GEOLOGY 305

SUSQUEHANNA RIVER FIELD TRIP

OCTOBER 16, 1993

DUCTILE DEFORMATION IN AN OROGEN:

FOLDS AND FOLIATIONS

<u>THEMES OF THE TRIP</u>:

folds and fold style

folds and tectonic transport

folds and foliations

cleavage and bedding

variation across and orogen

STOP 1

BLUE MOUNTAIN

THE ROCKS:

Exposed here are the following (see Figure 1):

Rose Hill Formation -	Silurian, shale and sandstone
Tuscarora Formation -	basal Silurian, gray sandstone and some shale
Juniata Formation -	Ordovician, red sandstone and conglomerate
Bald Eagle Formation-	Ordovician, gray quartz-pebble conglomerate
Martinsburg Formation-	Ordovician, gray shale and sandstone

These are all units of the Appalachian Basin, a Silurian and younger, foreland sedimentary basin that developed atop the Cambrian-Ordovician continental-margin platform sequence in response to the Taconic and later orogenies. All the units exposed here are part of the Taconic clastic wedge, a large slug of sediment shed source lands east and south of here. The clastic wedge is the sedimentary response to the Taconic orogeny of late Ordovician time.

REGIONAL STRUCTURAL GEOLOGY:

The structural relations involve not only these Ordovician and Silurian rocks here, but Devonian to Pennsylvanian rocks farther north also, and so must have post-dated deposition of those rocks. These structures here belong to the Alleghanian orogeny, of middle to late Pennsylvanian age. They are typical of deformation in the Valley and Ridge province from western New York to Alabama.

STATION 1: SOUTH END OF THE FENCE

Begin your examination with the Martinsburg rocks at and just south of the south end of the guardrail, and work your way north to the Juniata-Tuscarora contact behind the fence. Observe the strongly cleaved shales of the Martinsburg, and the faulted and folded rocks of the Bald Eagle, Juniata and Tuscarora formations.

Note that the cross-section shows Martinsburg-younger rocks contact up the slope as a **thrust fault**, with Martinsburg moving North (parallel to its cleavage) over the younger rocks. Try hard to locate and examine the actual contact, and look hard for slickenlines and other evidence of faulting on that surface.

- Which way does the Martinsburg cleavage dip? Take dip and strike.

- If you find slickenlines, look for steps; which side moved which way?

The Bald Eagle conglomerate here is the eastward-pinching-out, coarse, proximal feather-edge of a conglomerate-sandstone unit that reaches more than 1000 feet thick 30 miles west of here.

- From the composition and size of the pebbles, what was the overall makeup of the source area being eroded to supply the sediment?

- Can you find bedding in the Bald Eagle? If you can, measure dip and strike.

- Describe the Bald Eagle rock and the Juniata rock. How are they different? Different enough to warrant calling them two different formations instead of variations within a single formation?

- Describe the Bald Eagle-Juniata contact. In its present incarnation, is it stratigraphic or structural? (i.e. deposited or faulted?) What's your evidence?

- Examine the pervasive, small-scale faulting in Bald Eagle and Juniata. Any consistent orientations? Any consistent offset senses? Any consistent relation between orientation and offset sense?

- Is the Juniata -Tuscarora contact depositional or structural? What's your evidence?

- In what ways do the Juniata and Tuscarora formations differ?

STATION 2: JUST SOUTH OF THE RED VINES

- Sketch the folds in the rocks low on the cut at this stop. Show axial surfaces, and see whether the folding is rounded and continuous or can be separated into distinct hinges on a box fold:

STATION 3: JUST NORTH OF THE RED VINES

This station is near the top of the Tuscarora Formation; note the ratio of sandstone to shale. The Rose Hill Formation traditionally contains predominantly shale; look for a further decrease in sandstone/shale ratio going north.

- Sketch the relations in the small fold low on the ouctrop here.

- What kind of folding here? Parallel or similar? Flexural or passive? What's your evidence?

- Look for slickenlines on the sandstone surfaces. If you find any, what orientation of movement relative to fold axis?

- What is the relation of the two folds (left and right) to each other? Any other structures present? Are they mutually related? How?

- Any tension gashes in the sandstones? If you find any, draw them in relation to orientation of bedding.

- As you go north, look for cross-bedding and other evidence to determine whether the rocks are right-side up or overturned. Sketch some cross-beds and their bed boundaries.

STATION 4: 50 FEET NORTH OF CHANGE IN FENCE HEIGHT

- This location is low in the Rose Hill Formation. Any noticeable difference in general lithology between this and the Tuscarora of Station 3? What criteria do you think the original workers used to distinguish the two formations?

- Find the small fold low on the outcrop face. Describe this fold: aspect ratio, angularity, bluntness, symmetrical/asymmetrical, upright/inclined/recumbent, parallel/similar, flexural/passive/solutional, etc. Do a number on it.

Examine the fold in detail:

- Look for evidence that the sandstones deformed by orthogonal flexure: look for extensional strain on the outside edges and compressional strain on the inside edges. Draw the fold in profile view, and show the small-scale features you found:

Trace the bedding around the fold to the north:

- How far does the fold continue to the north? What happens? Draw the relationships:

- What direction does the fault dip? Any slickenlines to indicate motion?

- What is the sense of offset on the fault? Is the fault normal or reverse?

- Leaving Station 4, stand back at fence and see if you see other N-dipping faults in the crop. Do they have the same motion sense as the Station 4 fault? I.e. is there a **set** of N-dipping faults with the same offset? Use the outcrop diagram as a help here.

IN SUMMARY:

- Which direction do the beds face? Toward older or younger rocks?

- Which direction do the beds dip? Toward older or younger rocks?

- Are the rocks right-side-up or upside-down?

- What larger structures are these beds a part of (at least logically based on our present evidence)?

- If beds are upside-down, in which direction are the larger structures overturned? i.e. in which direction do they **verge**?

- Draw the larger structure, and show the present ground level running somewhere across the middle of your diagram:

- Now reconsider the thrust fault at the base of the Martinsburg. In its present position, the postulated motion was hanging wall moved north. Would this movement sense be consistent with the vergence of the larger structures?

- If you like that conclusion, what would be your postulated age of thrusting relative to age of folding?

- But suppose the thrusting was pre-folding, i.e. the thrusting, with the indicated **relative** offset sense, occurred before the rocks, both hanging wall and footwall, were folded into their present position. What would then have been the direction of thrusting and dip of cleavage?

- Sketch what the thrust fault and cleavage would look like if you unfolded the larger structures back to horizontal.

- What would then be the geometric relationship between the thrust-movement direction and the vergence of the larger structures?

- Sketch what that relationship would look like:

- Which scenario do you like better, pre-thrust folding or post-thrust folding? Why?

STOP 2

LITTLE MOUNTAIN

The Rocks: **MONTEBELLO FORMATION**, Middle Devonian deep-marine coarse sandstones and shales, of the lower parts of the Catskill clastic wedge. See Figure 1 for stratigraphic position of these rocks.

PROCEDURE:

Stay on the grass: stay off the paved shoulder. Traffic is dangerous here.

Examine the rocks up close, note whether they show evidence of strain in hand sample.

Examine the outcrop carefully, by walking the length of it from north to south. Look for the following features:

- **bedding:** how do you define bedding? What do you base your definition of bedding on? Convince yourself that this bedding is truly compositional layering as well as textural layering.

- **attitude of bedding:** what, in general, are the strike and dip of bedding?

- **facing direction of beds:** which direction do the rocks face, and what's your evidence?

- fractures: how do you distinguish fracture planes from bedding planes?

- sets of fractures: how many major sets of fractures in the outcrop? What requirements must be met before fractures can be said to constitute a set?

- Is there a consistent angular relationship between any of the fracture sets? If so, approximately what angle?

- faults: what evidence of faulting can you find? What is offset? Do faults relate to fracture sets in any consistent way?

- Make a sketch of the central portion of the outcrop, and show the relations you just found.

- Which occurred first, the folding or the fracturing? What is your evidence?

STOP 3

LEMOYNE — SPORTING HILL ROAD

THE ROCKS:

The rocks exposed here are very-fine-grained, thinly laminated limestones and black shales of the basal part of the **MARTINSBURG FORMATION**, or late Middle Ordovician age. The Martinsburg is several thousand meters thick in this part of Pennsylvania, and has a basal transition zone about 100 m thick from limestone to terrigenous shale. These rocks are in that transition zone.

