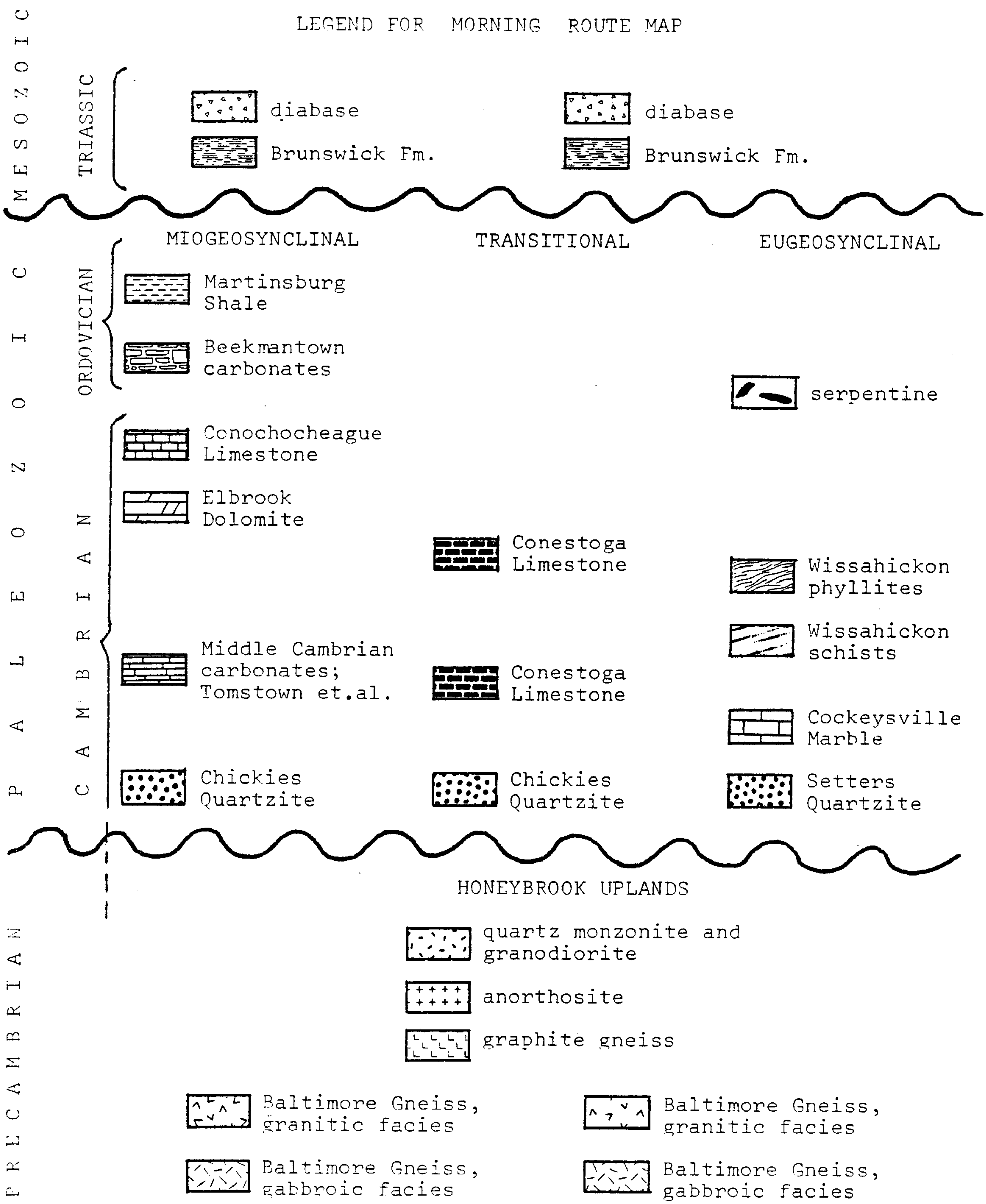
The Brandywine River here has developed a conspicuous flood-plain, visible just below the parking lot and across the river, downstream. Note that the river is essentially at the east valley wall where we are.

PROJECTS:

- Identify minerals in Wissahickon Formation.
- Outline folds in Wissahickon.
- Trace layering from weathered surfaces into fresh rock on Wilmington Complex gneiss.
- Locate folds in Wilmington Complex gneiss.
- Estimate average flood level of Brandywine River.


Reading
U.S. 422
I-176
Morgantown
Penna. Turnpike
U.S. 30
West Chester
Pa. 926
U.S. 1
0 5 10
miles
1
2
3
4
5
6

LEGEND FOR MORNING ROUTE MAP



ROUTE TO STOP 2. (15 miles)

- Leaving Stop 1, bear straight ahead at first intersection (Beaver Valley Road) past parking lot, and follow river to T-intersection at Smiths Bridge Road. Turn right onto Smiths Bridge Road. Route follows valley of Beaver Creek as it climbs out of Brandywine valley. Beaver Creek follows general NE-SW strike of foliation in Wissahickon Formation. See Delaware and Pennsylvania Morning Route Maps.

- Enter area of Pennsylvania Morning Route Map at state line.

- Turn left onto U.S. 202, northbound.

- U.S. 202 crosses U.S. 1. Rocks south of Route 1 are Wissahickon Formation; rocks north of Route 1 are Baltimore Gneiss, the Grenville basement rock. (See legend for foldout map for stratigraphic relations). The two units are in thrust-fault contact; the fault approximately follows U.S. 1 east of intersection.

- Union Oil Company truck stop. Outcrop behind gas station is weathered Wissahickon Formation (at least that's what the map says). It is quite sandy, however, with lots of tourmaline crystals, and at least superficially resembles the Setters Formation, below the Wissahickon. This is stratigraphically consistent, as the Setters is the first unit to be expected above the Baltimore Gneiss. Who knows.

- U.S. 202 crosses Ps. 926. The house on left at corner is constructed of serpentine, a distinctive rock type in the area. Numerous small bodies of serpentine dot the Piedmont; see Pennsylvania Morning Route map. A mile to the left on Pa 926 is Brintons Quarry which you visited last semester.

- Turn right onto West Chester Bypass. West Chester area is underlain by a relatively basic, gabbroic facies of the Baltimore Gneiss, and is similar in many respects to the Wilmington Complex.

- Exit right onto Pa. 100, northbound. Off-ramp, around bend, cuts through small serpentine body, mostly covered. Bedrock here is Wissahickon Formation.

- Descending long hill - outcrop on left at bend is shiny phyllites of Wissahickon Formation. Pull off at next outcrop on right.

STOP 2.

EXTON

Stop 2.

Low-Grade Metamorphism
Refolded Folds

This outcrop exposes low-grade metamorphic rocks and associated structural features. These rocks belong to the upper part of the Wissahickon Formation, and are widespread throughout the Piedmont. Rocks in the Wissahickon farther southeast have been metamorphosed to much higher grades than these, and reflect the generally more intense nature of metamorphism and deformation in the southeastern Piedmont.

The rocks consist of foliated, muscovite-chorite phyllite to very-fine-grained schist. Note the high sheen of the foliation planes; this is characteristic of phyllites. In addition to muscovite and chlorite, other major minerals present include plagioclase (probably albite) and probably Fe-Mg-rich phases such as epidote or actinolite. This assemblage of minerals is stable under conditions of relatively low temperature and low to substantial pressure, say 400-500°C. and 3 to 6 kilobars, and is characteristic of low-grade metamorphism.

Minor minerals are well developed. Quartz occurs in pods and lenses, elongate in the foliation; the pods may reach two feet thick. Good chlorite crystals, some quite large, often occur enclosed in the quartz. This is a different generation of chlorite from that in the phyllites. A red to pink feldspar, probably microcline, also occurs enclosed in quartz. Pyrite cubes occur throughout the rock, and often reach large sizes.

You should make an attempt to infer original rock type. It can be assumed that the parent rocks were sedimentary rather than igneous. The preponderance of clay minerals and micas, coupled with the low grade of metamorphism, would suggest that the parent rock was clay-rich, i.e. a shale or mudstone. Look for sandy, quartzose layers; these will probably be the only evidence you can find of variations in initial lithology. The sandy layers can be rocognized by the way a hammer blow rings rather than thuds. Try also the recognize relict primary sedimentary structures, such as graded bedding or cross-bedding.

The quartz pods should not be considered a primary lithologic feature; they were probably generated by the metamorphism. The chemical reactions generating muscovite, chlorite, actinolite and epidote from sedimentary minerals involve release of free SiO_2; this SiO_2 was carried by fluids for short distances and deposited in the pods you see now. They are evidence of local metasomatism.

The phyllites contain good examples of metamorphic structures. The most obvious structure is a foliation, or schistosity, which dips steeply to the southeast. The foliation consists of closely spaced splitting planes which contain mica grains lying parallel to each other; the rock splits along rather than across the parallel micas. The parallelism was generated by wholesale recrystallization during metamorphism; the direction of parallelism is oriented perpendicular to the direction of compression. Thus, the foliation may or may not be aligned parallel to original bedding in the parent rock.

If it is parallel to original bedding, then the initial deformation folded it into its present steeply dipping state. It is difficult to distinguish at this outcrop whether the beds are right side up or overturned; relict graded bedding would indicate tops.

The dipping foliation planes are not exactly planar, but are wrinkled, and have been folded by a second deformation into small, shallow, open anticlines and synclines. Axes of these second-generation folds are nearly horizontal, and trend northeast. Thus, there have been two separate episodes of deformation, the second milder than the first.

Other structures are plainly visible in the rocks. The major foliation planes contain a distinct lineation, which dips to the southeast. Several possible fault zones can be identified.

<u>Projects</u>:

- Infer original lithology.
- Which way is up? Are the beds steeply dipping normally or overturned?
- Identify two generations of folds.
- What does the lineation represent?
- Collect mineral samples.

ROUTE TO STOP 3. (21 miles)

- Leaving stop 2.- pass under two railroad bridges. Valley ahead is eroded in Middle Cambrian Conestoga Limestone.

- LOOK STOP. Beyond railroad bridges, outcrops on both sides of road contain thinly interbedded brown phyllites and gray calcitic limestones. Phyllites are the same rocks we just examined at Stop 1; the limestones are typical of the Conestoga Formation which occupies the valley ahead (see Morning Map). The rocks have been deformed and tilted into their present vertical position; tops of beds appear to face north. The north end of the outcrop appears more calcitic than the south end. These features indicate a transition (facies change) from the deep-water, eugeosynclinal shales of the Wissahickon to the shallow-water, miogeosynclinal carbonate bank muds of the Conestoga and of formations to the west. Several workers have interpreted this change to represent the esatern margin of the North American continent during early Paleozoic time, and the Conestoga to represent shallow- to deep- water deposition on the continental shelf edge and slope.

- Route crosses U. S. 30 in bottom of valley. Valley is termed the Chester Balley, is narrow and linear for more than 60 miles, and is underlain by the Conestoga Formation.

- Past U. S. 30: route climbs ridge forming northern border of Chester Balley, upheld by the Chickies Quartzite, a Lower Cambrian ridge-former beneath the Conestoga.

- Enter Pennsylvania Turnpike, westbound. Trip route now crosses what is called the "Honeybrook Upland", an oval-shaped area of rolling topography containing diverse igneous and high-grade metamorphic rock; see Morning Map. These crystalline rocks date at 1 billion years, and hence were probably formed during the Grenville Orogeny; they represent the "basement". Grenville rocks are distinctly out of place in the dominantly Paleozoic Piedmont and their presence here is a mystery. The Honeybrook crystalline rocks are flanked by lower and middle Cambrian carbonates and the Chickies Quartzite.

- On turnpike- outcrops on both sides are gabbroic gneisses of the Honeybrook suite.

- Brandywine Rest Center on right. Emergency stop.

