GEOLOGY 401

SUSQUEHANNA RIVER FIELD TRIP

BRITTLE STRAIN AND THE STRESSES THAT CAUSED IT

Themes of the Trip:

- Types of Strain - brittle, and ductile
- Stress orientations, determined from strain orientations
- Competence of rocks, and competence contrast
- Tectonic history, interpreted from strain
- Sequences of tectonic events

Field Trip Stops:

Leave Newark 0700

1. Rheems quarry, Rheems, PA: 3 hours
2. Blue Mountain cut, Dauphin, PA: 20 minutes
3. Bear Valley mine, Shamokin, PA: 3 hours

Return 2100

Report due: Tuesday, October 11, 1988, in class

APPALACHIAN BASIN STRATIGRAPHY

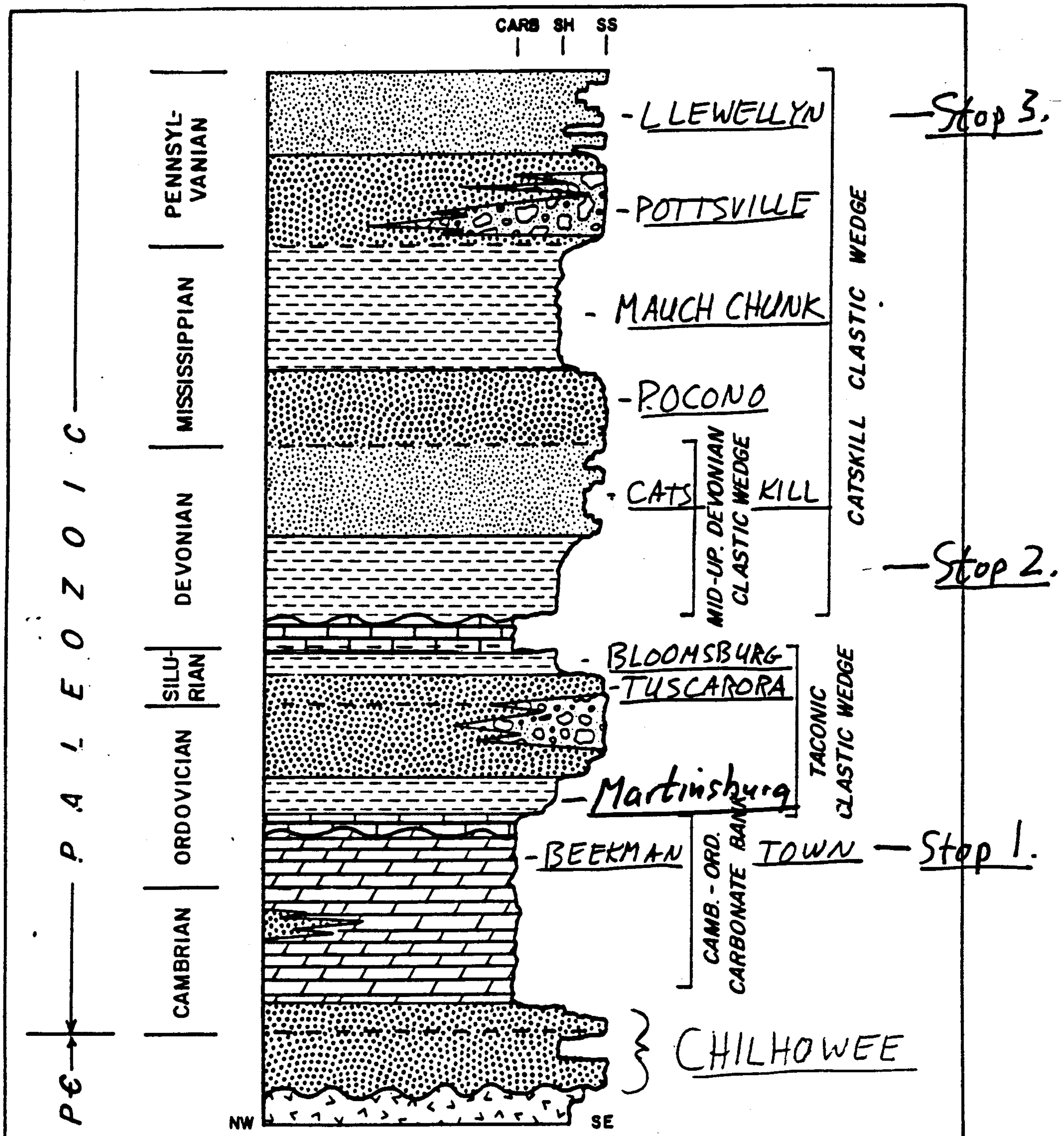


FIGURE 1. GENERALIZED STRATIGRAPHY OF THE NORTHEASTERN APPALACHIAN BASIN IN CENTRAL AND EASTERN PENNSYLVANIA.

from Thompson + Sevon, 1983

STOP 1: RHEEMS QUARRY

Location: Rheems quarry, operated by Union Quarries, Inc., Rheems PA.

