GEOLOGY 305

SUSQUEHANNA RIVER FIELD TRIP

# STRAIN TYPE AND STRAIN HISTORY

Saturday, October 10, 1998

Themes of the Trip:

Brittle strain and ductile strain

Stress orientation from strain orientations

Competence of rocks, and competence contrast

Strain sequence, interpreted from overprinting

Field Trip Stops:

Leave Newark 0630

1. Blue Mountain cut, Dauphin PA; 3 hours
2. Little Mountain cut, Dauphin, PA; 45 minutes
3. Bear Valley strip mine, Shamokin PA; 3 hours

Return 2200

Report due: Thursday, October 15, 1998

# Stratigraphic Sequence + Trip Stops

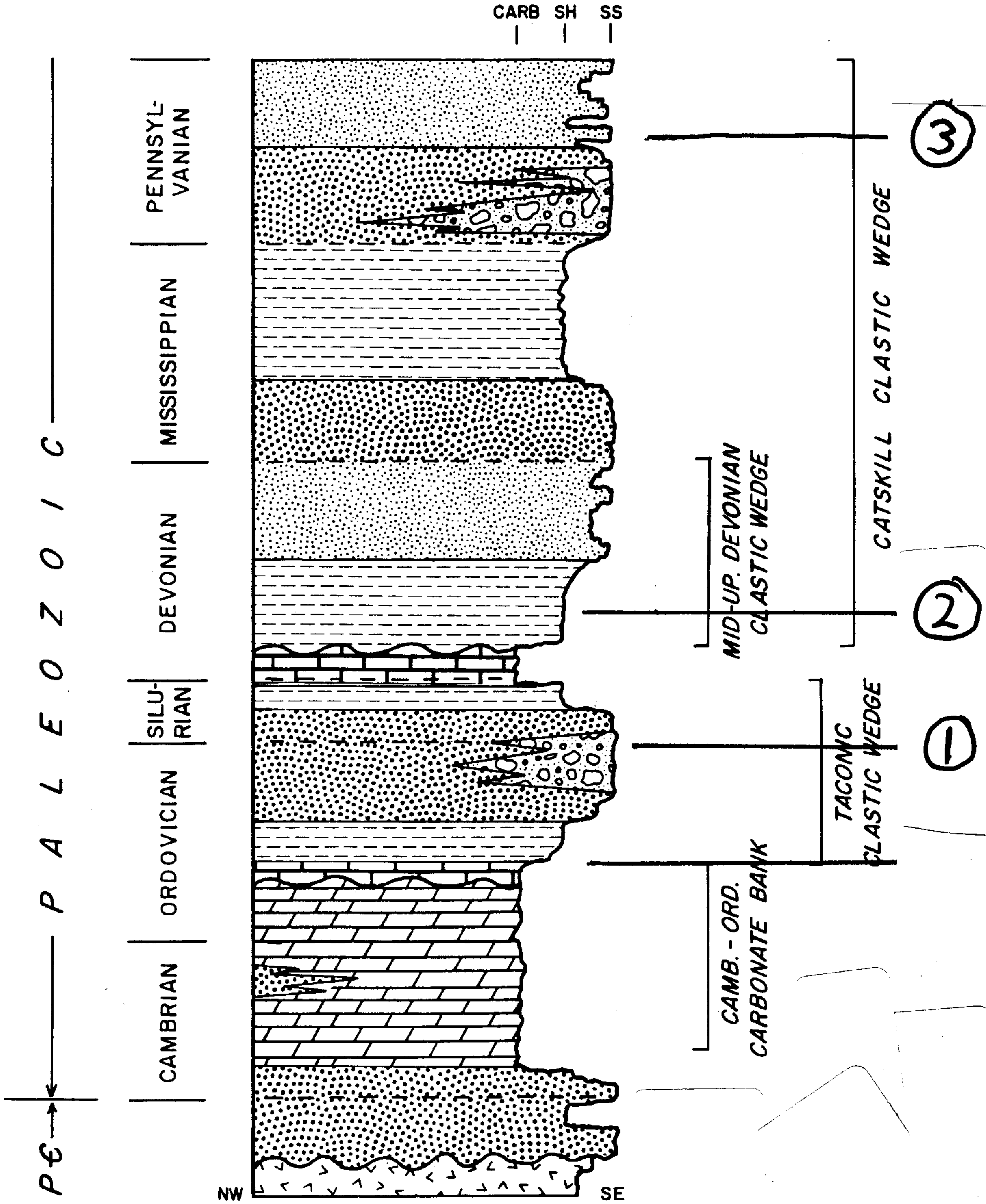



FIGURE 5. GENERALIZED STRATIGRAPHY OF THE NORTHEASTERN APPALACHIAN BASIN IN CENTRAL AND EASTERN PENNSYLVANIA.

○ = Stop

GEOLOGY 305

# *THE FIELD TRIP REPORT*

The report for this field trip will consist of this guidebook, with answers to the questions entered in the space provided. Those answers will be entered during the trip, as you collect the information. The work for the report will be done during the trip itself, and there should be very little to do afterward.

Your answers will be in pencil (probably); they will be messy and unpolished and the book will get dirty and wrinkled and bent up and you won't have a chance to neaten it up and make it all pretty as befits your high standards. But don't worry, because prettiness doesn't count for anything. What does count is that your answers are correct, that you see the relationships, that you're thinking the right way, that your drawings are legible and adequately labeled and not scribbled, and that your writing is succinct and in coherent sentences or phrases that make sense. Answers can be very short if they are to the point.

The only post-trip work for this report is to answer the final, **SUMMARY SYNTHESIS QUESTION**. For that question, write as much or as little as you need to say what you have to say. Legibly handwritten (in ink) is fine, typed is better (my eyes thank you).

The report is due **THURSDAY, OCTOBER 15, 1998,** at beginning of class.

## STOP 1

# BLUE MOUNTAIN

**DANGER:** Traffic here is high-speed and heavy and reckless (Penn State plays at home today); keep your butt off the roadway, behind the guardrail and fence at all times.

## *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 from source lands east and southeast of here. The clastic wedge is the sedimentary response to the Taconic orogeny of late Ordovician time.