- On turnpike- climbing vaguely defined ridge ahead and to right; this is the Chickies Quartzite forming the north flank of the Honeybrook Upland.

- LOOK STOP. Approaching Morgantown Exit (see Morning Map). At the "2 miles to exit" sign, the Turnpike has just crossed the Chickies ridge and has passed out of the Honeybrook Uplan(back into the Paleozoic rocks of the outer Piedmont. The meta morphism has died out here, and the first rocks visible on the right beyond the 2 mile sign are sedimentary miogeosyncli bank-type limestones and dolomites. Although still deformed, these carbonates may be traced northwestward into Valley and Ridge rocks.

  The view: To left: The ridge fading away to front is the Chickies Quartzite ridge. Center: bus is traveling over Middle and Upper Cambrian carbonates (in road cuts) of Elbrook and Conochocheaque Formations. These are first miogeosynclina units encountered. To right: the carbonate valley extends to the foot of the ridge ahead and in distance. That ridge is held up by Triassic gabbroic intrusions, occuring at or near the base of the Triassic sequence. A major unconformity separates folded Paleozoic from unfolded Triassic rocks, and is probably at the base of the ridge. Large mill on hill in distance is the smelter for the Grace iron mine, which extrac magnetite from Triassic rocks.

- Exit Turnpike at Morgantown Exit; 25-cent toll. Turn left, into Morgantown. Turn right onto Pa. 23, westbound; proceed west for 1/2 mile.

- Turn right, onto Interstate 176, northbound. Last outcrops on low hill to right before wide valley are Cambrian Elbrook Formation carbonates.

- As cross valley toward hill, note orange-brown, but not red, soils. Orange soils are developed on carbonates, red soils on the red shales of the Triassic. The absence of red soils in this valley indicates that no red shales are present here, and that the igneous intrusion of Stop 2 must lie at the base of the Triassic sequence.

STOP 3.

MORGANTOWN

Stop 3.

Diabase
Igneous Layering
Pegmatites
Secondary Alteration

Because this outcrop is located along an Interstate Highway, please BE AWARE OF THE TRAFFIC AT ALL TIMES, AND DO NOT STEP ONTO THE PAVEMENT. We will be concerned only with the northern half of this exposure, so do not proceed more than about halfway down the hill. Also, PLEASE STAY ON THE ROAD LEVEL.

This outcrop is at the base of the thick sequence of Triassic rocks filling a faulted valley; the geography is shown on both the General map and the Morning map. The rocks here are igneous, and show both primary and secondary features.

The rocks in the intrusion are uniformly dark-colored, and show little variation in either color or mineralogy throughout the section. The major minerals are calcic plagioclase (probably labradorite), a pyroxene (probably augite), and an amphibole (probably hornblende). Minor minerals include magnetite and quartz; olivine is probably absent. The rock is phaneritic and is called DIABASE, a varity of gabbro occuring in dikes or sills. The rock formed by crystallization of basaltic magma at high temperatures, probably 900-1100°C., and may be represented on the upper portions of Bowen's reaction series.

Although uniformly textured in most parts, the diabase contains several bodies of exceptionally coarse-grained rock. These bodies are termed pegmatites, and contain large (1/2-1 inch) crystals of the same minerals as occur in the rest of the rock (hornblende and plagioclase). The borders of many pegmatite bodies are sharp and slightly finer-grained than the interiors, and suggest that the pegmatites were intruded into slightly cooler normal rock after that rock had initially crystallized.

The diabase shows slight mineral and chemical variations from bottom to top. Silica content is probably slightly higher in upper portions, and hornblende is more common in upper than in lower levels. Plagioclase is probably more sodic in upper levels. These data suggest that the body underwent differentiation after intrusion, with the highest-temperature, first-formed crystals being poorest in silica and sodium, and accumulating near the bottom of the intrusion. Late crystallization products were enriched in silica and sodium, and occupy the upper portions of the mass.

The stucture and form of the intrusion presents an interesting problem: is it a sill or a dike? or some other form? Consider the following:

1. If a sill, then contacts must dip to the northwest, along with the rest of the Triassic sediments into which it was intruded.
2. If a dike, there is no necessary relation between contacts and bedding.

There are two types of data, bearing directly on the nature of the contact, which you can collect in the outcrop:

1. Joints: In many basaltic intrusions, cooling joints develop perpendicular to the cooling surfaces, i.e. to top and bottom, and assume the shape of polygonal (usually 5- and 6-sided) columns. The joints originated by contraction of the solidified magma with cooling. Usually this columnar joint pattern completely overshadows other jointing directions, and is easily recognizable.
2. Primary mineral layering: In a cooling, differentiating magma small inhomogeneities often develop, and result in greater proportions of some minerals than others. This results in a layering of slightly lighter and lightly darker bands, and in the accumulation of those bands parallel to the floor of the intrusion.

Thus, the orientation of joint sets and primary layering should give you clues about the orientation of the lower and upper contacts of the intrusion. Is it a dike or a sill?

Many of the joint planes and other fractures have provided pathways for percolating water. This water has caused alteration of the primary minerals, and has formed hydrous, generally low-temperature mineral phases in the fractures. The most common are quartz, chlorite (green, micaceous), and calcite (white, soft) rarely, prehnite (apple green) has been found. Representatives of the zeolite family of minerals, which are common in other Triassic diabases, have not been found here.

The diabase is high in iron, which has collected in pods during crystallization of the magma and in a minor vapor phase driven off from the magma during crystallization. The vapor phase caused replacement of calcite in limestones by magnetite, and generated sizable bodies of iron ore; these ore bodies are mined at such places as Cornwall and the Grace mine, whose smelter we saw from the Turnpike.

Projects:

- Identify the pegmatites.
- Are the pegmatites part of the original drabase? or are they intrusive into the original diabase?
- Identify columnar joints.
- Is intrusion a sill or a dike?
- What is orientation of primary layering?

ROUTE TO STOP 4(1 mile)

-Leaving stop 3: Pay attention to the location of the last exposures of good diabase. Despite the valleys and reentrants in the hillside along the route, the last exposures are probably part of the same intrusion.

-Contact-metamorphased shales and sandstones are exposed just beyond bridge over highway at top of hill.

INTERSTATE 176

STOP 4:

Red Beds
Fluvial Deposits
Cyclic Deposition

This stop is along Interstate Highway 176, which carries heavy and fast-moving traffic: DO NOT STEP ONTO THE PAVEMENT AT ANY TIME.

The rocks exposed in this road cut are red shales and sandstones of the Upper Triassic Brunswick Formation. The Brunswick and underlying Triassic formations reach 30,000 feet thick, and are confined to narrow, elongate basins in New Jersey and in eastern and southern Pennsylvania. The formations are thickest along the northwest sides of these basins. The basins are bounded on the northwest sides by normal faults of large displacement (up to 35,000 feet is estimated for some). The faults were produced by post-orogenic, tensional stresses in the earth's crust, and were probably the mechanisms by which isostatic balance was maintained after the final deformation in the Appalachian Geosyncline during Permian time. The mountain range lay to the northwest of the fault, and shed detritus onto the lower lands to the subsidence.

The strata presently dip about 30° to the northwest, or into the fault. However, there has been no large-scale, orogenic folding of the Triassic rocks, and the observed dips are due to mild downwarping during and shortly after deposition. The sediments were deposited horizontally, and were slowly and continuously tilted by hinge-like subsidence, generated by downward movement along the fault. The northwestern parts of the basin, closer to the active fault, subsided more than the southeastern parts, which were farther from the cause of the subsidence.

The Triassic sedimentary rocks consist of conglomerates, sandstones and shales; limestones are absent. The conglomerates contain mostly limestone and granite pebbles, and are confined to regions near the border fault. They are of fluvial origin, and represent the initial dumping of the coarsest stream loads near the mountain front. Because the streams probably flowed over alluvial fans at the valley edges, these conglomerates are often called fanglomerates. The cobbles and boulders are quite angular, and have been transported very short distances.

Southeast from the faulted basin margin the sediments become sandy, and further southeast, shaly. These sandstones and shales are of fluvial origin, and indicate steadily decreasing stream gradients away from the mountain front. Fluvial fining-upward cycles of this part of the basin are well exposed at this outcrop. Sandstones are 15 to 20 feet thick, are coarser at the base (often conglomeratic), and become finer-grained upward. They erosionally overlie shale beds, and are internally cross-bedded and thin-bedded. They pass gradationally upward into siltstones and then into shales which reach 20 feet thick. The shales are burrowed, thin-bedded and wavy-bedded, and the tops are erosionally scoured and channeled by the next overlying sandstones. Each sandstone-shale sequence indicates a point-bar deposit, wherein the sandstones represent channel deposition on the lower parts of point bars, and the shales represent overbank, floodplain deposition on the upper parts of point bars and across the meander belts. These floodplain deposits contain most of the dinosaur and other vertebrate footprints found in the Triassic.

The dark red color of the rocks is due to the presence of hematite, Fe_2O_3. Although many interpretations of the origin of red colors in rocks have been proposed, it is fairly certain that the colors of these rocks originated by deposition of detrital hematite along with the rest of the sediment. The hematite was formed prior to deposition, by intense chemical weathering in the mountain source region. Since hematite production by weathering today is limited to warm, humid regions, many geologists infer that Triassic climates in eastern North America were likewise warm and humid.

On the west side of the highway, a small normal fault offsets a sandstone bed. The displacement is about five feet, and the fault plane is probably exposed.

Projects:

- Define point-bar and floodplain deposits.
- Estimate maximum depth of Triassic rivers.
- Account for the uniform northwestward dip of the rocks.
- Did Triassic rivers flow northwest?

ROUTE TO STOP5. (12 miles)

- Along Interstate route- road cuts on both sides expose Triassic red beds at many places. Note that, as we proceed north, the overall grain size increases; there are progressively more sandstones and conglomerates, and fewer shales. This suggests that we are approaching the source of the sediment. Several good conglomerate beds are exposed.

- End I-176. Shillington Exit, and U. S. 422 exit. Major ridge ahead is called Reading Prong, and consists of Precambrian gneisses, quartzites and limestones. It forms the northern border of the Triassic basin. See Morning Map.

- Bear straight ahead on on-ramp to U. S. 422, westbound. Where ramp bends left, slow down and look at outcrops on right.

STOP 5. - ~~LOOK STOP~~. Dramatic exposures in road cuts of coarse boulder conglomerate. Boulders reach two feet in diameter, and are commonly quite angular; these features suggest very short distances of transport and little sorting or size reduction. Many types of rocks are represented in the boulders, including buff-orange quartzites, gray limestones and dolomites, granites, and metamorphic rocks. These rock types are found in the Reading Prong hills 500 yards to the right, and were very probably eroded from those very hills in Triassic time. They were probably transported a mile or so, then deposited on alluvial fans spread out at the foot of the hills, and are therefore termed "fanglomerates". These fanglomerates represent the coarsest, nearest-source facies of the Triassic sediments.

- Cross Schuylkill River: river valley to right contains a major normal fault bordering the Triassic valley. The fault dips to the southeast, and has an estimated displacement of up to 30,000 feet.

- Just beyond Schuylkill River- first road cuts in Cambro-Ordovician carbonates of miogeosynclinal sequence.

- Penn Avenue exit- good exposures of gray limestones and dolomites of the Conochocheaque Formation. These beds, now, dip to the southeast, but are not necessarily in correct vertical sequence; several workers believe that the entire sequence here is overturned.

- End of Reading Bypass. Bear straight ahead, following signs "To Pa. 61", up a grade and right onto bridge across Schuylkill parking lost of Stone Cliff Park.

STOP 6.

I-176 OFFRAMP

STOP 5.

Conglomerate
Edge of Triassic depositional basin

DANGER -- STAY OFF THE HIGHWAY: This is a blind curve, with high-speed traffic. Be careful.