REGIONAL STRUCTURAL GEOLOGY:

The regional structural relations in this part of the Great Valley are shown in Figures 2 and 3. Much of the rocks to the west and southwest of here are autochthonous (in-place, not thrusted) Precambrian and lower Paleozoic carbonates deformed in the Blue Ridge anticlinorium fold system of Alleghanian age. We will see these rocks at Stop 4. In this immediate area the autochthonous Martinsburg Formation is overlain by tectonically emplaced allochthonous rocks belonging to the **HAMBURG KLIPPE**. The Hamburg Klippe contains deep-marine sedimentary rocks, volcanic rocks, and tectonic melange, that were tectonically emplaced as thrust sheets within the Martinsburg Formation by either gravity sliding or orogenic thrust-faulting in late Ordovician time, as part of the Taconic orogeny. The Hamburg Klippe is similar in nearly all respects to the Taconic thrust faults and allochthons of Vermont and eastern New York. The thrust sheets, containing more proximal, nearer- (the eastern)-source, coarser-grained sediments were thrust NW over more distal, farther-away, finer-grained sediments. Melange was generated in the thrust zones themselves by tearing off pieces of the hanging wall as it moved. Although lithologically similar to Martinsburg rocks, the rocks in the hanging wall cannot be physically correlated with the Martinsburg, and are not given the name Martinsburg. As of now they have not been formally named.

The rocks exposed here are part of the footwall, the autochthonous Martinsburg Formation. They have not been thrusted as part of the Hamburg Klippe. They were not deformed in the Taconic orogeny; all the deformation here is of Alleghanian age. and includes both folding and some reverse faulting; see Figure 3. The map pattern there shows these relations well; this exposure is the **6** on that map.

PROCEDURE:

Examine all parts of the outcrop. Notice how "small", small-scale, and delicate the structures here seem to be compared to those at stops 1 and 2.

Examine the **BEDDING**:

- Look for primary sedimentary structures: graded bedding? (these rocks have been called distal turbidites by others) cross-lamination? truncations? others?

- Based on the structures, which way do the beds face? Left is North, right is South.

- Determine the strike and dip of bedding.

- Based on facing, is the bedding right-way-up or overturned?

- Which direction to the nearest syncline axis?

Check out the **STRAIN WITHIN BEDS**:

- Which rock is more competent? the shale or the limestone? What's your evidence?

- Would you describe the competence contrast as "large" or "small"? Why?

- Look in the competent beds: any evidence of **extension** within the beds? What structures indicate extension?

- What do gash veins perpendicular to bedding mean about the orientation of strain relative to bedding, and about the orientation of stress relative to bedding?

- Sketch a portion of a bed showing extension features. Show tension gashes and incipient boudinage.

- Look in the competent beds for evidence of **shortening**: look especially for **wedge thrusts** and **stylolites** normal to bedding. Sketch a bed showing both extensional features and shortening features.

- But how can the same bed have both extensional and shortening features? isn't that a contradiction? Explain.

Now examine the **FOLDING AND FOLD STYLES**: There are at least two kinds of folds here: folds **within** the bedding, and folds **of** the bedding. Folds within the bedding, called intrafolial or floating or rootless folds, fold only one or two layers, and form enclaves of folded rocks surrounded by unaffected layers that are not folded. Folds of the bedding, on the other hand, affect all layers, including the intrafolial folds, and are clearly later than the intrafolial folds.

- Pick a partner; one of you describe an intrafolial fold, the other describe a fold of the bedding. Compare and share. Any differences in shape or style or properties between the two.

- Is the folding dominantly flexural or passive? Any direct evidence for either type?

- Sketch an intrafolial fold and its relations to the surrounding bedding.

- Folds of the bedding are generally asymmetric, of unequal limb lengths, and may be described as **drag folds**. As you look at them, are they S-folds or Z-folds?

- If you can find one, measure the plunge of a drag fold axis.

- What is the sense of shear on the drag folds? State in terms of south side up or down and to north or south.

- Sketch a drag fold, and indicate the sense of shear.

- How does the shear sense here compare with that at Blue Mountain? What could that tell you about regional strain and stress patterns?

- Some fold axes appear to plunge steeply down the dip (= reclined folds?), while others appear to plunge gently. Why should there be two plunge directions in the same outcrop?

- Look for <u>**CLEAVAGE**</u> in both the limestones and shales. How well developed is cleavage in these rocks?

IN SUMMARY:

- Work out a deformation history for these rocks. How many generations of structures (= how many distinctly different strain types and stress fields) do these rocks record? Label them F_1, F_2, etc.

STOP 4

HAMMONDS ROCKS

THE ROCKS:

The rock here is well-sorted, super-mature quartz-pebble conglomerate and quartz arenite sandstone of the **CHICKIES FORMATION (WEVERTON** if you're in Maryland), of very late Precambrian or very early Cambrian age. The writeup below discusses the sedimentology of the rocks in the exposure.

REGIONAL STRUCTURAL GEOLOGY:

The Chickies Formation here is int he core of the **BLUE RIDGE ANTICLINORIUM**, a major NW-verging fold system that can be traced from near Harrisburg southwestward into North Carolina. The folding was part of the Alleghanian orogeny of middle to late Pennsylvanian time. The anticlinorium contains middle Precambrian gneiss/granite in the core, which is overlain by late Precambrian volcanic rocks (both basalt and rhyolite). Above the volcanics lie thick accumulations of very late Precambrian clean sandstones (including the Chickies) and early Paleozoic carbonate rocks (e.g. Rheems quarry rocks). In mid to late Pennsylvanian time all these rocks were stressed from the east to the west, and were deformed into a huge overturned fold system, with west limb overturned and dipping east. In most places south of Pennsylvania the overturned limb tore off and is now represented by a thrust fault, the **Blue Ridge Thrust**, with many tens of miles of displacement on it. Here in Pennsylvania the lateral shear was not as strong as farther south, and the fold structure remained intact. Toward the NE, toward Harrisburg, the folding dies out (or disappears from view through covering by later thrust sheets). See the map in Figure 2.

The following material on the sedimentary aspects of Hammonds Rocks is by Henry Hanson, and was taken from the Harrisburg Area Geological Society guidebook of 1982.

HAMMONDS ROCKS

Hammond's Rocks is one of a number of natural exposures of the Lower Cambrian (?) Weverton Quartzite along the crest of South Mountain. This outcrop differs from others of the Weverton nearby in its large size, bold topographic expression, and coarseness of the sediment. Exposure of conglomeratic Weverton is not particularly unusual, but most of the natural exposures are sandy rather than conglomeratic. The Weverton Quartzite was named by Keith (1893) at exposures along the Potomac River in Maryland. The thickness of the unit is probably 1200-1400 ft. (Fauth, 1968). No fossils have been found in the Weverton, but Early Cambrian fossils have been reported from overlying quartzites (Fauth, 1968). The unit is therefore generally assumed to be Early Cambrian. According to John Fauth (personal communication, 1982), who has mapped the Weverton in Maryland and Pennsylvania, there are substantial changes in the lithology along the strike of the unit that probably reflect a variety of depositional environments. Fauth (1968), working in the Caledonia area west of Hammond's Rocks, describes, but does not include on his map, four "lithologic intervals" in the Weverton. The basal member is phyllitic graywacke and quartzose graywacke. The lower middle interval is phyllitic quartzose graywacke. The upper middle interval is a graywacke conglomerate and the upper interval is protoquartzite and quartzite with thin interbeds of quartz pebble conglomerate. He notes that the two middle intervals are not well exposed. Freedman (1967), who mapped the Mount Holly Springs Quadrangle, including Hammond's Rocks, recognized and mapped two members of the Weverton: a lower conglomeratic member and an upper fine-grained member.

Any geologist who visits Hammond's Rocks has the opportunity to consider three challenges:

1) Interpret the depositional paleoenvironment of the rocks.
2) Gain instant fame by finding some fossils.
3) Interpret the structure of the exposure.

On a clear day, from the top of the rocks, one can get a magnificent view that extends from the southeastern Piedmont to the folded Appalachians.

The sketch map of Hammond' Rocks (Fig. 4) shows several points of interest at the site. The selected points show sedimentary and structural relationships with a clarity that is unusual at the site.