We will concentrate on the **FOLDS** here today, and not do much with the faults. There's too much to see here in the time we have, and we have to limit ourselves to structures we already know something about.

## *REGIONAL STRUCTURAL GEOLOGY:*

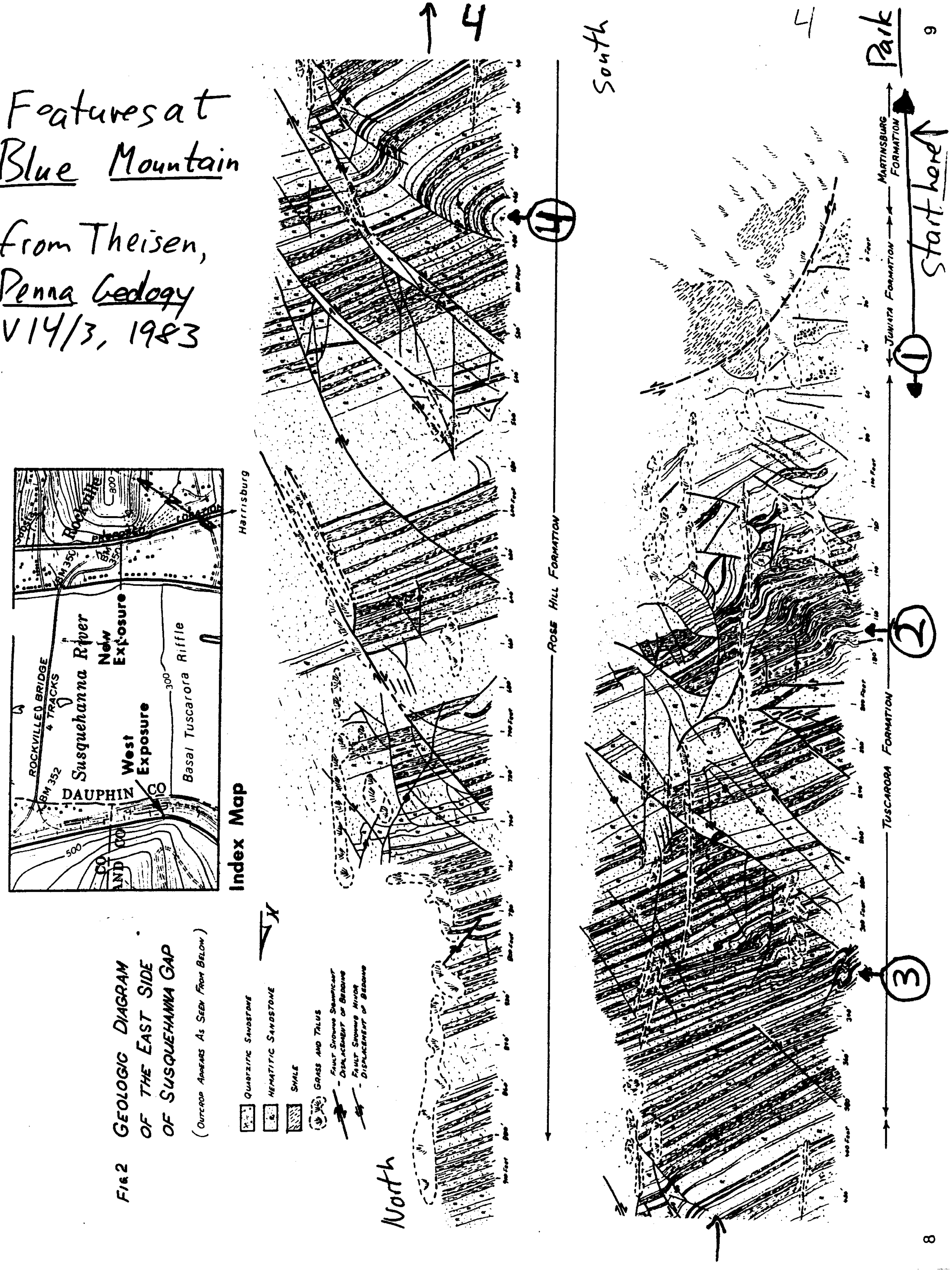
The structural relations involve not only these Ordovician and Silurian rocks here, but Devonian to Pennsylvanian rocks farther north also, and so must have post-dated deposition of those rocks. These structures here were created during the Alleghanian orogeny, of middle to late Pennsylvanian age. They are typical of deformation in the Valley and Ridge province from east-central New York to Alabama. At this location the Alleghanian orogeny developed folds in all rocks, and slaty cleavage in the weaker, finer-grained mudstones and shales, and late faults and joints.

## STATION 1: SOUTH END OF THE FENCE

Begin your examination in the gray, coarse-grained, pebbly Bald Eagle Formation.

Features at <u>Blue</u> <u>Mountain</u>

from Theisen, <u>Penna</u> <u>Geology</u> V14/3, 1983



The Bald Eagle, along with the Juniata above it, are the eastward-pinching-out, coarse, proximal feather-edge of a conglomerate-sandstone unit that reaches more than 2000 feet thick 30 miles west of here. This section of rock contains many internal faults

- Can you find bedding in the Bald Eagle? What properties of the rock define the bedding?

- What is the general shape of the Bald Eagle pebbles? Any sign of ovoid, non-spherical, flattened-looking shapes? Any preferred orientation?

- Work you way up-section into the Juniata 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? Sketch the contact below:

- If faulted, which way does fault dip? Identify hanging wall and footwall. Is motion normal or reverse?

- Which way does bedding in the Juniata dip?

- Using only stratigraphic sequence and dip direction, how can you tell if strata are right-way-up or overturned?

Walk south, back toward the vans, to

## STATION 2: SOUTH END OF THE GUARDRAIL:

At this location the Martinsburg Formation is partially exposed on the steep wall Climb up to the outcrops, and clear away what grass you can. Observe the strong **cleavage** in the shales and mudstones of the Martinsburg: the cleavage is very closely spaced, parallel splitting planes that run parallel to the fine, millimeter-scale compositional layering (which is probably original bedding. The cleavage is very poorly developed in the grainy rocks, and is visible only in the shales.