This outcrop exposes Triassic conglomerates and comglomeratic mudstones. The spectacular conglomerates contain boulders up to a foot across. Compositions of the pebbles and boulders include abundant limestone, chert and quartzite, and rare granite and granite gneiss. Pay attention to the angularity of the pebbles, and to the diversity of lithologies represented; you can see bedding and cross-bedding structures in many of the pebbles.

Logic: limestone is a weak rock mechanically; it cannot withstand even short distances of mechanical transport (like in rivers) before crumbling and breaking down. Therefore, since this conglomerate is full of coarse limestone boulders, how far from the source of the limestone must this outcrop be? Why is this the only place in the Triassic basin where you see limestone boulders? Which way were the streams flowing? What was the source area? Where was the source area? Can you see it from here?

This conglomeratic facies of the Triassic is confined to the northwestern margin, and extends only a few hundred yards to a mile into the basin to the south. The hills to the north are Precambrian, and are the source area for the pebbles you see here. The north edge of the Triassic basin is probably faulted, dropped down against the Precambrian.

As we leave this stop, look closely for the first evidence of different rock types.

STONE CLIFF PARK, READING

Stop 6.

Cambro-Ordovician Carbonates
Algal Stromatolites.

LUNCH STOP. We will eat lunch in the park below the parking lot. Plan to finish lunch in 1/2 hour. Rest rooms are in the pavilion building to the south of the table area. THIS IS ALSO A ROCK STOP, SO BRING GUIDEBOOKS. NO HAMMERS PLEASE.

The rocks exposed in the park are part of the Cambro-Ordovician carbonate sequence of the Appalachian miogeosyncline, which reach 16,000 feet in aggregate thickness. The unit exposed here is the Upper Cambrian Conochocheague Formation, which occurs in about the middle of the sequence; it is typical of the entire sequence.

The rock consists of gray-weathering carbonate, probably crystalline limestone, and buff-weathering shaly carbonate, interlayered throughout the outcrop on a scale of 1/2 to 1 inch. The unit is characterized by a remarkable, almost monotonous alternation ot these lithologies. Many thin, jagged dark lines termed stylolites may be seen in the rocks; these are evidence of differential solution during the recrystallization.

Very few diagnostic sedimentary structures are visible. The only evidence of current activity is a few small, shallow scour-and-fill structures, particularly near the north end of the outcrop. There are essentially no fossils. Some problematical structures resembling mud cracks are barely visible, but are not diagnostic. There are essentially no fossils in the rock, particularly in the picnic-table area.

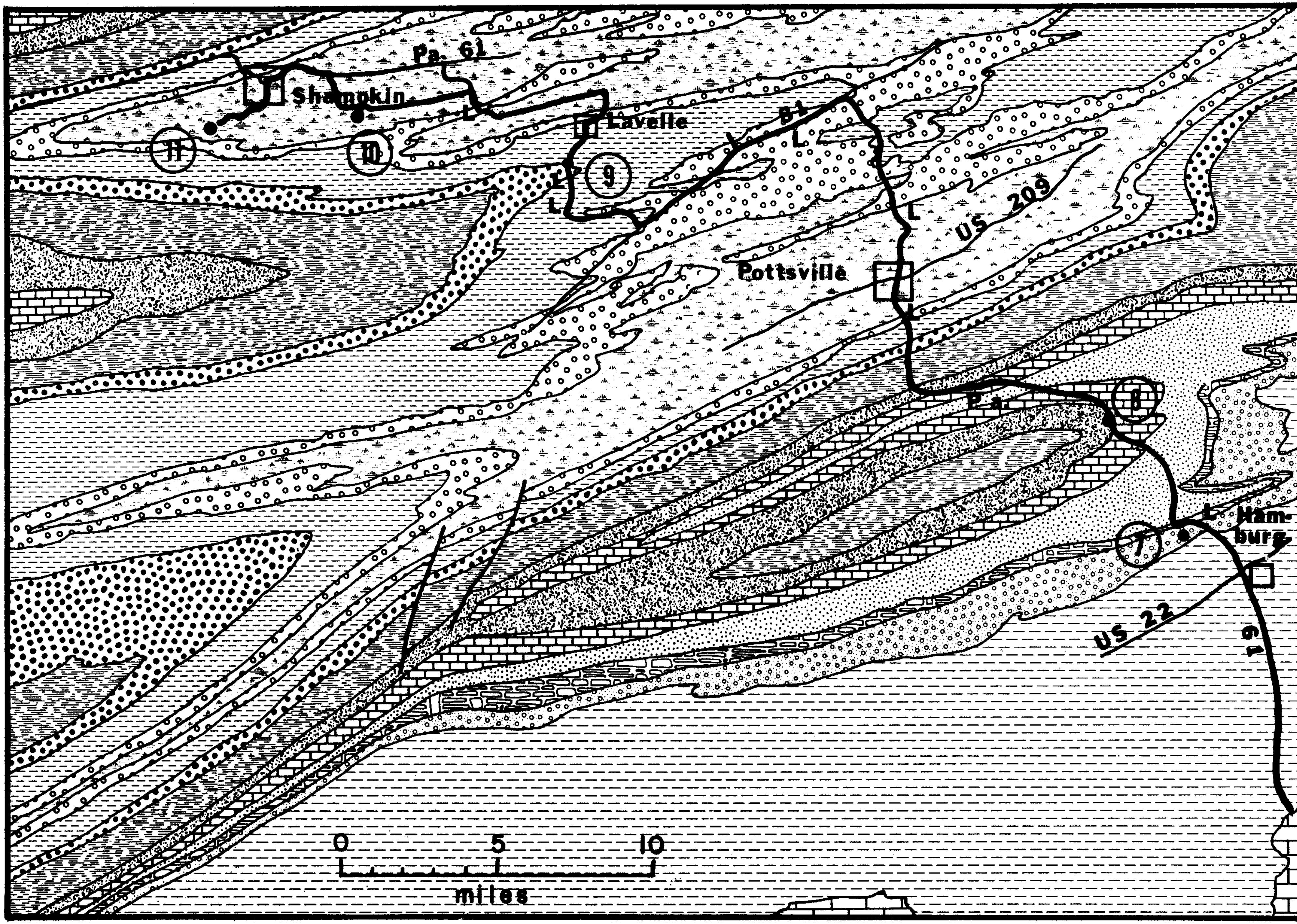
In the absence of fossil and current data, depositional environments in carbonates are hard to determine. However, near the south end of the outcrop, just north of the pavilion, there occurs an 8-foot thick zone of algal stromatolite. These structures consist of small (1 inch across), tufted, biscuit-shaped mounds of interlayered carbonate and clay growing vertically, or across bedding. This is a truly excellent exposure of stromatolitic structures.

Modern stromatolitic algae are confined to tidal environments, and are consistently found as mat-like coverings on supratidal flats. They are reliable indicators of mean sealevel today, and there is every reason to suspect that ancient stromatolites grew at ancient mean sealevels. On this basis, the algal structures and associated laminations of the Conochocheague may be interpreted to be tidal-related. Further, since the rest of the carbonate sequence also contains stromatolitic algae, the entire 16,000 feet of Cambro-Ordovician miogeosynclinal carbonate may be interpreted to have accumulated as very-shallow-water, essentially tidal-flat deposits.

The carbonate shows some interesting structures. Most obvious is a set of nearly vertical, closely spaced fracture planes, called cleavage, many of which are filled with secondary calcite. These developed in response to the stresses which caused folding of the rock. Other calcite-filled fractures are arranged *en echelon* and represent brittle "tear" fractures.

Projects:

- Find evidence of current activity.
- Locate stylolites.
- Document the occurrence of mud cracks (which you would expect to be associated with stromatolites).
- Find some fossils.
- Are rocks normal or overturned?


Pa. 61
Shamokin
Lavelle
81
US 209
Pottsville
Pa.
Ham-
burg
US 22
61
0
5
10
miles

LEGEND FOR AFTERNOON MAP

Allegheny Unconformity = present erosion surface

PENNSYLVANIAN

LLEWELLYN Formation: sandstone, shale, coal

POTTSVILLE Conglomerate: conglomeratic sandstone

MISSISSIPPIAN

MAUCH CHUNK Formation: red sandstone and shale

POCONO Sandstone: homogeneous tan sandstone

DEVONIAN

CATSKILL Group: red sandstone and shale

Marine Middle Devonian: includes PORTAGE and CHEMUNG Group dark sandstones and shales

Upper Silurian and Lower Devonian carbonates and clastics: includes HAMILTON Group

SILURIAN

BLOOMSBURG Formation: red sandstone and shale

CLINTON Group: red and white sandstone and shale

TUSCARORA Sandstone: white sandstone and quartz conglomerate

Taconic Unconformity

ORDOVICIAN

MARTINSBURG Shale: shale and turbidite sandstone

BEEKMANTOWN and TRENTON Group carbonates: mostly Middle Ordovician gray limestones

ROUTE TO STOP 7 (19 miles)

- Enter area of Afternoon Map. Turn right from parking lot, north.

- Turn right onto Pa. 61 North. City of Reading and surrounding area are underlain by carbonate sequence.

- Next two miles - several large outcrops of gray carbonate on both sides of road. As we proceed north the carbonate sequence becomes generally younger, and reaches Middle Ordovician age at the top.

- Town of Leesport. Just north of town, the first outcrops of the Martinsburg Shale can be seen. The Martinsburg overlies the carbonates, and represents Taconic-cycle flysh. The Martinsburg is intensely deformed internally, but the deformation appears to be confined to certain levels in the 13,000-foot-thick formation, so that rocks become generally younger to north.

Stop 6A

- Glen Gery brick factory on right - Clay for this brick operation is taken from the lower, totally shaly parts of the Martinsburg. Clay pits visible to both left and right.

- Town of Shoemakersville - good sandstone beds of middle Martinsburg visible in several road cuts north of town. Note the rolling topography developed on the Martinsburg; this low-elevation topography, combined with that developed on the carbonates, gives rise to the Great Valley, the first valley in the Valley and Ridge province.

- Town of Hamburg (a swinger) on right. Excellent view to front of Blue Mountain, a Silurian ridge held up by the Tuscarora Sandstone. The gap in the ridge is Schuylkill Gap, cut by the Schuylkill River as the ridge was being uplifted; river erosion kept pace with rising land level, and preserved the river's meandering course.

- Cross U.S. 22. Good view to either side of the contrast between the Great Valley and the long, sinuous ridges. This is shown especially well on the Afternoon Map.

- Cross Schuylkill River. Outcrop of Stop 7 is to left, across the gap. Rock exposed beyond north end of the bridge is Tuscarora Formation.

SHOEMAKERSVILLE

STOP 6A.

Deep-water limestones
Shale
Facies changes
Anticline
Cleavage

This outcrop, along Pa. 61 north of Shoemakersville, exposes an anticline containing thinly interleaved black shale and gray limestone. This rock is part of the basal Martinsburg Formation, of Middle Ordovician age, and represents a gradational facies change from limestone to shale deposition. Limestone underlies the Great Valley south of us, as we saw at the last stop; those limestones were Cambrian. Shales of the Martinsburg underlie the valley north of us, in the direction we are traveling; they are Ordovician, and thus the valley is part of a great syncline, in which the rocks get younger to the north.

The limestones are thin-bedded, and resemble the "ribbon" limestones of the last stop. However, dolomite laminations are absent, evidence of algae are likewise absent, and there is no evidence of exposure to the atmosphere, or currents or even of shallow water. No current-bedded structures have as yet been found. Thus these limestones probably formed in offshore, quiet, probably deep water.

The bedding in the limestones has been disrupted; lenticular and pod-like forms of limestone bodies are evident. These forms probably originated after deposition, maybe during folding. Some small, tight folds may be seen in the limestones.