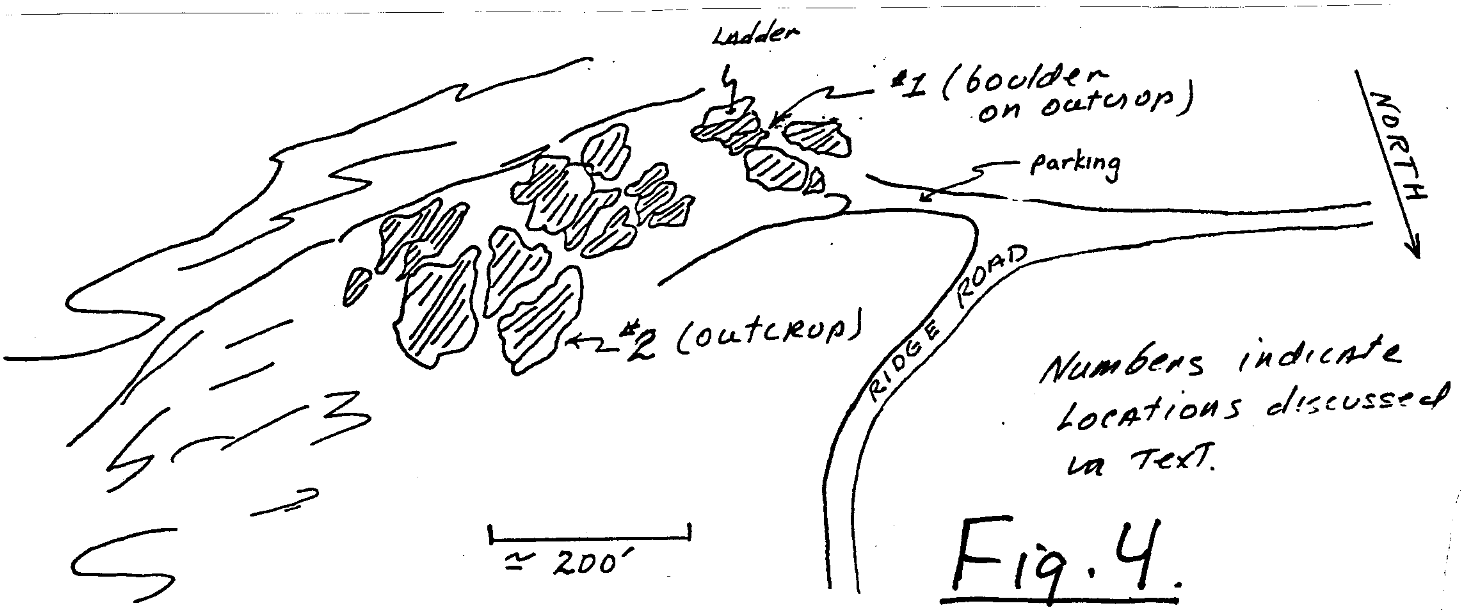


Fig. 4.

PROCEDURE:

There are a lot of rocks to look at here. Walk around at your leisure, be careful of your footing, no showoff climbing, and watch out for snakes soaking up the rays. Be sure to hit the syncline at the far east end, and the cross-bedded boulder at the west end.

Establish which is bedding and which is cleavage, and work at following bedding beneath the cleavage. Keep track of whether either bedding or cleavage or both is of consistent orientation throughout the outcrop. Keep track of which direction you're facing, and use your Brunton to keep oriented.

Examine **the rocks:**

- Use your hand lens to find grains, cement, pebbles. There are probably some small micas here also, that gives some surfaces a certain glimmer. What is the average grain size of the sand grains?

- Examine the pebbles. What composition? What average size?

- Look through the cleavage and define bedding. There are at least four ways to define bedding here: bases of pebble beds, dark thin layers of concentrate opaque heavy minerals like magnetite, graded pebble-sand couplets, and sets of cross-strata. Sketch an example of each below.

The following material on **LOCATION 1** on the map of Figure 4 is also taken from Hanson, HAGS guidebook, 1982.

Location 1

The boulder at Location 1 on the sketch map (Fig. 7) and illustrated in the sketch below (Fig. 8) shows several well-defined beds. The upper bed, about 1.5m of conglomeratic sandstone, is clearly cross-bedded. The maximum angle between the cross-beds and underlying beds is about 40 degrees, which is greater than the angle of repose (35 degrees) for moderately angular material with a 1cm diameter. This suggests thickening of the beds during deformation, perhaps by shear across the cross-beds which steepened their angle to the underlying beds. Cleavage is at an angle of about 75 degrees to the lower bed, a pebbly sandstone, but is refracted in the upper bed, where it is parallel to the cross-beds. The lower bed also shows cross-bedding on a smaller scale, with a different (opposite ?) direction of transport. Scour marks within this lower bed suggest that the boulder is "right side up." What kind of bed forms do these cross-beds represent? Some possibilities seem to be dunes, sand waves, or point bars.

There is both direct and indirect evidence of a somewhat localized paleotransport system, such as a river or tidal channel, at the location of Hammond's Rocks:

1) There is a local concentration of coarse material, exposed in bold relief.
2) There are channel structures, or at least scour structures preserved.
3) Cross-bed sets more than 1 m thick demonstrate the movement of large bed forms.
4) At times the channel(s) probably were on the order of 4 m deep.

The lack of terrestrial vegetation in Early Cambrian time makes it difficult to suggest that there is a strong similarity with modern environments. However, depths of 4 m are typical of rivers flowing over their own sediment and of the tidal channels between modern Atlantic barrier islands. Graf (1971 p.118) considers the ideal, stable cross-section of channels in granular material. According to his model, in an example (p.112), a stream with a depth of 3.7 m and a slope of 0.001 in granular material with an angle of repose of 37 degrees would have a cross-sectional area of 36 m^2 and a discharge of 935 m^3/sec (32,000 cfs). A model, such as this one by Graf, should be taken with great caution when considering ancient sediment transport systems. But it is helpful to know that these sediments may have been deposited by a system that carried, at least at times, a volume of water comparable to the average discharge on the Susquehanna River.

- Examine the cross-bedding in the big boulder at Location 1. Draw the relations between the cross-bedding and the bedding below.

Return now to examining the in-place rocks.

- Is bedding overturned or right-way-up (state where you are when you make your judgment)? What's your evidence?

The following summary of the structural geology here was prepared by Lisa Hardy as part o her senior thesis on the strain in the pebbles.

STRUCTURES PRESENT AT HAMMONDS ROCKS
Lisa M. Hardy, 1987

Here at Hammonds Rocks, you are standing at the northern terminus of the Blue Ridge Anticlinorium. The view to the south and east is into older Precambrian rocks; the view to the north and northwest is into younger, Paleozoic rocks. The rocks in front of you are the highly resistant **Weverton Quartzite** of Lower Cambrian age. The Weverton is in the core of the South Mountain anticline. So, now that you know what you're looking at, what's so important here?

The dominant foliation in the Weverton is northeast-striking, southeast-dipping, axial-plane cleavage. In the fine-grained beds the cleavage may be difficult to distinguish, but in the coarse-grained beds it can easily be found by noting the **elongate quartz pebbles.**

Because the cleavage is so pervasive, original bedding may be difficult to distinguish at first. If you look closely, **cross-bedding** and **heavy-mineral laminae** will help you orient original sedimentary bedding. Once you've located bedding take note of the **bedding-cleavage intersection** at several points in the outcrop. You'll notice that at some points the bedding dips more steeply then cleavage, and sometimes vice versa. This variation suggests that a **fold closure** at outcrop scale is present. See if you can find it.

Probably the most spectacular features here are the **quartz veins** These veins are **tension gashes**, and many are curved, or **sigmoidal**. You'll notice that they occur in a concentrated area in the eastern portion of the outcrop. The exact significance of this uneven distribution is uncertain, but I think it may have something to do with either warping of the axial plane, or a localized shear zone. In any case, the gashes have undergone significant **rotation** during growth. At this point refer to the diagrams in the following pages to help you establish the sense of shear during rotation. Try to establish the sense of shear for various sets of veins. How would you explain what you find?

Within some of the zones, **straight, unrotated, en echelon** gashes overprint the sigmoidal gashes. The lack of rotation, thinness, smallness and overprinting on the sigmoidal gashes indicates that these gashes represent less strain. Do these late-forming gashes show the same sense of shear as the rotated ones they overprint?

Superimposed on both the cleavage and the gashes is a set of NE-striking, vertical **joints**. There's nothing too interesting about them, but you can't miss 'em.

