FOLIATIONS AND SUPERPOSED FOLDING IN THE MARYLAND-VIRGINIA PIEDMONT: GREAT FALLS NATIONAL PARK

Saturday, December 2, 1995

OBJECTIVES:

By the end of today, you will be able to

- recognize several different styles of folding and deformation
- distinguish syn-deformation foliations from pre-deformation foliations
- recognize superimposed folds and the foliation patterns they produce
- map foliations and lithologies on limbs and noses of folds
- recognize non-tectonic, soft-sediment-deformation folds, and distinguish them from tectonic folds.

INTRODUCTION

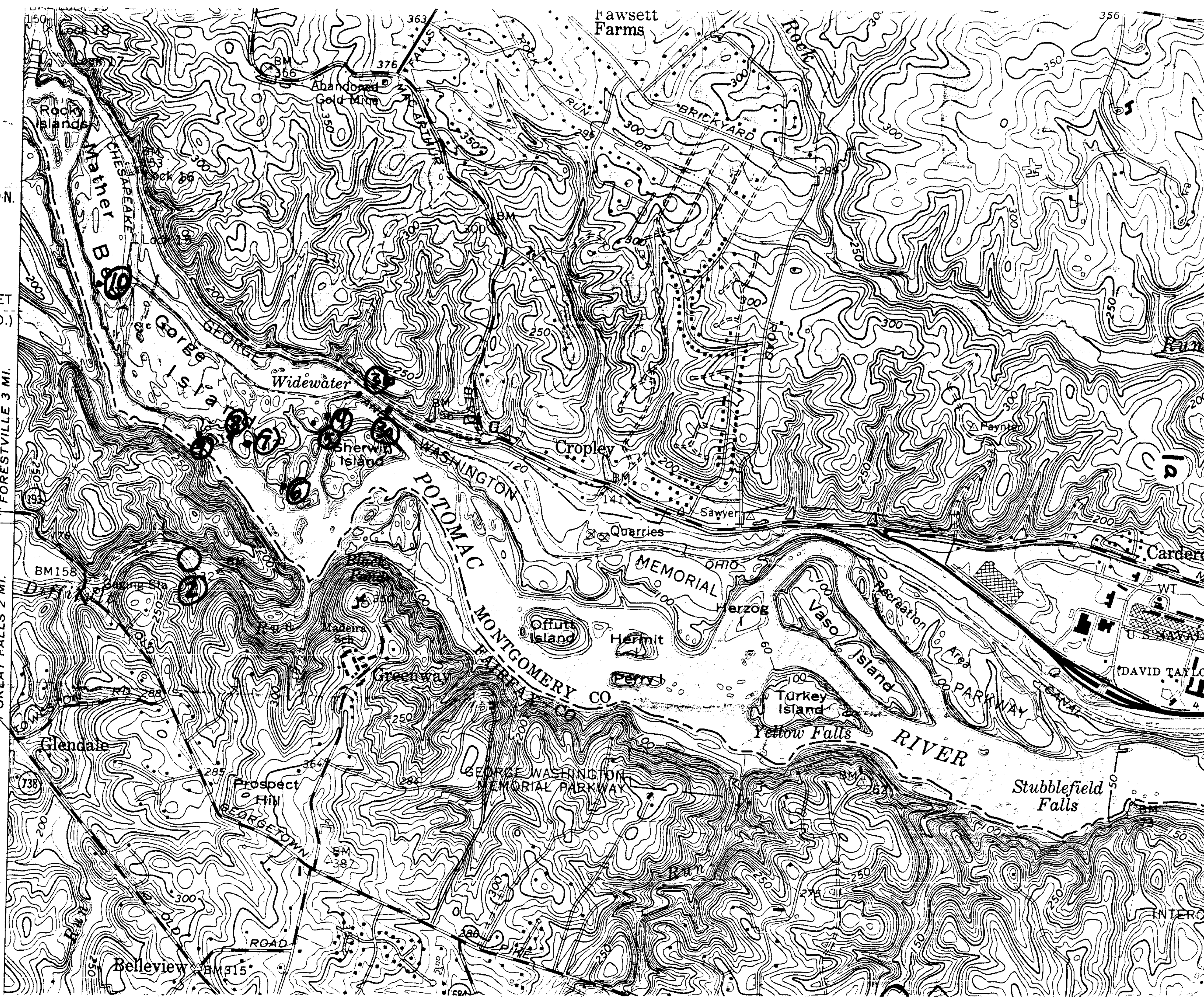
This field trip will view metamorphosed sedimentary and igneous rocks along the Potomac River at Great Falls National Park in Maryland and Virginia.

The emphasis of the trip is on **FOLIATION, FOLDING** types and styles, and **SUPERPOSED FOLD GENERATIONS**. The structural elements important today are **SCHISTOSITY, CLEAVAGE, COMPOSITIONAL LAYERING, CRENULATION FOLDS, FOLD AXES** and **LINEATIONS**. You will be asked to draw field relations, map contacts of rock bodies, outline folds and interpret competence relations among rocks.

You need to bring a notebook, hand lens, pencils and pens, rain gear, boots, warm clothing, and a lunch. We will be away from the vans for approximately seven hours.

Themes to be developed on this trip include these:

- competence and competence contrast
- fold styles and shapes
- primary sedimentary structures and soft-sediment deformation folds
- criteria for tectonic vs. non-tectonic origin of structures



POTOMAC
RIVER
MONTGOMERY CO
FAIRFAX CO
Fawsett Farms
Abandoned Gold Mine
BRICKYARD
MAC ARTHUR
BLVD
WASHINGTON
GEORGE
CHESAPEAKE
OHIO
MEMORIAL
PARKWAY
Rocky Islands
Mather
Gorge
Widewater
Sherwin Island
Cropley
Sawyer
Paynter
Quarries
Offutt Island
Hermit
Perry
Herzog
Vaso Island
Recreation Area
Turkey Island
Yellow Falls
Stubblefield Falls
Carderock
U S NAVAL
DAVID TAYLOR
Madeira Sch
Greenway
Prospect Hill
GEORGETOWN
Glendale
Belleview
GEORGE WASHINGTON MEMORIAL PARKWAY
Lock 18
Lock 17
Lock 16
Lock 15
4318000m.N.
000 FEET (MD.)
DRANESVILLE 6 MI.
FORESTVILLE 3 MI.
GREAT FALLS 2 MI.
4315

- cleavage and schistosity associated with folds
- strain mechanisms in production of schistosity and cleavage
- generations of folds and superposed folding
- timing of deformational events and sequence of deformation

STRATIGRAPHIC SEQUENCE

The stratigraphic sequence in the Maryland-Virginia Piedmont is given in Table 1. Since Table 1 was prepared in 1971, the rocks have been reexamined and renamed. The current name for the schists and metagraywackes is the **PETERS CREEK FORMATION**, of Late Precambrian to Cambrian age, of unknown but great thickness. The Peters Creek is of regional extent in the eastern Piedmont, and extends from Virginia up through Maryland and southeastern Pennsylvania nearly to Philadelphia. The Peters Creek represents original (almost certainly) oceanic sediment, and contains occasional large masses of serpentinite and other ultramafic rocks whose only reasonable origin was at a spreading center as part of an ophiolite sequence. Being of oceanic origin, the Peters Creek probably did not originate in its present position (it is not native to North America, it is not autochthonous), and is probably part of an exotic, suspect terrane that was accreted to the Laurentian margin during an early Paleozoic orogeny (probably Taconian). The Peters Creek has undergone at least two episodes of metamorphism, the first reaching high metamorphic grades (high enough to generate sillimanite and kyanite).