The shales are black and featureless, except where cleaved. These shales represent the first clay influx into the Appalachian miogeosyncline. They show an eastern source land, the first eastern source in Appalachian history. These shales near the base of the Martinsburg mark the initial phases of the Taconic orogeny.

The shales (much more than the limestones) show a penetrative, closely spaced fracture pattern, which looks like grooves or striations on any one surface. These fracture planes are cleavage, and penetrate throughout the rock. The cleavage was generated in weak rocks by compression during folding, and may be seen to vary in orientation through the outcrop.

The gross structure of the outcrop is an anticline; bedding dips south at the south end, is flat near the middle, and dips north at the north end. The axis of the antlcine strikes ENE, parallel to the axis of the Great Valley, and also parallel to the ridge which is our next stop.

Projects:

- Identify limestone and shale
- Look for current structures in the limestones
- Locate the cleavage
- Explain why shales are cleaved, but limestones are not
- Find fossils in the limestones
- Find small folds in the limestones

- Beyond bridge - slowing down for turn into Port Clinton: excellent exposure on right of Middle Silurian Clinton Formation. The rocks are standing vertically, and contain cyclically interbedded white sandstones and red sandstones and shales, with no limestones. The complete thickness of 500 feet is exposed.

- Turn left into Port Clinton, and proceed just across bridge and single track. Park somewhere. Valley here is carved on Clinton rocks.

STOP 7.

PORT CLINTON

STOP 7.

Flysch
Molasse
Taconic Unconformity
Graptolite fossils

This outcrop is located on the west side of Schuylkill Gap, a notch in Blue Mountain cut by the Schuylkill River. The rocks are exposed along an elevated railroad right-of-way. THE TRACK IS ACTIVELY USED, SO BE ALERT FOR TRAINS. We were almost demolished here last year.

Two distinctly different sedimentary rock facies are exposed here, and are separated by a major angular unconformity. Southward from the unconformity are exposed nearly horizontal beds of the Middle Ordovician Martinsburg Formation, the same formation that we saw on the highway approaching this stop. The Martinsburg here contains interbedded sandstone and shale, probably in the middle to upper parts of the formation. The sandstones are graywackes, containing many rock fragments and much matrix, and show well-developed graded bedding, small-scale cross-bedding and ripple-bedding. Flute casts and other bedding-plane sedimentary structures are sometimes visible. The sandstones contain both whole and broken shells of shallow-water fossils, including brachiopods, crinoids and pelecypods, which have obviously been moved from their site of living. The sandstones are of turbidity current origin, continuously sedimented out of open, quiet water onto a probably deep basin floor.

Graptolites and trilobites are major fossil types characteristic of lower and mid-Paleozoic pelagic shales and siltstones, and both are relatively common in the Martinsburg. Look for graptolites in the shales and especially in the siltstones; the best hunting is in the very finely gritted rocks. Trilobites have not been reported from this site.

The Martinsburg is an outstanding example of FLYSCH, and is the major Taconic-cycle flysch unit. It represents the initial clastic-sediment input into the Taconic miogeosyncline, and signifies the beginnings of the uplift and eugeosynclinal destruction called the Taconic orogeny. Paleocurrent determinations made on directional structures in the Martinsburg indicate that uplift occurred to the southeast of this site, and that sediment was shed to the northwest. The tectonic activity, probably in the form of earthquakes, was the triggering agent for the turbidity currents.

Northward from the unconformity occur vertically standing beds of the Lower Silurian Tuscarora Formation. This unit consists of up to 1000 feet of clean, well-sorted, coarse white sandstone. The predominance of quartz grains, and the absence of matrix, make this rock an orthoquartzite. The lower 100 feet contain small scattered one- to two-inch pebbles of white quartz and chert. The conglomerate is supermature, i.e. all pebbles are about the same size, and all are of the same composition (SiO_2). The sandstones are cross-bedded, in sets of channeling and channel cutting and filling. Bedding-plane sedimentary structures include ripples and parting lineations. Shelled fossils are absent, but several bedding planes contain burrow structures and organic trails. Shale is nearly absent.

The Tuscarora is a good example of MOLASSE and is one of several formations representing Taconic-cycle molasse. The sedimentary structures, lack of marine fossils, and other evidence point to a continental, braided stream regime for Tuscarora deposition. The sediment was derived from mountainous orogenic lands lying to the southeast (northwest-directed paleocurrents), and were laid down on the sides and downstream ends of bars built in the channels of wide, shallow braided streams which traversed a broad alluvial fan built at the foot of the orogenic highlands. The Tuscarora was not the initial molasse deposit; a thick sequence of Upper Odovician molasse occurs in place of the unconformity to the west in central Pennsylvania. The Martinsburg here was involved in the orogeny, and was uplifted and folded by it; the Tuscarora was deposited after the orogeny on the erosion surface.

The Taconic Unconformity separating Martinsburg and Tuscarora thus represents the occurrence of the Taconic orogeny in this region. The unconformity may be traced continuously from the Harrisburg region into Nova Scotia and Newfoundland. Here, the unconformity is standing vertically, but since unconformities do not form in this position, some event in addition to the Taconic must have affected this region. The defining features of the unconformity is not its present attitude but the angular relationship between Martinsburg and Tuscarora bedding directions. Other attributes are ancillary, and not directly related.

Projects:

- Are the Martinsburg beds normal or upside down? How can you tell?
- Outline, stepwise, the sequence of events involved in generation of the present Taconic unconformity as you see it.
- Find some graptolites.
- Calculate the maximum length of the Taconic orogeny.
- Compare sizes of these cross-beds with those of stop 8.

ROUTE TO STOP 8. (4 miles)

- Reenter Pa. 61 north at Maberry's Store.
- Port Clinton: route passes the length of Port Clinton, with stores on left. Complete section of Bloomsburg Formation on right.
- Climb long hill. Red beds in road cuts are Bloomsburg Formation.
- Crest of hill. This low ridge is probably upheld by Devonian Oriskany sandstones, and pure quartz sandstone which differs from Tuscarora, Pocono and Pottsville in being marine, and considerably less well cemented and therefore more susceptible to erosion. Oriskany ridges are generally low, and are ascendable by highways.
- Descend long hill. Slope and valley ahead and to right are underlain by Helderberg Group carbonates, Onondaga Limestone, and Lower and Middle Devonian marine shales of Marcellus and Mahantango Formations. These rocks represent the first clastic influx into the Acadian-orogenic-cycle geosyncline, have no known counterparts in the Taconic geosynclinal cycle.
- Road beds to right at bottom of hill; road-metal quarry in Mahantango Formation just ahead on left.

STOP 8.

DEER LAKE

STOP 8.

Shelf Association
Invertebrate Fossils
Paleoecology and Environmental Interpretation.

This outcrop is located in a road-metal quarry on the west side of Pa. 61. It exposes the upper portions of the Middle Devonian Mahantango Formation, a richly fossiliferous siltstone with rare sandstone and shale. Fine specimens of shallow-marine invertebrate animals and plants may be collected, including brachiopods, pelecypods, crinoids, coelenterates, bryozoans, trilobites, algae and others. The fossils are molds of the shell exteriors, and are best seen and found as rusty brown stains on slightly weathered surfaces. Diagrams of individual genera are shown on the following page as an aid to collecting. The most common fossil types are the razor clam Cypricardina, another razor clam not figured, algae, and the brachiopod Rhipidomella. Triobites are rare, and constitute the most significant, prestigious and status-generating finds.

Data on the paleoecology of modern relatives of these fossils are instrumental in environmental interpretations of the Mahantango. Many types, especially the corals and crinoids, require clear, warm water to survive. Bryozoans thrive in slightly agitated water where silt is the major sediment type. The abundance and diversity of pelecypods further suggest shallow-water environments, with several different sub-environments within the general shallow shelf. Several pelecypod genera are true clams, who have a moderate tolerance of salinity fluctuation and can withstand limited fresh-water dilution. Other pelecypods are primitive oyster, mussel and scallop types (Lioptera, Cypricardina and Gervillia, respectively), and not only had high salinity tolerances but built reefs and banks in the intertidal zone of brackish environments (i.e. at sea level, in nearshore zones). Calcareous algae are restricted to water less than 100 feet deep, and their delicate preservation precludes post-mortem transport. Bedding is scarcely visible, and the strike and dip of the formation must be read from a map. The bedding has probably been destroyed by an abundant burrowing fauna, including trilobites, gastropods and unpreserved worms, who lived on and within the bottom sediment and fed by ingesting sediment and extracting organic nutrients. But the bulk of the shelled animals were probably suspension-feeders, who extracted nutrients from the water itself by a filtration process. To support so prolific a suspension-feeding fauna, the water must have been continuously and gently agitated, i.e. shallow.

Purely on paleontology, then, you can interpret the Mahantango as representing shallow, gently agitated, relatively near-shore, open-marine shelf deposition. This agrees nicely with independent interpretations of other Devonian units. The Mahantango comprises the uppermost unit in the Hamilton Group, a series of dark, generally fine-grained, marine Middle Devonian rocks. The Hamilton rocks are dark because of their high content of finely divided organic matter. They overlie the early geosynclinal carbonate sequence of Upper Silurian and Lower Devonian age, and represent the last shelf-association deposits in the Acadian-cycle miogeosyncline; they are overlain by Portage group flysch. The Hamilton Group, and especially the Mahantango, represents a major lithologic type frequently found in the shelf association.

Projects:

- Collect a representative suite of fossils.
- Attempt to define the bedding direction.
- Describe sedimentary structures you may see.

ROUTE TO STOP 9. (31 miles)

- Town of Deer Lake. Drive-in movie theater on right. Route travels on Middle Devonian flysch, the Portage Group.

- Top of long hill - exposures of both sides of road of Upper Silurian Bloomsburg red beds. These red beds are caught in a narrow anticline between Oriskany sandstone limbs.

- Town of Schuylkill Haven.

- Leaving Schuylkill Haven - major ridge in front and to right, Second Mountain, in underlain by the Mississippian Pocono Sandstone. The Pocono and Pottsville Formations, both tough, resistant ridge-formers, are separated only by the relatively thin Mauch Chunk Formation; thus Pocono and Pottsville ridges occur in pairs, and are close together. The Pottsville ridge is visible through the gap.

- Gap in Second Mountain , cut by Schuylkill River. Opposite Hertz garage, outcrops of massive, thick-bedded Pocono sandstone. Pocono dips to northwest, into a major syncline containing coal and coal mining in center. Pottsville ridge visible ahead.

- Railroad overpass. Upper Mississippian Mauch Chunk red beds exposed on right. Almost continuous exposure from upper Pocono through all of Mauch Chunk into Pottsville.

- Gap through Sharp Mountain, just south of Pottsville. Outcrops to right are the type section of the Pottsville Conglomerate, i.e. the "standard", reference lithology, thickness, facies, etc of the Pottsville. The term Pottsville is applied to basal Pennsylvanian rocks as far away as central Alabama.

- Type section of Pottsville: rock here dips steeply northwest. See Afternoon Map for details.

- Enter Pottsville. Outcrops of Pottsville conglomerate now dip gently to southeast; apparently we have passed the axis of the syncline.

- Downtown Pottsville. Pottsville is one of the wealthier coal towns, being the center of much of the money, industry, and headquarters for two major coal companies.

- Leaving Pottsville. Outcrops of Llewellyn Formation, the major coal-bearing unit. Sandstone, black shale, coal. Note the extent to which the land has been disrupted.

- Town of St. Clair. Enough said. Road follows valley of Mill Creek across strike of coal-bearing units.

- Tailings piles and strip mine dumps everywhere. All trees you see are second or third growth, and all the land surface has probably been moved at least once.