While you're looking at bedding-cleavage intersections in the southwest portion of the outcrop, keep your eyes peeled for narrow (0.25-0.5 inch) **kink bands**. Unlike tension gashes, these are not restricted to one section of the outcrop. See if you can figure out the sense of rotation on the bands. Is it the sane as that of the sigmoidal gashes?

Examine the **CLEAVAGE:**

- Examine the cleavage with your hand lens. What expresses the cleavage?

  Continuous, disjunctive, or spaced?

  What makes up the M-domains?

  What makes up the lithons?

- Draw an example of cleavage intersecting bedding. State where you are in the outcrop.

- Take strike and dip of cleavage somewhere.

- Sketch the relations between cleavage and bedding on the south limb. Again, continue bedding in each direction to the nearest fold closures. Is south-limb bedding right-way-up or overturned?

- Make a careful sketch of the profile view of the syncline as seen from the east end. Lightly show cleavage superimposed on bedding.

- Find the axis of the syncline, and follow it west up the outcrop. Look for the hinge on the west end of the exposure. Determine the plunge of the axis, if you can.

Examine the **STRAIN IN THE PEBBLES**:

- Describe the general shape of most pebbles. Are they essentially one-dimensional or essentially two-dimensional?

- Using a ruler, measure some a, b and c axis lengths for a few pebbles. Multiply the numbers by 2, and draw a-b, a-c, and b-c profiles of one representative pebble.

- Show how the pebble shape is related to the strain ellipse.

- How is the general shape of the pebbles related to the cleavage?

- Would you describe the pebbles as "stretched" in the cleavage or "flattened" in the cleavage?

Examine the beautiful sigmoidal **GASH VEINS**:

- Sketch a sigmoidal gash vein. Show the gashes themselves, the rotated tails, and the sense of shear the produced the vein.

- Where do you suppose the quartz for the gash veins came from? How? What deformation mechanism may have been operating?

- Do the gash veins occur in trains or zones? Sketch an en echelon train of veins, and indicate sense of shear on the zone.

- What kind of mechanical behavior must the rocks have exhibited in order for gashes to develop? i.e. was the strain brittle or ductile?

IN SUMMARY:

- Why is cleavage so much more strongly developed here than it was at Sporting Hill Road?

- How many episodes of deformation are represented here? Could a single stress orientation have generated all the strain we see here? or must there be more than one to account for all the structures? If you think more than one is needed, describe each stage, and give the sequence of strain types and stress histories.

STOP 5

OTTER CREEK PARK

LOCATION: Otter Creek Park, PA 425 at junction of Otter Creek and Susquehanna River. See Figure 5.

THE ROCKS: Exposed here is the **PRETTYBOY SCHIST**, a muscovite-chlorite schist and phyllite with abundant 1-3 mm porphyroblasts of albite, and locally some almandine. The Prettyboy is probably very late Precambrian or early Cambrian in age, and of unknown original thickness. It probably represents offshore- (deep?)-marine shale deposition.

More detailed descriptions of the rock units in the Piedmont of eastern York County are given below by Scott Howard, who is completing a PhD thesis on the structural evolution of this area. This material is taken from a guide leaflet he gave to participants in a recent regional field trip that he led.

ROCKS IN SOUTHEASTERN YORK COUNTY

Scott Howard, 1993

PETERS CREEK SCHIST:

Two rock types are recognized, which are interlayered at variable scales: quartzo-feldspathic schists and muscovite-chlorite schist. In York County, the majority of the Peters Creek rocks are quartzo-feldspathic. Compositional layering ranges from millimeter to meter thick. Bedding structures are well developed in some areas. Layered quartzo-feldspathic schist and chlorite schist resemble sand and mud couplets. As noted by previous workers the proportion of sandy units greatly exceeds those in the Prettyboy. Assemblages are typical of greenschist facies, and contain muscovite, chlorite, plagioclase, and quartz, with or without magnetite, epidote, titanite, and carbonate minerals. No K-feldspar was recognized in York County. Plagioclase is significantly different from albite porphyroblasts of the Prettyboy Schist. Peters Creek albites are commonly within quartz and feldspar layers, rather than in the pelitic layers as in the Prettyboy. Peters Creek albites are smaller with more irregular shapes,and the contain no inclusions. Their aspect and occurrence is suggestive of detrital material.

PRETTYBOY SCHIST:

This rock is typified by albite-chlorite schist in which albite porphyroblasts are subspherical and contain numerous inclusions.

Inclusion patterns can be either random of oriented. Two units are recognized based on index mineralogy: paragonite-chloritoid-bearing schists and garnet-bearing schists. The paragonite-chloritoid schists are found to the northwest in contact with Marburg Formation. They are distinguished from the garnet-bearing schist by their finer grain size of darker blue-green color. Garnet-bearing Prettyboy Schist is found in the southern portion York County in contact with the Peters Creek schist. The contact of the two varieties of Prettyboy Schist is near the axis of the Tucquan arch. Assemblages in the Prettyboy Schist contain albite, chlorite, muscovite, sericite, and quartz, and oxides with or without minor amounts of tourmaline, biotite, garnet, chloritoid, paragonite, and pyrite. Assemblages corresponding to medium-to-upper grade greenschist metamorphism. The abundance of chlorite, muscovite and quartz is variable with any one being the dominant mineral. Relict grains of apatite and zircon occur in trace amounts. Iron oxides are magnetite, rutile, or ilmenite, and occasionally pyrite. Grain sizes in the Prettyboy schist range from coarse(granules) to fine (sand and silt). Fine-grained(<0.5 mm) schists can be confused with coarse-grained Marburg. The greater amount of quartz aggregate layers in schists is a distinguishing character. Psammitic schist has quartz>40%. Sandy, cohesive fragments, lenses, discontinuous layers that may or may not be folded, thick layers(1-2 meters) within the compositional layering of the Prettyboy schist are found. Typically they contain disharmonic folds and are interpreted as broken formations or autoclastic melanges

MARBURG FORMATION:

Three major rock types are recognized, corresponding to Stose and Stose(1944) and Weaver(1954): two phyllites and a granule polymictic metaconglomerate. Two other rock types are present in minor amounts, fine-grained albite-chlorite schist and metagraywacke. Previously mapped Wakefield Marble (Stose an Stose,1944) was not located. No metabasalt was observed within the Marburg. The phyllites are separated by color. Bluish gray phyllites are extremely fine-grained with planar and lustrous cleavage surfaces; they contain traces of silt-sized quartz, and thin quartz layers resembling bedding. Greenish gray phyllites are coarser grained, containing silt-sized quartz and plagioclase grains. Cleavage surfaces are planar, but not always lustrous. Blur phyllites invariably have fine-grained paragonite as a component, which may cause its dark color. Green phyllites appear gradational with metagraywackes. The most common green phyllite is more accurately a metasiltstone wacke. The metaconglomerates have greenish hues and represent the coarsest equivalent of the green metasiltstone wackes. Grain size ranges from coarse sand to pebbles with granules being the mean size. Granules are either quartz or plagioclase, and they can be rounded or stretched out in the major foliation. No K-feldspar clasts were recognized either by staining or optical techniques. All rocks in the Marburg contain chlorite, muscovite, sericite and quartz, with or without minor amounts albite, paragonite, pyrite, iron oxides, tourmaline, zircon, lithic fragments and epidote. Assemblages are typical of low grade greenschist metamorphism.

