G E O L O G Y   4 0 1

C E N T R A L   P E N N S Y L V A N I A
F I E L D   T R I P

November 5, 1988

Themes of the Trip:

folding, and geometry of folds

deformation styles: responses to stress

competence, and competence contrast

sequence of deformation

cleavage: its expression, and its origin

FIELD   TRIP   STOPS:

Leave Newark 0630

    1.   Blue Mountain, Dauphin, PA: 0.5 hour

    2.   Hammonds Rocks, Pine Grove Furnace, PA: 1.5 hours

    3.   Rainbow Rocks, Mifflin, PA: 1.5 hours

    4.   Laurel Creek Dam, Milroy, PA: 2 hours

Return Newark 2100

Report Due: Tuesday, November 15, 1988

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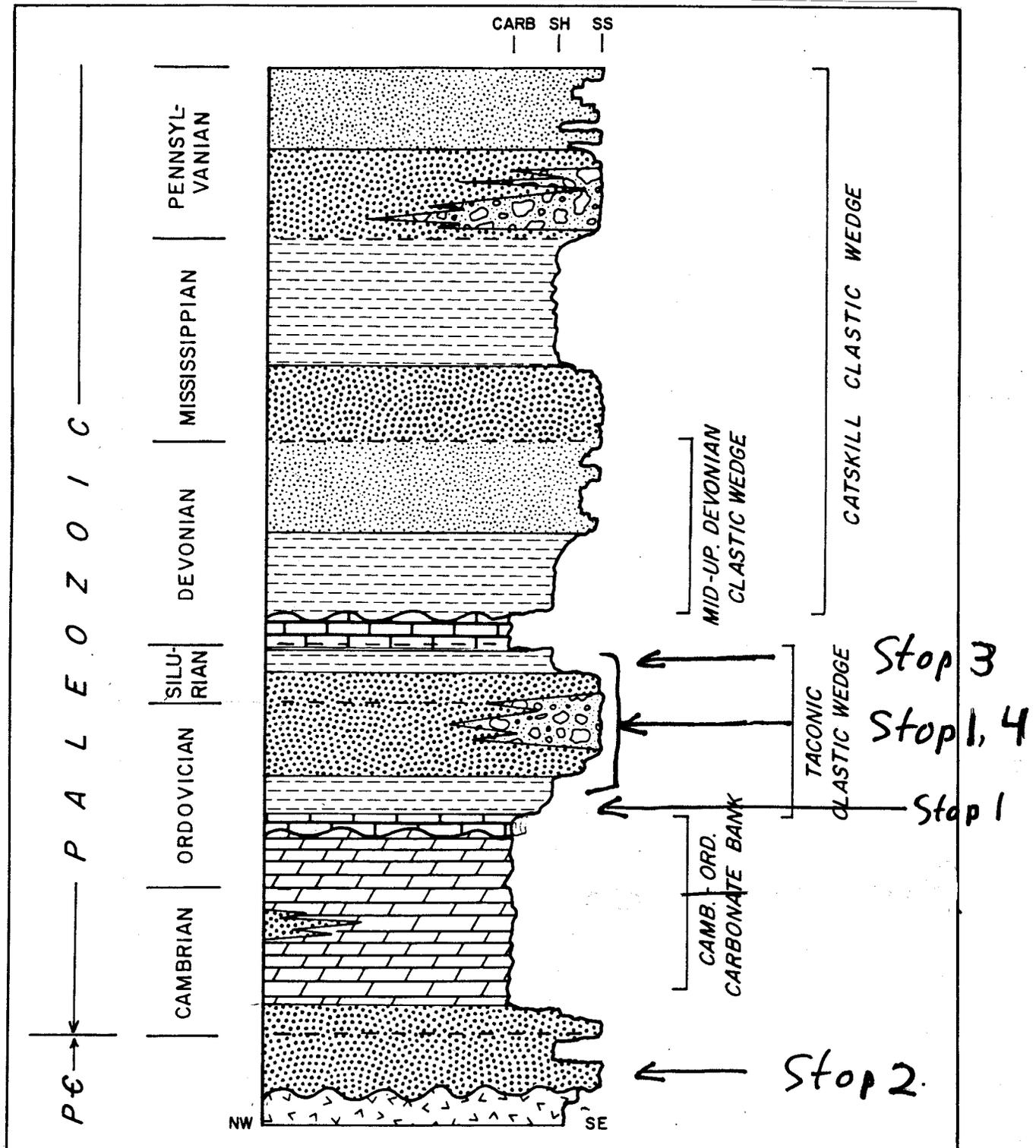
FIGURE 5. GENERALIZED STRATIGRAPHY OF THE NORTHEASTERN APPALACHIAN BASIN IN CENTRAL AND EASTERN PENNSYLVANIA.

from Thompson + Seron, 1982
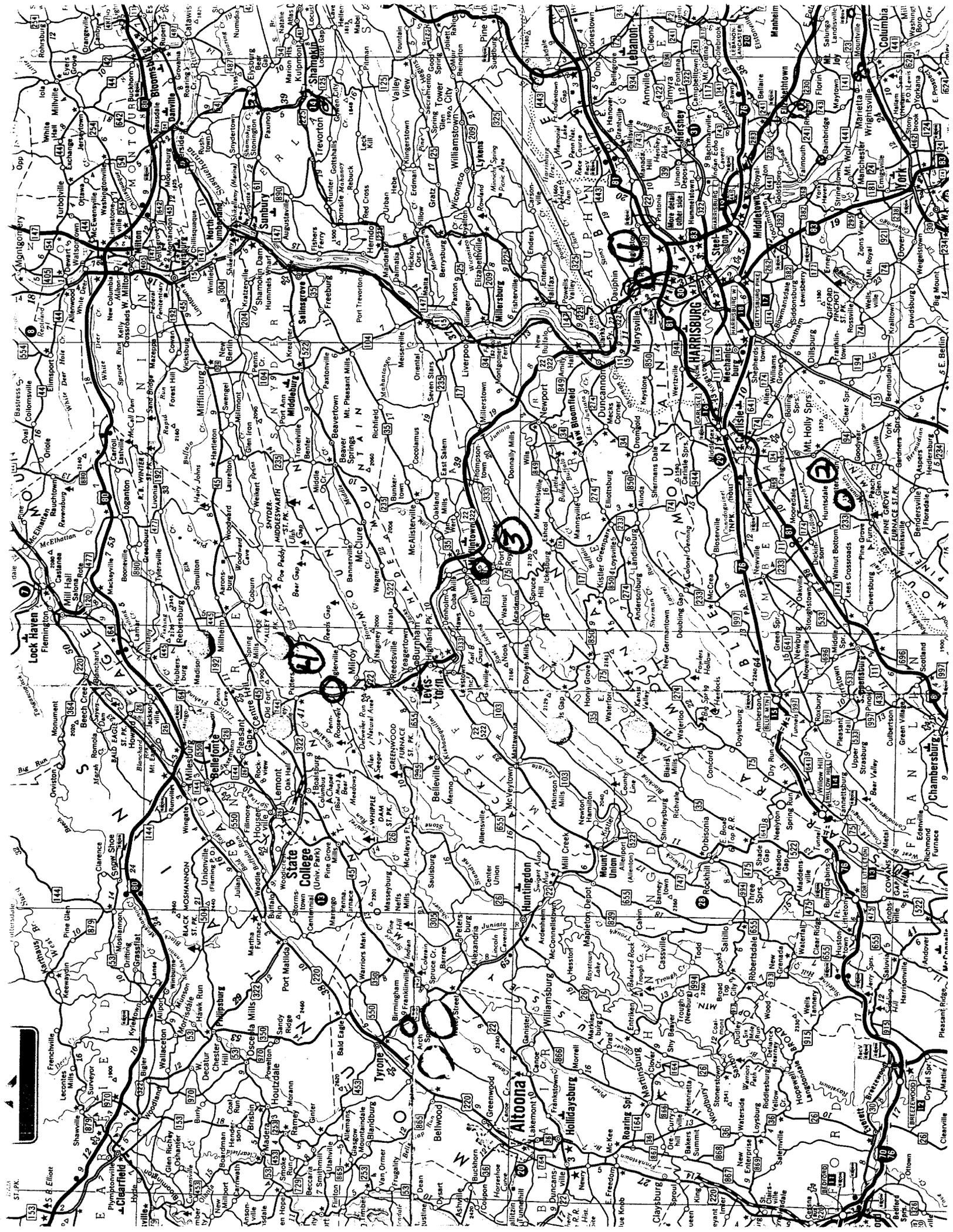
STOP 1:

BLUE MOUNTAIN

Rose Hill Formation, Middle Silurian, shales and sandstones;
Tuscarora Formation, Lower Silurian, white and gray sandstones;
Juniata Formation, Upper ordovician, red conglomerate and
    sandstone;
Bald EAgle Formation, Upper Ordovician, gray conglomerate and
    sandstone;
Martinsburg Formation, Middle Ordovician (?), gray shales

Features to look for at Blue Mountain:

- overturned beds, and evidence for overturning;

- **facing direction**: the direction toward younger rocks;

- the **Taconic Unconformity**, overturned, older on top of
  younger rocks with angularity between them;

- box folds, wedge thrusts, and evidence for layer-parallel
  shortening;

- sets of fractures and faults, and possible conjugate
  relationships;

- drag and offset beds along faults as evidence of sense of
  shear;

- good primary sedimentary structures in Tuscarora and Rose
  Hill.

Look for sets of fractures/faults with consistent orientations
and senses of shear. Are they conjugate sets?

NOTES AT BLUE MOUNTAIN:

Features at
Blue Mountain

from Theisen,
Penna Geology
V14/3, 1983
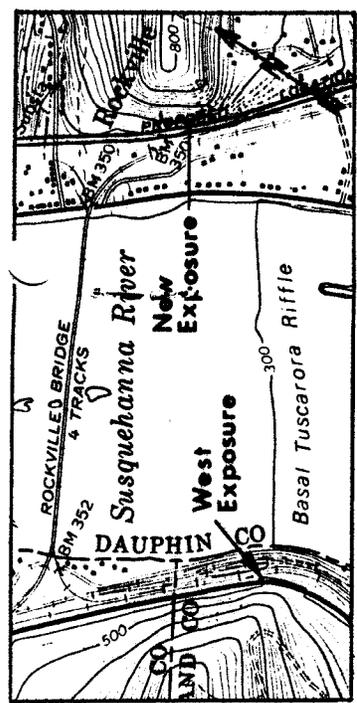
Features at Blue Mountain from Theisen, *Penna Geology* V14/3, 1983. Geologic diagram of the east side of Susquehanna Gap with index map.