The rocks: BEEKMANTOWN GROUP, Middle Ordovician shallow marine and tidal dolomites and limestones of the Appalachian miogeoclinal prism; probably fossiliferous, but no fossils found here so far. See Figure 1 for stratigraphic position of this stop.

OVERVIEW OF THE QUARRY:

Rheems quarry is a famous stop for geology field trips. It contains exposures of strongly folded and transported miogeoclinal rocks that were deformed in the Taconian orogeny in middle to late Ordovician time. The rocks are interbedded limestones and dolomites; although both carbonates, these different rocks are of different competence, or mechanical strength, and thus they deform respond to the same stress in different ways. These will become clear as you walk around the quarry.

The two main themes of deformation in the quarry are folding and fracturing. The folding is immediately obvious, the fracturing less so, but will become clear as you walk around. The folds are not upright, and have nearly horizontal axial surfaces. Several types of folds are present, but you will see that regardless of their specific form their axial surfaces are nearly parallel. The clearly defined fold on the east wall is probably not the same fold as those exposed on the southeast corner and on the north rim; those two may be the same fold. Try to connect them in the air.

The fractures are both conjugate pairs and tension gashes, representing both compressional and extensional stress regimes. See whether the stress orientation is the same for each.

The quarry is actively working, and the exposures are different each year. Figure 2 represents the quarry in 1956, and is hopelessly outdated.

PROCEDURE:

We will make three extended stops inside the quarry. _Observe, examine, and study the following features as we go around the quarry. Make sketches and drawings of them in the space provided on these pages. Collect evidence in the quarry to answer the **QUESTIONS** on separate paper.

Features at Rheems Quarry

from D. Wise, Penna Field conference, 1960

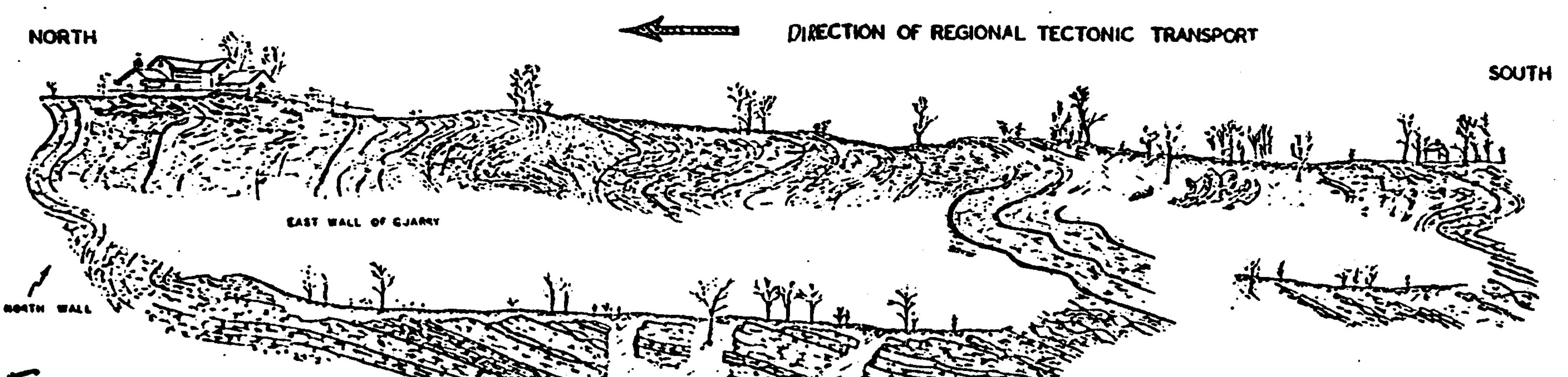


Figure 2.

MIRROR IMAGE OF THE WEST WALL PROJECTED INTO THE SECTION BY PLUNGE OF FOLD AXES
STRUCTURAL CONTROL BY PLANE TABLE AND ALIDADE