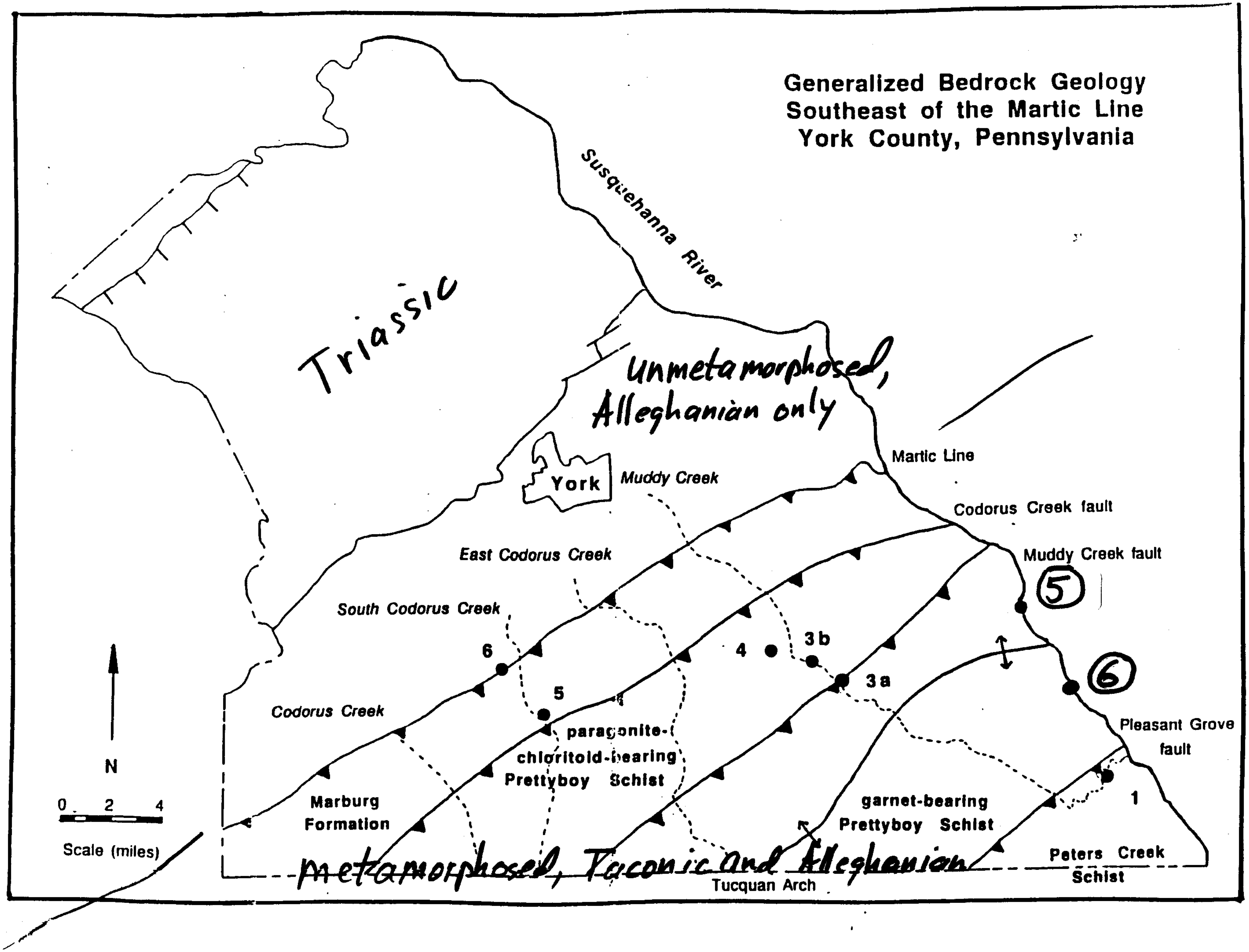
METABASALT:

There are two occurrences in York County. One occurrence, eastern metabasalts, is along the Susquehanna River, at Holtwood Dam where a unique exposure is in the spillway. Another similar exposure is found near the Peach Bottom nuclear power plant. The second occurrence, western metabasalts, is in western York County. The best exposures are found along the South Branch Cordorus Creek and the old Maryland and Pennsylvania rail line from New Freedom north to Glen Rock. These rocks have a greenstone mineralogy of quartz, plagioclase, chlorite and epidote, Actinolite was identified as a minor phase in one sample(YCP-130) through x-ray diffraction. Minor amounts of carbonate phases, probably siderite, are present. Muscovite and white micas are noticeably absent of present in only in minor amounts, and biotite is present in minor amounts in only the Susquehanna samples. All metabasalts contain magnetite. Metabasalts along the Susquehanna are schistose with a strongly granular texture. Moderate to dark yellowish green colors(10GY 6/4-4/4) are common. One variety shows a millimeter thick compositional layering parallel to the major foliation. Layers are colored black, green, and yellow. A second variety is more massive. Elongate carbonate lenses are within the foliation. These rocks have a lower quartz content then those to the west. The textures and fabrics of YCP-130 exhibit high strain; they are mylonitic. To the west, in the lower grade paragonite-chloritoid-bearing schist, metabasalts are characterized by granular and pitted textures with greenish gray colors(5G 8/1-4/1). The rocks contain quartz possibly suggesting a volcaniclastic rock. Pitting is due to the weathering out of carbonate. Rust stains form weathered pyrite are common.

REGIONAL STRUCTURAL GEOLOGY:

This area is situated southeast of Sporting Hill Road, and east-southeast of Hammonds Rocks, considerably farther SE across regional strike and deeper into the Alleghanian orogen than rocks seen earlier today. Regionally, the rocks strike ENE and dip 20-30° SE. The rocks here are clearly and thoroughly metamorphic, adn have been subjected to higher temperatures and pressures than rocks farther north. Competences of rocks under these conditions were lower due to the greater strain rates, and the deformation was more completely ductile than farther north.

The rocks show at least four episodes of compressive deformation and folding; three of them will be examined here. The regional structure is dominated by SE-dipping thrust faults that bring up successively deeper and more highly deformed/metamorphosed rocks from successively farther SE on more SE faults. See Scott Howard's


Generalized Bedrock Geology
Southeast of the Martic Line
York County, Pennsylvania
Triassic
Susquehanna River
unmetamorphosed, Alleghanian only
York
Muddy Creek
Martic Line
Codorus Creek fault
Muddy Creek fault
5
6
East Codorus Creek
South Codorus Creek
Codorus Creek
6
5
4
3b
3a
1
paragonite-chloritoid-bearing Prettyboy Schist
Marburg Formation
garnet-bearing Prettyboy Schist
Pleasant Grove fault
Peters Creek Schist
Tucquan Arch
metamorphosed, Taconic and Alleghanian
N
0 2 4
Scale (miles)

generalized geologic map of York County in Figure 5.

The rocks have undergone at least four separate episodes of deformation, of which three will be seen here. Scott Howard describes the characteristics of each phase in the following account. As you read, keep these items in mind:

- each deformation has a type section and is given a name. Each deformation event is represented by folds and associated foliations, and possible faults also.
- folds of the different deformation events have distinctive shapes and styles that can be consistently told apart.
- the main event, the "major foliation", is the second phase termed **Susquehanna**.
- Muddy Creek phase is the earliest phase, and is not well represented. It is distinguished as enclaves (large lithons lying in Susquehanna foliation) containing distinctive folds.
- Tucquan phase is latest, and folds all earlier folds and foliations.

DEFORMATION PHASES AND METAMORPHIC EPISODES

Scott Howard, 1993

MUDDY CREEK - This is both a deformational phase and a metamorphic episode. Primary metamorphic evidence is microscopic basal flakes of muscovite lying in the major foliation. Remnant metamorphic assemblages have not been found more advanced than quartz-albite-muscovite-chlorite. Isoclinal folds are refolded by Susquehanna isoclines as seen at Otter Creek Park. Some isoclines in between the major foliation may also be Muddy Creek folds. The evidence for this phase and episode is scanty due to obliteration by later deformation and metamorphism. The question remains whether this is a separate, earlier event ($M_{0.5}$) or if it is the remnants of the initial stages of M_1.

SUSQUEHANNA - This is a protracted event involving several deformational styles and formation of the major greenschist assemblages. A period of progressive deformation, which appears to have been coaxial, was accompanied by the major prograde metamorphic event; both are referred to as Susquehanna. Early and late stages of deformation and metamorphism have been recognized:

early - early phase of isoclinal folding is recognized in compositional layers and vein quartz layers. Susquehanna fold remnants are recognized as floating isoclines between major foliation; fold hinges lie approximately parallel to the strike of the major foliation and perpendicular to the tectonic transport direction. Prograde metamorphism resulted in development of major assemblages. Pelitic material altered to albite-chlorite schists and phyllites. Metamorphic grade eventually reached garnet in deepest portions of the Prettyboy.

late - progressive deformation in a simple-shear regime continued, overturned isoclinal folds became extended, and the limbs were drawn out and t fold trains were disrupted. The major foliation parallels the limbs of early Susquehanna folds, so the major foliation results from the reorientation of earlier-formed foliation. By definition, this is a **transposition cleavage**. Shear-band foliations are another typical expression of this stage of deformation. Minor, if any, mineral growth attends the late states of this deformation. Intense transposition zones are recognized as minor intraformatinal ductule faults of local extent. A very late metamorphic growth is recognized in albite porphyroblasts that overgrew transposed oxide trails.