- Climb 2- to 3-mile hill, up the gorge of Mill Creek. Route crosses generally anticlinal structure. We are going down-section, through Pottsville and Mauch Chunk, then up again into Pottsville. See Afternoon Map. Top of hill is on an extensive high plateau on Pottsville Formation at elevation of 1700 feet, 1000 feet above elevation of St. Clair.

TOP 9 ENTER I-81 NORTHBOUND, PROCEED 15 miles TO STOP 9, then return

TOP 9

- Enter Interstate 81, southbound. Major strip mining area lies to right, at lower elevations.

- Abandoned strip mine and dumps on right, in small downfolded syncline of Llewellyn. See Afternoon Map.

- All along I-81 - there are good outcrops of Pottsville conglomerates. Pottsville contains distinctive large, rounded white quartz pebbles in a tan to dark matrix. A spectacular outcrop of Pottsville, Mauch Chunk and a major thrust fault may be seen on I-81 near Hazleton to the northeast.

- Minersville exit off I-81, onto Pa. 901 west.

- Pa. 901, past off-ramp: route descends steeply off Pottsville plateau into narrow, plunging anticlinal valley underlain by Mauch Chunk red beds. Ridges to either side are plunging Pottsville synclines.

- Cross-roads; signs indicate Hegins (left) and Gordon (right). Valley floor is underlain by Mauch Chunk Formation.

- Same cross-roads - gently sloping ridge ahead and to left in distance is the plunging crest of a major anticline in the Pocono Formation. An excellent example of a plunging fold. Stop is on the crest of this fold where intersected by the highway.

- Whithin the next mile - extensive outcrops on both sides of road of Mauch Chunk red shales and sandstones. Dip is to southeast, or away from the axis of the anticline. Good bedding-plane exposures and good jointing are visible.

STOP 10.

Stop 9. HAZLETON

Pottsville Conglomerate; Thrust Fault.

This exposure is in a spectacular road cut, 275 feet deep, on Interstate 81 southwest of Hazleton, Pa. WE ARE ILLEGAL IN STOPPING HERE, SO STAY OFF THE HIGHWAY SURFACE. A view of the fault from the west side is actually better than one from the east side or median strip. BE EXTREMELY CAREFUL OF FALLING ROCKS FROM THE VERTICAL WALLS OF THE ROAD CUT.

The ridge containing the road cut is underlain by the Pottsville Conglomerate, a resistant, coarse sandstone and quartz-pebble conglomerate of lower Pennsylvanian age. The Pottsville is probably of fluvial origin, deposited as bars and channel fills in braided river systems traversing extensive alluvial fans. Cross-bedding can be seen dimly in the exposures on the west side of the cut.

One of the most distinctive beds in the Pottsville here is a four- to six-foot-thick, lightcolored white-quartz-pebble conglomerate which very nicely outlines the major structures in the road cut. This conglomerate bed is massive and internally unbedded, and probably represents a channel island in the process of building across the river complex.

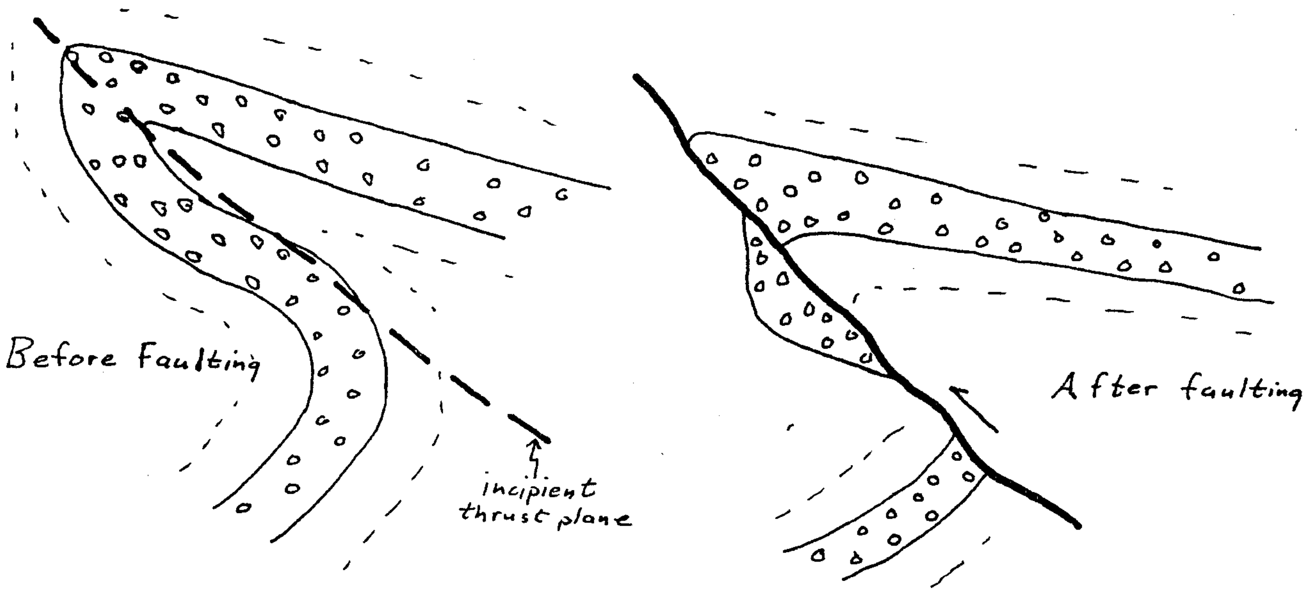
The thrust fault which cuts the sandstones and conglomerates of the Pottsville is very sharply defined; the entire movement on the fault surface took place in a zone no more than six inches thick; the fault surface is less than a handspan across. The fault is exposed at the south end of the road cut at about road level; at the middle of the cut it rises diagonally across the outcrop face to the north. The upper side of the fault, the hanging wall, moved upward and to the north.

There is folding of the Pottsville beds associated with the thrust fault, and several beds appear to have been "dragged" along the fault surface. Actually, the fault and an overturned anticline on the hanging wall are related features, and the history of development of the fault-fold system can be read by following the conglomerate bed mentioned above through the north end of the cut.

The observed deformation in the Pottsville is the result of the Permian-age Alleghenian orogeny, which consisted of compressive folding and faulting from southeast to northwest. In many instances, including this exposure, the rate of compression and deformation exceeded the rocks' ability to deform plastically (to fold), so that the rocks fractured (faulted) instead. This resulted in large thrusts faults, many of great displacement, which carried rocks to the northwest. In most cases some folding took place before the plastic limit of the rocks was exceeded and fracturing ensued.

This sequence of events is well illustrated by this exposure. The anticline was developing in the Pottsville conglomerates and resistant, relatively brittle and nonplastic sandstones, and had actually reached the stage where the lower limb was overturned when the plastic limit was exceeded and faulting started. The resulting thrust fault "sheared off" the upper, right-side-up lim of the anticline and moved it up and over (to the north) the overturned bottom limb and adjacent limb of the adjoining syncline. Part of the overturned limb is visible in the footwall just below the fault surface.

A series of crude schematic diagrams illustrates various steps in the evolution of the fault-fold system:



The key to the structural interpretation here is the light-colored conglomerate bed. Try to follow it completely through the fold and across the fault; imagine what the structure would have looked like when the conglomerate was a continuous stratum.

LAVELLE

STOP 10

Axis of Fold
Cross-bedding
Braided-Stream Deposits
Pre-Depositional Topography (?)

This outcrop is in the Lower Mississippian Pocono Sandstone, precisely on the axis of the plunging anticline formed by the junction of Mahantango and Line Mountains. In the last two miles of bus trip (see route log), you have seen the plunging fold and the topographic slope generated by it, and you have also seen the Mauch Chunk red beds, overlying the Pocono, dipping southeast (away) from the ridge. In this outcrop you can see the Pocono change progressively from south-dipping at the south end of the cut through horizontal to north-dipping at the north end, in a continuous, gentle arc. Even where the bedding appears horizontal, in the center of the cut, the rocks are still dipping slightly to the east, i.e. into the cut; this reflects the plunge of the fold.

If you are to make the above interpretations of structure, you must be certain that you are using true bedding planes rather than apparent bedding or cross-bedding planes to define bedding orientation. One of the most visible features of the rock cut, which may be mistaken for bedding, is a fracturing that is not at all horizontal but appears to dip to the north. This is the predominant set of fractures in the outcrop; another set is horizontal and much less common.

High up on the east face of the cut is a relatively unfractured, continuous bed of sandstone that is the best definer of structure. It shows that, in the middle of the cut, the beds are essentially horizontal. They begin to dip gently south at the south end of the cut, as this bed indicates.

If the major bedding is in fact horizontal, then what do the north-dipping fractures signify? Look closely at them, and you will find that they are parallel to thin layers of differing mineral composition, i.e. light and dark layers. The fractures developed parallel to inhomogeneities in the rock rather than across them. So, about the only origin we know of inclined beds in horizontal strata is forsest beds in sets of cross-strata. In fact, the inclined fractures define directions of foreset bedding, and parallel the individual foresets. Sets of cross-strata here are up to eight feet thick, and are separated by thin sets of horizontal fractures; these horizontal fractures represent tops and bottoms of sets, and are parallel to the true bedding direction. The purpose of this stop is to see cross-bedding, so be satisfied that you see and recognize the different sets of fractures before you leave.

Other features of current flow include channeling and scour filling, and possibly also some bedding-plane features such as current crescent casts.

The uniformly thick sets, the uniform direction of foreset inclination (northwest), the planar bases of sets and the overall large scale of the bedding strongly suggest a fluvial origin for these sands. The paleocurrent directions (directions of foreset inclination) show remarkably little variablity, and point strongly to the northwest. This low variability of current-flow direction, coupled with the other data, suggests that the cross-strata originated by deposition on the downstream ends of alluvial bars in braided channel complexes.

An unusual feature is exposed at the north end of the cut. On the west side, a low, rounded hummock is exposed. It appears to poke up through the sandstones, and resembles an anticline. Bedding in and near this structure appears to be up-folded, i.e. anticlinal, and conforms to the shape of the hummock. However, several bits of evidence suggest that this is not an anticline, and that variations in rock thicknesses may be causing the apparent structure. The rocks of the hummock itself are weathered more extensively than the overlying sandstones, and something approaching a fossil soil may be preserved at the top of the hummock. If all this is so, then the hummock has somehow been exposed to weathering longer than the surrounding sandstones. Moreover, the sandstone beds alongside the hummock, at road level, are continuous across the crest, but thin drastically, from eight feet on the sides to two feet over the crest. This indicates that the hummock is not a tectonic fold, but must have already existed when the sandstones were deposited. The entire hummock was under water, but more sand was deposited on the flanks than on the crest. Analogous situations have been documented in modern braided environments, where water flows more easily around bars or impediments than over them. So what we are looking at may be an original, pre-depositional topography: an impediment to water flow, a topographic "high", maybe even a bedrock island poking up into a braided channel complex and offering resistance to flow. The local nature of this obstruction is indicated by its failure to carry across the road to the east side of the cut (although there are hangups with the east side also).

Projects:

- Locate the fold axis.
- Distinguish bedding planes from cross-bedding planes.
- Explain the lack of shale.
- Locate channel-fill structures.
- Find cross-bed sets whose foresets dip to the southeast.
- Propose another interpretation of the fine-grained sediments at the north end of the cut.

ROUTE TO STOP 11. (12 miles)

- Just past Stop 10 - Mauch Chunk red beds dipping north, away from the axis of the anticline on the north side.

- Town of Lavelle. In center of town, turn right onto major road. Road carries east to a slanting T-intersection; turn left (toward mountain) at the intersection.

- Road carries through gap in Mahanoy Mountain, upheld by Pottsville conglomerates. On north side the basin contains Pennsylvanian Llewellyn Formation, and is mined for coal (obviously).