FIG 2 GEOLOGIC DIAGRAM
OF THE EAST SIDE
OF SUSQUEHANNA GAP

(OUTCROP APPEARS AS SEEN FROM BELOW)

Index Map

QUARTZITIC SANDSTONE
HEMATITIC SANDSTONE
SHALE
GRASS AND TALUS
FAULT SHOWING SIGNIFICANT DISPLACEMENT OF BEDDING
FAULT SHOWING MINOR DISPLACEMENT OF BEDDING
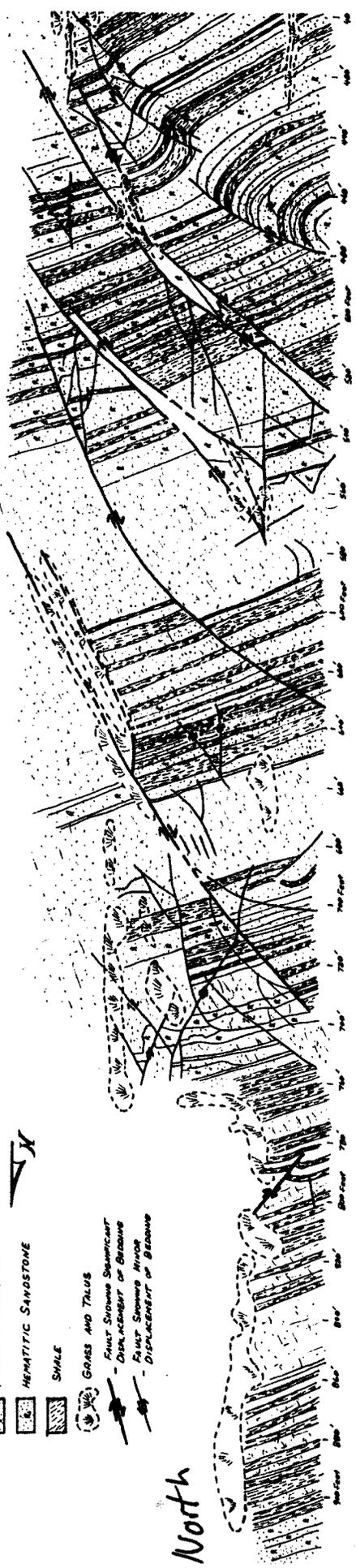
Draw the relations seen on a north-dipping reverse fault. Show
drag if you see it, and offset bedding.

Draw a box fold in its current orientation in the outcrop, and
indicate the major compression direction σ_1 .

Sketch the sets of fractures, with sense of shear, and indicate
maximum and minimum compression directions.

QUESTIONS TO ANSWER:

1. Which occurred first, the box folding or the faulting? What is your evidence?

2. Starting with deposition of Martinsburg, what is the sequence of events that led to the rocks as we see them?

STOP 2.

HAMMONDS   ROCKS

Weverton quartzite, latest Precambrian - lowest Cambrian, lowest
    formation in the Chilhowee Group.

Features to look for at Hammonds Rocks:

- Original rock type: what is it?

- **bedding** and original bedding features like **cross-bedding** and graded bedding.

- **facing direction** of bedding: which way is tops?

- **Cleavage**

- Strained, **stretched pebbles**

- **quartz veins** and their distribution

- **sigmoidal gashes,** and sense of rotation and shear

- **cleavage-bedding intersection,** and how to use it

NOTES   AT   HAMMONDS   ROCKS:

STRUCTURES PRESENT AT HAMMONDS ROCKS

by

Lisa M. Hardy
November, 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 than 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 on 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 indicate 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 same as that of the sigmoidal gashes?
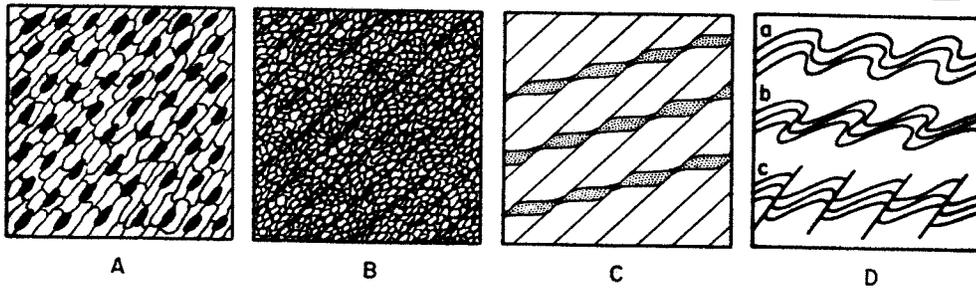
Fig. 18-2. Kinds of cleavage. (A) Slaty cleavage or schistosity. (B) Fracture cleavage. (C) Shear cleavage. (D) Slip cleavage.
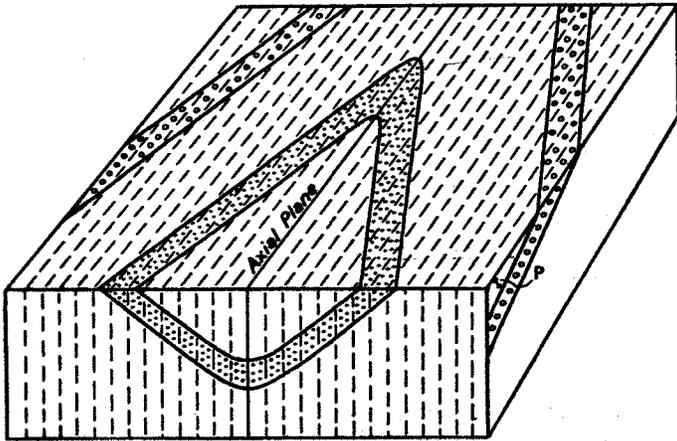
Fig. 18-10. Three-dimensional representation of slaty cleavage. Cleavage represented by broken lines. Value of plunge of fold is equal to *P*, which is measured on the cleavage; it is the angle between the trace of the bedding and a horizontal line.
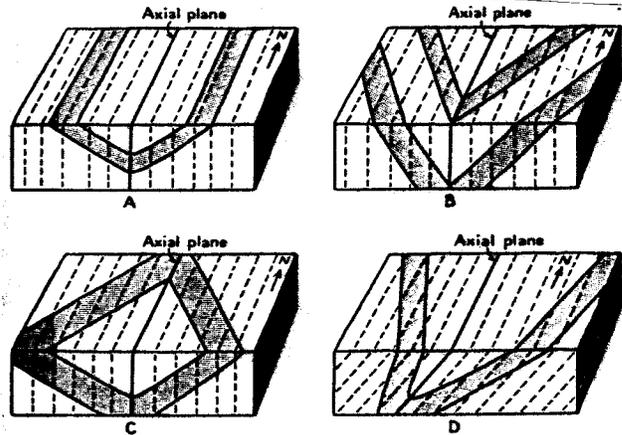
Fig. 18-8. Relation of slaty cleavage to folds in three dimensions. Cleavage represented by broken lines. Rigorous parallelism of cleavage to axial plane is diagrammatic; in many anticlines the cleavage diverges downward. (A) Symmetrical nonplunging fold. (B) Symmetrical fold plunging north. (C) Symmetrical fold plunging south. (D) Overturned fold plunging north.

Fig. 18-9. Use of slaty cleavage to solve structure in three dimensions. Cleavage represented by broken lines. (A) Syncline to right, does not plunge. (B) Syncline to right, plunges north. (C) Syncline to right, plunges south.
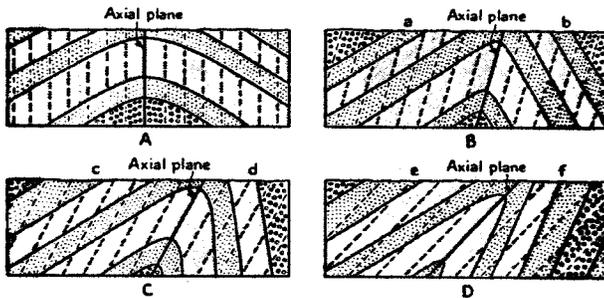
Fig. 18-6. Relation of slaty cleavage to folds in two dimensions. Cleavage represented by broken lines. Smaller letters are referred to in text. Rigorous parallelism of cleavage to axial plane is diagrammatic. (A) Symmetrical fold. (B) Asymmetrical fold. (C) Asymmetrical fold with one steep limb. (D). Overturned fold.
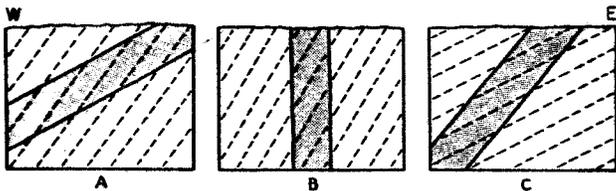
Fig. 18-7. Use of slaty cleavage to solve structure in two dimensions. Cleavage represented by broken lines. (A) Syncline is to left. (B) Syncline is to right. (C) Syncline is to right.

Fig. 18-11. Fracture cleavage. (A) On the limbs of a fold. (B) In isolated outcrops. Relations at *a* indicate a syncline to the right; relations at *b* indicate a syncline to the left.

Sketch examples of the following, and in each case state which direction you are looking:

- graded pebble-sand bedding in the conglomerate:

- some pebbles. Show both top view and side views. Label the three principal strain axes $\lambda_1, \lambda_2, \lambda_3$. Orient σ_1 and σ_3 relative to the pebbles.

- cleavage and bedding. Show the pebble preferred orientations.

- cleavage and bedding, where bedding dips steeper than cleavage. In your sketch, extend bedding in both directions across the nearest (hypothetical) fold noses.

Rotation of Tension Gashes

135°

135°

Ramsay, 1985

Figure 2.11. Progressive development of extension fissures developing in a shear zone (Answer 2.11).

fibres

crack seal inclusion
lines
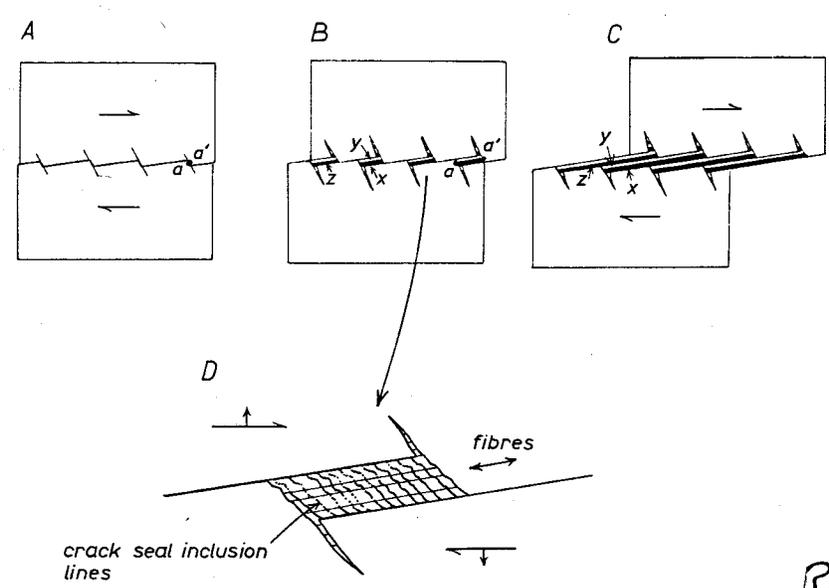
Ramsay, 1985

Figure 13.32. Features of shear fibre veins. A shows an initial fracture surface with irregular form due to alternating shear and extension sectors. B shows the type of fibre geometry induced by sliding movements on the shear sectors with fibres connecting points originally in contact (a–a'). There is often a geometrical link between the fibres developed in en-echelon extension fissures and the shear fibres. C illustrates the build up relatively thick shear fibre packets with increased shear displacement. D shows the type of inclusion structure which may be developed as a result of progressive crack–seal activity.

TENSION GASHES AND FIBER GROWTH

Vein & fiber development - simple shear

A.   B.   C.

principal increment extension
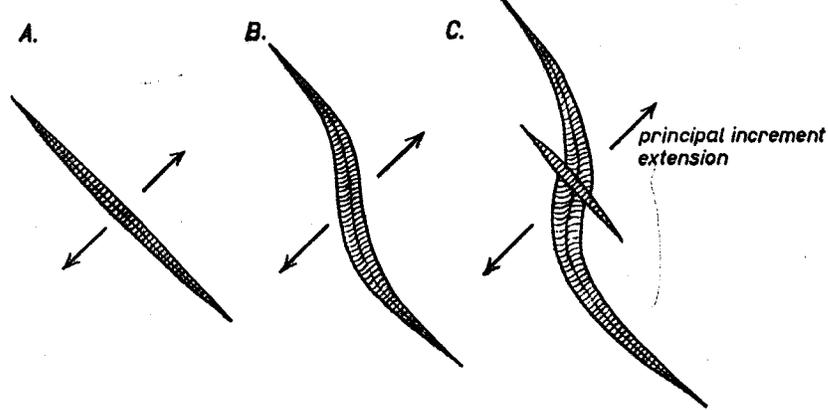
FIG. 16 Progressive evolution of stretched crystal growth fibers in the shear zone illustrated in Fig. 13.