SEVEN VALLEYS - This is a restricted deformational and metamorphic event. The major structural features result from the formation of the major ductile faults. The formation of these faults was accompanied by localized retrogression of mineral assemblages. Late brittle motion is recognized by quartz invasions and minor cataclastic zones within the earlier ductile zones. These faults formed initially at higher P-T conditions, and then continued to develop under lower P-T conditions. This early-ductile/late-brittle behavior suggests overthrusting as the fault mechanism. In ductile fault zones Susquehanna isoclines were reoriented and not plunge down the dip of the the major foliation, in the direction of tectonic transport. Phyllonites were formed through deformation and retrograde metamorphism, which distinguishes them from earlier-formed phyllonites. Dark green chlorite is present in Seven Valleys phyllonites, occurring on the most recent movement surfaces. This gives the rock a mottled appearance, which Knopf referred to as a "diseased" look. Garnets in the Prettyboy schist exhibit various stages of retrograding. Complete alteration is present in fault zones. Along Muddy Creek, near its confluence with the Susqyehanna River, diaphthoritic phyllonites overlie prograde garnet-bearing schists of the Prettyboy. The pattern also suggests thrust emplacement of the Peters Creek.

TUCQUAN - Latest deformational phase responsible for forming the Tucquan arch, a megascopic antiform plunging gently SW. There is a strong axial-planar spaced cleavage associated with Tucquan folds. This spaced cleavage is a crenulation cleavage that exhibits buckle morphology in the crest of the arch and extensional morphology on the limbs. In places on the limbs, Tucquan spaced cleavage transposes the major foliation. Examples of pressure-solution cleavage have also been recognized as a Tucquan structure. This deformation is interpreted to result from the formation of a lower fault duplex system, probably in platform units.

PROCEDURE:

Work your way south along the "inland" exposures that show the up/downdip direction. Then proceed to the exposed large knob at the riverbank.

- Find the main, dominant, "major" foliation in any of the exposures. Would you call it **cleavage**? or **schistosity**? or **gneissic layering**?

- Determine strike and dip of the major foliation. It may vary between measurement sites.

- How continuous and how planar is the foliation? Describe its continuity.

- Examine the foliation with your hand lens. What minerals predominate on the foliation?

- With your finger or hand trace some planes of foliation through the outcrop. What structures do yo soon encounter?

- The folds you find are Susquehanna-generation folds. Find a hinge (or hinges), and with your finger trace the limbs away from the hinge. How far can you trace them? Can you trace them into other hinges? or is the hinge unconnected, isolated, "floating", **rootless**? Sketch such a hinge here.

- On your sketch show any foliation cutting the hinge of the fold. Is it axial-planar or not?

- Look carefully and closely at exactly what is folded: sedimentary bedding? or an earlier mica-rich foliation? Stated another way: what is it that wraps around the hinge?

- Sketch the relations between main hinge and any axial-planar foliations and wrapping foliations. Which is older? younger?

The Susquehanna folds are mostly rootless, **intrafolial** folds that have been stretched, distorted, and rotated into this current SE-dipping plane and tectonically transported to the NW, through a tectonic process called **TRANSPOSITION**. See Figures 6 and 7 on the next pages about how transposition works. These transposed folds originally formed in some other shape, orientation and location, and were transposed and transported into their present shapes and locations by strong, regional, thrust-related simple-shear forces. They have been intensely deformed, and the net tectonic transport within the Prettyboy is probably on the order of tens of miles.

- Sketch the example of early Muddy Creek folds. Show the boundaries of the enclave containing the Muddy Creek folds. How do they differ in style from Susquehanna folds?

- What is the relation between Muddy Creek and Susquehanna axial surface orientations?

- Sketch small crenulation folds overprinting earlier folds. These are Tucquan folds.

- Determine the attitude of the axial surface of a crenulation fold.

- Look for gentle, open warps of earlier foliation. These upright warps are Tucquan folds. Sketch a Tucquan open fold.

- Tape a piece of acetate to the outcrop over a fold nose and trace the boundaries of one or two folded layers on the acetate. Before you turn this in, draw Ramsay isogons on the acetate and determine the Ramsay fold class.

Now examine the excellent horizontal exposures on the **LARGE KNOB NEXT TO THE RIVER**:

- Determine strike and dip of the major foliation on the knob. The nearly horizontal attitude places the rocks near the crest of the **TUCQUAN ANTIFORM**, a major antiformal structure plunging SW across southern Lancaster and York Counties and into Maryland. The foliation folded here is Susquehanna, but its present orientation is due to later, Tucquan folding.

- Look for a **lineation** on the exposure, elongated mica enclaves or intersections. This lineation should plunge downdip, to the southeast. It represents the intersection of bedding and cleavage, and represent the direction of tectonic transport. If you find it, determine the plunge.

- Look for folds of the foliation (Susquehanna folds) on the vertical faces having a downdip direction.

- Look for the fold profile on the NE-SW vertical face. Measure the plunge of this fold.

- Does this plunge make sense for NW-directed shear/compression? Explain.

- What geologic processes (related to transposition) could account for this plunge direction?

- Sketch some of the large quartz veins in the outcrop. Show their relation to the lineation.

- Examine the pod of nearly black, epidote-chlorite schist. It represents a piece of meta-basalt, metamorphosed basalt. How could a piece of basalt this size be in this unit? Could it be a very very small lava flow? or a piece of a dike? or a piece broken off and included in this formation? Speculate on how it could have gotten here, given the fact that most of the foliation here is transposed.

STOP 6

HOLTWOOD DAM

THE ROCKS: more Prettyboy Schist. The schist here contains significant almandine garnet. It contains a large block of epidote-chlorite meta-basalt, which is in clear, sharp contact with the schist.

PROCEDURE: **CAREFULLY** descend to the retaining wall, and **CAREFULLY** walk out to the second retaining wall and descend to the rocks at the bottom. We will make a clockwise loop from here.

- Take strike and dip of foliation here. Notice this foliation dips SE, and is different in attitude from that at Otter Creek 10 miles to the NW. The SE dips indicate we are on the SE limb of the Tucquan antiform.

- Examine the contact between metabasalt and schist. Sketch it.

- Examine the excellent **INTERFERENCE FOLD PATTERN**, of domes and basins. Find the two fold trains in the neighboring rocks, and convince yourself you understand how domes and basins are produced. Which set, the-SW plunging or the SE-plunging, was earlier?

- Sketch the plan view of the pattern.