Note that the cross-section shows the 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.

- Find **BEDDING** in the Martinsburg. Look for thin, brown-weathering laminae of siltstone and vfg sandstone, from mm up to 2-3 cm thick. The cleavage is stronger and more closely spaced in the finer-grained rocks, weaker to absent in the grainy rocks. Draw some folds in bedding, and show cleavage.

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

- Find the Juniata-Tuscarora contact. Take strike and dip. Is the contact right-way-up or overturned? What's your evidence?

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

- Using only primary sedimentary structures, how can you tell if strata are right-way-up or overturned?

- Find cross-bedding in the Tuscarora. In its present orientation, are foresets concave upward or concave downward? Are the beds right-way-up or overturned? Sketch an example.

## *STATION 2:* <u>11 POSTS NORTH OF SOUTH END OF HIGH FENCE, AT THE HIGH SYCAMORE/ASPENS</u>

- Find the folds low on the cut at this stop. Identify two axial surfaces, on two separate folds, which have different dips. Sketch the folds in the region where the axial surfaces are close together. Sketch them again in a region where the axial surfaces have diverged some distance. Compare the sharpness of the folds, the tightness of the hinges, in the two regions.

- Notice the tension gashes in the red sandstone just N of the folds. What is the orientation of the tension gashes relative to bedding? What is the relation of tension-gash orientation to stress orientation? What was the local orientation of $o_1$ and $o_3$ relative to bedding?

Walk north past Station 1 to

## *STATION 3:* 7.5 POSTS SOUTH OF THE FENCE-HEIGHT CHANGE

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 and dark red-brown, hematitic sandstone; look for a further decrease in sandstone/shale ratio going north.

There are **TWO FOLDS AND A FAULT HERE**. The fault dips south.

- Find the **fault**. Look closely and carefully for the fault surface. Look for interrupted and non-continuous beds to locate it. Trace the fault with your finger. Notice how the fault locally cuts up into the sandstone, and isolates part of the sandstone bed into the footwall. Sketch that relationship.

- Note the **folds** in the strata of both hanging wall and footwall close to the fault plane. What is the sense of motion on the fault? HW up or HW down? normal or reverse?

- Sketch the relations between the folds and the fault.

- How did the folds form? Why did the folds form in the place and in the shape they did? Did formation of the fault have anything to do with formation of the folds?

- Any tension gashes in the sandstones? If you find any, draw them in relation to orientation of bedding. What orientation were $o_1$ and $o_3$?

- As you go north, use primary structures to determine which way the rocks **FACE**, i.e. which way is toward younger rocks. Take strike and dip of bedding. Why are facing direction and dip direction opposite?

***STATION 4:*** **5 LOW FENCE POSTS NORTH OF THE CHANGE IN FENCE HEIGHT**

This location is in the lower Rose Hill Formation.

- Find the open fold at about eye level on the outcrop face. Sketch this fold carefully and exactly. Locate the axial surface on your sketch.
  Notice how the shape and form of the fold changes from bed to bed - different rock types, and different bed thicknesses, express the folding differently. Start with the large, fat hematitic sandstone bed in the middle of the stack of beds, then note variations both downward toward the closure and upward away from the closure. Which beds are more intensely folded: thicker or thinner? coarser- or finer-grained? closer to or farther from the closure?

- The **<u>wavelength</u>** of the folds that affect any one bed are pretty consistent, and frequently differ considerably from the wavelengths of folds in adjacent beds. Is there any consistent relationship between fold wavelength and layer thickness? If so, what? Any ideas on why that might be?

- Notice in the higher layers on the large fold, bedding is stepped down progressively along small faults.

- Trace the layering northward from the fold hinge. Does it define a companion syncline to the north? If not, why not? What IS to the north? Describe what happens to the north.

- What is the sense of offset on the fault? Normal or reverse? Which side up or down?

- What is the relation of the fold to this fault?

- Examine the 15-20-cm-thick gray sandstone bed high on the fold, above the zone of buckles. Sketch the form of this bed across the fold.

- Note the **flame structure** high on the right side. Sketch the contact of the gray sandstone with the underlying shale to show the flame structure.

- Is the flame structure of tectonic or non-tectonic origin?

## *IN SUMMARY:*

- Which compass 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 overturned?

- Work out and state a general, use-anywhere guideline for telling right-way-up from overturned bedding using only facing direction and dip direction.

- What very large 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, show our little outcrops on it, and show the present ground level running somewhere across the middle of your diagram:

- Now draw the supposed thrust fault at the base of the Bald Eagle. Indicate the sense of motion on this fault. In its present position, the postulated motion was hanging wall (Martinsburg) moved north. Is the sense of movement on the fault consistent with what you would expect on this limb of your large fold system?

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

- Could the thrusting have occurred synchronous (coeval) with the folding? Or must it have occurred before? or after? Explain.

## STOP 2

# LITTLE MOUNTAIN

The Rocks: **MONTEBELLO MEMBER** of the Middle Devonian Mahantango Formation. Deep-marine, coarse quartz arenite sandstones, turbidite graywackes, 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:

# BEAR VALLEY MINE

Location: abandoned strip mine 2 miles SW of PA 125, Shamokin, PA

The Rocks: Llewellyn Formation, lower Pennsylvanian, nonmarine sandstones, shales, and coal

## *OVERVIEW OF THE MINE:*

The Bear Valley strip mine was excavated to get at the coal contained in the "Mammoth Number 8" seam, which was about 20 feet thick. Mining went only as far as the base of the No. 8 coal, and the rocks in the footwall (the rocks below the seam) were left intact in their original positions, because they were of no economic concern to the coal company. The base of the pit and the surrounding highwalls thus expose structural relations of quality not often found in eastern states.

The floor of the pit exposes, as topographic expressions, three anticlines and two intervening synclines. The central anticline is termed the whaleback anticline, for reasons that will become obvious.

The east highwall contains an open, upright syncline in sandstones, and a tight, asymmetrical, overturned anticline in shales immediately to the north (look hard to see it).