ORDOVICIAN BEEKMANTOWN LIMESTONE, 1/4 MILE SOUTH
OF THE TRIASSIC LOWLAND, 40° 7.6'N 76° 34.6'W

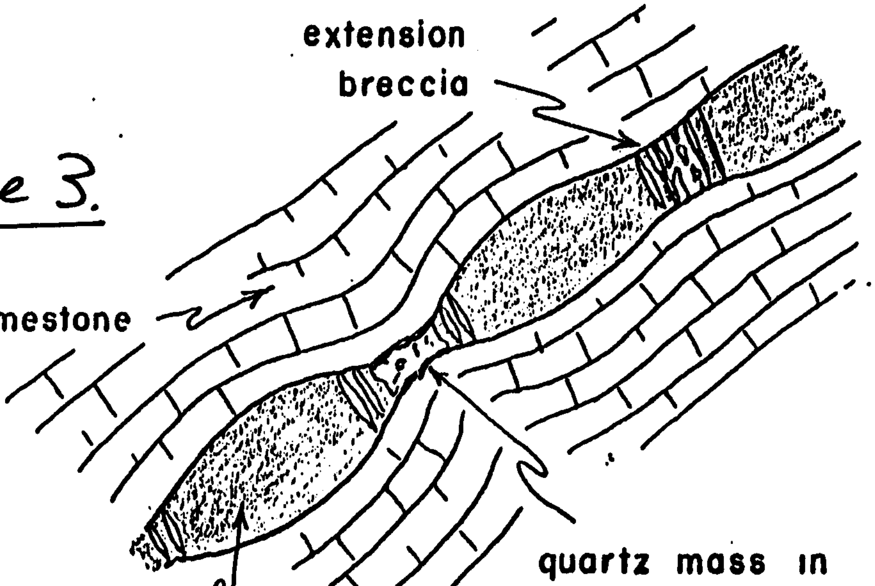
HEISEY BROTHERS QUARRY AT RHEEMS, LANCASTER COUNTY, PENNA.

25 0 50 100
HORIZONTAL AND VERTICAL SCALE IN FEET

RECUMBENT FOLDING AND TECTONIC TRANSPORT IN LIMESTONE

J G WISE 1958

Figure 3.



"HOURGLASS FOLDING" INTO THE LOW
PRESSURE ZONE BETWEEN BOUDINAGE

TYPES OF STRAIN:

TYPES OF COMPRESSIVE STRAIN:

- conjugate shear fractures and sense of motion? :

- slickensides and steps: (see Figures 4 and 5) draw both plan view and cross-section view, and orient the shear stresses:

- similar fold: (see Figure 7) show thickening in the hinge zone:

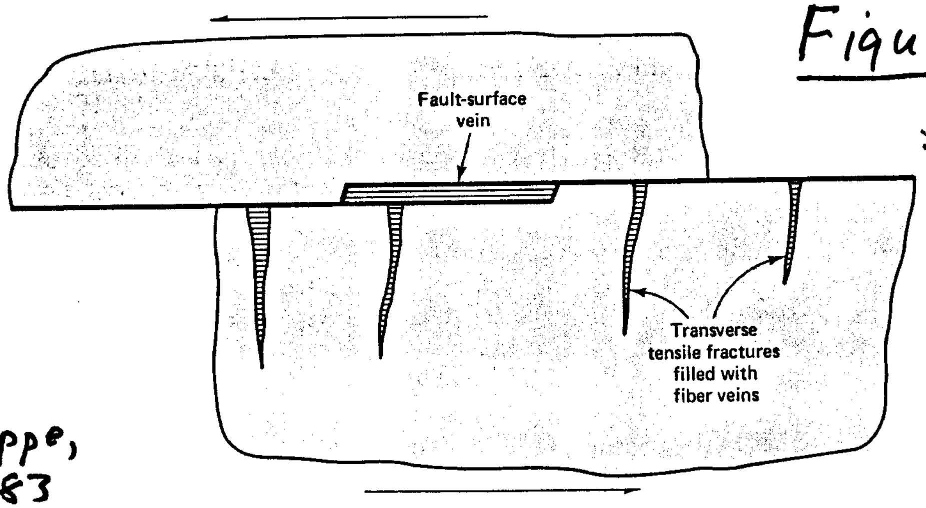
TYPES OF EXTENSIONAL STRAIN:

- a single tension gash, and show the internal fiber orientation (see Figure 8) if visible:

- a bed containing tension gashes. Orient the principal stresses.

Slickenside Fiber Growth

Figure 4.



Suppe, 1983

Figure 5.

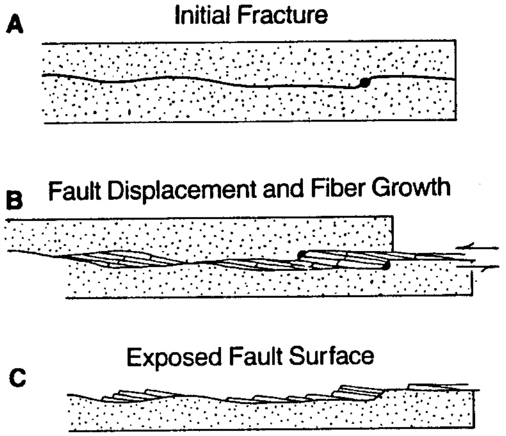


Figure 10.19 Steps in the kinematic evolution of crystal fiber lineation on a "striated" surface. (*A*) Formation of fault surface. (*B*) Fault displacement and simultaneous growth of crystal fibers in the direction of least stress. (C) Striated surface as exposed by weathering and erosion. [From Durney and Ramsay (1973). Published with permission of John Wiley and Sons, Inc., New York, copyright ©1973.]