- Town of Locustdale. Turn left (west) at the stop sign onto major road. Route now parallels Pottsville ridge on northside, and shows strip mining to left.

- Rejoin Pa. 901, westbound, at stop sign. Pa. 901 has come over the hill from Lavelle; the bus won't make the grade (we tried it one year, and walked up the hill).

- Town of Locust Gap. Continue through town to northwest, and through the gap called Locust Gap. The ridge is an anticline in the Pottsville conglomerates, with younger coal beds to either side.

- Turn left, following Pa. 901, and proceed west along abandoned strip mines to left and right.

- Town of Excelsior.

- About a mile west of Excelsior - large abandoned strip mines on right showing orange colors. Large outcrop on left; pull off and stop.

STOP 11.

EXCELSIOR

STOP 11.

Coal-bearing Strata
Possible Cyclothems
Sedimentary Structures
Lateral Facies Changes

This stop will be made only if time permits. The stop is new this year, and has not been pre-examined in detail, so the following descriptions are approximate and in need of revision. Most of the information has been taken from photographs. We thus need your help in gathering detailed lithologic and structural data for these rocks, so that a more coherent summary may be presented next year.

The rocks in this outcrop belong to the Llewellyn Formation, and probably occur low in the unit; the road is nestled up against the Pottsville ridge on the south, and this spot is not far from the ridge. The rocks are probably lower to middle Pennsylvanian in age, and can be precisely correlated with rocks in western Pennsylvania and Ohio. The Llewellyn is structurally beat up, and these units here probably do not carry across the valley without folding and faulting.

The rocks consist of interbedded sandstones, siltstone-shales, and black rocks resembling organic-rich shales. There may or may not be true coal in this outcrop. The generally dingy, dark color of the rocks is due to fine-grained plant remains, which have been distilled to the carbon residue you see. The sandstones have not been washed and sorted, and all the rocks are probably quite immature.

The most interesting aspect of this outcrop is the manner in which the lithologies are related to each other. A sketch map is provided on the next page to help you in tracing units through the outcrop. The different rock units are vertically interbedded in several different ways. The focus of interbedding is on the contacts between lithologic units; pay attention to whether they are erosional, scoured surfaces, or gradational over some distance. There are several undoubted erosion surfaces in the outcrop; un its are of quite irregular thickness, and often fill depressions in the tops of underlying beds. Several other contacts appear gradational, but when you look closely they may in fact be erosional.

The rocks appear to contain well-developed primary structures. The lowest sandstone is cross-bedded, as is the sandstone at mid-crop level. Channeling is developed in several units. Look at the rocks closely, on a small scale, and you will probably find many more primary structures.

Although these rocks belong to what we have called the Cyclothem Association, it is hard, in this outcrop, to recognize any sedimentary sequence that is indeed repeating or cyclic. Maybe we are looking at a small part of a larger cyclothem; maybe we don't know how much variation to allow and still call it a sequence. Eastern Pennsylvania is not known for well-developed cyclothems; they are more common and spectacular in western Pennsylvania and the Mid-Continent.

One feature contributing to non-repeating lithologies here is the lateral impersistence of rock units. Lithologic units change shape along the outcrop, and some almost die out entirely. The black, almost-coal bed thins, over a "high" near the center of the cut, and thickens to either side. The bed immediately below the almost-coal nearly disappears to the west, below a probable erosion surface. The channel sand at the east end, if it is in fact a channel sand, is lens-shaped. The resulting picture one gets is of a depositional environment with ultra-rapid lateral facies changes- bedrock islands of "highs" in low-lying areas, probably swamps, which were flanked by encroaching forests and other organic growths. These conditions are identifiable in the Recent in the Everglades and other swamps.

Fluvial fining-upward cycles, which are expectable in Cyclothem Association rocks, may or may not be present here. It depends on what one expects the cycles to look like. We can argue about this point if you like.

Note the delightful sight on the other side of the road. The large hole in the ground is an abandoned strip mine, which probably took coal out of close relatives of these rocks we are looking at.

<u>Projects</u>:

- Trace lithologic contacts to see if they are gradational or erosional.
- Look for fluvial fining-upward cycles.
- Look for sedimentary structures.
- Examine the rocks, and name the lithologies.
- Report your findings to trip leaders, and correct any misstatements in this description and diagram.

ROUTE TO STOP 12. (5 miles)

- Continue west on Pa. 901.

- Turn left onto Pa. 61, westbound. Outcrops along onramp are steeply dipping, fractured sandstones of Llewellyn Formation. They are relatively barren, above the lowest coal-rich zones.

- Enter Shamokin. This city is the center of the coal industry in the Western Middle Anthracite Field, and is relatively wealthy compared to other coal towns. Continue on Pa. 61.

- To right all through town - the high hill to right is a tailings dump for strip and underground mines high on the hill. Although nestled up against a high Pottsville ridge behind, all you can see here is nam-made, moved earth; you can't see the ridge itself.

- In several places you can see smoke and steam rising from the tailings dump -- there is enough unoxidized carbon in the waste rock to catch fire, and subterranean fires are continually burning on this mountain.

- Turn left onto Pa. 125, southbound, and continue through Shamokin and out the south side.

- In center of town - if you look back to right rear you can see the lip of a tailings dump projecting out into the gap. The slip face is at the angle of repose, i.e. the maximum inclination it can stably maintain without sliding down into the valley. Think what a slight earthquake would do.

- Pa. 125 turns sharply left and starts up a hill. Continue straight ahead on paved road, through village of Bear Valley, to end of paved road.

- Turn right onto dirt road. Climb hill, turning first left, then right, for 0.25 mile to point where road levels off and widens. Pull off and stop.

- DINNER. In the Scenic Appalachian Mountains!

- Descend along inclined rampway, avoiding old stoves, tires, etc., to gap in tailings piles. Go through gap, and look to left.

- STOP 12.

BEAR VALLEY STRIP MINE

STOP 12.

Llewellyn Formation
Pennsylvanian Plant Fossils
Complex Structure of Allegheny Orogeny

This outcrop contains some of the best displayed structure and fossil in the entire Appalachians, and provides a reasonably spectacular final stop.

Suggested Procedure:

The best way to systematically examine this outcrop is:

1. Read the guidebook description of the setting and the rocks.

2. Proceed to the lower levels and examine the mine and the structure. Take your guidebook and hammer along, as you will need them.

3. Slowly work your way back up to the road level continuily collecting plant fossils.

THE SETTING.

The rocks here in the Bear Valley strip mine are part of the Llewellyn Formation, a sequence of conglomerate, sandstone, shale and coal which occupies the entire valley. Its outcrops underlie the Western Middle Anthracite field, which includes the towns of Shamokin, Mount Carmel, Shenandoah and Mahanoy City. The Western Middle field comprises a tightly folded syncline, with the Pocono Sandstone and Pottsville Conglomerate forming the major ridges on the borders of the fold (see Afternoon Map); we just came across the Pottsville ridge forming the southern margin of the coal basin. The Pocono and Pottsville sandstones are extremely strong, competent and hard to deform, and during formation of the syncline they transmitted the stress without being greatly affected. The overlying Llewellyn, however, containing weak lithologies, absorbed most of the stress, and deformed extensively. Some of the resulting structures are seen in the strip mine.

As the major syncline developed, the competent limbs of Pocono and Pottsville closed in on the weak Llewellyn like jaws of a vise, and caused much internal folding and thrust faulting near the margins of the syncline. The thrust planes dip steeply toward the center of the syncline, and the inner blocks have moved up and past the outer blocks. A good analogy is the sliding of inner sheets up and over outer sheets when a thick stack of sheets of paper is down-folded in the center; each slip plane represents a thrust fault. One of these thrust faults may be exposed in the mine.

As a result of the intense folding and thrusting, the mineable coal beds have been difficult to locate; consequently the entire valley has been torn up in the search.

THE ROCKS.

The Llewellyn Formation, which contains the coals, includes all post-Pottsville strata in eastern Pennsylvania, and in this area consists of 1900-2000 feet of interbedded conglomerate, sandstone, shale, organic shale and coal. The initial thickness is not known because of modern erosion. The formation contains more than 30 mineable coal beds, with 10 of those in the lower 300 feet.

No rock in the Llewellyn contains marine fossils; the considerable amounts of finely disseminated organic matter are due to the presence of abundant terrestrial plant remains. Precise time correlations of these plant species with those in the coals of western Pennsylvania and the continental interior establish the Middle Pennsylvania age of the rocks, and support the idea that these rocks are the eastern, landward equivalents of time-equivalent marine deposits of the Mid-Continent.

The Llewellyn, classically, contains cyclothems, i.e. repeating alternations of sandstone, shale and coal. However, cyclothems have not been recognized in the anthracite fields, due largely to the continental nature of the deposits, the nearness to the sediment source, and the complex deformation.

THE MINE.

The Bear Valley strip mine consists of an elongate gouge in the ground about 100-150 feet below road level and extending westward from this site for several miles. The coals taken out from this mine were the Mammoth No. 8 and No. 8-1/2 coals, totalling about 20 feet in thickness. These coals occur in the basal 300 feet of the Llewellyn Formation, and crop out low on the flanks of the Pottsville ridge forming the southern margin of the basin; the ridge is just beyond the south face of the mine. We will examine the eastermost part of the mine.

Almost all lithologies in the Llewellyn can be seen in the mine, except coal; every piece of coal has been picked up. In the east face of the pit, several thin coal zones can be seen, these are too thin to be economical, and are left behind. The south wall of the mine is composed of carbonaceous shale (not coal), which directly underlay the coal which was mined.

Many parts of the mine, particularly the south wall, contain numerous large concretions made up of siderite (iron carbonate, $FeCO_3$). Siderite was chemically precipitated secondarily, after deposition of the sediment, probably in stagnant-water environments which became deficient in oxygen.

THE STRUCTURE.

The economics of strip mining dictate that a minimum of rock other than coal be moved; therefore strip mining is prone to mine around rather than through structures, and to leave the structures behind. Abundant evidence of this procedure is exposed in the mine.

A mined-out, isoclinal anticline forms the base of the strip mine. No better example of folding and fold geometry is exposed anywhere. It is possible to walk out on the crest of the anticline, but be EXTREMELY CAREFUL, AND DO NOT APPROACH THE EDGE, for the drop is stratight down for 50 feet. You can attempt to locate the crest and axis of the anticline by walking it out.

Even more spectacular than the anticline is its termination. This anticline abruptly disappears at east face of the pit, and is replaced in that wall by a symmetrical, open syncline strikingly outlined by light-colored sandstones. The anticlinal axis can be traced to within 10 feet fo the syncline. This structural juxtaposition is quite difficult to interpret, and presents a good exercise in geologic reasoning. So try your luck: How do you explain your ability to look along the axis of an anticline directly into the axis of a syncline? Hints:

1. To the left of the syncline on the east wall, there occurs an asymmetric anticline, whose north limb is overturned. This could be the continuation of the anticline in the pit. However, if so, the axis must take a right-angle bend to be continuous and yet so close to the syncline axis.

2. Consider why the coal company stopped mining at this particular place: could it have anything to do with the disappearance of the anticline? Perhaps there is a cross-fault between anticline and syncline, and the coal company mined up to the cross fault and stopped.

3. Consider next the extensive bedding plane forming the south wall of the pit. This slopes to the bottom of the pit, below the level of the anticlinal crest on which you stand. Intuitive ideas of continuity would suggest that the bed exposed on the south wall is the same as that capping the anticline on which you stand, i.e. that there is a small syncline between the two anticlines. Likewise, the wall on the north side is anticlinal, and borders another small syncline. In this case, there is no break in the sequence.