The folds appear to be stacked on one another in strange fashion (see Figure 10). The whaleback anticline apparently plunges directly beneath the highwall syncline. According to the conventional rules of structural geology, these stacking relations are unacceptable, and must have some other cause: perhaps the folds are not continuous along plunge, and either die out or flatten or have curved axes.

## *NATURE OF THE DEFORMATION*

Deformation in this mine resulted from the Late Pennsylvanian Alleghanian orogeny, which involved decollement thrusting and folding of shallowly buried, unmetamorphosed rocks such as these.

The deformation here comprises brittle fracturing, and ductile folding, each of which occurred at least twice. Dick Nickelsen of Bucknell University has identified seven stages of deformation in this mine. They are given schematically in Figure 7 (keep track of the north arrow), and are summarized below:

Stage I: early joints (brittle) in coal beds

Stage II: joints (brittle) in sandstone and shale (and also in coal), different orientation from joints in coal

# ASPECTS OF ALLEGHANIAN DEFORMATION

by

Richard P. Nickelsen

## Introduction

The structural part of this field conference could deal with a number of timely aspects of the Alleghany Orogeny in central Pennsylvania: fold geometry and fold mechanics, thrust-fault tectonics, description of finite strain and its origins, the sequence of structural stages, strain mechanisms, and environmental conditions during the Alleghany Orogeny. We will limit the scope because of time, suitability of outcrops of certain features, and our current level of interest and understanding, to 2 major topics: the sequence of stages of the Alleghany Orogeny, and the description of finite strain and its origins. These topics impinge on many of the others. A minor topic to be discussed in two other introductory sections by Levine and by Nickelsen and mentioned at several field-trip stops is the growing evidence about environmental conditions (primarily temperature) that may have existed during the Alleghany Orogeny.

## Sequence of Structural Stages of the Alleghany Orogeny

Underlying other structural considerations is the relative sequence of structural stages that has been established at the Bear Valley Strip Mine and extended to the rest of the Valley and Ridge Province in Pennsylvania (Faill and Nickelsen, 1973; Nickelsen, 1979). Others have recognized a similar sequence farther south (Perry, 1978; Burger, Perry, and Wheeler, 1979). The overlapping sequence of different structures was established and corroborated by many observations of structural overprinting, but is also indicated by the spatial distribution of different structures (Means, 1976). Early structures in the sequence occur alone farthest northwest and are successively overprinted by later structures as one proceeds southeast (Nickelsen, 1980). A few places such as the Bear Valley Strip Mine have almost all stages of the presently known sequence superimposed and are important museums of structural relationships and mechanisms for future restudy, evaluation, and debate. What is equally important about Bear Valley is its stratigraphic position near the top of the sedimentary prism that was deformed by the Alleghany Orogeny. It can't be claimed that the Bear Valley structural sequence and mechanisms, which are identical with those down to the Cambrian within the geographic area of the Pennsylvania salient, are Taconian or Acadian features. The Alleghany Orogeny apparently deformed, for the first time, a thick pile of Paleozoic sediments in a miogeocline that had already achieved temperatures and pressures sufficient for coalification and sedimentary compaction. This fact is perhaps significant in the creation of the particular array of structures in overlapping sequential stages that we call the Alleghany Orogeny.

Stage I, Alleghany Orogeny. The seven stages of the Alleghany Orogeny listed in Figure III-9 and illustrated in Figure III-10 include Stage I, joints in coal, which have no known connection with the Alleghany Orogeny and were overprinted by Stage II joints in coal and joints in shale and sandstone that are of Alleghanian age. Stage I joints in coal arc across the northern Appalachian Plateau trending NE, E-W and NW (Nickelsen and Hough, 1967) and can be found with NE strikes in the Anthracite Region. They are obscure due to overprinting by all later stages.

Stage II, Alleghany Orogeny. Stage II joints of several regional sets (A,B,C,D,E, of Nickelsen and Hough, 1967) are also best observed in the Appalachian Plateau (Parker, 1942; Engelder and Geiser, 1980) but can be identified at most Valley and Ridge Province exposures by careful measurement and rotation of data. Intersecting Stage II extensional joint sets are not conjugate but rather make up a cumulative pattern (Nickelsen, 1974) requiring different orientations of the least strain axis at different times during Stage II. For example, Engelder and Geiser (1980) have proven the different relative ages of two acutely intersecting Stage II joints of the Appalachian Plateau in New York State. Our field trip will demonstrate the creation of a cumulative joint pattern at Stop VI that is interpreted to include fractures of Stages II, IV, and VI. Joints at this stop include Stage II and IV syntectonic, quartz-filled hydraulic joints related to fluid pressure (Secor, 1960) and different, Stage VI, extensional joints due to late tectonic buckling or relaxation during unloading (Price, 1966). The same differences in joint characteristics are illustrated by the Stage II and Stage VI joints at the Bear Valley Strip Mine, Stop III.

Stage III, Alleghany Orogeny. The Bear Valley Strip Mine is the best place to view overprinting and overlapping relationships between Stage II joints and Stage III rock cleavage. Some Stage II joints are perpendicular to rock cleavage and the same age as the cleavage, while others of the joint array are intersected by cleavage at angles less than 90°. In places, these have been offset by pressure solution and can be proven to be pre-cleavage in age.

Stage IV, Alleghany Orogeny. Cleavage at Bear Valley has been dragged against Stage IV wrench faults and cut by the gash veins that commonly form along these faults. Small thrust faults have tip lines consisting of strongly cleaved rock that rides on the brow of the fault and is dragged against the fault. The relations of Stage III cleavage to Stage IV thrusting is particularly well demonstrated by the cleavage halos, strain gradients, and drag of cleavage against thrust faults at Stop IV. Small-scale examples of the relation of cleavage to wedge and wrench faults in a low-strain environment are at Stop VIII. Cleavage is either rotated or created anew during simple shear against faults, but the most dramatic examples of rotational deformation are on fold limbs such as Stop I.

As shown schematically in Figure III-9, the time of cleavage formation overlaps Stage II jointing but continues through Stage IV faulting into Stage V folding and beyond. Evidence of pure shear in certain beds at Station H, Stop I, may manifest Stage VI inhomogeneous bulk flattening and layer-parallel extension.