Rotation of Tension Gashes

ID RAMSAY

from Durney & Ramsay, 1973
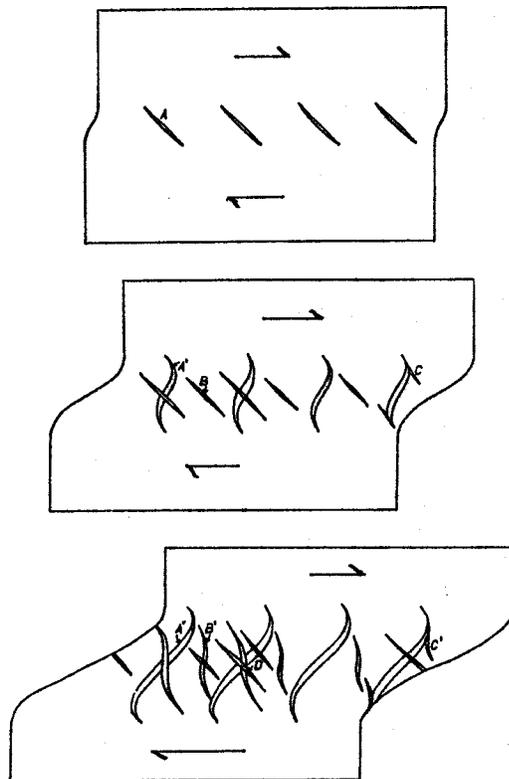
FIG. 15 Sequential development of arrays of en-echelon and sigmoidal tension veins in a progressively evolving shear zone. Arrows indicate the sense of relative shear displacements across the shear zone.

Sketch the syncline. Show bedding, cleavage, and pebble
orientation across the fold.

Sketch some sigmoidal gash veins. Show the gashes themselves,
the gash zones, and the sense of shear on the zones.

Sketch the intersection of two gash zones. Show the sense of
shear on each zone, as indicated by the gash rotation.
Conjugate? or not?

QUESTIONS TO ANSWER:

3.   Sketch some sigmoidal gash veins, and show the sense of rotation.

4..   What is the relation between pebble stretch direction and the cleavage?

5.   Could a single stress orientation have generated all the strain we see here> If you think so, draw a diagram showing maximum compressive stress σ_1 and the structures it produced, in the orientation we find them today.   If you think more than one stress direction is needed, give the sequence of stress positions.

STOP 3. HAMMOND'S ROCKS.   *H. Hanson, 1982*

Introduction

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's Rocks (Fig. 7) 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. Look around at other parts of the exposure to see whether you can figure out the stratigraphic and structural relationships.
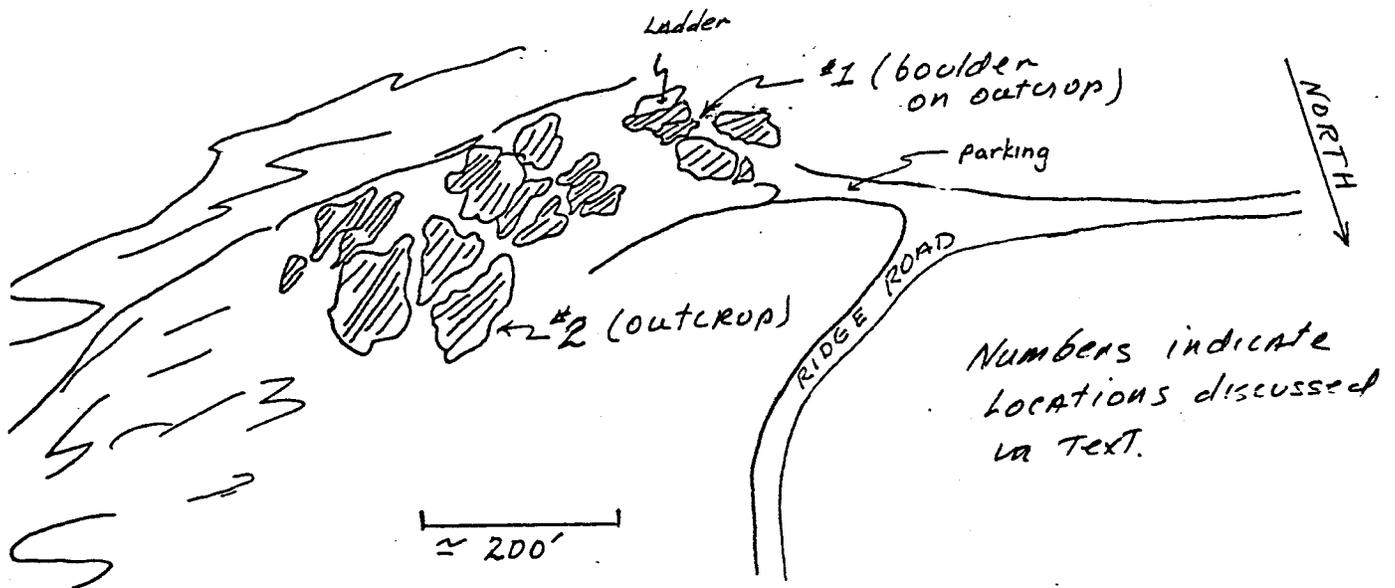
Figure 7. Hammond's Rocks. Sketch map.

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 1.5 m of conglomeratic sandstone, is clearly cross-bedded. The maximum angle between the cross-beds and underlying beds is about 40°, which is greater than the angle of repose (35°) for moderately angular material with a 1 cm 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° 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.

~ 1.5 meter thick bed o conglomeratic sandstone

Fig. 8

sandstone and pebbly sandstone

30cm
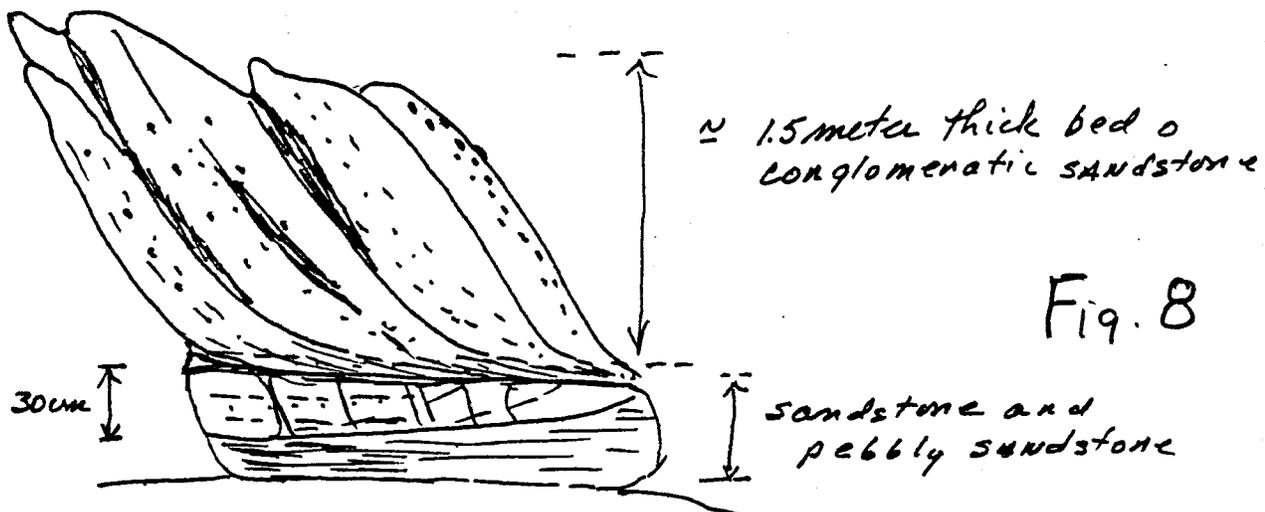
U.S. 322 - Tuscarora Anticline

STOP I, APPENDIX

The Tuscarora anticlinorium is characteristic of many of the first-order folds in the Valley and Ridge province. These major folds have been described for many years as parallel, or concentric, and at first glance they appear to be so, particularly in exposures such as the Tuscarora hinge that we just passed on our way to this stop (Fig. I-B). However, what we are seeing in this exposure is only a part of the Tuscarora fold, and a very small part indeed. This exposure is only 0.6 miles long, yet the wavelength of the Tuscarora anticline is 11 miles.
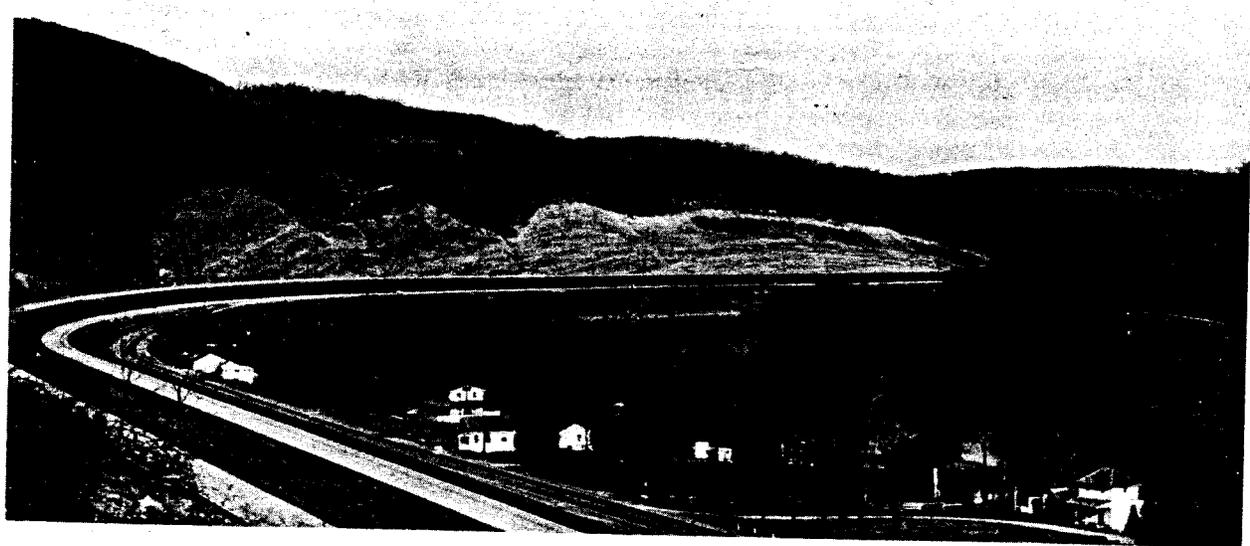
Figure I-B Hinge of the Tuscarora anticlinorium in the Juniata River gap north of Millerstown. Although the hinge possesses a concentric geometry, it is but a small part of a non-concentric, kink band fold.