4. Consider next the southeast corner of the pit, where the synclinal east wall meets the extensive bedding plane of the south wall. The bedding plane, while dipping steeply, contains some large wrinkles, which are not reflected in the overlying synclinal sequence. This lack of continuity of structure would suggest that the two sequences are in fault contact, and that the contact is a thrust fault, with the synclinal sequence moved up relative to the bedding plane.

If this is true, and if number 2 above is also true, then the thrust fault must pass through the pit at the east end, between the anticline and the wall. But this is not how you would expect the thrust fault to behave; you would expect it to parallel the long dimension of the valley, i.e. parallel the length of the mine.

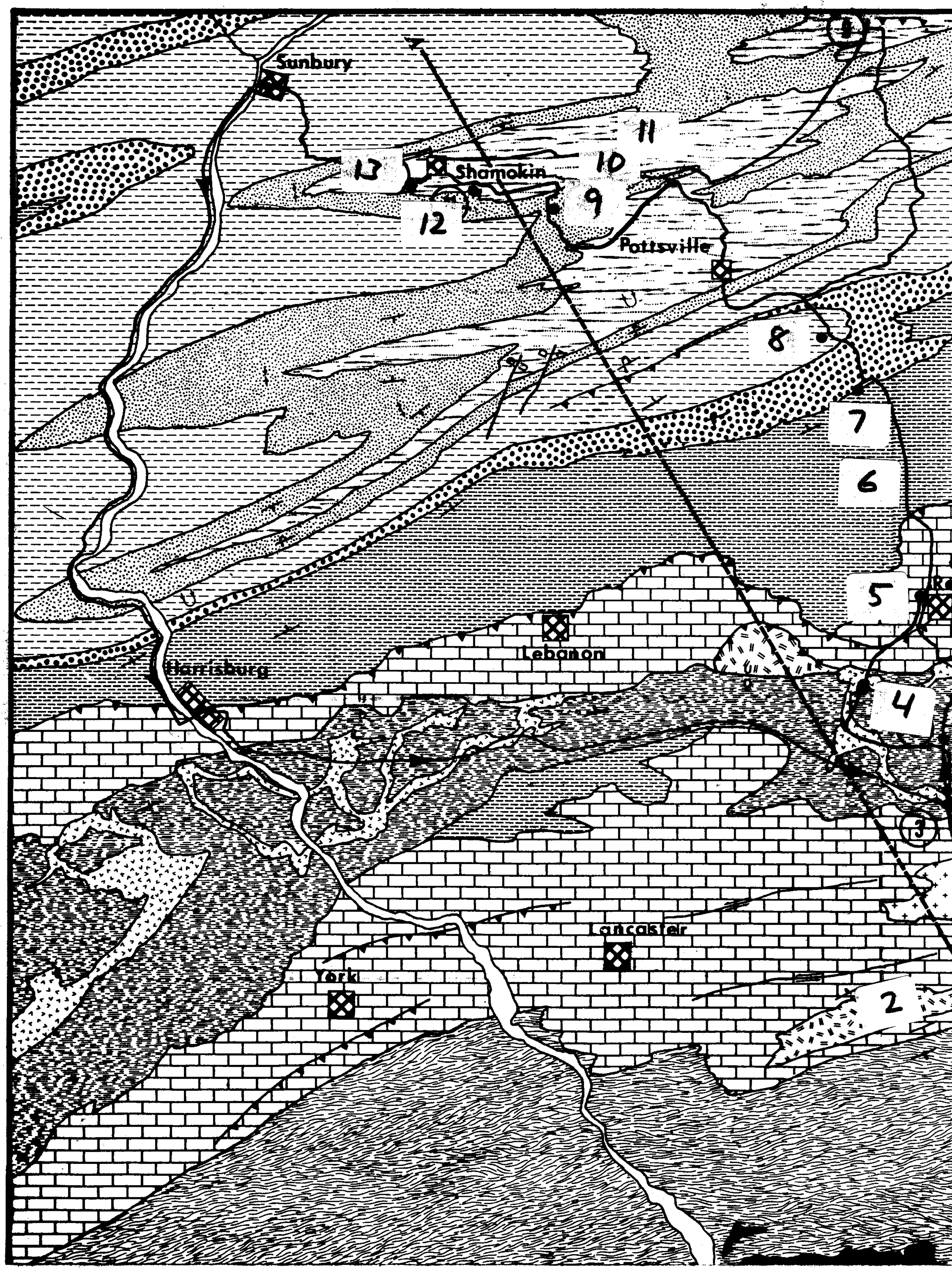
In summary, your opinions are as good as anybody else's.

THE FOSSILS.

The debris from the mining operations, which may be found anywhere in the mine area, contains abundant fossil remains of terrestrial plants. Most of the plants occuring as fossils were unique to the Pennsylvanian Period, and include scale trees, other types of trees and large plants, ferns, and other plant types. Diagrams of the more commonly found plant types are shown on the following page. Leaves, bark, stems, scales, branches, logs, and occasional stumps and other parts of the plants may be found in abundance. Virtually every piece of shaly rock is fossiliferous. Collect away, with the coal company's blessings; the best collecting is probably on the tailings piles at road level.

<u>Projects</u>:

- Account for the juxtaposition of anticline and syncline.
- Decide whether a thrust fault is or is not necessary to explain the observed structure.
- Collect plant fossils.
- Note the rape of the land.


Sunbury
Shamokin
Pottsville
Harrisburg
Lebanon
Lancaster
York
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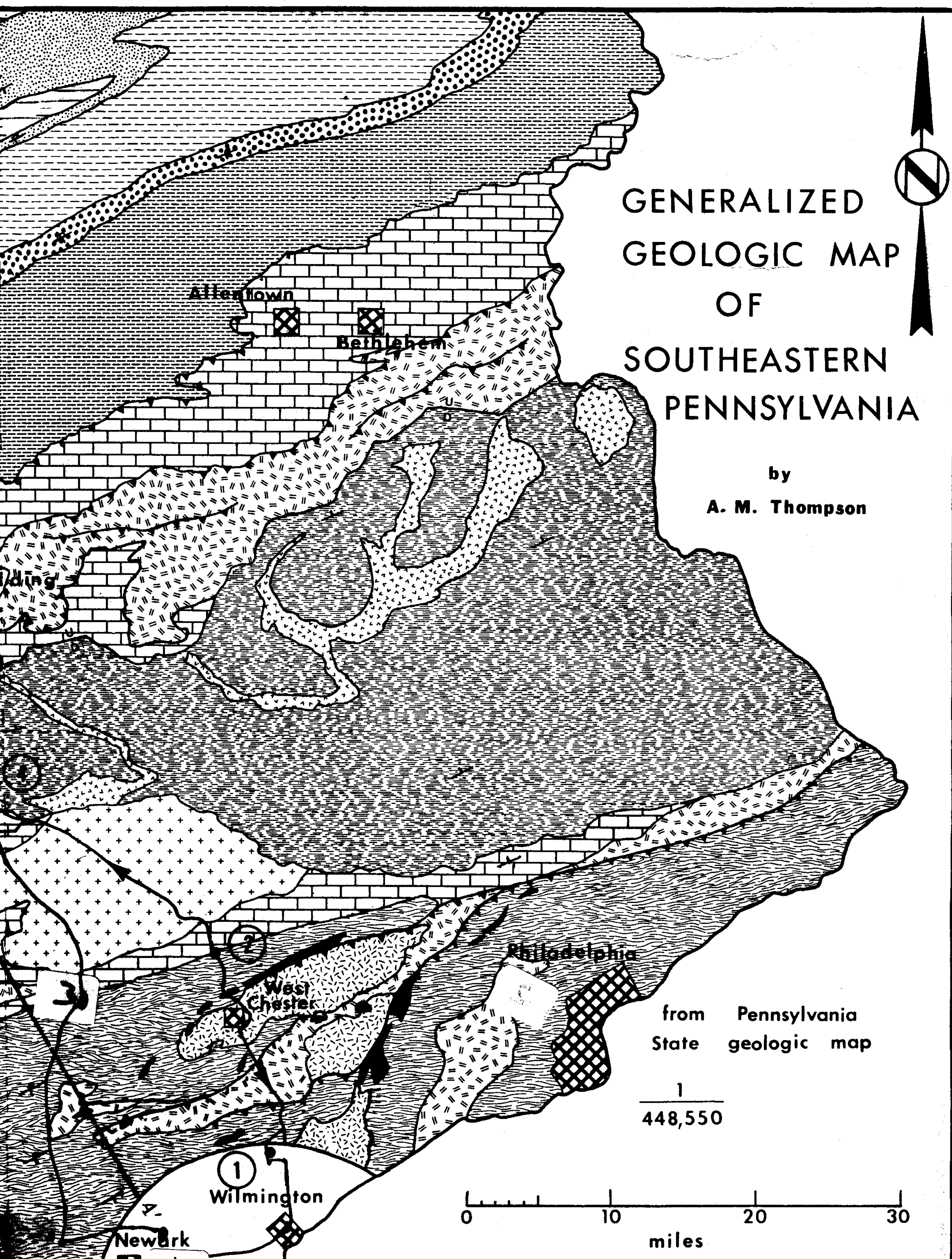
GENERALIZED
GEOLOGIC MAP
OF
SOUTHEASTERN
PENNSYLVANIA
by
A. M. Thompson
Allentown
Bethlehem
ding
West Chester
Philadelphia
Wilmington
Newark
from Pennsylvania State geologic map
1
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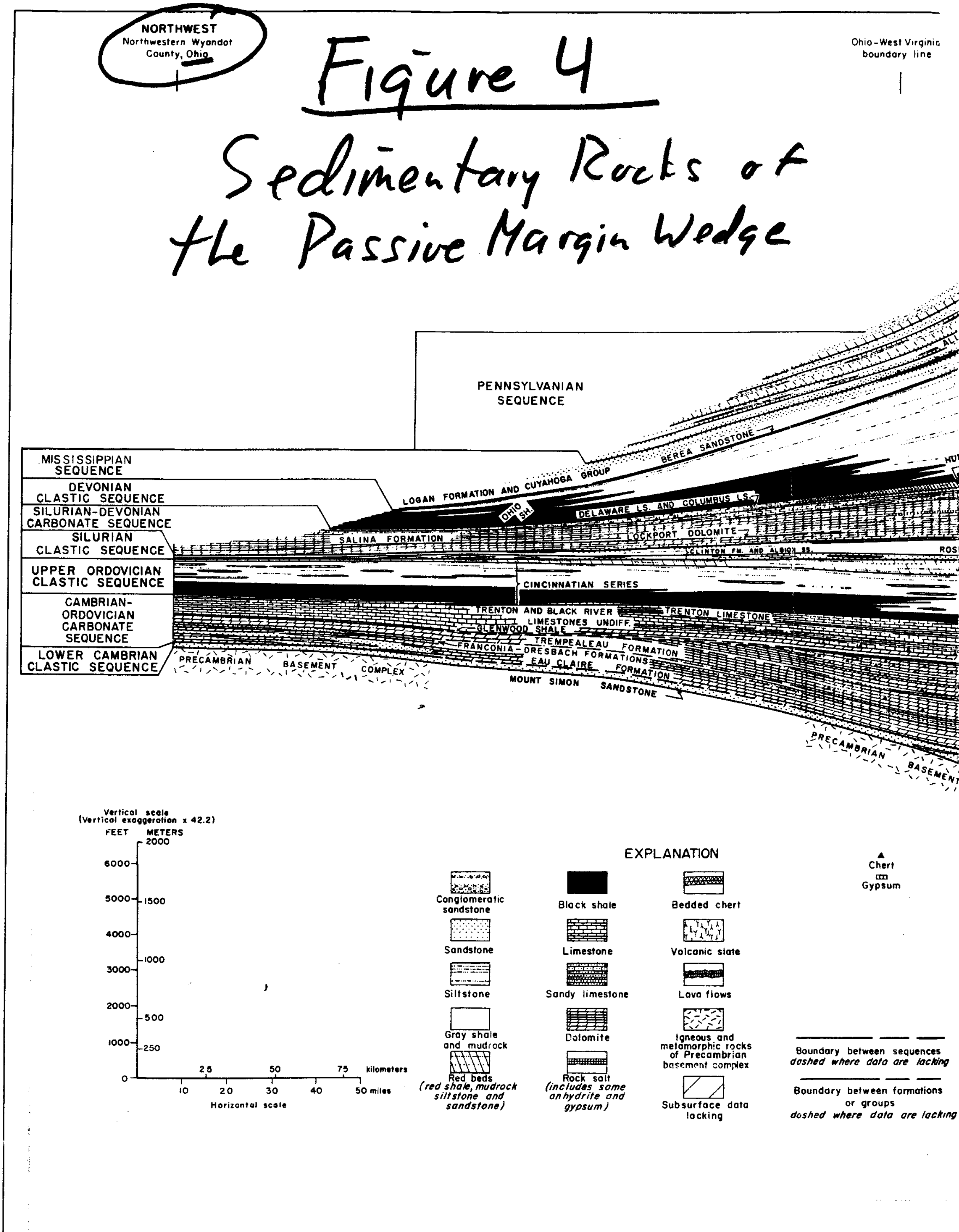
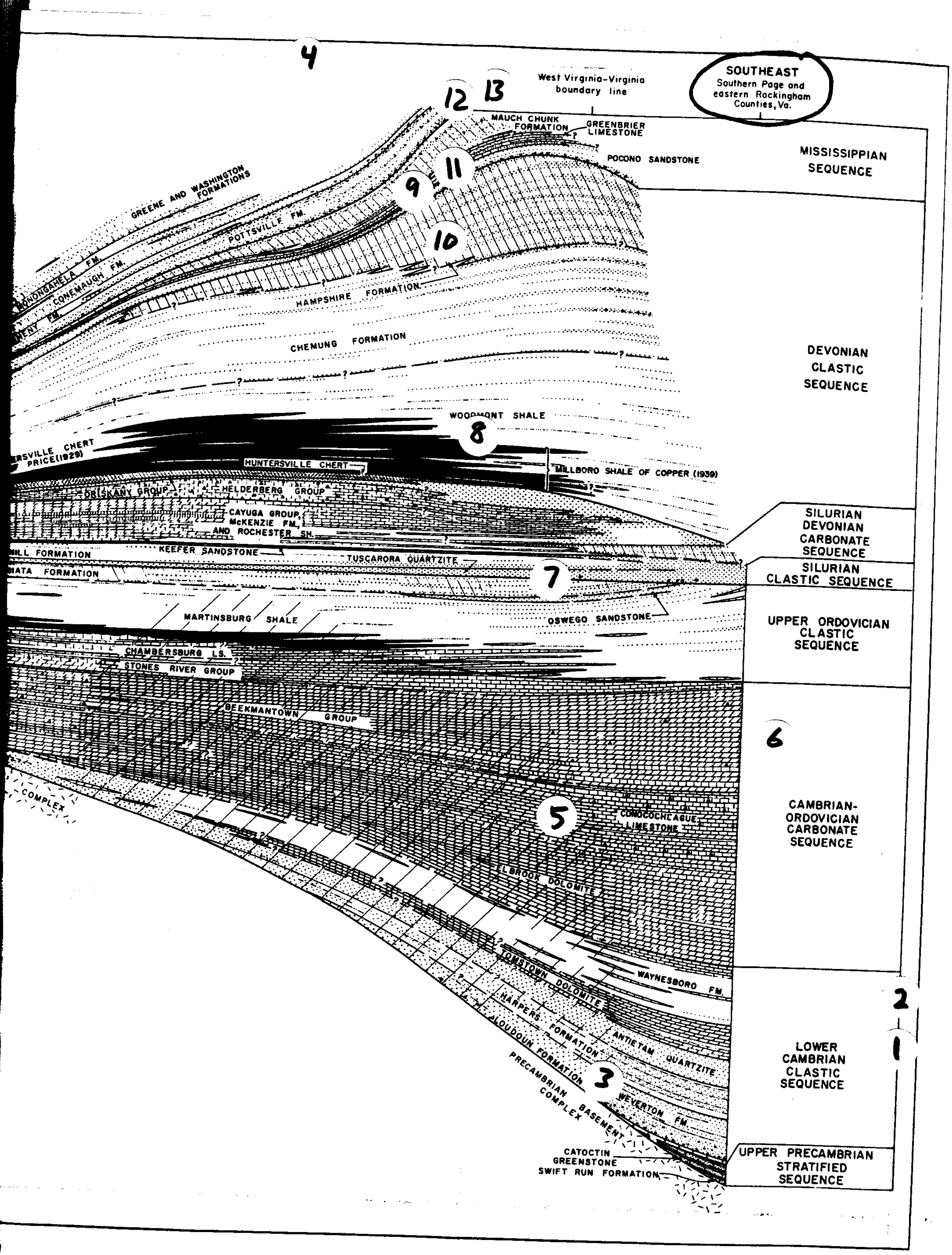
miles