Stage V, Alleghany Orogeny. Stage V folding has rotated previous structures as demonstrated at Stops I, III, VII, and VIII. The best evidence of rotation is provided by pre-folding Stage IV wrench faults which can be described by two structural elements - a slickensided fault plane perpendicular to bedding and slickenlines (Fleuty, 1975) parallel to the bedding-fault intersection. During Stage V folding these slickenlines are bent with bedding as is demonstrated throughout Bear Valley (Stop III) and at Stop VII. When Stage IV and V overlap, curving slickenlines such as at Station G, Stop III, are formed, but they are relatively rare. Slickenlines on wrench-fault surfaces throughout the region most commonly parallel fault-bedding intersections, whatever the bedding dip angle, thus proving that most wrench faulting precedes Stage V folding. Acute bisectors of conjugate wrench faults commonly trend obliquely to the strike of strata or fold hinges as shown at Stop III, Station A, and Stop VI and VIII. This suggests a change in orientation of the principal stress axis between wrench faulting and folding (Figure III-7B). The evidence for relative timing of wedge (thrust) faults is less certain. They seem to be slightly later than associated wrench faults as at Stop II and Stop VI and prior to Stage V folding as at Stop III (Figure III-7). Generally, wrench faults and wedge faults are placed together in Stage IV, preceding Stage V folding but perhaps continuing into the period of folding.

Finally, some wedge faults seem to form as a consequence of folding as demonstrated at Stop VII in stratigraphic Unit C.

Stage VI, Alleghany Orogeny. Late in the history of the Alleghany Orogeny all rocks were subjected to flatterning and vertical extension, predominantly by brittle mechanisms. Where beds had been rotated to dips of greater than 45° by Stage V, this resulted in layer-parallel extension. At Bear Valley, Stop III, this flattening and extension is primarily manifested in local fault "grabens" on the north limb of the Whaleback Anticline (Figure III-3, Stations B and F) but may also form faults like the Bear Valley fault under the North Anticline. To explain higher coal ranks at the surface in coals of the center of western Middle Field Synclinorium, Levine (see accompanying article) invokes significant uplift of the center of the basin along such high-angle reverse faults. Where bedding had remained nearly horizontal as at Stop V the late extension appears as quartz-filled extension joints in sandstone dikes and fiber-filled wedge faults.

Stage VII, Alleghany Orogeny. The evidence for Stage VII is graphically shown in Figure III-10 but will not be seen at any stop on the field trip. Late wrench faults that are restricted to major gaps on lineaments have horizontal slickenlines cutting the fault-bedding intersection at angles approaching 90°. These wrench faults cut all previous structures including the extensional faults of Stage VI. In some gaps there is evidence of wrench faulting initiated during Stage IV, prior to folding, that has remained continuously active until Stage VII. This wrench faulting has segmented the fold belt into blocks, deforming independently, that may reflect pre-existing sedimentation patterns, basement fractures, or major changes in trend. The lineaments paralleling these long active wrench faults have been identified by Kowalik and Gold (1975) as likely spots for mineralization.

In summary, the stages of the Alleghany Orogeny that are now widely recognized and will be demonstrated on the field trip include Pre-Alleghany joints (Stage I) of uncertain basinal origin and Stage II joints related to the gradual increase of horizontal stress difference that lead to the orogeny. Before major folding, layer-parallel shortening was accomplished by formation of Stage III spaced cleavage and Stage IV conjugate wrench and wedge faulting. Stage V folding was followed by Stage VI layer-parallel extension or general flattening and vertical extension by wedging, extension faulting, high-angle reverse faulting, and inhomogeneous bulk flattening in ductile beds. Stage VII wrench faulting is found in a few places cutting all previous structures.

This structural sequence has served as a framework for identifying the time of origin of potentially economically important structural features (eg., the fracture porosity of Stop VI) and as a help in separating the strain increments of the heterogeneous, finite strain pattern in the region (see below). We hope that continuing study of the mechanisms and environmental paramenters associated with the various stages will lead us to a better understanding of how rocks deform.

Figure 7.