The Peters Creek contains several distinct kinds of metasedimentary rock, all mappable and all recognizable. We will meet two of them today.

METAGRAYWACKE:

fine-grained (compared to mica schist), relatively even-grained, granular (like sand), **quartz-feldspar-muscovite gneiss**; often lacks true gneissic layering. Weakly foliated, due to lack of micas. Even-grained character often called **psammitic**. Poor in micas compared to pelitic schist. Often contains relict coarse-to-fine graded bedding. Contains minor beds of pelitic schist. Often contains a mica-film pseudolamination that resembles bedding, but is actually a pressure-solution cleavage.

PELITIC SCHIST:

coarse-grained (compared to metagraywacke), uneven-grained , muscovite-quartz schist, with sillimanite. Strongly **foliated**, with an uneven, wavy schistosity, that often looks clotted. Contains abundant laminae and lenses of quartz and cross-cutting quartz veins. Contains locally abundant porphyroblasts of Al-rich metamorphic minerals such as kyanite, andalusite, cordierite. Contains some thin metagraywacke beds.

Sedimentary rocks only

Table 1

Stratigraphic Units in the Maryland Piedmont

(After Southwick and Fisher, 1967, Cleaves and others, 1968, Higgins and Fisher, 1971)

Coastal Plain Sediments (unconsolidated sediments; Cretaceous to Recent)

- - - - - - - - - unconformity - - - - - - - -

Newark Series (red sandstone and shale; Triassic)

- - - - - - - - - unconformity - - - - - - - -

Peach Bottom Slate (black slate; Ordovician?)

Cardiff Conglomerate (quartz pebble conglomerate; Ordovician?)

- - - ? - ? - - - - unconformity - - ? - - ? - - -

Glenarm Series (Late Precambrian or Cambrian)

Wissahickon Formation = Peters Creek

Quartzite facies (Micaceous quartzite interbedded with quartzose graywacke and subgraywacke).

Metagraywacke facies (Graded metagraywacke, rhythmically interbedded with pelitic schist).

Metaconglomerate facies (Quartz pebble conglomerate).

Diamictite facies (Massive, uniform metamorphosed sandy mudstone with scattered quartz granules, pebbles, and contorted slabs of metasedimentary rock).

Pelitic Schist facies (Pelitic schist with local psammitic beds and calc-silicate rocks).

Cockeysville Marble (Impure phlogopitic marble, metadolostone and calc-silicate gneiss).

Setters Formation (Micaceous quartzite, with subordinate mica gneiss and schist)

- - - - - - - - - unconformity - - - - - - - -

Baltimore Gneiss (Migmatitic quartzofeldspathic gneiss, augen gneiss, and amphibolite; zircons indicate age 1100-1300 my).

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Table 2

Composition of Metagraywackes

From Hopson, 1964

Modal Analyses

Mineral Compositio

	1	2	3	4	5	6	7	8
Quartz	60.1	18.2	39.2	53.7	38.7	46.1	58.9	-
Plagioclase	20.9	32.1	26.5	22.6	31.7	27.2	15.7	-
Muscovite	8.3	26.9	17.6	10.3	14.6	12.4	18.8	-
Biotite	.3	13.5	6.9	6.1	4.1	5.1	4.7	-
Chlorite	3.0	.4	1.7	.9	3.2	2.1	0.9	-
Epidote	5.8	4.9	5.4	3.1	3.9	3.5	-	-
Tourmaline	tr	-	tr	-	-	-	tr	-
Sphene	.4	.7	.5	.8	1.1	1.0	-	-
Apatite	.1	.4	.2	.3	.4	.3	tr	-
* Heavies	tr	tr	tr	.1	tr	.1	tr	-
Magnetite	1.1	2.9	2.0	2.1	2.3	2.2	.1	-
Calcite	-	-	-	-	-	-	.9	-
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
Points	2,997	3,192	6,189	3,119	3,073	6,192	1,285	

Chemical Composition, Calculated from the Modes

	1	2	3	4	5	6	7	8
SiO_2	78.0	55.0	66.5	73.7	66.3	70.0	79.4	68.1
TiO_2	0.2	0.7	0.4	0.6	0.7	0.6	0.2	0.7
Al_2O_3	11.1	21.4	16.3	11.7	16.1	13.9	11.8	15.4
Fe_2O_3	2.3	4.8	3.6	3.4	3.8	3.6	0.4	1.4
FeO	1.3	4.1	2.7	2.5	2.7	2.6	1.1	3.4
MgO	0.4	1.4	0.9	0.8	0.8	0.8	0.7	1.8
CaO	3.2	3.9	3.5	2.8	3.8	3.3	0.8	2.3
Na_2O	1.7	2.7	2.2	1.9	2.6	2.3	2.0	2.6
K_2O	0.9	3.7	2.3	1.6	1.8	1.7	2.3	2.2
H_2O	0.9	2.1	1.5	0.9	1.3	1.1	1.3	2.1
P_2O_5	tr	0.2	0.1	0.1	0.1	0.1	-	-
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

1. Base of 10 inch graded metagraywacke bed (M479-1).
2. Top of 10 inch graded metagraywacke bed (M479-2).
3. Metagraywacke (average of 1 and 2).

Potomac River at head of Rocky Island, Montgomery County.

4. Base of 30 inch graded metagraywacke bed (M478-1).
5. Top of 30 inch graded metagraywacke bed (M478-2).
6. Metagraywacke (average of 4 and 5).

Potomac River at head of Rocky Island, Montgomery County.

7. Metasubgraywacke (M429-3). Potomac River at Bear Island, Montgomery County.
8. Average of 30 graywackes (Tyrrell, 1933). Includes 0.2% MnO.

* Zircon, monazite, xenotime, and other unidentified high-index minerals.

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CaO	3.2	3.9	3.5	2.8	3.8	3.3	0.8	2.3
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Table 3

Sequence of Events at Bear Island

Lithologic Units		Structures	Metamorphism
Deposition of graywacke and shale			
	F_1	Slump deformation of partly consolidated sediments (F_1)	Diagenesis
Intrusion of mafic sills (550 my)			
	F-2	Isoclinal folding (F_2) with schistosity (S_2) nearly parallel to bedding	Prograde
	F-3	Major folds (F_3) with crenulation cleavage (S_3) cutting S_1 and S_2	Peak
Emplacement of granite bodies			
	F-4	Crenulation cleavage (S_4) locally axial to folds (F_4)	
Intrusion of lamprophyre dikes (360 my)			Retrograde
Emplacement of gold-quartz veins		Development of steep, north-trending faults and shear zones	

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Emplacement of granite bodies			
	F-4	Crenulation cleavage (S_4) locally axial to folds (F_4)	
Intrusion of lamprophyre dikes (360 my)			Retrograde
Emplacement of gold-quartz veins		Development of steep, north-trending faults and shear zones	

are common. Plunge is of variable direction. Visible F-2 folds are generally small (0.1-2 m), and rare; much more common is a strong schistosity. Compositional layering is transposed into near parallelism with schistosity. This S-2 foliation defines the predominant schistosity in pelitic and many psammitic rocks. It is a transposition foliation.