Davis, 1983

Boudinage

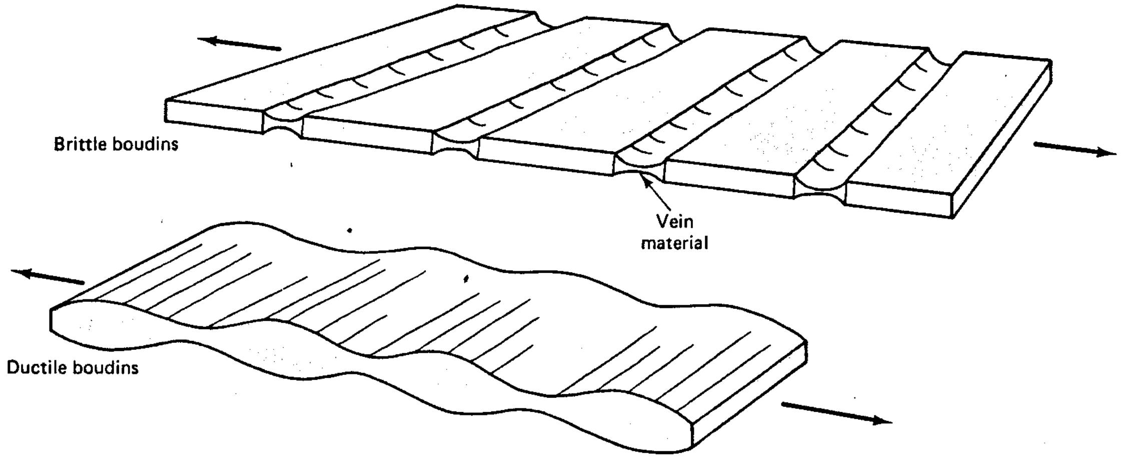


FIGURE 9–53 Schematic brittle and ductile boudins.

Suppe, 1983

Figure 6.

Figure 7.

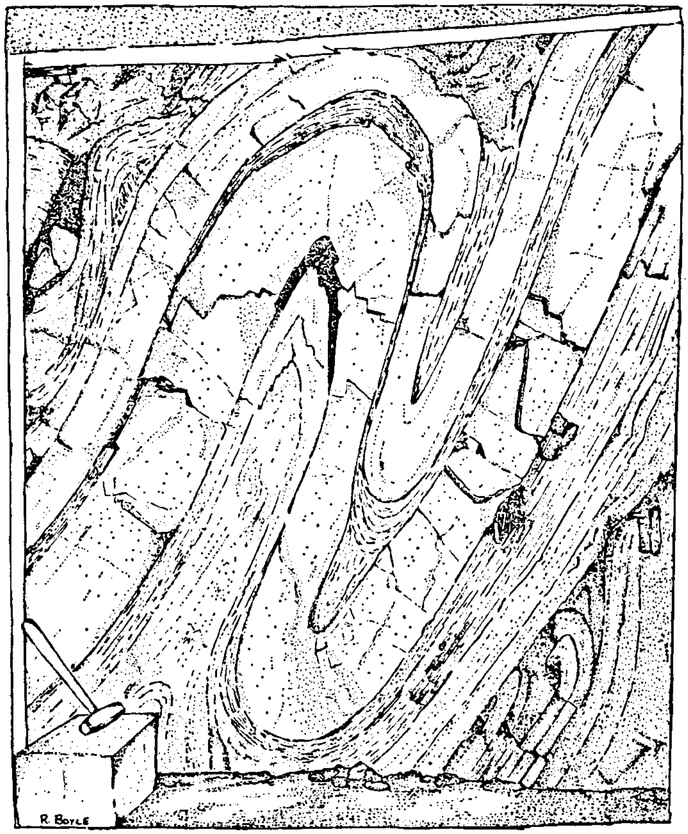


Figure 7. Flexural-flow fold in thick- and thin-bedded shales, Black Rock Mine, Northwestern Queensland, Australia. Drawn from a photograph (Blanchard, 1942, p. 152).

Similar Folds

from Donath + Parker, 1964

Figure 8.