Figure

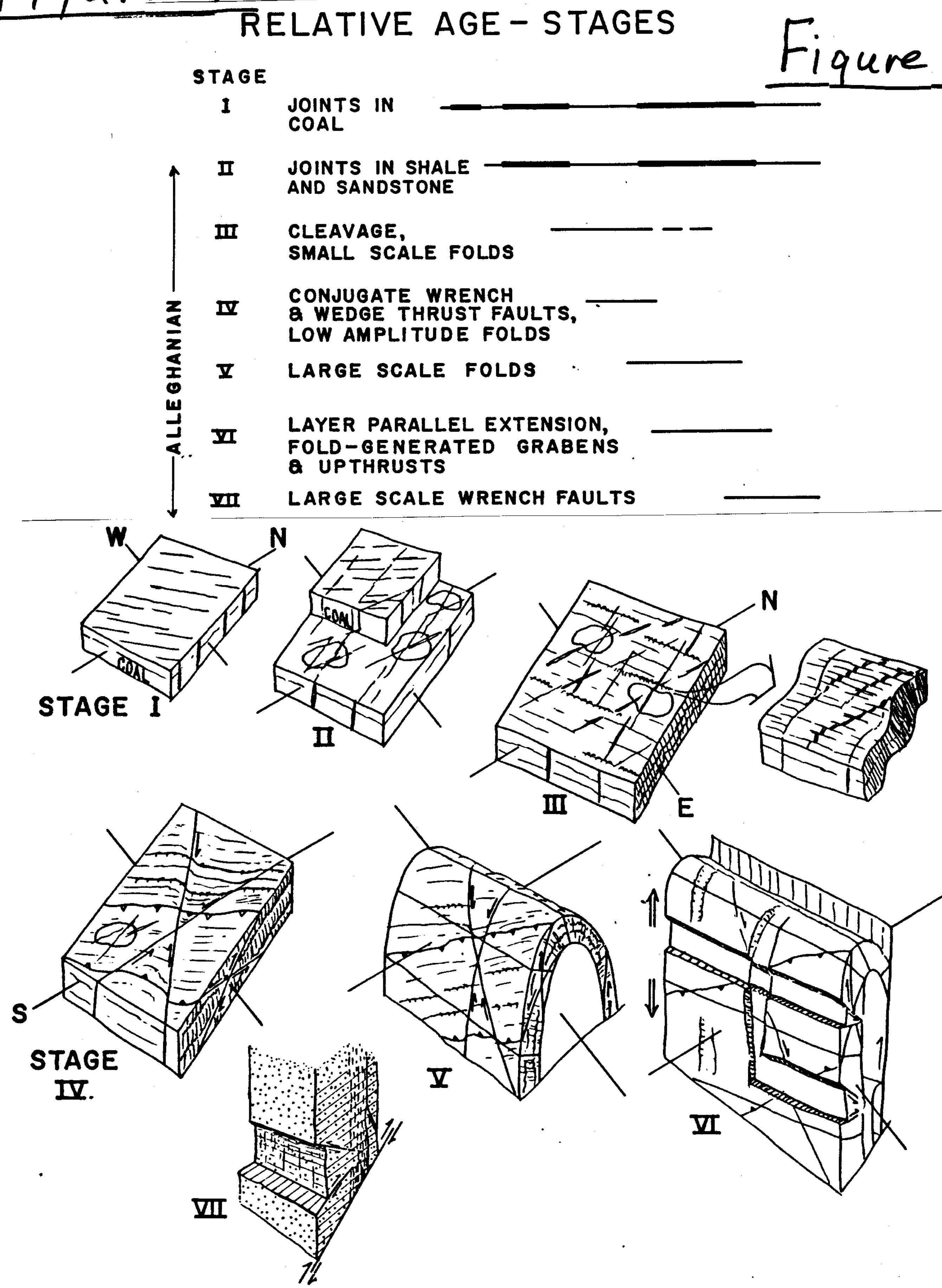



*Figure III-10* *Cartoon schematically showing the sequential development of structures in the Bear Valley Strip Mine through stages I–VI.*

Stage III: Cleavage and small-scale folds (ductile) in all rocks, but primarily in shales, different orientation from earlier joints

Stage IV: conjugate strike-slip faults (= wrench faults) (brittle), with slickenlines, and wedge thrust faults, usually without slickenlines

Stage V: large-scale folds (ductile); formed the visible large folds, including whaleback anticline and other anticlines and synclines

Stage VI: extensional faults and grabens (brittle), formed by layer-parallel extension and adjustment of folds, and upthrusting (hard to see)

Stage VII: large-scale wrench faults ( + strike-slip faults; brittle).

Additional information about the stages of deformation is given in the following pages, taken from Nickelsen's field trip description.

These seven stages of deformation are all contained in the same rocks, and must be deciphered systematically. You must try to mentally isolate structures of one stage from all the other structures in the rock, that may be affecting the ones you care about. The rationale for recognizing stages of deformation is this: **Later structures OVERPRINT, and deform, earlier structures, and move the earlier structures to NEW POSITIONS and NEW ORIENTATIONS, in which the origin of the earlier structures is improbable** according to your current understanding of the laws and processes of geology. For example, attitudes of bedding, senses of motion on faults, orientations of folds, plunges, etc., don't make sense in their present (later) orientations, and in your judgment couldn't have formed the way they are now; therefore they must have been deformed into their present positions after they originated in other, more probable positions. We will have ample opportunity to practice seeing through deformations.

Based on this logic, your mission here (should you decide to accept it) is to recognize as many of the seven deformational episodes as you can.

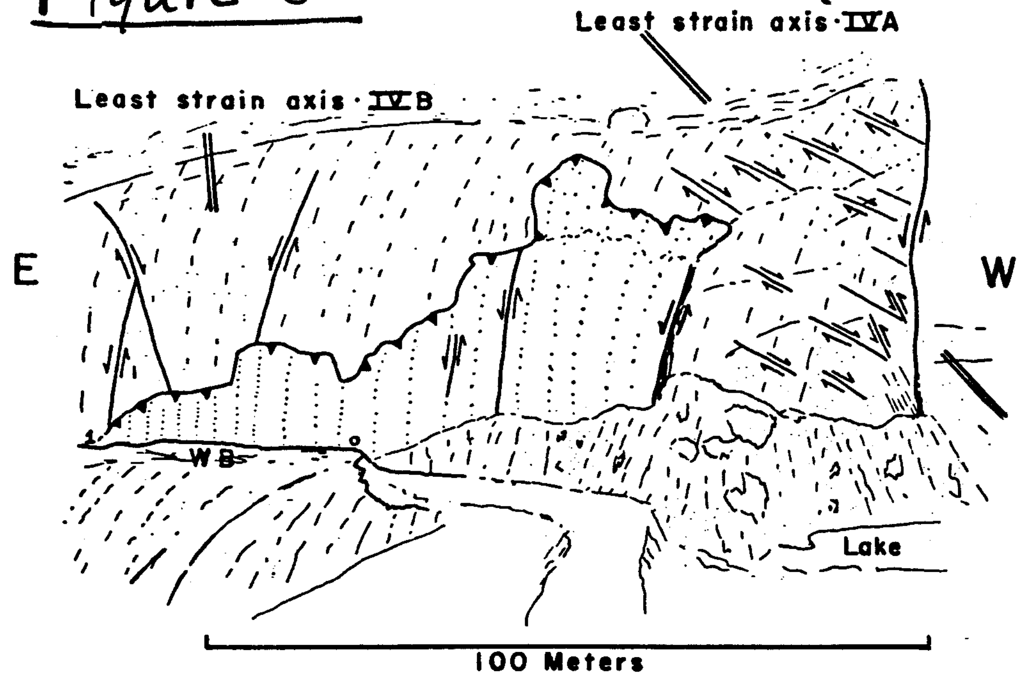
## *PROCEDURE*:

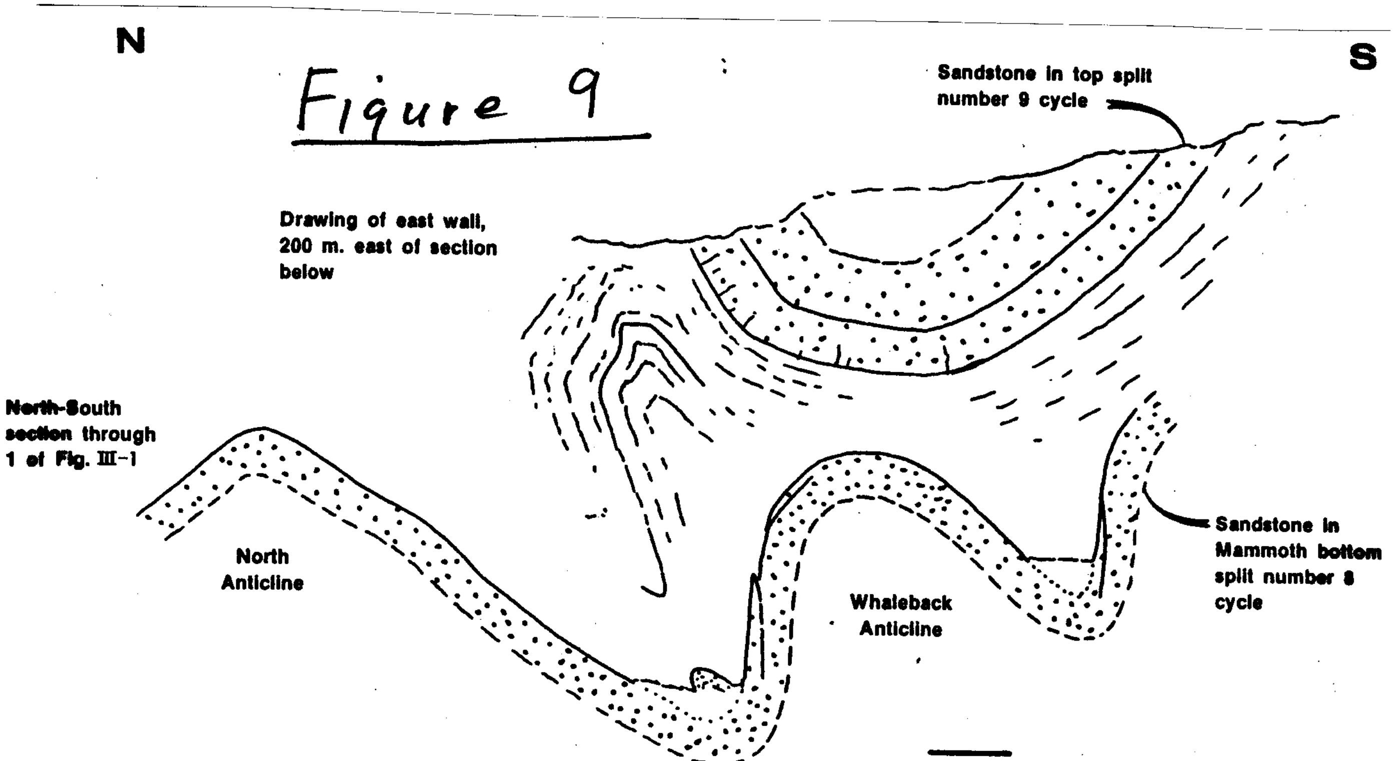
We will spend three hours here, and will concentrate our examination at four locations in the mine. We will see evidence for stages I, II (maybe), III, IV, V, and VI.

## *STATION 1:* THE NORTH ANTICLINE

Consult the geologic map for your location in the mine. It's a hard map to read, and finding your position may be difficult.

Figure 8




This drawing depicts structural disharmony between the sandstones in the number 8 and number 9 cycles of sedimentation. The Whaleback anticline decreases in amplitude and plunges east under the syncline in the number 9 cycle, which is exposed in the East Wall of the mine. Thus this composite section overemphasizes the disharmony between the two sandstones.

*Figure III-2* *Section of Bear Valley Strip Mine*

from Nickelsen, 1985

Do these things here:

- Determine the trend and plunge of the axis of the north anticline. Use your Brunton. This number becomes important in the stress and strain story of the mine.

- Take strike and dip of bedding in several places on the limbs.

- Examine the slickensides on the fault surface. Determine the plunge of slickenlines.

- Look for steps on the slickensides. What was relative motion? What kind of fault?

- Draw a profile cross-section of the probable relations as you look east along the fault.

## ***STATION 2:*** THE SOUTH WALL

Figure 8 shows a drawing of features on the south highwall, which is the north limb of the south anticline.

Look for these features:

- **<u>conjugate wrench faults</u>:** What is the strike of one set of major fractures affecting these rocks?

- Examine the **<u>slickenlines</u>** on the fracture surfaces: These are faults, not just fractures. Determine the <u>pitch</u> of the slickenlines in the fault plane.

- Notice the **<u>steps</u>** on the slickenlines. What is the sense of motion on the faults?

- Determine the strike of the other set of fractures. Are they faults too? What sense of offset do they have?

  What is the angle between the strikes?

  Draw a map view of the conjugate pair, and indicate senses of relative motion on each set. What was the compass orientation of $\sigma_1$?

- What's strike and dip of bedding here?

- What is the **<u>pitch</u>** of each set of slickenlines in their respective fault planes?

  What's the <u>pitch</u> of the slickenlines relative to dip of bedding?

- What is the angle between bedding planes and the fault planes?

- From the slickenline orientation, what was the orientation of fault movement relative to bedding?

- This slickenline orientation has some interesting consequences up at the top of this ridge, where the sandstone rolls over the crest of the south anticline. What relation between slicks and bedding would you expect to find up there if the faulting occurred **after** the folding? Draw a schematic cross-section of the sandstone and slickenlines at the nose showing your scenario.

- What would you expect to find up there if the faulting occurred **before** the folding? Draw a cross-section showing this scenario.

- Which stage of deformation is represented by these conjugate faults?

## *ALONG THE SOUTH HIGHWALL:*

- **Drag as a strain indicator:** Look for **cleavage** in the shales. Observe how cleavage is bent, or **dragged**, next to a wrench fault. The direction of drag indicates where the **opposite side** went. Draw an example of drag of cleavage near a wrench fault.