F-3: major, **large-scale, tight but rarely isoclinal,** similar folds of compositional layering and F-2 schistosity. Axial-planar schistosity (S-3) is **weak to absent**; at times it is expressed as a crenulation cleavage developed on small folds. F-3 folds apparently have variable plunge, but often plunge steeply SE.

F-4: weakly developed, open, asymmetrical crenulation folds, rarely seen, but with widespread crenulation cleavage (S-4) cutting most rocks. Developed probably during a retrograde metamorphic event.

At least two of these fold generations are probably phases of an intense orogeny in the suspect terrane, which is dated by radiometric ages on the cross-cutting Bear Island Granite as early Cambrian. Depending on when the terrane docked with the North American margin, one or both of the remaining fold generations probably represent phases of the Ordovician Taconian and/or late Paleozoic Alleghanian orogenies. In post-orogenic time additional, mainly brittle deformation affected the rocks, including emplacement of gold-bearing quartz veins, brittle faulting, and development of several strong sets of systematic joints.

TRANSPOSITION FOLIATIONS:

A transposition foliation is one formed by the tectonic rotation of an existing foliation into a new orientation, usually accompanied by considerable simple shear. During transposition pre-exciting folds are rotated, flattened and dismembered, new simple-shear foliation zones are created, whole new schistosities are created, great amounts of extension take place parallel to schistosity on overturned and stretched fold limbs, and extensive pressure solution removes quartz and feldspar grains. The pressure solution can remove whole lithons and even boudins, and leaves behind grain-free, mica-rich schistose zones showing strong schistosity and very-closely-spaced foliation. These are zones of concentrated, high strain, where major transposition took place.

Consult the diagram on the next page. Concentrate on following the dotted, sandy layers through the four panels of the diagram; notice how the folds progressively lose definition, the thinned limbs basically disappear (by pressure solution), significant flattening takes place, and in the final panel how it's very difficult to tell that there were preexisting folds. This famous diagram (representing the first serious treatment of the concept of transposition in 1963) was drawn to illustrate transposition in a pure-shear-compression regime, but by adding simple-shear arrows the same result can be produced by extended simple shear. In addition, simple shear can go on basically forever, and can totally dismember the folds shown, well beyond the remotest possibility of reconstructing (or even realizing that there were) earlier folds. Most workers today favor simple shear over pure shear as the dominant mode of transposition.

34a

Fig 6.

Transposition

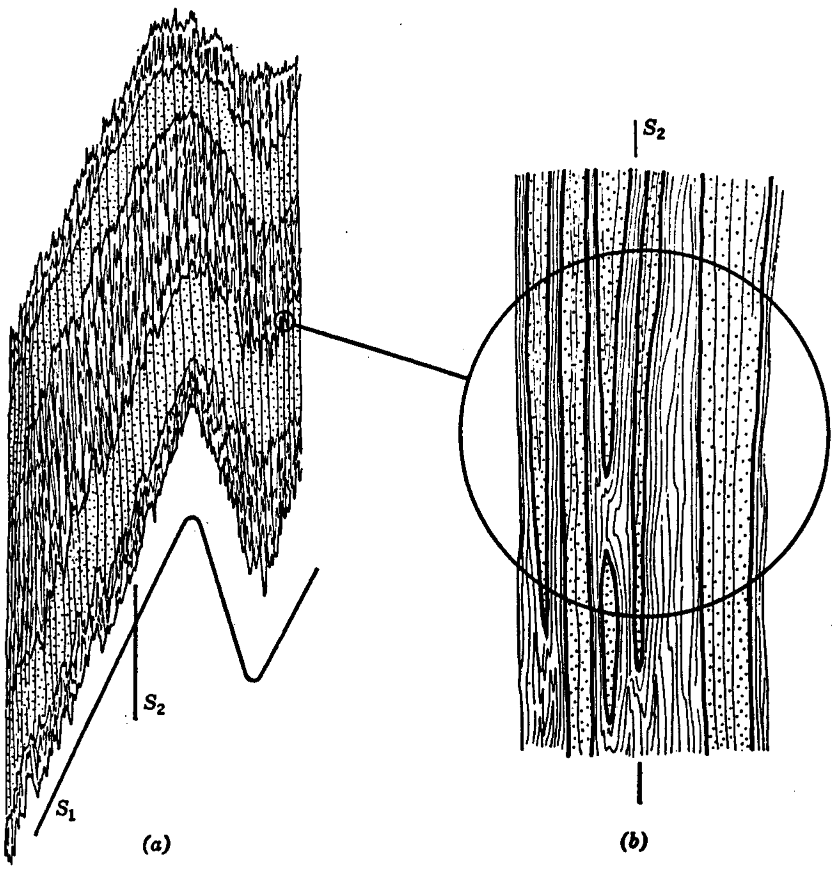


FIG. 4-12. Lithologic contact on two scales. (*a*) Large scale; generalized contact is S_1. (*b*) Small scale; contact is S_2.