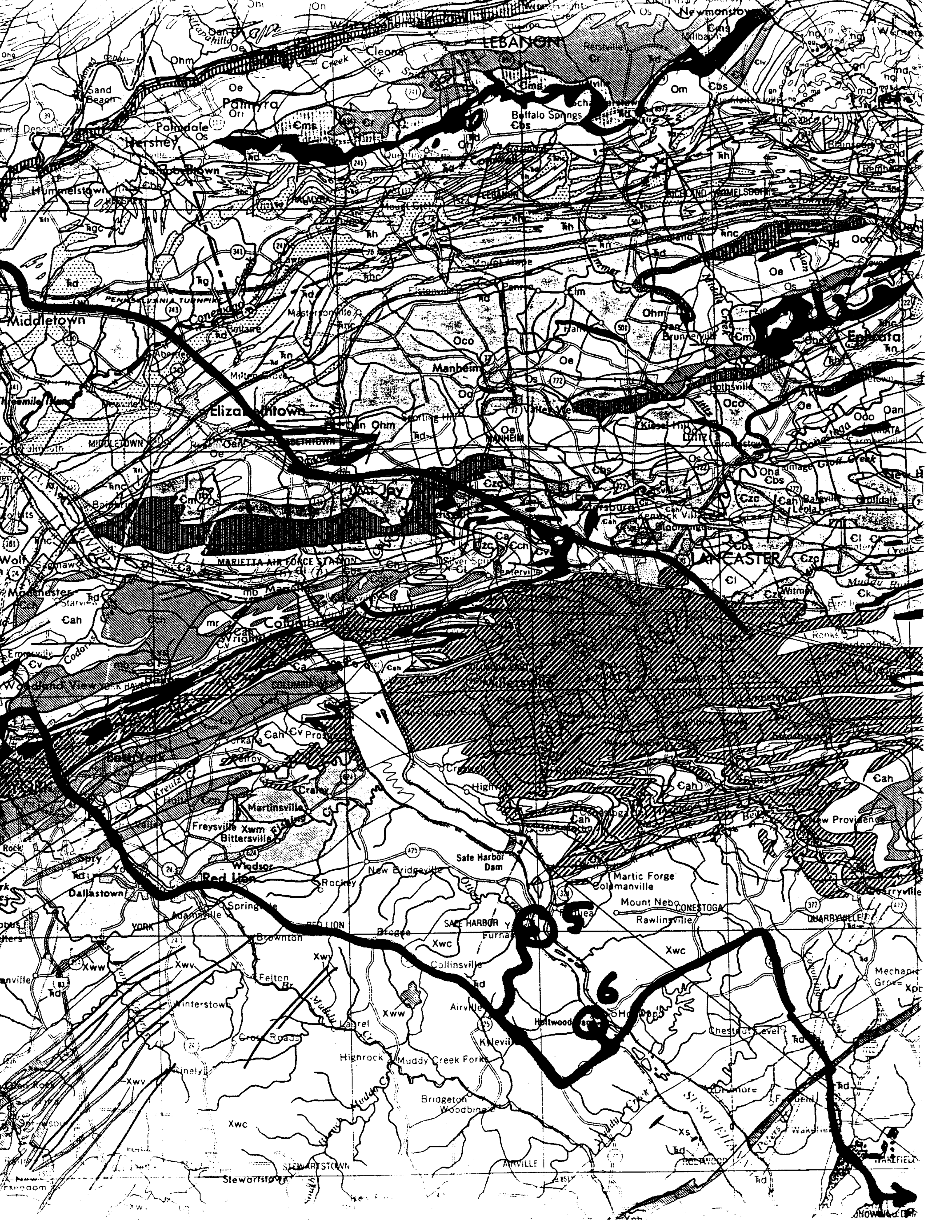
Climb back over the second retaining wall, and examine the epidote-rich metabasalt between the walls.

- Measure the plunge of the strong lineation in the epidote-rich rocks. This lineation may be a stretching lineation, in the direction of tectonic transport. Look for tiny tension gashes in the epidote as evidence of stretching. May or may not be there. Or it may be a bedding-cleavage intersection lineation. Check out what may be intersecting to form the lineation.

WHOLE-TRIP SUMMARY QUESTION:

In proceeding from Stop 1 to Stop 6, in what ways does the deformation change? Include in your statement anything and everything you think changes, including statements about metamorphism, ductility, position within the orogenic belt, and anything else you think affects the types of strain that developed.


Marysville
Shermans Dale
Enola
Progress
Penbrook
Paxtang
Steelton
Highspire
Landisburg
Carlisle Springs
Middlesex
New Kingstown
Mechanicsburg
Naval Supply Depot
New Cumberland
Greason
Carlisle
Shepherdstown
Allen
Williams Grove
Springville
Boiling Springs
Siddonsburg
Lewisberry
Goldsboro
Huntsdale
Holly Springs
Beavertown
Dillsburg
Franklintown
Rossville
Wellsville
Mount Royal
Conewago Lake
Zions View
Eastmont
Kralltown
Bermudian
Dover
Dickinson
Bendersville
Florence
Center Mills
Heidlersburg
Foustown
Davidsburg
Weigelstown
East Berlin
Hampton
Biglerville
Arendtsville
Table Rock
Newchester
Abbottstown
Hunterstown
New Oxford
New Salem
Stoverstown
Menges Mills
Seven Stars
Granite Hill Sta
Cedar Ridge
Brush Run
Gettysburg
Bonneauville
Lake Heritage
Centennial
Hanover
Jefferson
Whitehall
Two Taverns
Littles Run
Mount Pleasant
Brodbecks
Greenmount
Fairplay
Littlestown
McSherrystown
Conewago
Bermudian Creek
Yellow Breeches Cr
Willoughby Run


LEBANON
Cleona
Palmyra
Hershey
Palmdale
Sand Beach
Hummelstown
Buffalo Springs
Newmanstown
Middletown
PENNSYLVANIA TURNPIKE
Bellaire
Elizabethtown
Masterson
Manheim
Oco
Oe
Ohm
Ephrata
Brunnerville
Rothsville
Valley View
MANHEIM
MIDDLETOWN
MARIETTA AIR FORCE STATION
Mount Joy
LANCASTER
Kenwick Village
Columbia
Cah
Woodland View
Millersville
Martinsville
Freysville
Bittersville
Windsor
Red Lion
Dallastown
Safe Harbor Dam
New Bridgeville
Rockey
Martic Forge
Colemanville
Mount Nebo
CONESTOGA
Rawlinsville
Quarryville
QUARRYVILLE
New Providence
SAFE HARBOR
RED LION
YORK
Brownton
Collinsville
Felton
Winterstown
Airville
Holtwood
Laurel
Highrock
Muddy Creek Forks
Bridgeton
Woodbine
Stewartstown
STEWARTSTOWN
AIRVILLE
Chestnut Level
Drumore
Mechanic Grove
WAKEFIELD
Xwc
Xww
Xwv
Xs
5
6

Marysville
HARRISBURG
Progress
Enola
Penbrook
Paxtang
Steelton
Highspire
Mechanicsburg
Shiremanstown
Carlisle
Greason
Middlesex
New Kingstown
Hogestown
MECHANICSBURG NAVAL SUPPLY DEPOT
Camp Hill
New Cumberland
Lemoyne
Shepherdstown
Allen
Williams Grove
Springville
Boiling Springs
PLAINFIELD
Mt Holly Springs
Huntsdale
Siddonsburg
Lewisberry
Newberrytown
Goldsboro
Franklintown
Rossville
Wellsville
Mount Royal
Eastmont
Zions View
Kralltown
Bermudian
DILLSBURG
WELLSVILLE
Dover
DOVER
Davidsburg
Weigelstown
Foustown
Shiloh
DICKINSON
Idaville
Center Mills
Bendersville
Florabelle
Arendtsville
ARENDTSVILLE
Biglerville
BIGLERVILLE
Table Rock
Hampton
HAMPTON
East Berlin
Abbottstown
ABBOTTSTOWN
New Chester
Hunterstown
Cross Keys
New Oxford
Menges Mills
Spring Grove
Seven Stars
Gettysburg
Granite Hill Sta
Cedar Ridge
Brush Run
Bonneauville
Lake Heritage
Centennial
Hanover
Whitehall
Two Taverns
Mount Pleasant
Xwm
Brodbecks
Jefferson
Stoverstown
New Salem
GETTYSBURG
HANOVER
Greenmount
FAIRFIELD
Fairplay
Littlestown
Bandanna
McSherrystown


