SUNDAY, NOVEMBER 7, 1993

FOLIATIONS AND SUPERPOSED FOLDING IN THE MARYLAND-VIRGINIA PIEDMONT

GREAT FALLS NATIONAL PARK

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 and interpret departures from expected, normal structural relations.

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 four hours or more.

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

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- criteria for tectonic vs. non-tectonic origin of structures
- 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 slammed into the Laurentian margin during one of the Paleozoic orogenies (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 get to 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 foliation, 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-grains 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 wavy schistosity. 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).

Table 2

Composition of Metagraywackes

From Hopson, 1964

Modal Analyses

Mineral Compositic

	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.

Mineralogical and chemical compositions of these rocks are given in Table 2.

The Peters Creek metasediments have been intruded by two types of igneous rocks:

amphibolite:

dark-gray to greenish black rock, generally lacking schistosity. Coarse- and fairly even-grained, but locally sheared; look for lineations caused by aligned hornblende needles near contacts. Probably metamorphosed basalt or gabbro. Original coarse igneous texture still visible. Originally pyroxene and plagioclase, now metamorphosed to hornblende and plagioclase. Occurs as tabular bodies, that were probably originally dikes and sills, and is confined to the Peters Creek Formation.

granitic intrusive rocks: termed **BEAR ISLAND GRANITE:**

leucocratic (few dark minerals), quartz-microcline-albite-muscovite granodiorite. Generally fine-grained, and often shows a sugary, even texture termed **aplitic**. Generally unfoliated, but locally contains aligned grains and a weak, coarse foliation near margins. Often shows **aplitic** texture, a sugary, even-grained, fine-grained texture that originated from crystallization under low water pressures. Occurs as small as plugs, dikes and sills throughout Great Falls area, but is confined to Peters Creek Formation. Ordovician (?) in age.

STRUCTURAL GEOLOGY

The rock on Bear Island contain evidence of four episodes of deformation, and deciphering these stages is the primary focus of the field trip. A very brief sketch of the sequence of events here is given in Table 3, taken from George Fisher's field trip guidebook of 1971. Fisher's descriptions can be updated and elaborated, as I try to do here. **F** stands for fold generation, **S** stands for schistosity developed during that folding; higher numbers are younger generations of folds; younger generations affect all older generations.

F-1: slump folds, soft-sediment deformation folds of compositional layering. These folds are generally confined to single beds, have variable (= not parallel) axial surfaces, and very different limb geometries. Generally no cleavage or schistosity is associated with these folds. These are considered to be pre-tectonic, non-tectonic folds, for reasons you will work out by yourself.

F-2: Isoclinal to very tight, similar folds of compositional layering, with strong axial-planar schistosity (S-2) on limbs and passing through noses. Common intrafolial, floating fold hinges. Compositional layering is transposed to near parallelism with schistosity. Variable plunge. S-2 foliation defines the predominant schistosity in pelitic and many psammitic rocks. It is a transposition foliation.

Table 3

Sequence of Events at Bear Island

Lithologic Units		Structures	Metamorphism
Deposition of graywacke and shale			
	F1	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	
Emplacement of granite bodies			Peak
	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	

F-3: major, <u>large-scale, tight to isoclinal</u>, similar folds of compositional layering <u>and F-2 schistosity</u>. Generally <u>weak axial-planar schistosity</u> (S-3), that can at times be a crenulation cleavage developed on small folds. These folds generally <u>plunge steeply SE</u>.

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

These four events are probably all phases of an intense orogeny that predated the Taconian orogeny. Regional correlation suggests a Cambrian age for the deformation. In post-orogenic time additional, mainly brittle deformation affected the rocks, including emplacement of gold-bearing quartz veins, brittle faulting, and development of systematic joints.

FIELD TRIP ROUTE AND STOPS

<u>STOP 1:</u> GREAT FALLS PARK HEADQUARTERS

VIRGINIA SIDE

the rocks: metagraywacke facies, with some interbedded pelitic schist

Features to look for here are:

- **<u>PIT STOP</u>**
- **<u>GEOMORPHOLOGY:</u>** the main falls and gorge of the Potomac River, the Piedmont erosion surface, and the Coastal Plain erosion level.