Turner + Weiss, 1963

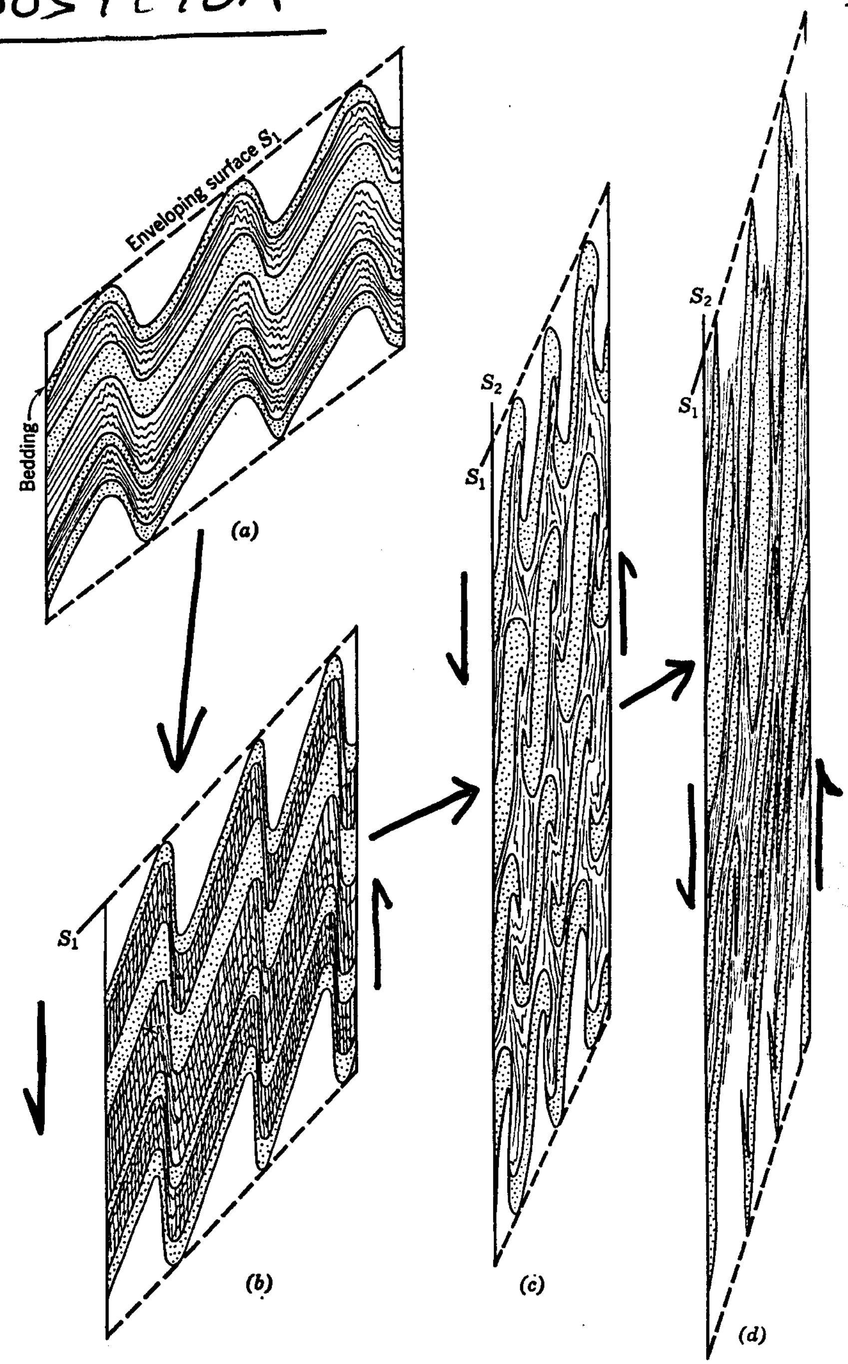


FIG. 4-11. Sequence of transposition of bedding S_1 into a foliation S_2.

Trademark signatures of transposition in the rocks include the following:

- disjunctive cleavage containing grain-free or grain-poor cleavage domains surrounding grainy microlithons that show a different-oriented foliation;

- essentially grain-free, strongly foliated mica schist zones;

- high-strain, relatively smooth-textured mica-schist zones, alternating with lower-strain, more grainy, rougher-textured "mega"-lithon zones;

- boudinage, especially boudined quartz veins and widely separated boudins with lens-like form and long, thin tails;

- fishhook folds, and floating (unattached) fold hinges, and floating, unattached layers or batches of layers.

FIELD TRIP ROUTE AND STOPS

Park at either the east end, across from Angler's Inn restaurant, or the west end, at the park headquarters. West end has pit stops.

Consult the map on the next page. **THE TRIP STARTS AT STOP 3a**, at the only outcrop along the towpath east of the elongate "lake" called Widewater. Along the way, sharpen your skills at telling pelitic schist from psammitic gneiss along the trail. Remember, be honest: call it psammite only if it **looks like** psammite. If it looks like a horse, call it a horse. But only if it actually does look convincingly like a horse. Unless it does, don't call it a horse, even if everyone else does. Remember, the Emperor has no clothes on.

STOP 1: TOWPATH

- Pelitic schist, with domainal schistosity.

This place is the **ROSETTA STONE** of the entire region - it shows **THREE GENERATIONS OF FOLDS**, F-2, F-3, and F-4, **SUPERIMPOSED ON EACH OTHER**. This is a great place to start the trip.

- On the front face: excellent development of the **F-4 CRENULATION FOLDS** with the F-4 crenulation cleavage parallel to the thin limbs. Look up close and personal at the folds, and trace layering continuously through long, thick limbs and short, thin limbs.

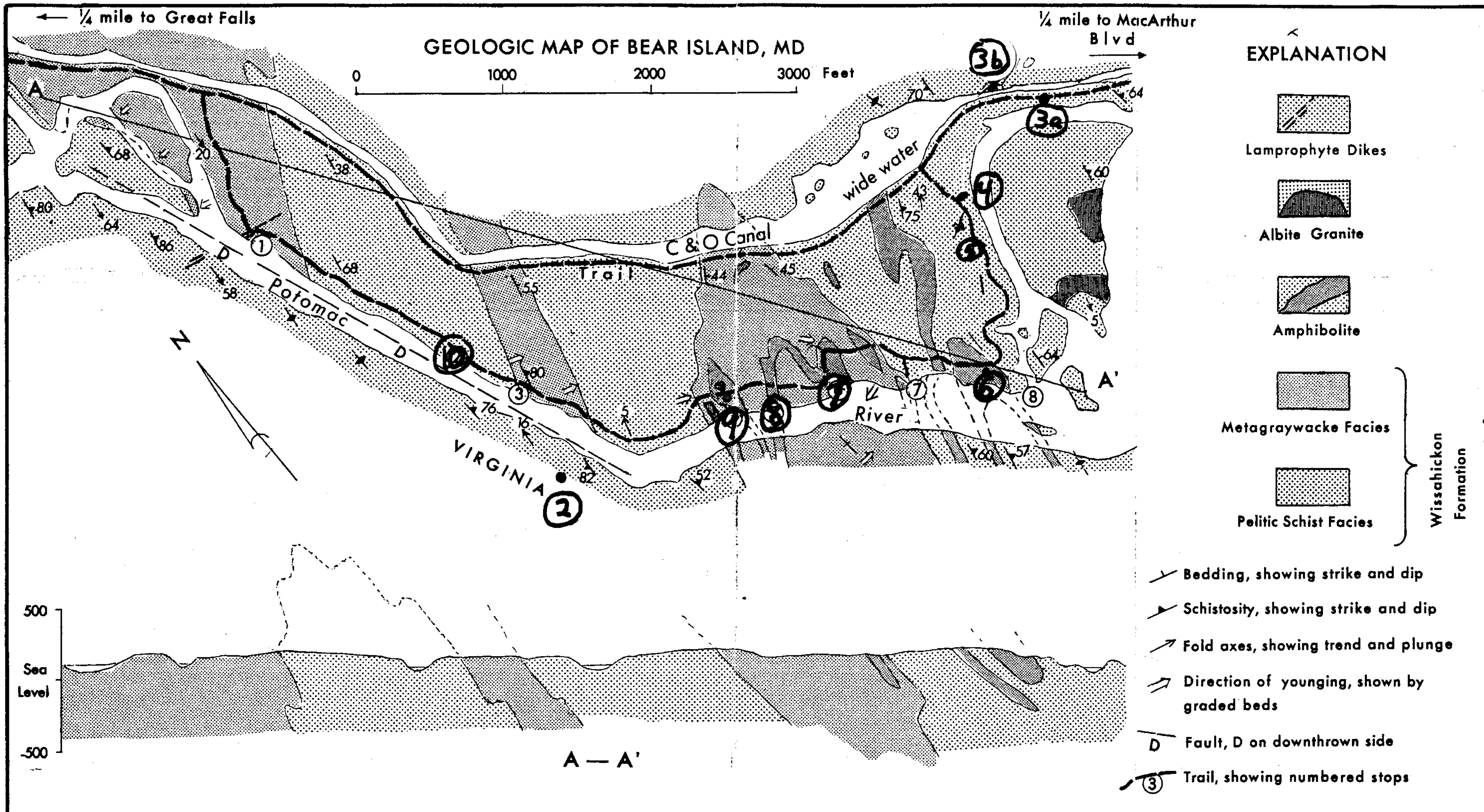

← ¼ mile to Great Falls
¼ mile to MacArthur Blvd →
GEOLOGIC MAP OF BEAR ISLAND, MD
0 1000 2000 3000 Feet
C & O Canal
Trail
wide water
Potomac River
VIRGINIA
N
A
A'
500
Sea Level
-500
A — A'
EXPLANATION
Lamprophyte Dikes
Albite Granite
Amphibolite
Metagraywacke Facies
Pelitic Schist Facies
Wissahickon Formation
Bedding, showing strike and dip
Schistosity, showing strike and dip
Fold axes, showing trend and plunge
Direction of younging, shown by graded beds
Fault, D on downthrown side
Trail, showing numbered stops

Figure 1

- Sketch the F-4 crenulation folds, and show the geometric differences.