But it is the total geometry of this fold that does not fit
the concentric fold model. In a concentric fold, the radius of
curvature must be at least 1/2 of the fold wavelength, and 1/2 of
the structural relief. The radius of curvature in the hinge of the
Tuscarora anticline in this exposure is 4,200 feet (0.8 miles)--
yet the wavelength is 9 miles and the structural relief is 2.7 miles
(Fig. I-C). Clearly, this fold does not possess a concentric profile.
Furthermore, the bed attitude does not progressively increase as
one moves away from the hinge as it should in concentric folds. In
this anticline, the bed attitude increases 50 to 60 degrees within
1/2 mile of the fold hinge--from this point southward to the Buffalo-
Berry synclinorium hinge (with the exception of a faulted fold) the
bed attitude remains fairly constant at approximately 40 degrees
south dip. This constancy of bed attitude over rather large areas
is an aspect of the structure that is encountered over and over again
throughout the entire province, as in the Cove syncline, illustrated
in Figure 4 of the Structural Geology text. As a consequence, folds
in the Valley and Ridge province cannot be reconstructed in cross
section using the concentric arc methods of Busk (1929).
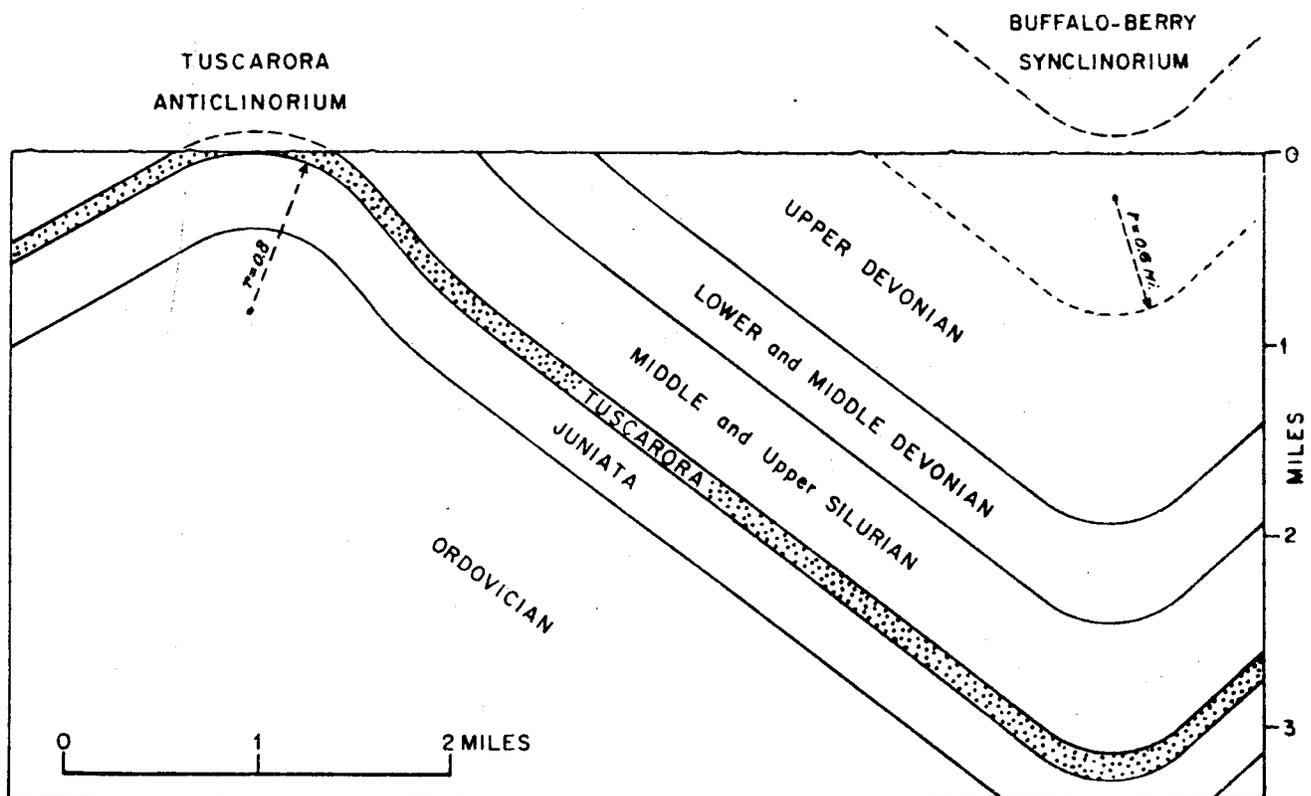
Figure I-C   Simplified cross-section of south limb of the Tuscarora
             anticlinorium (north limb of the Buffalo-Berry synclinorium).
             The radii of curvature calculated from exposures in
             both hinges are much too small for these folds to be
             concentric.

Returning to the Tuscarora anticline, another aspect of it should be discussed--the change in geometry of its hinge. The Tuscarora anticlinorium plunges about 4 degrees to the east-northeast. At the Juniata River, the cross-sectional geometry of the hinge is a simple anticline (Fig. 1-D). 0.3 miles to the east, the hinge is conjugate, with an interlimb 0.1 miles across. 0.2 miles further east, two small anticlines are present on each side of the interlimb. Further eastward, both of these anticlines plunge to the east and enlarge, with a decrease in the flat bottom syncline (interlimb) between them. The fold on the north changes trend to a more easterly direction and becomes the hinge of the anticlinorium; the anticline on the south persists in its trend, and diminishes in size and vanishes. Four miles east of the Juniata River, the hinge of the anticline is once again a simple fold area.
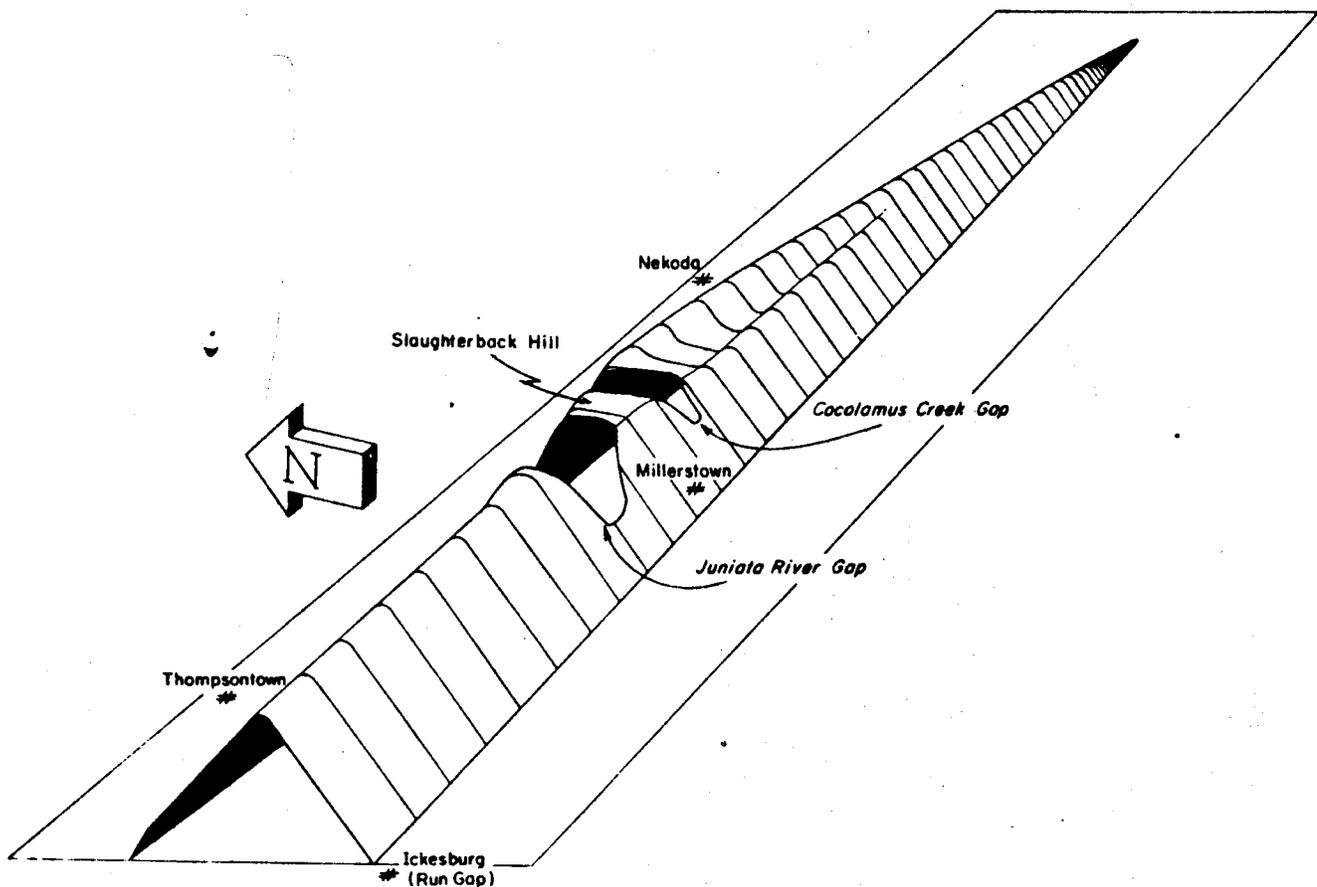
Figure 1-D   Variation of the Geometry of the Tuscarora anticlinorium hinge along trend where it changes from a cylindrical fold in the west to a plunging non-cylindrical fold in the east.

Now, this interpretation can be argued. No single cross-section exhibits all of these fold forms, and no single bed exhibits all these changes in structure along trend. The Tuscarora Formation exhibits the simple anticline at the Juniata River. The conjugate form and the two small anticlines are expressed in the Rose Hill, Keefer and Blooms- burg formations. The larger pair of anticlines with the diminishing intervening syncline are expressed in the Bloomsburg, Wills Creek and Tonoloway formations. The simple anticline at the east end is expressed in the Keyser and Old Port formations. The point that can be argued is whether this change in geometry is real regardless of a lithic type involved. That is, are these small structures on the hinge of this major fold a result of a major tectonic trend change, or are they a reflection of different responses of different lithic sequences (formations) to a fairly uniform tectonic environment. This difference in interpretation bears directly on the discussion of the applicability of a concept of lithic tectonic units to this province as discussed in the Structural Geology text. Evidence for and against each interpretation will be found at a number of the stops for the next two days.

STOP   3:

RAINBOW   ROCKS

Wills Creek Formation, Upper Silurian, red mudstones, gray
    shales, ribbon limestones

Features to look for at Rainbow Rocks:

- Geometry of folds, and styles of folds: be able to
distinguish **concentric** from **chevron** fold forms. Be
able to recognize **symmetrical** and **asymmetric** fold
forms.

- **Axial surfaces** of folds, even though they are
imaginary surfaces.

- **Axial-plane cleavage**, and **refraction of cleavage** as
controlled by lithology.

- The considerable array of **mechanisms of deformation**
seen in action here, including:

  - mesoscopic **folding**

  - **microfolds**, indicating layer-parallel
    shortening of the folded layers;

  - **flattening**, of original spheres, look at
    orientation of flattened ellipsoids;

  - **stylolites**, indicating pressure solution;

  - **wedge thrusts**, indicating layer-parallel
    shortening;

  - **bedding-plane slip**, again indicating layer-
    parallel shortening;

  These are all **micro**-mechanisms that, taken
  together and summed, produce the **mesoscopic** and
  ultimately the **macroscopic** folding seen in the
  outcrop and the region.

- the **flexural slip** model of folding, involving
concentric folds and their dying out.

Stop 2 : Rainbow Rocks

STOP II: "RAINBOW ROCKS", AN EXPOSURE OF FOLD GEOMETRY AND MINOR
STRUCTURES IN THE WILLS CREEK FORMATION.