Fiber Growth

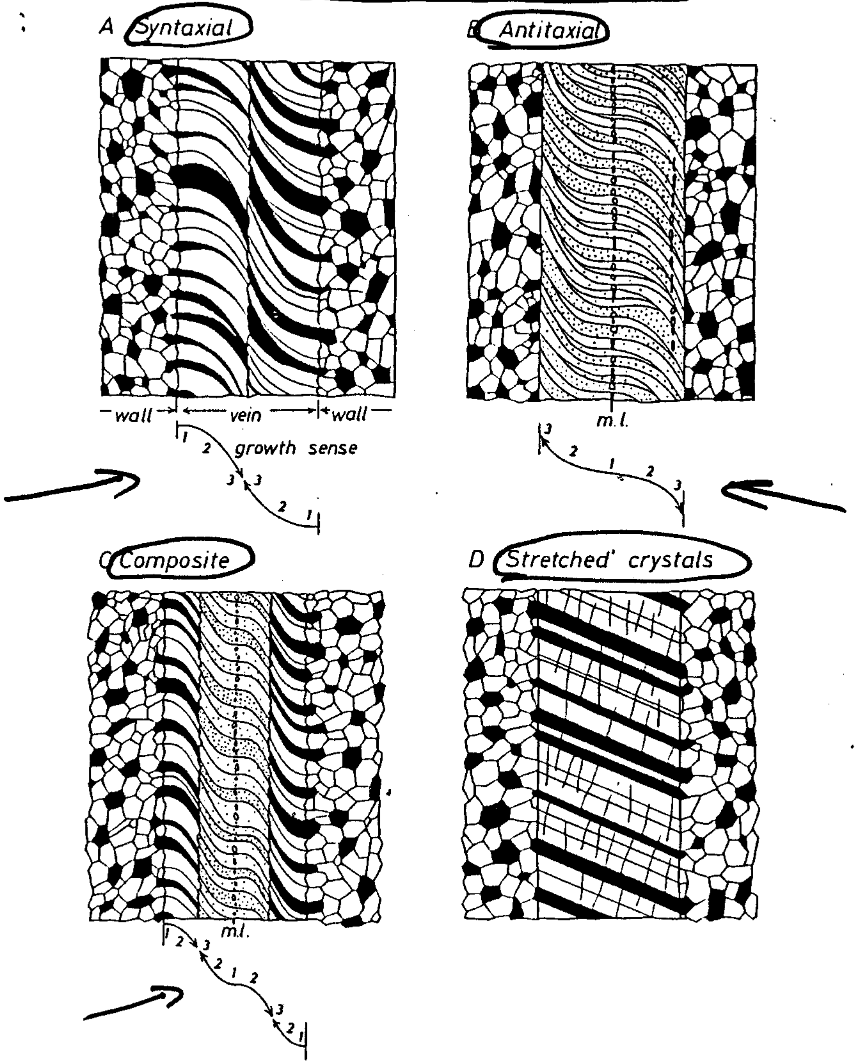


Figure 13.9. Principal features of the four main types of fibrous vein systems showing the relationship of the composition and crystallographic orientations of vein and wall rock crystals. The black and white unstippled areas are crystals of the same species but with differing crystallographic orientations. The stippled areas are crystals of another species, and their crystallographic orientations are indicated by differing intensities of stippling.

from Ramsey + Huber, 1984

- <u>boudinage</u> (see Figures 3 and 6) showing form of both competent and incompetent beds. Orient the principal stresses.

QUESTIONS:

1. Diagram the recumbent fold on the east wall. Show correctly the distribution of bed thickness, tension gashes, ductile deformation.

2. Which is stronger rock (at the conditions of deformation), limestone or dolomite? Why? What criteria did you use to make your choice?

3. What are some <u>descriptive</u>, non-genetic differences in form and contained structures between <u>north-dipping</u> rocks and <u>south-dipping</u> rocks in the quarry?

4. Did tension gashing occur before or after the folding? What is your evidence?

5. If these rocks are "strongly folded", why aren't there more north-dipping rocks? What is the shape of the folds?

STOP 2: BLUE MOUNTAIN CUT

Location:	rock cuts along US 22/322 1 mile south of Dauphin, PA, along the Susquehanna River.
The Rocks:	Montebello Formation, Middle Devonian deep marine sandstones and shales, of the lower parts of the Catskill clastic wedge. See Figure 1 for stratigraphic position of these rocks.

PROCEDURE:

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

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

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

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

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

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

- sets of fractures: what requirements must be met before fractures can be said to constitute a set?

- how many sets of fractures can you identify?

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

- any consistent relation between sets of fractures?

QUESTIONS:

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

7. Develop from scratch the hypothesis that the fractures represent a conjugate pair. What theory do you base your hypothesis on, what evidence here supports it, and what additional evidence would you like to have before you rush your hypothesis into publication?

8. Which came 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, or 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.