- **<u>METAGRAYWACKE THE ROCK</u>**:
    - grain size: = fine and even, sand-size, - **<u>PSAMMITIC</u>**
    - mineralogy: = quartz and feldspar grains, some opaque minerals, and a little muscovite, dominantly grainy.
    - competent rocks, frequent lack of schistosity or foliation
    - **<u>GRADED BEDDING</u>**: coarse, feldspathic sand, medium sand, fine-grained sand with a depositional break. Cm to m thick. Can recognize good Bouma cycles in the turbidites. Can establish **<u>FACING DIRECTION</u>** with certainty. But look out; it changes without

warning across isoclinal fold hinges.

- **PELITIC SCHIST THE ROCK**:

  - grain size: = coarse, uneven, dominated by platy phyllosilicates, Quartz masses of many sizes and irregular shapes.

  - mineralogy: = muscovite and maybe some biotite, and a little quartz. Probably chlorite too.

  - no graded bedding in pelitic schist; occasionally see gradual contacts with metagraywacke.

  - Compositional layering here is probably S-0, original bedding.

- **SCHISTOSITY AND CLEAVAGE**:

  - **spaced cleavage** in some metagraywackes = thin films of fine mica separated by 1- to 3-mm-thick lithons of metagraywacke. Probably of pressure-solution origin. These are axial-planar to folds, probably F-2 folds.

  - **domainal schistosity** in the pelitic schists, with M-zones and lithons of quartz. The schistosity is more crinkly and rougher, and more visible, than good slaty cleavage.

- **FOLDS**:

  - can find isoclinal and tight similar folds, but not many hinges.

  - can infer the locations of hinges from changes in graded bedding and facing directions without change in dip; must be strictly isoclinal.

  - small, late crenulations are everywhere. Look like fish bones.

  - can work out F-2, F-3 and F-4 fold generations here. The major foliation was probably generated in the F-2 event. Its present attitude, dip and strike, are probably largely the result of F-3 folding. The cross-cutting crenulation folds are F-4.

GO FOR IT. Examine both rock types, find graded bedding, find facing, find facing reversals, locate fold axes.

STOP 2: DIFFICULT RUN

Location: ledge outcrops in bed of Difficult Run, about 0.25 mile north, downstream, from VA 193 bridge over the stream. Park in lot east of bridge, walk back.

Features to look for here:

IN THE GRANITE:

- mineralogy and texture: aplitic texture (sugary, fine-grained), leucocratic (few mafic minerals), quartz and two feldspars
- near the margins: preferred orientation of mineral grains, strings of mafic minerals, a **flow layering**. General swirling of flow pattern. Maybe finer-grained (chilled) near margin; check it out.

IN THE AMPHIBOLITE:

- look for mineralogy and texture
- mineral **lineation** of aligned hornblende needles is weak at best; maybe stronger near margins? relict igneous texture?
- check orientation of contact with pelitic schist.

IN THE SCHIST:

- mineralogy: muscovite, quartz, plagioclase, cordierite, andalusite
- **porphyroblasts** of cordierite and andalusite.
- stronger schistosity than other rocks, because more micas, more folding and swirling.
- zones of no schistosity, little mica, abundant feldspar and quartz grains, no mineral alignment = migmatite, an igneous rock produced by local melting of the schist. Texture reflects that rock crystallized evenly and without strain.
- **ductile shear zones** in schist: more mica alignment, closer-spaced schistosity, finer-grained schist.
    - discrete shear zones, finite width, with less-sheared "lithons" between them.
    - ductile shear zones more concentrated near contact with amphibolite.

- porphyroblasts less abundant and more elongate in shear zones; they show tails and sense of rotation.

- by contrast, porphyroblasts in lithons are larger and more equidimensional.

- Make a **sketch map** of the outcrop. Show the distribution of the rock units, their contacts, and their geologic features.

- Draw the relations in a ductile shear zone. Show the schistosity, the porphyroblasts, the tails, and sense of rotation if you can.

- Interpret the geologic nature and strain significance of the contact between pelitic schist and amphibolite. State the evidence on which you base your conclusions.

- List in order the sequence of geologic events that are represented in this outcrop. Include deposition, intrusion, metamorphism, etc, in addition to the specific structural events.