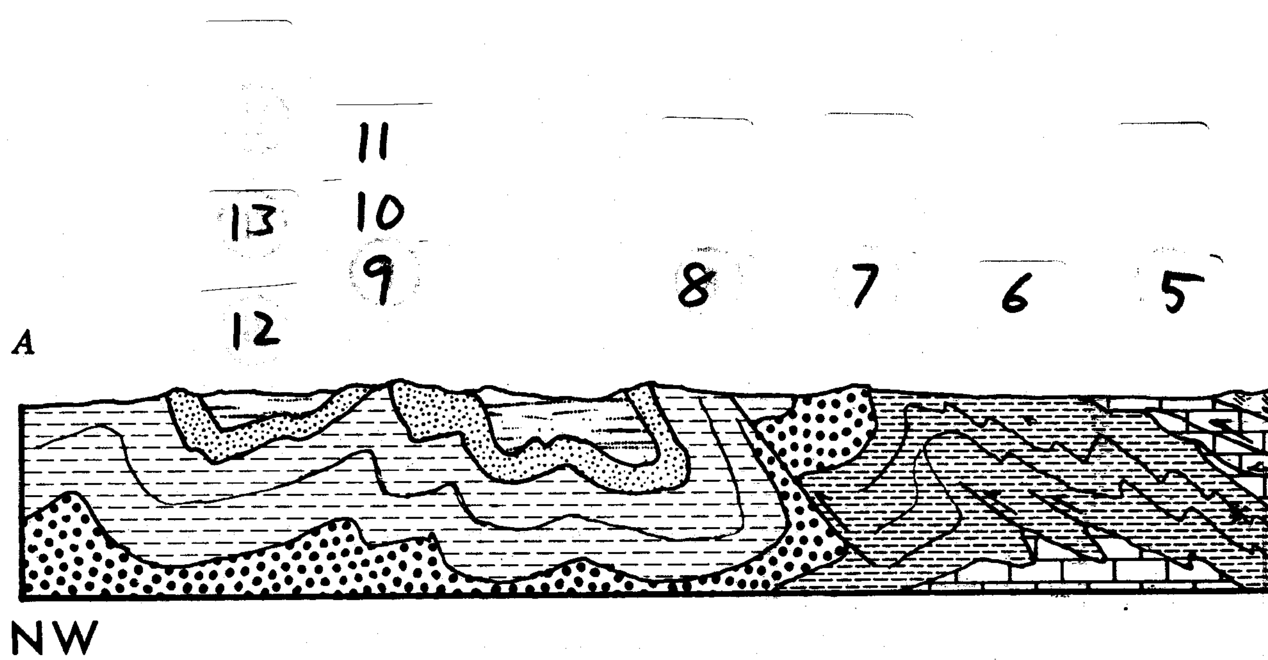
Figure 4

Sedimentary Rocks of the Passive Margin Wedge

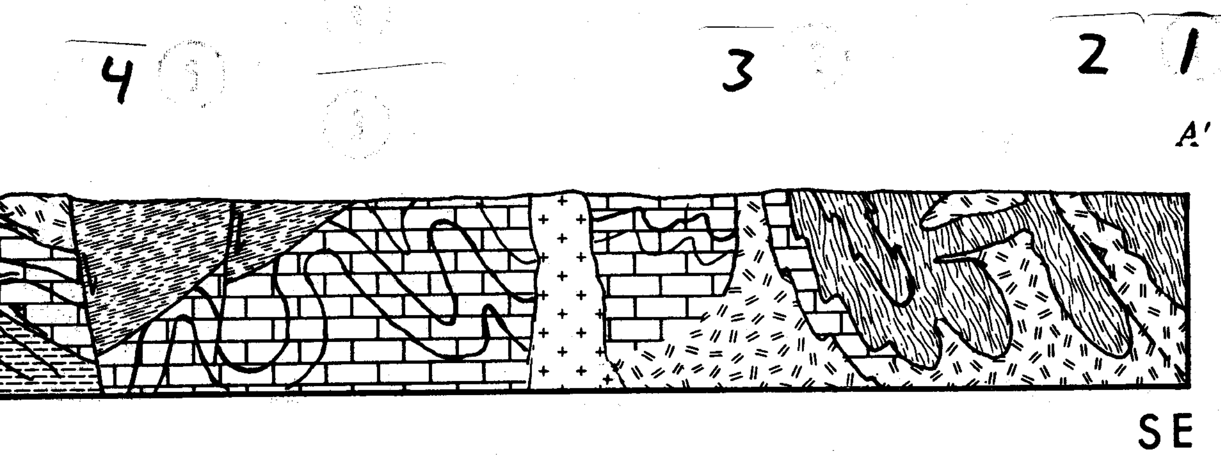




SOUTHEAST
Southern Page and eastern Rockingham Counties, Va.
West Virginia-Virginia boundary line
MAUCH CHUNK FORMATION
GREENBRIER LIMESTONE
POCONO SANDSTONE
MISSISSIPPIAN SEQUENCE
GREENE AND WASHINGTON FORMATIONS
POTTSVILLE FM.
MONONGAHELA FM.
CONEMAUGH FM.
HAMPSHIRE FORMATION
CHEMUNG FORMATION
DEVONIAN CLASTIC SEQUENCE
WOODMONT SHALE
PRICE (1929)
HUNTERSVILLE CHERT
MILLBORO SHALE OF COPPER (1939)
ORISKANY GROUP
HELDERBERG GROUP
CAYUGA GROUP, McKENZIE FM., AND ROCHESTER SH.
KEEFER SANDSTONE
TUSCARORA QUARTZITE
SILURIAN DEVONIAN CARBONATE SEQUENCE
SILURIAN CLASTIC SEQUENCE
MARTINSBURG SHALE
OSWEGO SANDSTONE
UPPER ORDOVICIAN CLASTIC SEQUENCE
CHAMBERSBURG LS.
STONES RIVER GROUP
BEEKMANTOWN GROUP
CONOCOCHEAGUE LIMESTONE
ELBROOK DOLOMITE
CAMBRIAN-ORDOVICIAN CARBONATE SEQUENCE
WAYNESBORO FM.
TOMSTOWN DOLOMITE
HARPERS FORMATION
ANTIETAM QUARTZITE
LOUDOUN FORMATION
WEVERTON FM.
PRECAMBRIAN BASEMENT COMPLEX
COMPLEX
LOWER CAMBRIAN CLASTIC SEQUENCE
CATOCTIN GREENSTONE
SWIFT RUN FORMATION
UPPER PRECAMBRIAN STRATIFIED SEQUENCE



SCHEMATIC CROSS - SECTION



ALONG LINE A-A'