Stratigraphy: Wills Creek and Tonoloway formations,
    The succession of calcareous shale and limestone cycles of the
Wills Creek Formation over the red mudstones of the Bloomsburg Formation
reflects the eastward retreat of the shoreline of the Bloomsburg-Vernon
delta. The cyclicity, the presence of algal mats, and evidence of high
salinity indicate that the Wills Creek environment was an arid tidal flat
with very low wave energy, in which alternating subtidal, intertidal, and
supratidal sediments were deposited. Two successions of calcareous silt-
stones and sandstones in the middle and upper part represent influxes of
quartz-rich detritus.

    The lower part of the Wills Creek exhibits extensive large-scale
(10 to 30 feet) interbedding of gray shales and limestones and grayish
red-silty mudstones, which represents a lateral shoreline fluctuation.
The increasing amount of red beds to the east points to an interfingering
of the Wills Creek into the Bloomsburg, and an eastward shift up-section
of the contact between the two. To the west and south, the Wills Creek
occurs lower in the section than here, at the expense of the Bloomsburg.

    The upper contact of the Wills Creek with the Tonoloway Formation
is very gradational and interbedded. The upper part of the Wills Creek
(apart from the siltstones and sandstones) contains more limestone than
the underlying parts, and the lower part of the Tonoloway contains a fair
proportion of gray shale interbedded with limestone. To the north and
and west, the upper part of the Wills Creek increases in limestone
content, and thus grades laterally into the Tonoloway Formation.

    The lesser amount of fine detritus in the Tonoloway indicates
deposition further from the source area than suggested by the Wills
Creek lithologies, yet the laminated beds, dessication cracks, and
anhydrite laminae throughout much of the Tonoloway point to a cont-
inued intertidal environment, one that was occasionally interrupted
by a more normal marine environment in which medium bedded, fossili-
ferous micrites were deposited.

    In this exposure at Rainbow Rocks, the lower part of the Wills
Creek Formation is displayed, with portions of it repeated along the
railroad cut because of the extensive folding. Many of the sedimentary
structures and features typical of the Wills Creek are present here,
such as the interbedding of red and gray mudstones, thin limestone
beds alternating with calcareous shales, dessication cracks etc.
These features will be pointed out during the structure discussion,
for the variation of structure with lithology is an important aspect
of the Valley and Ridge deformation observable here.

from Pa. Field Conference, 1973

Structure. First, a short note on the regional setting. STOP II is located in the center of the Valley and Ridge province (Fig. I, Introduction). To the north is the Shade Mountain anticlinorium, and to the south is the Tuscarora Mountain anticlinorium, both of which expose Upper Ordovician and Lower Silurian rocks. STOP II rests in the hinge of the intervening synclinorium (Fig. 2, Introduction), underlain by Middle and Upper Silurian and Lower Devonian rocks. As is so common in the Valley and Ridge province, this synclinorial hinge is comprised of several second-order synclines arranged in an en echelon pattern. The exposure along these tracks occurs in the hinge of one of these second-order synclines, and consists of a train of third-order folds.

Turning now to the fold geometry, recall that the Appendix to STOP I pointed out that the large, first-order folds in the Valley and Ridge province are not concentric, but, rather, possess narrow hinges and planar bedding (constant bed attitude) in the limbs. But this geometry is not easily appreciated in folds this large, for nowhere can such a fold be seen in its entirety from a single vantage point. This railroad cut at Mifflin exposes much smaller third-order folds which can be examined along their entire length. As with the first-order folds, these third-order folds are not concentric--rather, they possess narrow hinges and planar bedding in the fold limbs (Fig. II-A). In each of the 3 anticlines and 2 synclines, the change in bed orientation from one limb to the other occurs within a narrow zone (the fold hinge). Thus, the radius of curvatures are much less than the fold wavelengths. Between the fold hinges, the bed attitude remains fairly constant. As pointed out before, this geometry is common throughout the entire Valley and Ridge province, in folds of all sizes, ranging from hand specimen size to the largest in the province. And, this geometry conforms neither to concentric (parallel) folds, nor to similar folds.

Although slickensides are not common on the bedding surfaces in this exposure, they are frequently encountered throughout this province. The presence of these slickensides on bedding surfaces indicates that slip has occurred along the bedding surfaces. In addition (and this can be seen in this exposure), the bed-normal thickness of the layers does not change appreciably around the fold. There is little or no thinning or thickening of beds in one limb as opposed to the other limb, even though the steepness of bedding can differ greatly between the two. Although there is some thickening of beds within the fold hinges (to accomodate local space problems), it is remarkable that so many of the beds pass through the hinge with virtually no change in bed-normal thickness. These two aspects of folds, the constant bed-normal thickness and the slickensides on bedding, indicate that the deformational mechanism by which these folds developed was flexural slip. In flexural slip folds, deformation within layers is confined to bedding surfaces and associated low-angle faults (wedges).

Yet, the natural world is never as simple as the theoretical model that one creates to explain it, and this is amply demonstrated in this railroad cut. In walking through this exposure, one will see numerous structures in the rocks which do not accord well, or are even inconsistant, with the flexural slip mechanism just described. In that Dr. Richard Nickelsen will describe these "inconsistant" structures, it may seem that two geologists looking at the same rocks see two entirely different deformations. In a sense, this impression is correct, for the total deformation in these rocks is more complex than the simple fold geometry suggests. However, the apparently contradictory details should not obscure appreciation of the overall fold geometry. In walking from one fold hinge to the next, keep in mind that the monotonously constant dip of bedding in the fold limb you are passing is just as much a part of the fold as is the more interesting hinge.

SE   NW
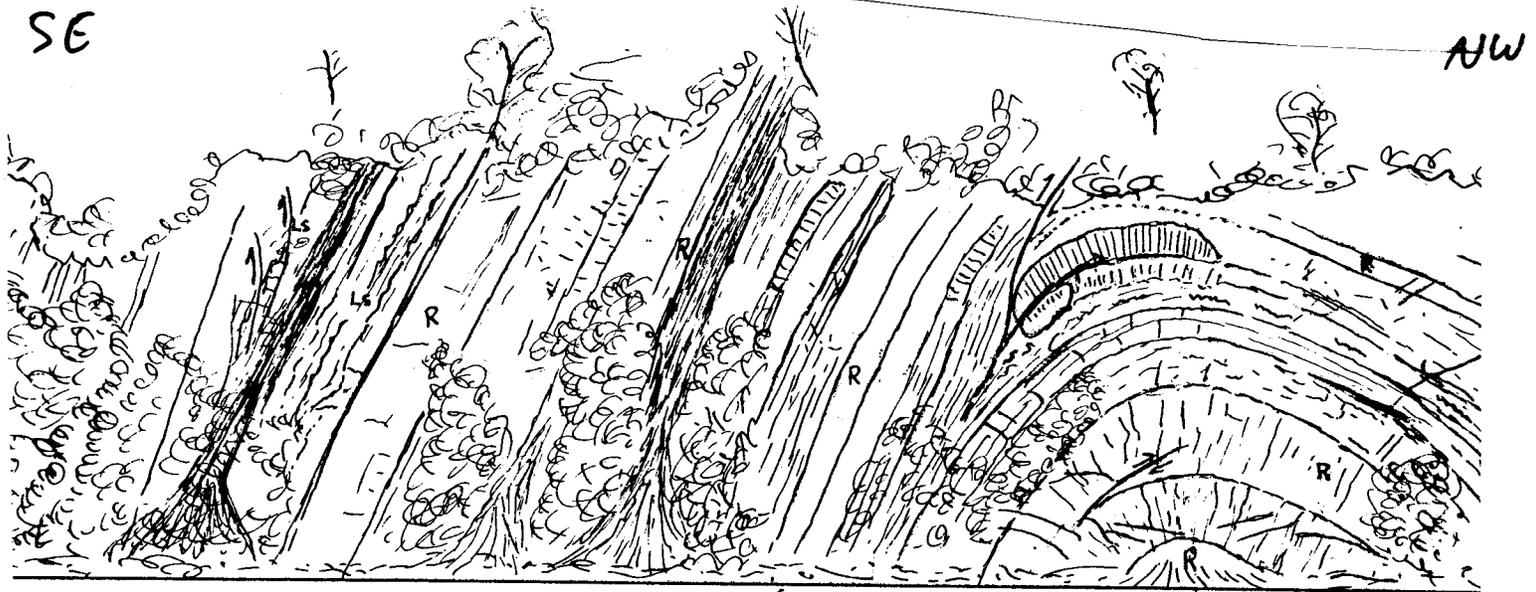
Station 7 - This major anticline is faulted and asymmetric to the south. Beds have been thickened in the core by fracture cleavage, by intra-bed wedging as in the lower beds of the core, and by wedging duplication of bed as in the upper part of the anticline. The south limb has ridden up over the crest and north limb along a bedding fault that contributes to thinning along the south limb and breaks through the crest of the anticline.

South of Station 7 nothing new is seen but there are repetitions of features previously pointed out; micro-folds in thin-bedded limestones, well-cleaved mudstones and sandy mudstones, and thick, clay-carbon partings in thicker-bedded limestones produced by solution and residual accumulation of insoluble clay.

Sketch the wedge thrusts at station 7.
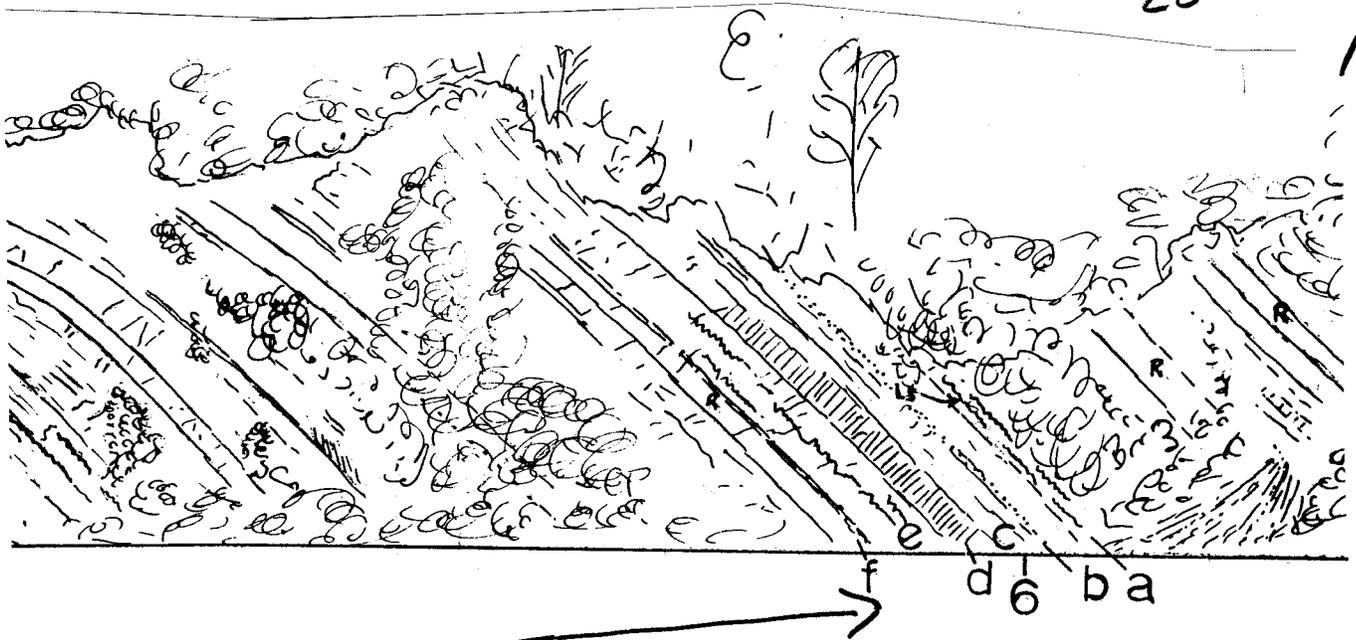
Station 6 — A variety of sedimentary rock types on the south limb of the syncline at Station 3 demonstrates the different structural behavior of different lithologies. From north to south we encounter:

a. thin-bedded limestone with micro-folding
b. thin-bedded sandstone with micro-folding
c. thin-bedded limestone with micro-folding beheaded by bedding plane slip during flexural slip folding
d. well-cleaved reddish mudstone
e. intensely micro-folded, thin-bedded, fissile limy shale
f. dolomitic limestone with larger folds and stylolite-like clay-carbon partings perpendicular to bedding

Bed parallel shortening is accomplished by micro-folding in thin bedded limestone and sandstone, by fracture cleavage development in mudstones, by micro-folding in thin-bedded fissile shales, and by longer wavelength folding and solution in thicker-bedded dolomitic limestone.