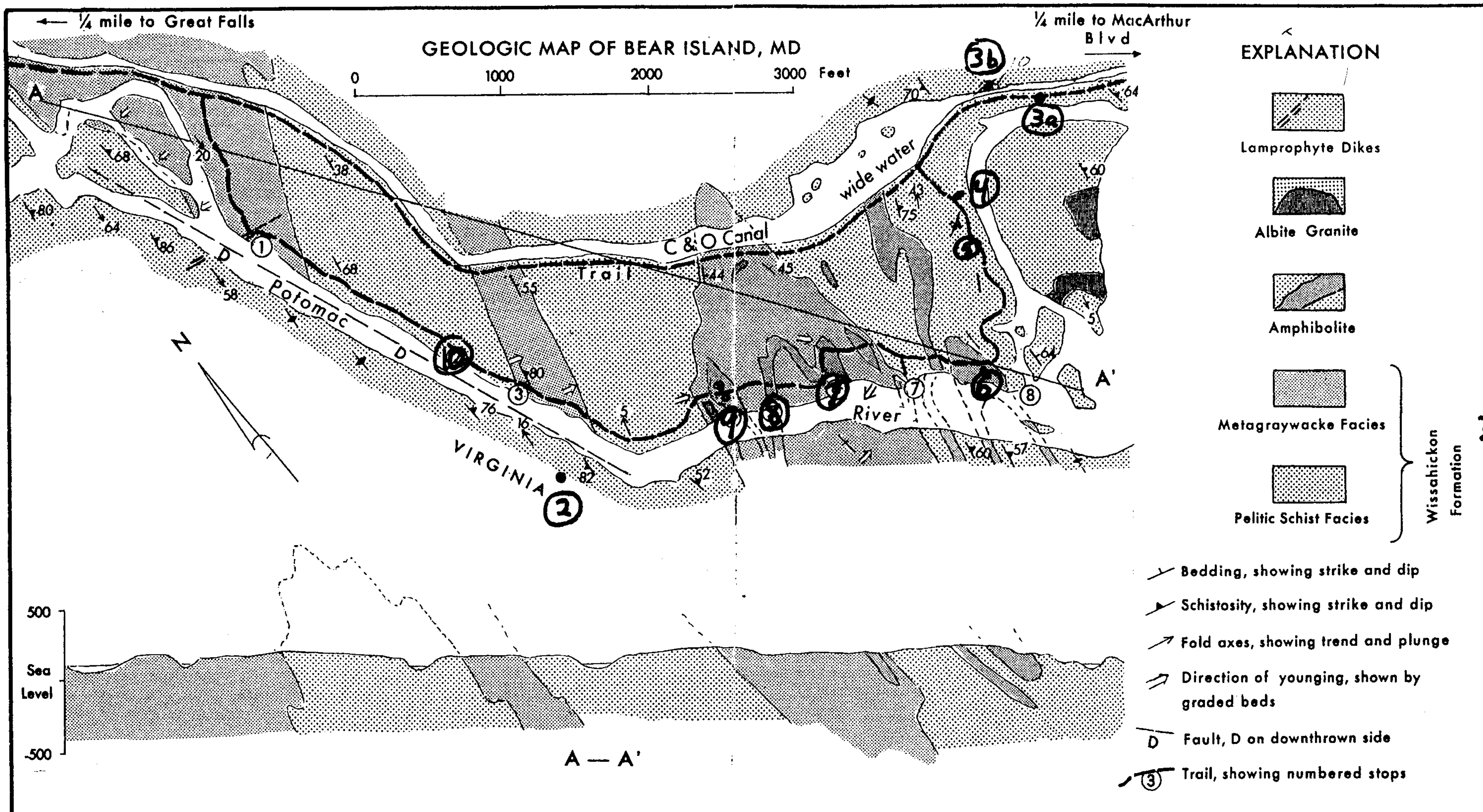

← ¼ mile to Great Falls
GEOLOGIC MAP OF BEAR ISLAND, MD
0 1000 2000 3000 Feet
¼ mile to MacArthur Blvd →
EXPLANATION
Lamprophyte Dikes
Albite Granite
Amphibolite
Metagraywacke Facies
Pelitic Schist Facies
Wissahickon Formation
Bedding, showing strike and dip
Schistosity, showing strike and dip
Fold axes, showing trend and plunge
Direction of younging, shown by graded beds
D Fault, D on downthrown side
③ Trail, showing numbered stops
C & O Canal
Trail
wide water
Potomac
River
VIRGINIA
N
A
A'
500
Sea Level
-500
A — A'
9a

Figure 1

GREAT FALLS NATIONAL PART, MARYLAND SIDE

At the Canal House and parking lot, do **PIT STOPS** and lunch if you're inclined.