- What's the orientation of the F-4 axial surface? Measure the plunge of the crenulation folds.

- Climb to the top (be careful not to fall off; it's a long way to the river). The layering here is thin pelitic schist and psammite "gneiss". These different compositions probably reflect original bedding differences, but these layers are not "bedding" now; they have been transposed to such an extent that now they are simply "compositional layering".

- Observe excellent example of **DOMAINAL SCHISTOSITY**, with relatively thin, parallel-layered, mica-rich layers defining the cleavage bands and thicker, visibly folded layers defining the microlithons (actually macrolithons). The cleavage domains are loci of intense layer-parallel shear and extension. The foliation here is a good example of rather intense transposition in action.

- What fold generation is this transposition foliation?

- Note in one lithon an outstanding example of a **FISHHOOK FOLD**, a rootless, floating S-fold. Draw the fishhook fold and the layering around it, and indicate the sense of shear in the C domains.

- If this fold were a "drag fold", as in flexural folding, what sense of shear would it indicate?

Conclusion: "**DRAG FOLDS**" **AND** "**FISHHOOK FOLDS**" **INDICATE OPPOSITE SENSES OF SHEAR**.

- THE ROSETTA STONE: Beyond the fishhook fold, under the big tree, is an outcrop that shows **THREE GENERATIONS OF FOLDS**: the major, isoclinal antiform is F-3: note the drag folds on the limbs. Good comparison to the fishhook fold for shear sense. The rock BEING FOLDED by F-3 is F-2 transposition layering, and you can see real foliation (not bedding) wrapping around the F-3 nose, meaning that foliation was in existence at the time of F-3 folding, and must be earlier. The F-3 fold is itself folded by weak, small F-4 crenulation folds, particularly on the east limb.

  Make a sketch of the relations here, and show all three sets of folding.

- Also on top: examine beautiful small, **PLUNGING ANTIFORM**. This small fold is probably mimicking the large fold it is a part of.Based on the criteria for the different generations of folds, what generation is this fold, most probably?

STOP 2: WIDEWATER

Follow towpath west toward Widewater. Across the canal just at the east end of Widewater is a large outcrop of folded pelitic schist with granitic material at strategic locations.

- The fold over there is probably an F-3 fold based on its form and the fact it folds foliation, but its plunge is wrong for F-3. Folded by F-4?

- Is the fold

    - antiform or synform?

    - anticline or syncline?

    - parallel or similar?

    - passive or flexural?

    - kink, solutional or buckle?

- What's the orientation of the axial surface?

- What is the apparent plunge?

- Sketch the fold carefully. Show the axial surface. Indicate and , and indicate o_1 and o_3.

- Note the granite material in the hinge region of the fold. Why it is located there? What does it represent?

Follow towpath North, to head of **BILLY GOAT TRAIL**. Turn left, and follow trail into the woods.

STOP 3: BILLY GOAT TRAIL - THE F-2 FOLIATION

This is a several-part exposure.

ALONG THE TRAIL JUST INTO THE WOODS:

- The rocks here afford an excellent look at the major foliation, the F-2 foliation, in pelitic schist. Make sure you observe all of the following:
  - lenticular quartz masses and pods, possibly boudins of former quartz veins
  - boudinaged quartz, = layer-parallel extension
  - floating, rootless, intrafolial hinges that often are very tightly appressed (= pressed tightly together), both small and fairly large
  - thicker short limbs on asymmetric folds, thinner long limbs
  - Sense of shear in the foliation - S and Z folds

The foliation is a transposition foliation, and is shearing out earlier folds and foliations. Both shear and extension are taking place at the same time. The areas of thinner-layered, more strongly parallel quartz, micas, C domains and lithons represent **higher-strain zones**, or more intense shear and transposition; these zones probably come close to representing true ductile faults. The areas showing thicker, less strongly parallel and more uneven foliations represent the lower-strain zones, the "lithon" zones between the high-strain C zones.

- Note the difference in form, size and shape of quartz between these two zones. In which zone is the quartz larger?

- In which zone are most of the visible fishhook folds?

- What deformation processes do you think have been important in determining the quartz forms?

- What is the strain significance of the lenticular form of the quartz?

- What is the sense of rotation in the quartz? Is it consistent?

<u>**FARTHER ALONG THE TRAIL**</u>:

- Off the trail to the left, excellent example of <u>**SUPERPOSED FOLDS**</u> in the low outcrop. Possibly three generations are shown here, if you believe the little Z folds wrap around the larger fold and are not parasitic on it.

  - Sketch the superposed folds, and show all fold axial-surface traces.

THE STEEP DROP IN THE TRAIL:

- The outcrops just above the steep drop in the trail show good transposed **fishhook folds**: intrafolial, rootless fold hinges, with thin, extended long limbs and relatively fat short limbs. Check the transposition diagram on next page; these are right from that diagram.

  - What is the **apparent** sense of shear/rotation on this fishhook? Is it an S or Z form?

  - Is there other evidence for shearing in the F-2 foliation here? Could the fishhook fold have been formed purely by flattening?

  - What is the geometric relation between attitude of schistosity and attitude of axial surface of the fishhook folds?

  - Look closely at the schistosity in the hinges of the fishhook folds, and determine whether it wraps around the hinge, or cuts through it. Draw your findings here:

  - If the schistosity wraps around the fold noses, it is of an earlier generation than the folding. If schistosity cuts through the hinges parallel to the axial surface, it's the same generation as the folding. Which generation is the schistosity, same generation? or earlier?

- Which fold generation does the fishhook most probably represent?

THE EDGE OF THE LEDGE:

Exposed here is what appears to be a **GRANITIC DIKE** in various stages of structural disarray. It's probably Bear Island granite.

- What's the evidence that the rock is of igneous origin, i.e. that this is a dike?

- Get up close and personal, and describe the **TEXTURES** of the dike mineral grains. Coarse? Fine? evenly textured (= massive)? porphyritic (= phenocrysts)? foliated or layered? are inequant grains aligned? any difference in textures between central parts and close to the contacts? etc. etc.

- Draw the dike and its relations with the schistosity. Be careful to correctly show fat and thin portions of the dike.

- How many different orientations relative to the schistosity does the dike have? Describe the fat segment and the thin segments separately.

- For the fat segment - what does the shape of the lower contact surface remind you of? Let your imagination run wild.

- Why are the dike segments running across schistosity fatter than those running parallel to schistosity?

This rock body is interpreted by those who know it well as a **SYNTECTONIC DIKE**, that was intruded **DURING DEFORMATION**. It crystallized from magma, but that magma was under, and was responding to, tectonic stress.

- What are some of the IGNEOUS features of the dike?

- What are some of the STRUCTURAL features of the dike?

- If the dike crystallized from liquid magma, why are some grains (hornblende, etc) aligned parallel to the schistosity?

- The fishhook folds nearby strongly suggest that simple shear was operating during their formation. Could the magma mineral alignment have originated in that same simple-shear regime? Why or why not?

- What was the orientation of σ_1 relative to dike geometry?

THE BIGGER PICTURE:

- IF the granite is syntectonic with the transposition foliation in intrudes, and IF it is Bear Island Granite, what is the age of the transposition foliation?

  Is there a contradiction here?

  How could you resolve that contradiction?