Sketch the relations between bedding and stylolites in limestones near station 6.

3

SE   NW

5   4
C
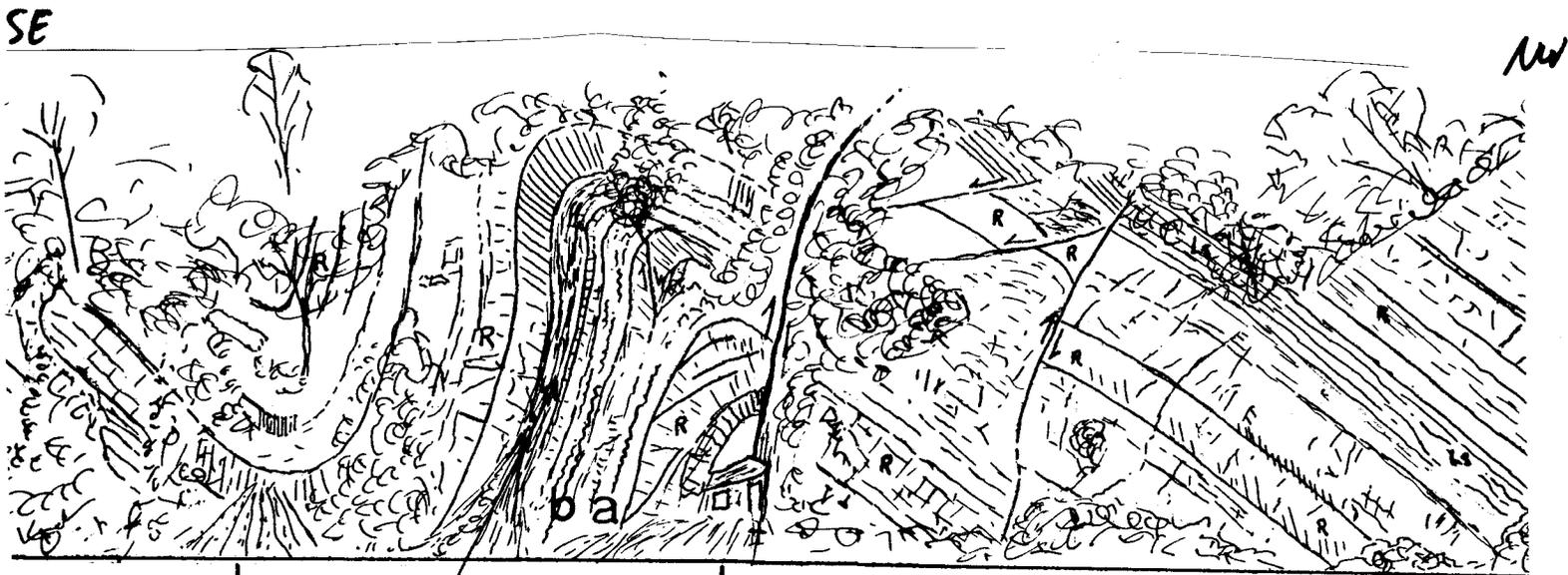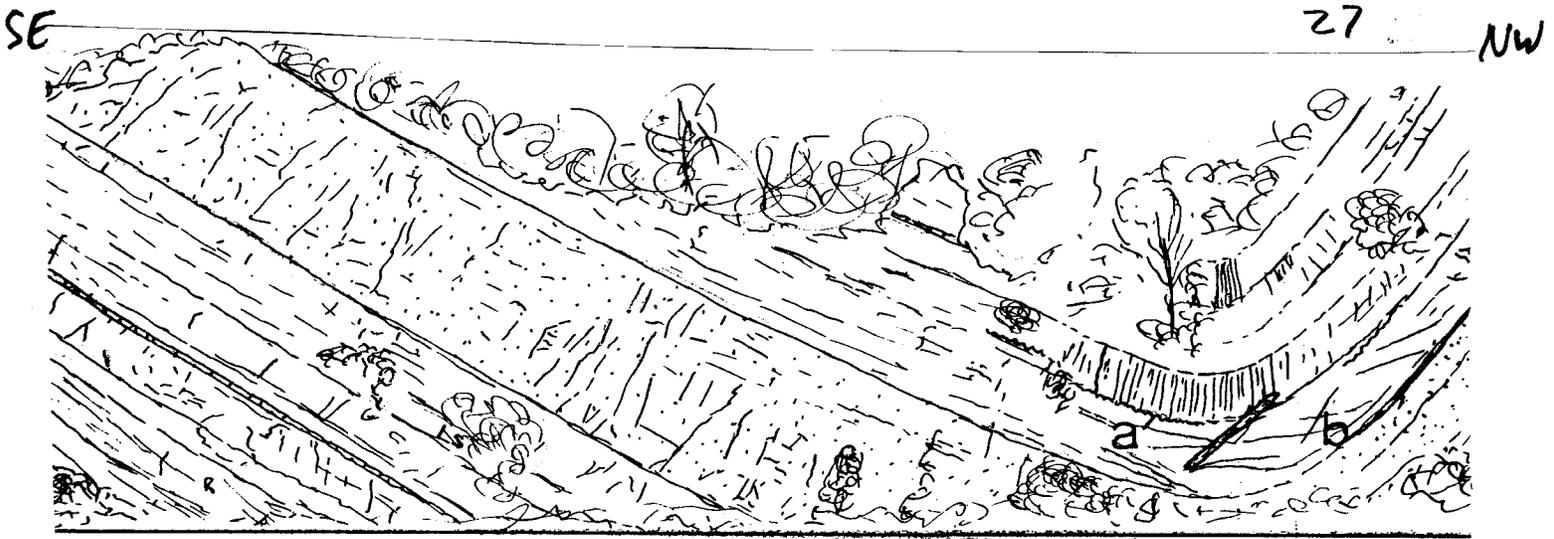
Station 4 - South of the faulted anticline of Station 4, interesting features are
present at a, b, and c. At a a micro-folded thinly-bedded limestone
shows 27% shortening parallel to bedding, whereas at the next thinly-
bedded limestone b 12% shortening is recorded. In the thicker limestone
at c no micro-folding is present but bed parallel shortening of unknown
amount has occurred by pressure solution. The bedding surface is inter-
sected by strike joints containing thick, clay-carbon partings resulting
from solution of calcite and residual accumulation of clay. Fracture-
bounded blocks of the bed have been displaced perpendicular to bedding
either by slip along cleavage or solution juxtaposition of irregularities.
Figures 11-C and 11-D show that the thick, clay-carbon partings are not
part of a penetrative structure; they are separated by intervals of 1/2
to 2 inches of uncleaved limestone.

No station 5

Sketch the concentric fold at station 2, and show the cleavage fanning across the fold.

Sketch the fold and fault relations at station 4. Be as detailed as possible, and try to show how the shape of the fold differs in competent and incompetent beds.

Summary This railroad cut at Mifflin exposed two general aspects of the Valley and Ridge deformation: 1) a moderately brittle, non-penetrative folding by slip on bedding surfaces and associated wedges; and 2) a more ductile, penetrative deformation consisting of cleavage development, micro-folding, and solution activity. Mechanically, these two aspects are mutually exclusive, but the evidence suggests that the more ductile, penetrative processes preceeded the more brittle folding. The implication then, is that the deformation proceeded from a ductile phase to a more brittle phase. Apparently cleavage development spanned both phases to some extent.

In addition, we have seen how different lithologies (or lithic sequences) have responded differently under the same deforming environment. Thick, argillaceous beds have developed cleavage, less argillaceous beds solution clay-carbon partings, and laminated beds micro-folding. This pattern of different responses seems to lend credence to the concept of litho-tectonic structural units. Or does it?

3 → 2
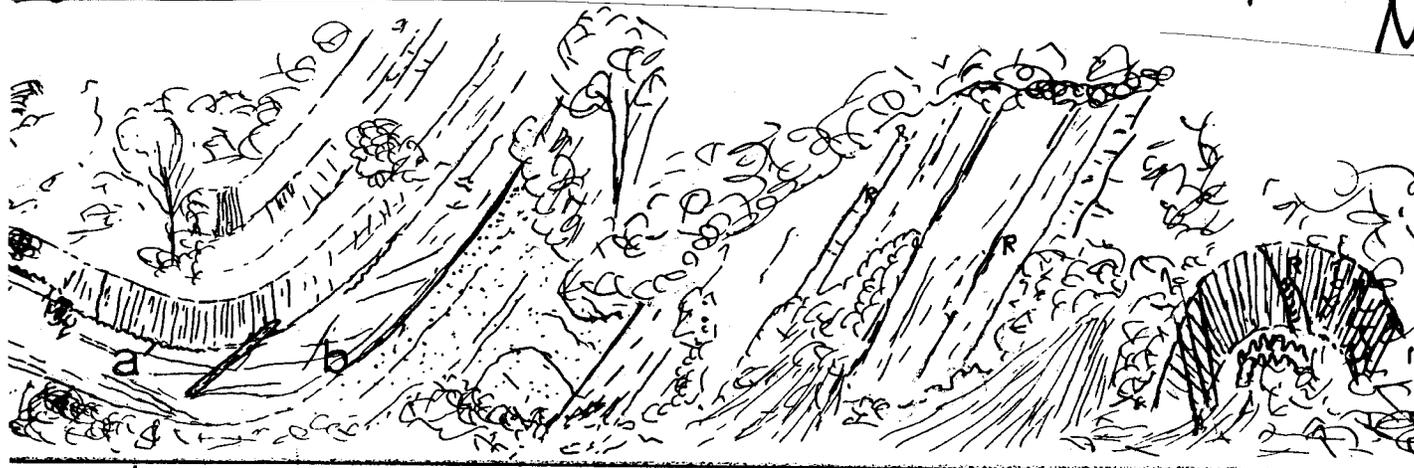
We turn now to the "inconsistant", minor structures which consist of cleavage, "micro-folding", and stylolite-like clay-carbon partings. (They are minor only with respect to size as compared to the third-order folds--they have as much significance as the folds in terms of the total deformation). This Stop is broken into 6 stations along the railroad cut, beginning with Station 2 (Fig. II-B).

Station 2 - At this station a tight anticline with an interlimb angle of 65° shows excellent fracture cleavage in ductile shales fanning upward through an angle of 45°. This cleavage has been rotated 10° toward the axial plane on each limb of the fold. In less ductile thin limestones and sandstones, cleavage remains nearly perpendicular to bedding. On the crest and south limb of the fold a later fracture cleavage dipping 65° to 80° north has been superimposed on bedding and the early cleavage. In the crest of the fold, faulting and drag along planes parallel to the cleavage has disrupted and folded the early cleavage. The core of the fold shows characteristic complex folding in limestones, probably related to late fold flattening or lack of room for flexing below the fold center of curvature.