LEBANON
Newmanstown
Palmyra
Cleona
Buffalo Springs
Hershey
Palmdale
Sand Beach
Union Deposit
Hummelstown
Middletown
PENNSYLVANIA TURNPIKE
Elizabethtown
ELIZABETHTOWN
MIDDLETOWN
Manheim
MANHEIM
Mount Hope
Elm
Ephrata
Rothsville
Lititz
Valley View
Mt Joy
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Wrightsville
Woodland View
Millersville
Rocky Springs
Martinsville
Freysville
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Windsor
Red Lion
Dallastown
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Martic Forge
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Mount Nebo
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Rawlinsville
New Providence
Quarryville
QUARRYVILLE
RED LION
YORK
SAFE HARBOR
Brogue
Collinsville
Airville
Holtwood Dam
Kyleville
Chestnut Level
Muddy Creek Forks
Highrock
Bridgeton
Woodbine
Winterstown
Cross Roads
Felton
Stewartstown
STEWARTSTOWN
AIRVILLE
HOLTWOOD
New Park
New Freedom
Wakefield
WAKEFIELD
Drumore
Leola
Witmer
Conestoga
Muddy Creek
Xwc
Xww
Xwv
Xs
Xpb
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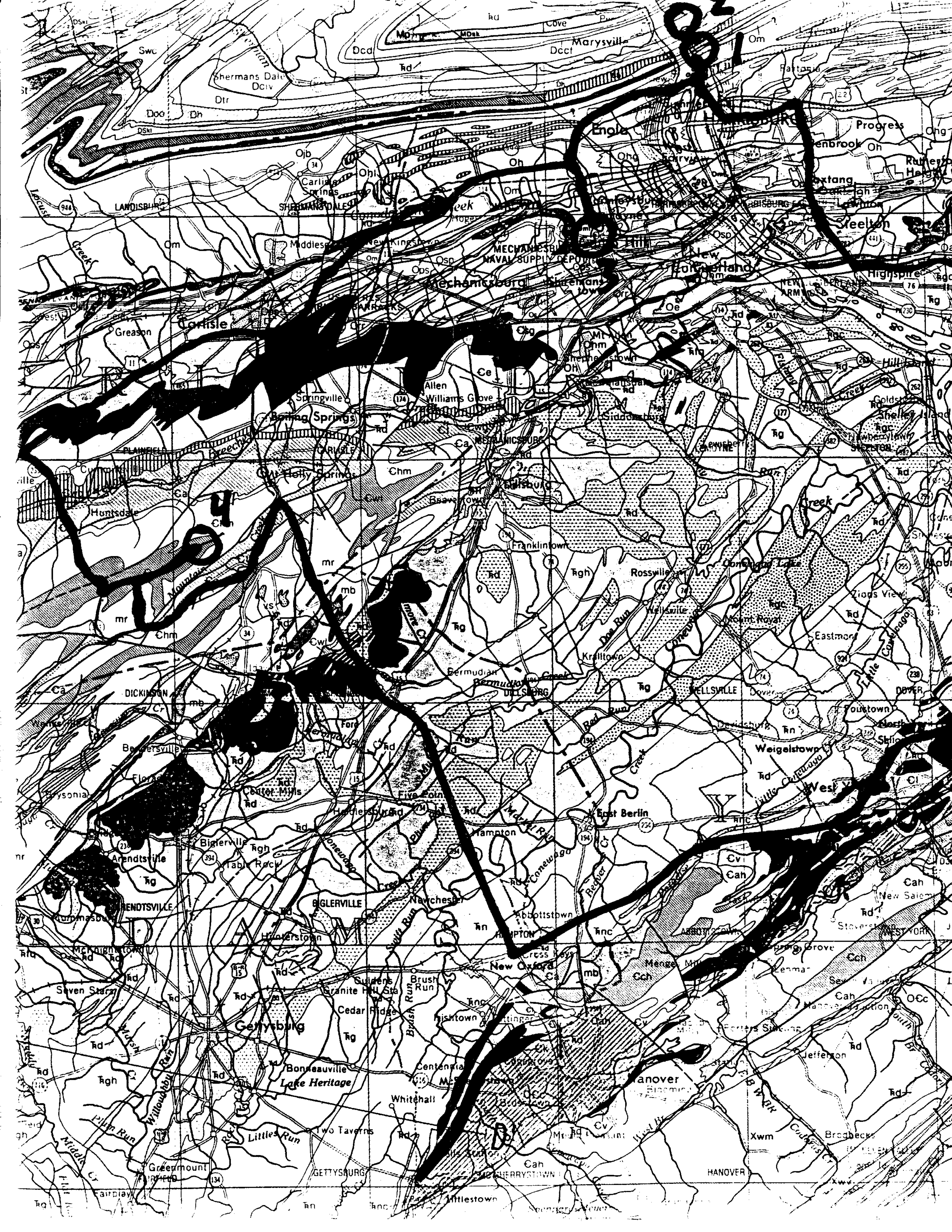

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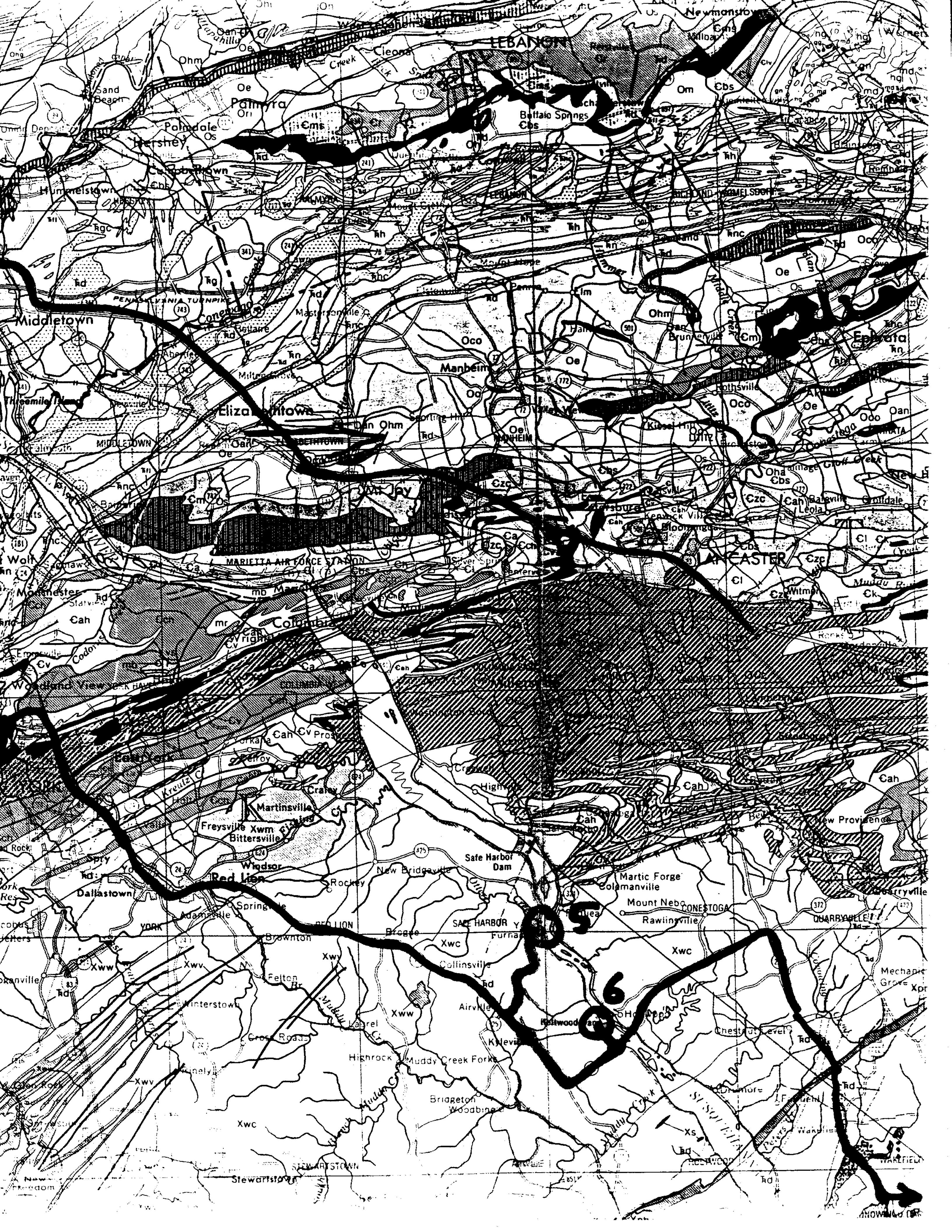

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Buffalo Springs
Palmdale
Hershey
Hummelstown
PENNSYLVANIA TURNPIKE
Middletown
Mastersonville
Bellaire
Manheim
Brunnerville
Ephrata
Elizabethtown
MIDDLETOWN
Sporting Hill
MANHEIM
Rothsville
Lititz
Kissel Hill
Conestoga
EPHRATA
Mt. Joy
Leola
Bareville
Groffdale
MARIETTA AIR FORCE STATION
Silver Spring
LANCASTER
Witmer
Muddy Run
Columbia
Woodland View
COLUMBIA
Washington Boro
Creswell
Highville
Martinsville
Craley
Freysville
Bittersville
Windsor
Red Lion
New Bridgeville
Rockey
Safe Harbor Dam
Martic Forge
Colemanville
Mount Nebo
CONESTOGA
Rawlinsville
New Providence
Quarryville
QUARRYVILLE
Dallastown
Spry
Springvale
Adamsville
YORK
RED LION
SAFE HARBOR
Brownton
Brogue
Collinsville
Felton
Airville
Holtwood
Chestnut Level
Mechanic Grove
Winterstown
Laurel
Cross Roads
Kyleville
Highrock
Muddy Creek Forks
Glen Rock
Bridgeton
Woodbine
Drumore
Fairfield
STEWARTSTOWN
Stewartstown
New Freedom
Wakefield
WAKEFIELD
Middle Creek
Muddy Creek
Kreutz
5
6
9