STOP 4: ANDALUSITE KNOB

the rocks: pelitic schist, and Bear Island granite masses

features to look for:

- andalusite **porphyroblasts**: rectangular and irregular cm-size gray masses, often in herds (they're gregarious). They don't contain andalusite now; the original andalusite has been replaced by sillimanite (same composition), which is stable at higher metamorphic grade, through a polymorphic inversion. So these rocks went through **prograde** metamorphism, forming andalusite first and then sillimanite.

- the foliation generation here is anybody's guess, but I sort of side with F-2.

- Is the schistosity axial-planar to the folds? Does it cut through the hinges? or does it wrap the hinges? Draw the relations:

- and is there a later schistosity axial-planar to the folds folding the early foliation?

- **migmatite** is well-developed here.

- granite, intrusive, with discordant contacts to prove it.

STOP 5: SOUTH POINT RIDGE

Several locations on this ridge and point jutting into the Potomac. If water's low, we can get to the isolated rocks at the tip of the point.

THE FAULT:

- From the high ridge, look down the cliff; the rock beyond the notch, including South Point, is cut off from the mainland by a fault, running through the notch and basically parallel to the river. What is the horizontal component of the net slip? dextral or sinistral?

SOUTH POINT: if water's low, cross the fault and go to South Point.

great geomorphology here: enormous potholes in the rocks, cut by channel-bottom action of the river. Either there are hellaceous floods here, or the rock has been uplifted from its elevation when the potholes were cut. Look around for high driftwood and/or boulders.

THE ROCKS:

interbedded pelitic schist and granular, psammitic gneiss, genetically termed "metagraywacke" by people who work here. The layering probably reflects original bedding differences, but has been strongly transposed and otherwise tectonized.

The pelitic schist contains abundant porphyroblasts of andalusite and cordierite, and even kyanite, and shows a distinctly clotted fabric. The psammitic gneiss contains greenish, granular calc-silicate gneiss as well as quartz-feldspar granofels. Black amphibolite is part of the layered sequence, and dikes and stringers of Bear Island granite are everywhere.

THE STRUCTURES AND DEFORMATION:

The interlayered pelitic schist and psammitic gneiss here are showing the elements of cleavage on a grand scale - the schist zones are huge cleavage zones, and the gneisses are "mega"lithons, without much shearing. Look for evidence of more competent behavior in the gneiss layers, and more incompetent behavior in the schist layers.

- Look for evidence of **EXTENSION** in the psammitic layers: **boudinage**, with quartz veins and pelitic schist filling in the necked-down portions. The quartz veins in between the boudins look like **tension gashes** to me. Agree or disagree?

- Examine the **halos** on the outer parts of the psammitic layers, near their contacts with pelitic schist. Are the halos different rock types from the psammites?

- What's the orientation of σ_3 during formation of the boudinage?

  during formation of the tension gashes?

  Which occurred first, the boudinage or the tension gashes?

  What do boudinage and tension gashes tell you about changes in rock behavior during the strain history?

Look for evidence of **SHEAR AND TRANSPOSITION** in the pelitic schist layers: fishhook folds, floating hinges, domainal schistosity. Especially note the deformation of the tension-gash tails.

- Draw the relations between psammite and pelitic schist showing the boudinage, tension gashes, shearing of the gashes, and sheared pelitic schist.

SEQUENCE OF DEFORMATION:

- From these exposures, list the sequence of deformational events that you observed or can infer. From the tension-gash deformation, indicate the sense of shear in the schist.

- Which folding generation would you assign these structures to? On what basis?

COMPETENCE AND COMPETENCE CONTRAST, PART 1:

- Which rock type in these outcrops has the higher competence? What do you base your decision on?

THE GRANITE:

The granite comprises a swarm of cross-cutting, anastomosing dikes that become so concentrated that the resulting rock is actually a migmatite, mixed igneous and metamorphic rock. This is an **injection migmatite**, in which the igneous material was injected directly into the metamorphic rock via dikes. You can observe several generations of dikes, based on cross-cutting relationships.

HIGH RIDGE, WEST SIDE

- **THE AMPHIBOLITE:**

- Descend the ridge on the west side and find **amphibolite.** Describe the orientation of the contact relative to layering and foliation in the adjacent pelitic schist. Is it concordant or discordant?

- Describe the amphibolite near the contact: fine/coarse? foliated/unfoliated? Look for small, black needles of hornblende, and look especially for a **lineation**, a preferred alignment, of the hornblende needles, well shown on fresh surfaces that parallel the contact.

The amphibolite shows well the **joints** and joint sets that affect all the rocks in this area. The joints are brittle structures, and probably formed long after the Paleozoic ductile deformation had ceased.

- Walk into the amphibolite, away from the contact, and observe the a **coarse texture**: 5mm-1cm-size, round, knubbly clots visible on weathered surfaces are relict outlines of pyroxene grains in the original gabbro.

  Is there a foliation in the coarse amphibolite? If so, would you describe it as strong or weak?

  Why haven't the clots been flattened or stretched out?

  How much deformation has this coarse amphibolite undergone? compared to the pelitic schist?

- Starting from a place where there are good relict pyroxene clots, walk **toward the contact** with pelitic schist, and observe **changes in texture and grain size** in the amphibolite. How do texture and grain size and foliation change toward the contact?

There are two frequently cited models for the origin of the grain-size change at contacts like this: CHILLED IGNEOUS MARGIN, and MYLONITIZATION, involving grain-size reduction by intense shearing along the margin.

- Which of these do you think the weight of the evidence supports more strongly? Cite some of that evidence.

Leaving South Point Ridge: Watch for lithology change along the trail, and keep track of what you've passed through.

STOP 6: THE POND, AND PINE KNOB

This area contains the final group of rocks to be examined today, and we will spend the rest of the afternoon here.

STOP at the first location you encounter amphibolite beyond South Point Ridge. You should be on the west side of a low ridge coming into a valley ahead, with a large pond on your left and the river visible beyond it, and a high, pine-covered knob at about 10 or 11 o'clock.

Follow the trail past the pond on the left. Check for float and outcrop as you pass the top of the pond. When the trail turns left, leave the trail and climb straight ahead.

- Examine the **amphibolite** here. Coarse or fine? Look for **foliation**, and for **lineation in the plane of the foliation**. If you find them, take strike and dip and pitch of lineation. What's the extent of parallelism between plunge trend and strike of foliation?

- Scramble up the rocks and find the **contact between amphibolite and schist**. Which way does layering dip? Take strike and dip.

Climb higher up the east face of the knob and look back to view a large **drag fold**. The folded rock is gray metagraywacke, with clearly visible graded bedding, and it is surrounded by reddish-weathering pelitic schist.

- Does this fold affect all the beds visible? or just a few?

- Look in the reddish pelitic schist for **small drag folds** that can give you a sense of shear on the limbs of the large drag fold. What doe the drag folds say about the formation of the fold - tectonic? or soft-sediment deformation?

- Look in the hinge region for **foliations** in the schist, and determine whether any foliation **cuts through the nose** or **wraps around the nose**.