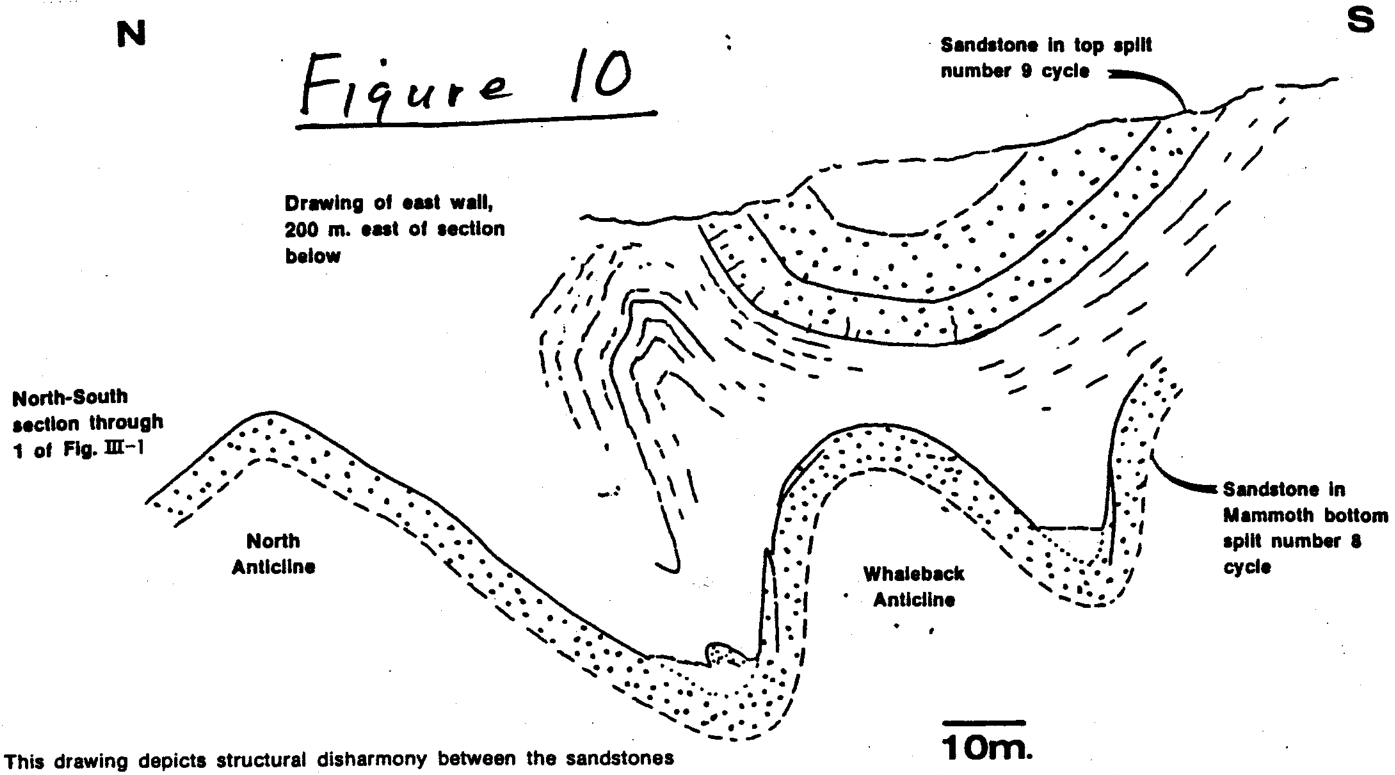
NATURE OF THE DEFORMATION

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 11 (keep track of the north arrow), and are summarized below:

Stage I:	early joints (brittle) in coal beds
Stage II:	joints in sandstone and shale (and also in coal), different orientation from joints in coal
Stage III:	Cleavage and small-scale folds (ductile) in all rocks,

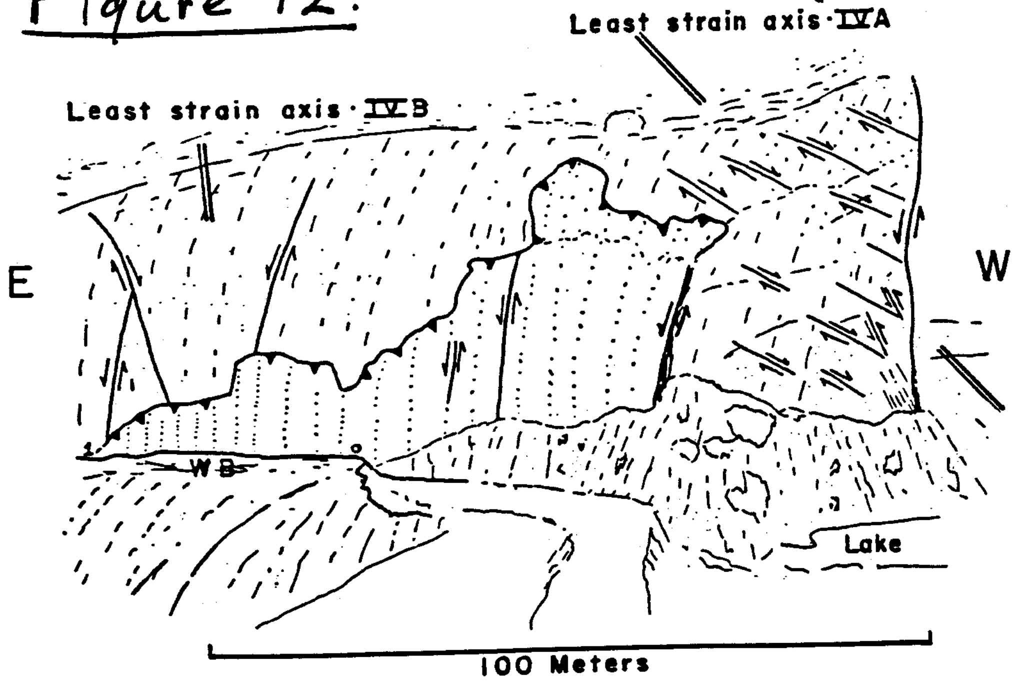
Figure 10



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*

Figure 12.



but primarily in shales, different orientation from earlier joints

Stage IV: conjugate <u>strike-slip faults</u> (= wrench faults), with slickensides, and <u>wedge thrust faults</u>, usually without slickensides

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

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

Stage VII: large-scale <u>wrench faults</u> (+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. The rationale for recognizing stages of deformation is this: **<u>Later structures OVERPRINT, and deform, earlier structures, and move earlier structures to new positions and orientations in which the origin of the earlier structures is improbable.</u>** Attitudes of bedding, senses of motion on faults, orientations of folds, plunges, etc., don't make sense in the later orientations, and in your judgment couldn't have formed the way they are now, and 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 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 (maybe), II, III, IV, V, and VI.