- the wedge thrust high on the south wall both contains and covers wrench faults. Which stage of deformation?

- On south limb, the large siderite concretions are deformed in a consistent way, and act as strain ellipsoids. Notice the flattened shape, and the tension gashes inside. Use them to draw a schematic strain ellipsoid, and indicate compression and extension directions.

## *STATION 3:* THE SOUTH SYNCLINE

Our position here is on the axial trace of the south syncline, although it is covered with fill. See Figure 9 for location.

- Describe the syncline: small or large? tight or open? rounded or angular? etc.

- Take strike and dip of both limbs.

- Draw a schematic cross-section of the south syncline, looking east.

- What stage of deformation is the south syncline? your evidence?

**Steep to vertical faults in whaleback limb:**

- western fault: what is strike and dip of the fault plane?

    slickensides: what is pitch of the slicks in the western fault?

- eastern fault: what is strike and dip of the fault plane?

    slickensides: what is pitch of the slicks on the eastern fault?

- Draw a cross-section of the faulting relations here. Show stress arrows on the cross-section.

- In what compass direction did the extension take place?

- What is the direction of extension relative to the whaleback axis?

## *STATION 4:* THE WHALEBACK ANTICLINE

- **Folded slickenlines:** At west end of whaleback, follow the sandstone bed through the anticlinal crest and look for slickenlines on the vertical joint/fault surfaces. The slicks stay parallel to bedding across the crest. This is a miniature of what happens at the top of the south anticline at station 2.

- **Fiber growth** of crystals in tension gash veins: look in the gash veins for quartz fibers; their long axis traces the direction of opening of the fracture.

Walk out on the crest of the anticline, and walk to the east end. Don't fall off. See Figure 9 for location.

- **plunge:** Using the Brunton held out at arm's length, estimate the plunge of the anticline near the western end.

Estimate plunge near the eastern end.

- Is there any evidence that the anticline steepens, or flattens, or lessens, or turns, as it approaches the east highwall? Explain.

- **What stage of deformation** is the whaleback? What is your evidence?

## *STATION 5:* THE NORTH SYNCLINE

Walk west in the excavated trough of the north syncline, and examine the north wall of the whaleback anticline. See Figure 9 for location. Follow Figure 10 (next page) as you traverse.

- Take strike and dip of bedding in the whaleback wall. Find the maximum dip.

- **extensional faults**: are these extensional faults "normal" faults? any giveaway angular relationships between any of these extensional faults?

Figure 10.

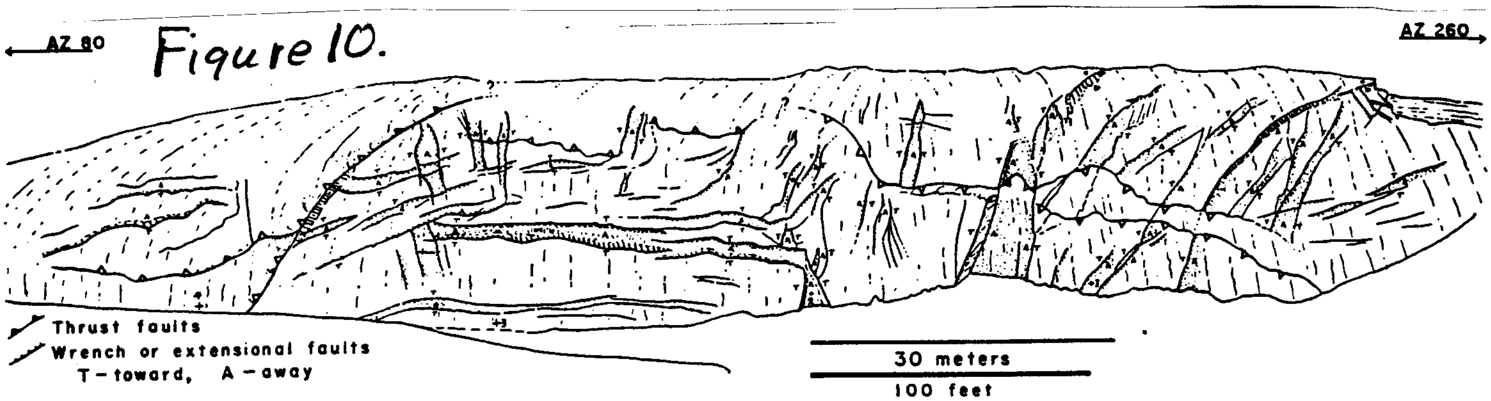



*Figure III-3* *Drawing of structures exposed on the north limb of the Whaleback Anticline. View from Station B*

- Note the **pairs of extensional faults**, and the thrust faults, in the north wall of the whaleback. How many orientations of faults do you see?

- Look west along the limb of the whaleback, and draw a profile section of a small graben. This graben is not in the orientation you normally expect for grabens. Draw principal stress orientations on the diagram.

- In what direction was the extension taking place?

- These extensional fault/graben pairs are common on this north limb of the whaleback; just look around. Why might there be so many of these structures?

- Compared to this north limb, on the south limb these extensional graben faults are rare to nearly absent. Why should they be so unevenly distributed?

- **What stage of deformation** are these fault pairs? What is your evidence?

- **slickenlines**: draw curved slickenlines, and trace the trajectory of movement they record.

## ***GENERAL QUESTIONS***:

- What is the evidence that the conjugate wrench faults predate the formation of the large anticlines and synclines (e.g. whaleback)?

- Cite evidence from the field that the deformation sequence followed the path

  brittle ductile brittle

**SUMMARY SYNTHESIS QUESTION:**

- Compare and contrast the styles of deformation at Shamokin with those near Harrisburg. As you do so, consider the possible effects of overall rock competence in controlling deformation at each site, and of contrasts in rock competence as a factor in the development of the strain. Which was, for example, colder/hotter? more brittle/more ductile? shallower/deeper? more/less tectonic transport? more upright/more overturned? earlier/later? N-S/E-W/NE-SW/NW-SE? Which deformation was more intense? Were the stages of deformation comparable? Were they deformed in the same orogeny? etc.