- According to the graded bedding, what kind of fold is this

The logic about fold generations goes like this: The foliation of a particular fold generation is axial-planar to the folds of that generation, and cuts through layering on the hinges (and is perpendicular to layering along the axes) of cogenetic folds. Foliations of earlier generations are folded by (i.e. wrap around the hinges) of folds of later generations. The earliest tectonic foliation is assumed to be F-2. If a foliation parallels a fold axial surface and cuts through layering in the hinge, the fold and the foliation are the same generation, and may be the F-2 generation. If foliation wraps around a fold nose, the fold itself is F-3 or later. If the rocks on a fold contain layering but no foliation, the implication is that a foliation did not grow during that folding, and those folds are then probably not tectonic folds. The layering is then very possibly original bedding, and the folds formed in a non-tectonic way, and may be F-1 folds. Non-tectonic folds do not form in a single stress field, and may have differing shapes and sizes, curved axial surfaces, different plunges, etc.

- What generation do your data suggest this fold belongs to?

- On the flat ledge below the drag fold, look for other folds in metagraywacke. Look hard for foliations in these folds, and try to trace the axial surface. Are the axial surfaces parallel? straight or irregularly curved?

- These folds are good candidates for early, **soft-sediment, slump folds** in unconsolidated sediments.

THE F-3 FOLDS:

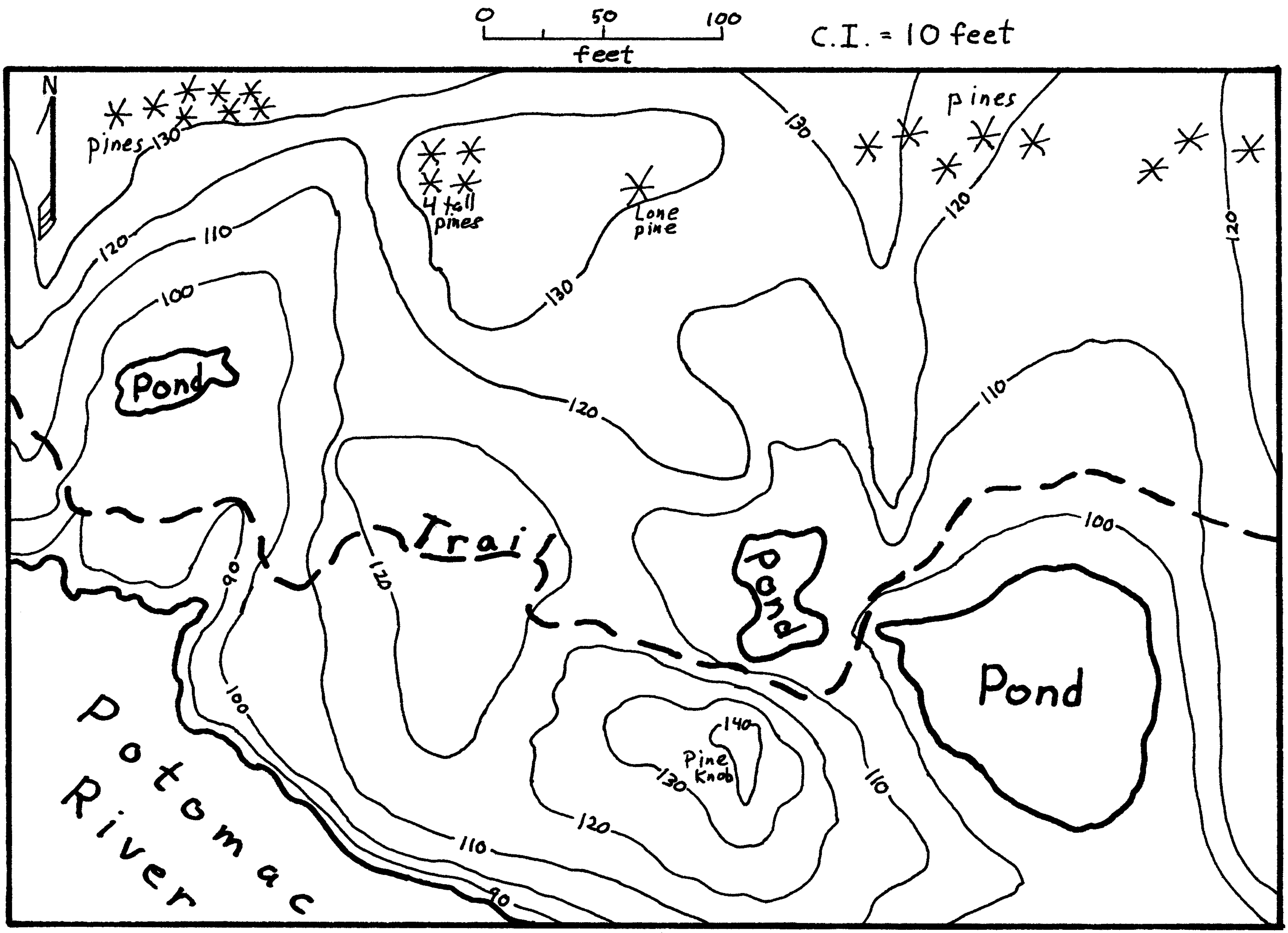
MAPPING FOLDS, EARLY FOLDS AND LATE FOLDS, SUPERPOSED SCHISTOSITIES

Return to the trail, and find the schist-amphibolite contact again. Find the other contact. Those contacts define the amphibolite. Follow the amphibolite wherever it goes. Show the locations of the contacts on the topographic base map of this area on the next page.

The contact will go around several fold noses, so you have to be trace the contact through potentially all directions. You will have exposures every now and then, but for the most part you will have to locate the amphibolite based on float blocks, and concentrations of float blocks. in many cases you won't be able to see the contact, or locate precisely; you'll have to guess, to restrict it to some width of ground. Use a solid line when you can see the contact or are sure of where is. Use a dashed line when you are guessing (based on float data) where the contact goes.

- Describe the structures outlined on your map by the amphibolite. What generation are they?

Stand on the end of the ridge and look south, down the nose of the large F-3 anticline. See beautiful M-folds in the nose, and upright cleavage cutting foliation.



0
50
100
feet
C.I. = 10 feet
N
pines
130
4 tall pines
Lone pine
pines
120
110
100
Pond
Trail
Pond
Pond
90
140
Pine Knob
Potomac River

STOP 7: The Barrens

THE F-1 FOLDS

TECTONIC VS. NON-TECTONIC STRUCTURES -

THE IMPLICATIONS OF COMPETENCE CONTRAST

In the hinge region of the western amphibolite syncline, where there is extensive bare rock, the strain is weak, and much original bedding and pre-tectonic features are exposed here. The plan is to wander around the area, both before and beyond the cove and its beautiful sand bar, looking for evidence of facing direction, primary sedimentary structures, data confirming this fold is a syncline, and data helping to locate the axial surface. There will probably be little daylight left.

Look for foliations in the folded rocks you find.

RELICT PRIMARY SEDIMENTARY STRUCTURES:

Excellent examples of primary sedimentary bedding, graded bedding, slump folds, load casts, rip-up structures, and maybe even cross-bedding are abundant in these rocks. These features have survived two metamorphisms and four deformations. This sort of unusually good preservation happens more often that you would imagine.

The pelitic schist in these outcrops weathers distinctly red-brown east of the amphibolite and blue-gray west of it. It contains kyanite porphyroblasts everywhere, and other galactic debris.