STATION 1: THE SOUTH WALL:

Figure 12 shows a drawing of features on the south highwall, which is the north limb of the south anticline.

Figure 11.

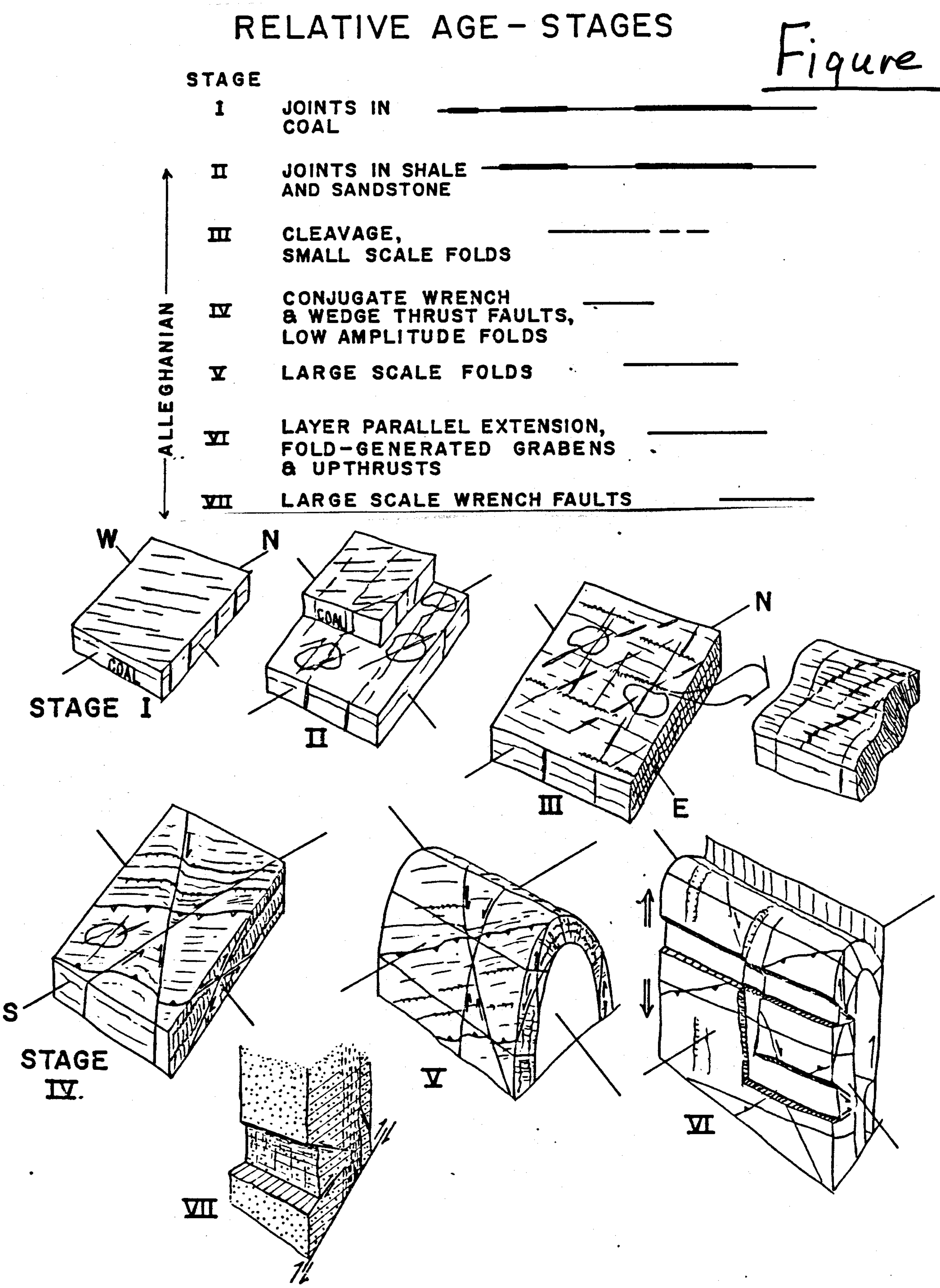


Figure III-10 *Cartoon schematically showing the sequential development of structures in the Bear Valley Strip Mine through stages I-VI.*

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.