Station 3 - At this open syncline with an interlimb angle of 120°, homogeneous strain in different rock types has been accomplished by either micro-folding, wedging or cleavage development. Ductile shales have cleaved, sandy mudstones have shortened by wedging, and thin-bedded limestones and sandstones have micro-folded. If we assume that strain has been approximately equal from bed to bed it is possible to compute how much shortening is associated with the penetrative strain that has led to cleavage development, using the shortening expressed by trains of disharmonic, intrabed micro-folds. Two such determinations have been made. In the limestone layers exposed at (a) just to the south of the trough of the syncline 30% shortening is recorded in a train of small amplitude folds that extends for a distance of approximately 3 feet. In thin sandstone beds at the top of the sandy mudstone to the north of the synclinal trough (b) 57% shortening is recorded in a train of folds extending for a distance of 6 inches. These amounts of shortening are both probably unrepresentative and too high in value - similar determinations elsewhere have yielded values of 15 to 20% in folded layers adjacent to well-cleaved rock. Although no late cleavages are present here as they were at Station 2, it is possible that post-folding flattening has occurred locally near the trough of the fold to increase shortening. If it could be measured accurately at all points on the large folds, the shortening expressed as wedging, cleavage development and micro-folding should be added to the strain recorded by the folds, in order to find the total strain.

QUESTIONS TO ANSWER:

6. List some of the mechanisms of micro-deformation you saw. Use sketches if appropriate.

7. Which mechanisms of deformation affect generally competent rocks? Which affect incompetent rocks?

8. How can microfolding take place in one bed, while the beds surrounding it (which have undergone equal deformation) are not microfolded?

STOP 4:

LAUREL CREEK DAM

Rose Hill Formation; Lower and Middle Silurian, red shales;
Tuscarora Formation; Lower Silurian, white and gray quartz
    sandstones; Castanea Sandstone Member (red sandstones) in
    upper part;
Juniata Formation, Upper Ordovician, red sandstones and shales

Features to look for at Laurel Creek Dam:

- strike and dip: use Brunton compass to determine one strike and one dip.

- **facing direction:** Which way is tops? Are rocks overturned or right-side-up?

- Styles of folding: **chevron, asymmetric, kink** fold styles.

- The major fold considered as a **drag fold** or as a **kink fold,** and the geometric consequences of each.

- **Flexural-slip** deformation mode during folding, and the

- Influence of **competence contrast** on mechanics and styles of folding.

- Faults and offsets: are they **conjugate pairs?** or are they not? If so, what was the **stress orientation?**

- **Deformed fossils** and their strain significance.

Look hard for folds, either large or small, whose axial surfaces dip **north** rather than south. These have special significance in interpreting fold origins.

Look for faults that cut across the quarry face. See if offset directions and dips are consistent with conjugate shear origin.

NOTES AT LAUREL CREEK DAM:

Stop 3: Laurel Creek Dam

STOP III.   LAUREL CREEK RESERVOIR AND FILTRATION PLANT, LEWISTOWN
WATER SUPPLY SYSTEM.   Allotted time: 90 minutes

We are presently standing on the west end of the dam built two
years ago across Laurel Creek by the Lewistown Water Authority (see
discussion of engineering geology by Kenneth A. Young, P.E., in
separate article in this guidebook).   This locality is in the north
limb of the Kishacoquillas or Jack's Mountain anticlinorium, which
consists of a series of second-order folds exposing the Upper Ordo-
vician-Lower Silurian clastic wedge, comprised of the Bald Eagle,
Juniata and Tuscarora formations.   Because these formations consist
predominantly of siliceous sandstones, their resistance to erosion
has resulted in a series of ridges and intervening valleys that has
been called the Seven Mountains Area.   The dam lies across Laurel
Creek in line with one of these ridges, Spruce Mountain.

STRATIGRAPHY

The rocks underlying Spruce Mountain are the Tuscarora and upper
Juniata sandstones, which are exposed on the west side of the valley
in the roadcut, and along the dam construction road on the opposite
(east) side.   To the north along the east edge of the reservoir is the
Castanea, the red sandstone at or near the top of the Tuscarora, and
the lower portion of the Rose Hill Formation.

The oldest beds exposed are the upper part of the Ordovician Juniata
Formation, along the road leading south from the dam (Fig. III-A,
Stations 1 and 2).   The Juniata Formation is predominantly sandstone:
brownish gray, fine to very fine grained, medium and thick bedded
subgraywacke, containing occasional thin zones of grayish red shale
pebbles.   Interbedded with these sandstones are beds of siltstone:
grayish red, argillaceous, medium bedded, with locally well-developed
cleavage.   The contact of the Juniata with the overlying Tuscarora
Formation lies in an interbedded zone, approximately 150 feet thick
(Station 3), of gray and reddish sandstones.

The Tuscarora Formation (Fig. III-A, Stations 4, 5 and 6) is
sandstone: mostly light gray, medium grained, siliceous, and
ranging from a very pure quartz arenite in the lighter beds to an
argillaceous subgraywacke in the dark gray beds.   This contrast in
composition between adjacent layers accentuates the fold and kink
band structures in the quarry (Station 5).

The red sandstones in the uppermost part of the Tuscarora Forma-
tion comprise the Castanea Member (Fig. III-A, Station 7).   The ten
feet of Castanea sandstone is lithically similar to the Juniata, being
grayish red, very fine grained, argillaceous and silty.   It also
contains distinctive closely spaced burrows perpendicular to bedding
which are nearly cylindrical and less than one inch across.   These
burrows were formed by some unknown animal and are characteristic of
the Castanea.

from Pa. Field Conference, 1973

At the north end of this exposure, approximately the lower 200 feet of the <u>Rose Hill Formation</u> can be seen (Fig. III-A, Station 8). It consists of a brownish gray to light olive gray silty shale. The "Iron Sandstones" seen at STOP I do not extend this far to the northwest.

STRUCTURAL GEOLOGY

The overall structure, that is, the <u>enveloping bedding</u>, is vertical, with beds becoming younger towards the north, upstream. The most prominent structures within this framework of vertical enveloping beds are large kink bands, the parallel-sided structures which dip moderately to the south in the quarry across the valley. Bedding is continuous across these kink bands, and has been rotated (within these kinks) 90 to 120 degrees relative to the enveloping bedding. Smaller kink bands with an opposite sense of rotation are gently north dipping. These two kink band sets form a conjugate kink band fold system. In addition, conjugate faulting is developed, and seems to be somewhat related to the kink banding. In the Rose Hill Formation to the north is a well-developed cleavage and <u>passive folding</u>.

STOP III consists of 8 stations along the road on the east side of the reservoir, beginning with Station 1 at the south in the Juniata Formation (Fig. III-A).

<u>Station 1</u>: (approximately 350 feet south of crest of dam) These solid grayish-red sandstones and interbedded silty shales constitute the resistant, upper sandstone portion of the Juniata Formation.

Two types of structures are present in the steeply south dipping (overturned) enveloping bedding. The beds are not planar, but have been "bent" in a number of places by kink bands that dip gently to moderately to the north. Rotation in the kink planes has resulted in the overlying beds moving north relative to those under the kink band (Fig. III-B). Faulting has also occurred in these rocks. Some faults are parallel to the kink planes, with movement of the upper block to the north. In addition, steeply north dipping faults have caused the north block to be displaced upwards relative to the south block. Because the geometries (and the slickensides) of the faults and the kink bands are concordant (Fig. III-C), these two types of structures are probably related. In fact, in places, the low dipping faults appear to replace the kink bands suggesting contemporaneity or penecontemporaneity of development.
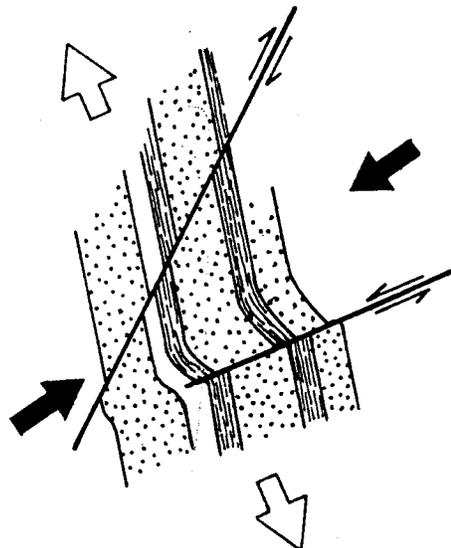
Figure III-B. Schematic relation of the faults and kink bands at
Station 1, and the faults at Station 4. The solid arrows parallel the
acute bisectrix of the faults, indicating the direction of maximum
shortening. Maximum extension was subparallel to bedding, as indicated
by the open arrows.

A word about fault terminology and the efficacy of the concept of
the enveloping bedding--calling these faults low angle normal or high
angle reverse faults does not help in explaining the structures and
their relation to the overall folding. Use of the enveloping bedding
as a datum, rather than the horizontal plane, aids in deciphering the
structural sequence. Relative to the enveloping bedding, the two
fault orientations constitute a conjugate fault system somewhat inclined
to bedding, movements on which resulted in a lateral extension of bedding
(indicated by open arrows in Fig. III-B). This implies a subhorizontal
shortening of the rocks in a direction subperpendicular to bedding
(indicated by the solid arrows). This type of movement accords well with
the overall horizontal maximum principal stress that produced the major
folds here. The kink bands, with a similar sense of displacement as the
gently dipping faults, indicate an alternation of mechanism for movements
in this orientation.

Station 2: (approximately 300 feet south of crest of dam) The structure is a much larger kink band which is dipping moderately to the south, similar to those in the quarry. As at Station 1, the enveloping bedding is overturned, dipping 65° to the south. Bedding in the kink band has been rotated to 40° to the north, a rotation of 75°. Virtually all this change in orientation occurs within a three to four foot length of the bed. The locus of these sharply bent beds are the kink planes, the boundaries of the kink bands. This sharp bending of beds represent a high amount of strain within each layer, yet there is little megascopic evidence of brecciation, flow or thickening of beds. The bed-normal thickness is remarkably constant across the kink planes, and bed thicknesses within the kink bands are nearly identical to those outside the kink bands. Slickensides on the bedding surfaces indicate that the primary mechanism of deformation was by slip on the bedding surfaces. Although this kink bank is only 15 to 20 feet wide, its extent is considerable--it continues downward along this slope and extends up the other side of the valley to the Juniata exposures in the roadcut.

Fracture in crest?

Sketch the fold at station 2. Draw and label the axial surface

Station 3: (50 to 200 feet south of dam crest) The Tuscarora and the upper part of the Juniata together constitute a single, resistant sandstone unit which underlies many of the major ridges in the province. Lithically, they are quite different, the major factor being the nature and grain size of the matrix. The sandstones characteristic of the Tuscarora are very pure quartz arenites, being 95+ percent detrital quartz and silica cement; the sandstones typical of the Juniata are subgraywacke and graywacke with a minimum of 10 percent silt and clay matrix and generally about 20 percent rock fragments. This contrast in composition is responsible for the color contrast between the grayish-red Juniata and the very light gray Tuscarora.

The contact between these two stratigraphic units varies--in some localities, the change from grayish-red subgraywackes to quartz arenites is singular, providing a sharp, well-defined contact. Generally, however, as here at STOP III, the change in lithology is repeated, resulting in an interbedded contact. This interbedding probably reflects lateral shifting, back and forth over this locality, of the two depositional environments, one (Juniata) of rapid deposition and burial that preserved the rock fragments and fine matrix, the other (Tuscarora) a more mature one in which the sands were reworked and the fine material winnowed out.