The metagraywackes are light colored, in both areas, buff to gray to white. The graded bedding in the graywackes developed in turbidites on the ocean floor. Originally, the graded bedding was both **size** grading and **compositional** grading: coarse-grained to fine-grained (involving Bouma sequences, what we normally think of as graded bedding), and also sand-to-mud grading (quartz-feldspar sand to pelitic illite-chlorite-kaolinite mud). However, as a result of metamorphism a **grain-size inversion** has occurred: the originally sandy grains didn't recrystallize much and maintained their original size (more or less) as they became metagraywacke, while the originally clayey, very fine grains recrystallized extensively into coarse mica grains that were larger than the sand grains. So now the pelitic, original-mud schists are coarser-grained than the quartz-rich, original-sand metagraywackes.

- Look for facing direction in the metagraywackes; figure out which way is up. Show facing on your map by a double arrow.

- Is facing consistent through the exposure area? Does it change? Can you locate the fold axis using facing?

Observe the considerable irregularity in the shape and lateral persistence of the graywacke beds; the irregularity argues against a tectonic imprint on these rocks. They display no consistent foliation. You can observe sandstone "dikes" (small to large beds of sand cutting across, truncating, pelitic schist layers. Look for load casts and slump folds. Look for sand cut-outs, where one sand bed cuts across layering in another sandstone bed. There are no persistent, harmonic fold trains, and what folding there is is disharmonic.

Look for pelitic schist behaving as relatively coherent **blocks** surrounded by metagraywacke. Look for metagraywacke showing odd and non-tectonic shapes - single-layer folds, disharmonic folds with curving axial surfaces, "intrafolial" rootless folds, folds with no axial-planar foliation, metagraywacke surrounding pelitic schist, evidence of flow, and evidence of apparently extreme ductility.

- Draw an example of some relations between graywacke, schist and folds.

COMPETENCE AND COMPETENCE CONTRAST, PART 2:

Keep competence in mind as you look around, and don't be surprised if things seem out of whack with your current thinking about competence. Because they are.

The normal expectations about competence are that grainy rocks are more competent than phyllosilicate rocks; sandstones and granites are tougher than shales and schists, and deform less readily. These expectations are consistent with many experiments, much field observation, and a sound theoretical base. They underlie nearly all your geological observations to this point. More grainy rocks are more competent than more mica-rich rocks; they deform at lower rates in a given stress field, they withstand stress better, they control the form of flexural folds, they don't develop drag folds while the less competent rocks do, and on and on. Your experience today verifies this: at South Point, the grainy rocks had boudined competently while the mica-rich schists had assumed considerable layer-parallel shear strain.

But the relations here **clearly contradict our normal expectations**.

- Which rock type appears to be more competent, stronger, deformed more brittlely?

- Which rock type appears to be less competent, weaker, flowed more, deformed more ductilely?

- Draw and label an example showing different competences.

These appearances are real; the metagraywacke actually was less competent than the schist. There has been a **COMPETENCE INVERSION**. **In these particular situations**. Metagraywacke is normally more competent than schist, but here in this setting it wasn't.

- When the rocks are solidified, lithified and hard, what is the relative competence of metagraywacke and pelitic schist?

- Think back to the original parents of these rocks. How competent or incompetent might the parents have been?

- What physical events take place for each sediment type on the diagenesis trip from sediment to rock?

- Is there any stage on that trip during which the competence contrast might be **reversed**? What would happen to cause the reversal?

- So, how can you explain this competence inversion?

- What generation are these competence-inversion folds?

- How come these early folds have largely escaped the rigors of F-2 and F-3 deformation? Why isn't there widespread shear strain in the pelitic schists here?

STOP 8: BEAR ISLAND GRANITE

Find the trail again, and proceed west. Near the river there are several big exposures of the Bear Island Granite. The granite is sugary-textured (aplitic, no water), and contains quartz and a perthitic feldspar. It has been radiometrically dated at 525 my (middle Cambrian).

- What evidence is there for the igneous origin of this rock?

- Look for foliation in the granite. Is the granite deformed?

- What is the time of intrusion relative to other events seen today?

Conclusion to the Metamorphism Story:

On eastern Bear Island, the prograde metamorphism created andalusite first; then sillimanite replaced the andalusite and occupied the andalusite grain forms (=pseudomorphs). The metamorphism may have followed some path in pressure-temperature space similar to line A on the stability diagram below.

In central and western Bear Island, the prograde metamorphism created kyanite first, then sillimanite replacing it. Metamorphism there may have followed a path similar to line K on the diagram.

This difference in path means that central/western Bear Island evolved (that is, reached sillimanite temperatures) under higher-pressure conditions than eastern Bear Island. This strongly suggests that somewhere in east-central Bear Island the rocks evolved along a path that passed precisely through the Al-silicate triple point, at which all three polymorphs were stable together. It isn't very often that one gets to pin down the triple point so exactly.

Regardless of the prograde-evolution path followed, all rocks underwent a second, lower-grade, **retrograde** metamorphism at lower P and T conditions, where muscovite + quartz is the stable assemblage of aluminosilicate material. This event represented on the diagram by arrows returning to low P and T.

To observe all this at the surface, considerable erosion and stripping of overlying rocks must have occurred, maybe 15 km of rock. In addition, the area must have been tilted regionally, up to the west and down to the east, to expose deeper levels to the west.

THE TRIP'S OVER.

Crash through the woods moving directly away from the river, and you'll come to the towpath. Turn **LEFT** to return to the Canal House, or turn **RIGHT** to return to Angler's Inn. Happy trails.

- Nearby are abundant porphyroblasts of kyanite in the pelitic schist. Again, they are replaced by sillimanite and then by muscovite.

Conclusion to the Metamorphism Story:

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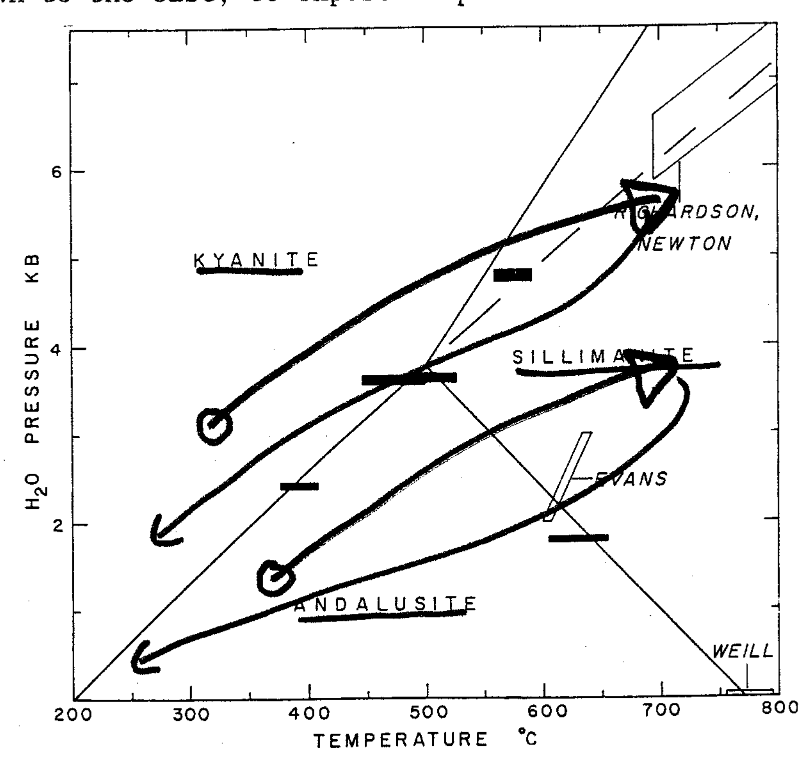

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