Look for these features:

- conjugate wrench faults: which stage of deformation? What is the evidence for that?

- slickensides on the wrench faults: what direction of motion?

- cleavage in the shales; draw drag on cleavage near wrench faults:

- draw a conjugate fault pair, and indicate evidence for offset:

- draw a rhomb pull-apart on a wrench fault, and indicate sense of motion.

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

STATION 2: THE SOUTH SYNCLINE

Our position here is on the axial trace of the south syncline, although it is covered with fill. See Figure 10 for location.

- Describe the syncline: tight or open? small or large? upright or overturned? etc.

- slickensides: what is direction of bed movement (dip slip or strike slip)?

- steep to vertical faults in whaleback limb:

  - western fault: what is orientation of the fault plane?

  - slickensides: what was direction of motion on western fault?

  - eastern fault: what is orientation of the fault plane?

  - slickensides: what was direction of motion on eastern fault?

  - what is relation between eastern and western faults?

- Draw a hypothetical stress orientation diagram below, relating eastern and western faults to the stresses. Make it a map view, so the stresses are acting horizontally.

STATION 3: THE WHALEBACK ANTICLINE

Walk out on the crest of the anticline, and walk to the east end. Don't fall off. See Figure 10 for location.

- plunge: what is the plunge of the anticline near the western end?

- plunge: what is the plunge near the eastern end?

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

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

STATION 4: THE NORTH SYNCLINE

Walk west in the excavated trough of the north syncline, and examine the north wall of the whaleback anticline. See Figure 10 for location. Follow Figure 13 as you traverse.

- extensional faults: what is relation between pairs of extensional faults? What is your evidence?

- Sketch pairs of extensional faults: How many orientations of pairs do you see?

Figure 13.

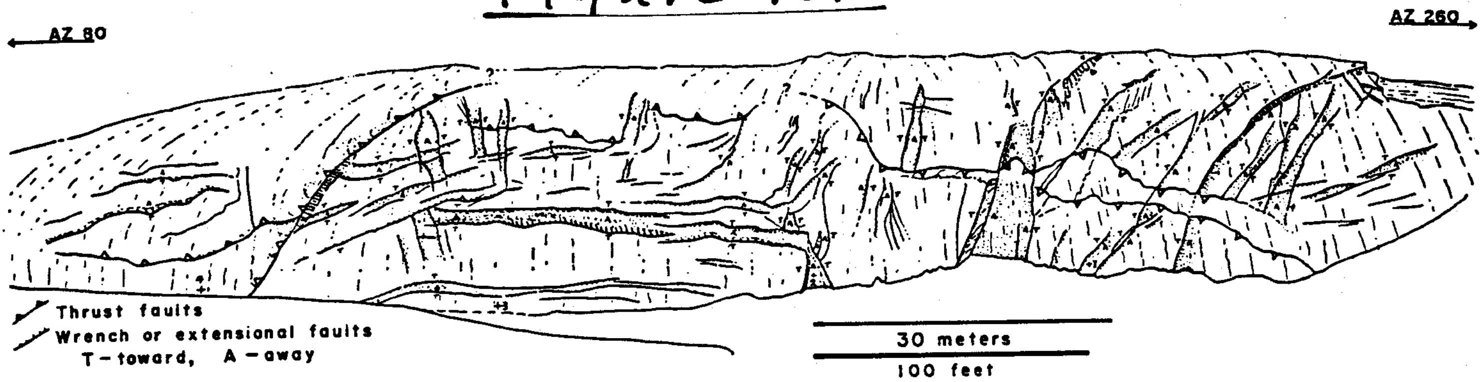


Figure III-3 *Drawing of structures exposed on the north limb of the Whaleback Anticline. View from Station B*

- Sketch <u>stress orientation diagrams</u> for each major orientation of fault pairs. How do you reconcile these diagrams with each other?

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

- <u>slickensides:</u> draw curved slickensides, and trace the trajectory of movement they record.

QUESTIONS:

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

10. Cite evidence from the field that the deformation sequence followed the path

brittle ductile brittle.

11. Did the orientation of the stress field change significantly during the Alleghanian orogeny, or did it remain about the same? What is your evidence?

GEOLOGY 401

INSTRUCTIONS FOR PREPARING FIELD TRIP REPORTS

Field trip reports consist of cogent and complete answers to sets of direct questions about the rocks and relations seen on the various trips. Address each question directly. Ask yourself what the question asks, or asks you to do (if not already clear).

Answer the questions not on the guidebook, but on separate paper, neatly written (not necessarily typed, but <u>very</u> legible if not typed). Use clear, succinct prose; use your very best English. Concentrate on complete, declarative sentences, coherent paragraphs, good organization, and brevity. Answers need not be long if they are to the point.

For drawings - make your drawings clear and complete. Each diagram must have a border. Run lines into each other or into the border; lines hardly ever just stop. Give on your drawing:

- a rough scale, and
- an orientation, either North (if a map) or the direction of each end (if a cross-section).