At 140 feet south of dam crest is a steeply south dipping fault with displacement down on the south--a good normal fault. But what is its relation to the other structures? Relative to the subvertical enveloping bedding, this is a low angle wedge fault of the type common to the flexural slip folds in this province which resulted in a lateral shortening of the beds. However, note that it offsets the gently north dipping kink bands, an indication that it was developed late in the deformation.

Station 4: (130 feet north of dam crest) At this station faults are of two orientations. One orientation is gently north dipping with displacement of beds above the fault northward relative to those underneath, a displacement similar to that at Station 1 (Fig. III-B). The other fault set dips steeply to the north, with displacement of the northern beds upwards.

These two faults, then, constitute a conjugate system (although mutual offsets cannot be proven here), in which the acute bisectrix (the line dividing the acute angle between the faults) plunges moderately to the north at approximately 40 degrees. This is the direction of the maximum principal stress (compression) which produced this conjugate system, which in turn resulted in lateral extension of the beds. That is, the major axis of extension (lengthening) plunges steeply south at 50 degrees, subparallel to the steeply south dipping (overturned) enveloping bedding.

Station 5: (315 feet north of dan crest) This quarry was opened to provide the fill for the dam. The rocks exposed are entirely within the Tuscarora Formation, consisting of light gray, medium to thick bedded quartzite with some interbeds of thin to medium bedded dark gray silty shale. This contact in lithologies accentuates the structure present here.

In detail, one can see that there are two south dipping kink bands, one completely exposed, and the second one underneath it only partly exposed. Both are similar in size and orientation as the one at Station 2. Within both kink bands, bedding has been rotated 90 to 120° from the vertical to slightly overturned enveloping bedding. As with other kink bands and folds in this province, the most prominent aspect is the planarity of the bedding across the kink band, and the sharp bending at the kink planes. Comparing this exposure with the folds at Mifflin (STOP 2), the similarities are quite obvious because both exhibit the planar bedding, narrow hinges and constant bed thickness, the kink band and the Valley and Ridge folds are inferred to be closely related, geometrically and mechanically. And, in fact, these folds can be constructed from two joined kink bands, as described in the article "Structural Geology".

In the upper kink band one can see a considerable change in geometry from bottom to top, induced not only by the subsequent faulting, but also to a lesser extent by flow within the shalier beds. Yet, the width of the kink band and its attitude remain relatively unchanged from the lowest to the highest. The adjacent kink band to the left (to the north or underneath) shows a similar change in geometry. Near the upper part, a 1-foot thick quartzite bed is so tightly appressed that it possesses the geometry of an isoclinal fold. Immediately to its left, is a "box" or conjugate fold.

The other structures that are common in this exposure are gently north dipping faults similar to those seen at Stations 1 and 4. The four or five faults in this exposure, with displacements of 1 to 2 feet offset the kink band structures and thus are later than the south dipping kink banding (Figure III-D).
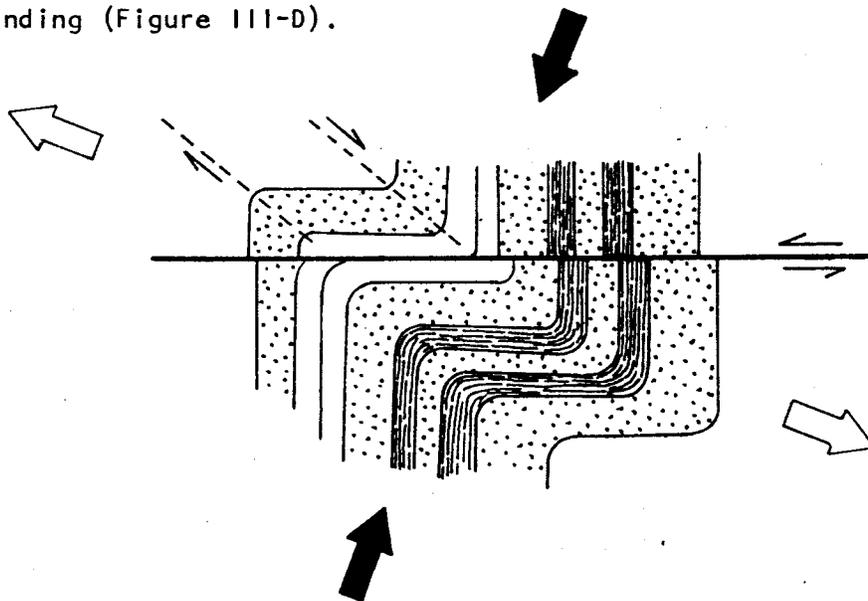
Figure III-D. Schematic relation of kink bands and faults at Station 5. Offset of the kink bands by the faults indicates the faulting is later. Although these two structures are not contemporaneous, the net effect of both is a shortening parallel to the obtuse bisectrix (shown by the solid arrows), with the maximum extension at right angles (open arrows).

Sketch the major fold in the quarry wall. Be detailed; show
    bedding as completely as possible, and show the small
    faults.

Draw a concentric fold near station 6. Show the detachment
plane.

Station 6: (400 feet north of dam crest at corner on north side of entrance to quarry) At the top of this exposure is the lower part of the kink band partially exposed at Station 5 dipping moderately southward. Below it is a smaller kink band dipping gently to the north, but with opposite sense of bed rotation, similar to those at Station 1. Together, these two kink bands produce a conjugate fold geometry. As with the conjugate fault system observed at Station 4, the acute bisectrix of the two kink planes is at a large angle to bedding; but plunging gently to the south, rather than to the north. In addition, these kink bands have resulted in lateral shortening of the enveloping bedding in contrast to the lateral extension of the enveloping bedding resulting from the conjugate faults. Although one set of kink bands and one set of faults of both deformational systems possess an identical orientation and sense of displacement, mechanically they are different.

The simplest explanation is as follows: In the initial stages of the folding of the Jack's Mountain anticlinorium, when the dips in the north limb (here) were still quite low, the subhorizontal maximum principal stress caused a conjugate kink band structure to be developed within this north limb. Because the enveloping bedding had some dip to it, the deforming stress was not symmetrically oriented with it (Fig. III-E) and the kink band array was consequently asymmetric, with the larger ones being north dipping (presently south dipping and thus overturned). It can be inferred that the rocks at this stage were moderately ductile to moderately brittle, because the kink banding is a continuous (though not really a penetrative) deformation.
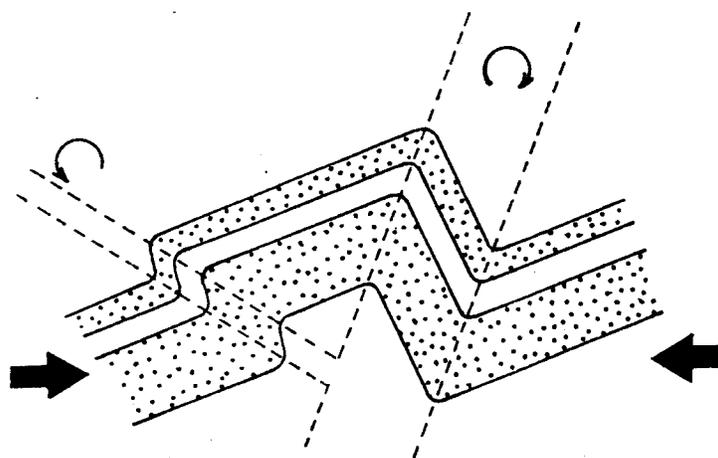
Figure III-E. Asymmetric conjugate kink band array developed at an early stage in the overall folding when the dip of the enveloping bedding was low and its angle to the deforming stress (solid arrows) was small.

As folding proceeded and the enveloping bedding steepened, the angle of the deforming stress to the bedding increased and further deformation by kink banding was thereby suppressed. Instead, particularly in the larger, initially north dipping kink bands the local deformation was replaced by a conjugate fault system (Fig. III-F), with one set of faults parallel to the smaller, initially south dipping kink bands (as in Fig. III-B). Because of this change in mechanism to a discontinuous deformation (faulting), it can be inferred that the rocks at this stage in the overall folding had become more brittle. (On the other hand, though, this change may not reflect a changing character of the rocks, but merely the increasing angle between the enveloping bedding and the deforming stress.) Thus, as the dip of the enveloping bedding in this north limb of the Jack's Mountain anticlinorium increased to its present overturned attitude, an initial shortening of the beds by kink banding was followed by an extension of beds by conjugate faulting.
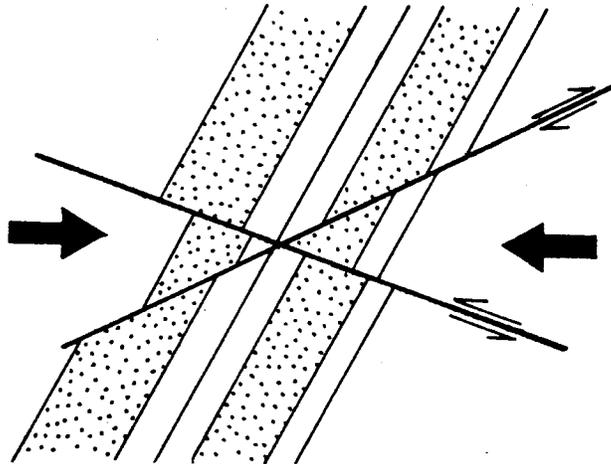
Figure III-F. Conjugate fault system developed at a later stage in the folding when the dip of the enveloping bedding was steep, at too large an angle to the deforming stress (solid arrows) for continued kink banding. The change in mechanism from kink banding to faulting may represent an increasing brittleness of the rock as the deformation proceeded. On the other hand, the alternation of kink band and fault at Station 1 suggests that the material itself did not change, but rather the change in mechanism was solely a result in change of attitude of the enveloping bedding.

Station 7: (720 to 740 feet north of dam crest) In the south-eastern part of the Conference area, the Tuscarora grades upwards directly into the olive gray shales of the Rose Hill. To the northwest, an interval of grayish-red sandstones (Castanea Member) occurs at or near the top of the Tuscarora. Because these beds are lithically similar to the Juniata sandstones, they apparently represent a return of the Juniata depositional environment. In places, as here, there is only one set of red beds; elsewhere, two or three intervals of red sandstones are interbedded with white sandstones.

Sketch a fold, or a series of folds, near station 7. Draw and label the axial surface. Draw cleavage crossing the fold.

Station 8: (980 feet north of dam crest) In contrast to the rocks to the south, the Rose Hill shale has a strong cleavage developed throughout, which does not quite obliterate bedding. At this station, an approximate kink band fold has been formed, with a strong axial plane cleavage. Within the synclinal hinge is a small fold which appears not to have developed by kink banding (flexural slip) but rather appears to be a passive flow or passive slip fold, one produced as a consequence of the cleavage development and lateral shortening. This marked contrast in deformational style and mechanism reflects the contrast in rock material between the Rose Hill and the Tuscarora.

Scattered about in the rubble fallen from this cut are a few specimens of deformed fossils, particularly crinoid stems. Their present ellipticity indicates a penetrative deformation in the rocks which may or may not be related to the cleavage development.

QUESTIONS TO ANSWER:

9.   Draw the fold and fault relations seen on the major quarry
     face. Indicate the relative location of the nearest major
     anticline and syncline.

10. Draw examples of concentric folding, and chevron folding.

11. Which came first, the folding or the faulting? Why?

12. Draw a schematic diagram interpreting the major fold as a
     kink fold. Show how south-dipping and north-dipping axial
     planes are related in the kink model. Pay attention to the
     fold relations at station 6 in doing this. You may want to
     consult Davis for help.