Consult the map on the next page. Walk south along the towpath for about a mile, to the south end of the elongate "lake" called Widewater. Along the way, sharpen your skills at telling pelitic schist from psammitic gneiss along the trail. Look for the same features we saw on the Virginia side. 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 dies, don't call it a horse, even if everyone else does. Remember, the Emperor has no clothes on.

Walk to the first large outcrop on the towpath beyond the south end of Widewater.

STOP 3A: WIDEWATER I

- Pelitic schist, with domainal schistosity.
- Excellent development of the **F-4 CRENULATION FOLDS** on the front face, with the F-4 crenulation cleavage parallel to the thin limbs. You can trace individual layers though both limbs and the hinges or these folds.
- Sketch the form and orientation of the F-4 folds.

- What's the orientation of the F-4 axial surface? Can you tell plunge?

STOP 3B: **WIDEWATER II**

Across the canal, a large outcrop of 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?

    - slip or flow?

    - kink, solutional or buckle?

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

- Sketch the fold. Show the axial surface. Indicate λ_1 and λ_3, and indicate σ_1 and σ_3.

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

STOP 4: 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
  - 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.

  - Check out the quartz in the schist here. What is the strain significance of the lenticular form of the quartz?

  - Is there a sense of rotation in the quartz?

JUST ABOVE THE MAIN LEDGE:

- Excellent example of **SUPERPOSED FOLDS** 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 outcrop here, and show all fold axial surface traces.

- The next outcrop, if I can find it, shows 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 sense of shear/rotation on these folds?

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

Fig 6.

Transposition

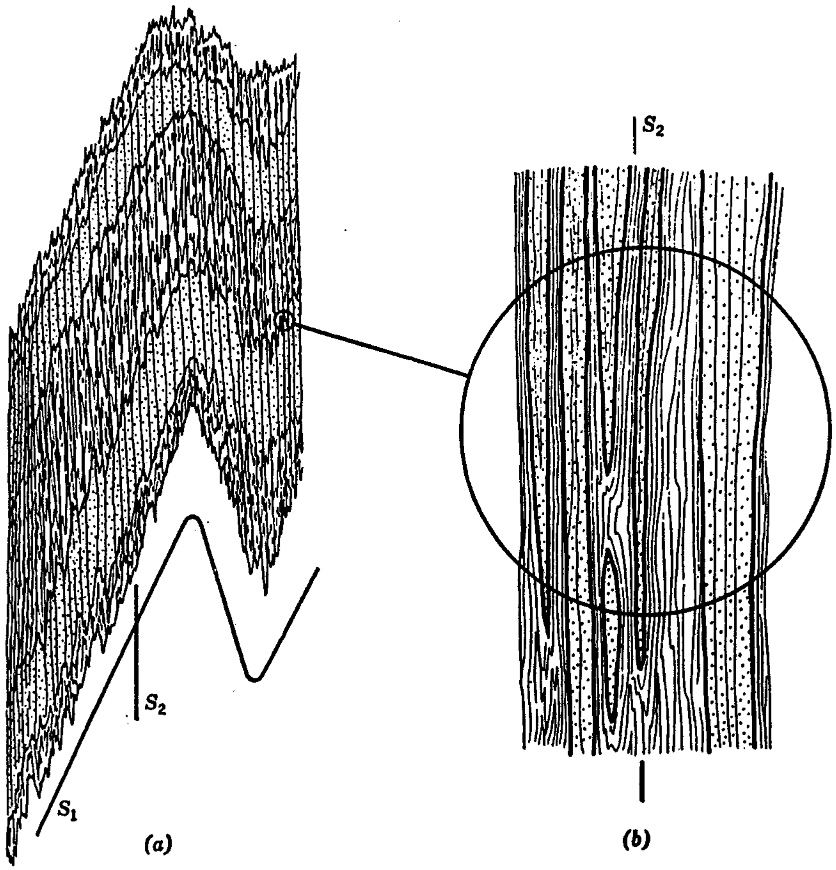


Fig. 4-12. Lithologic contact on two scales. (*a*) Large scale; generalized contact is S_1. (*b*) Small scale; contact is S_2.

Turner + Weiss, 1963

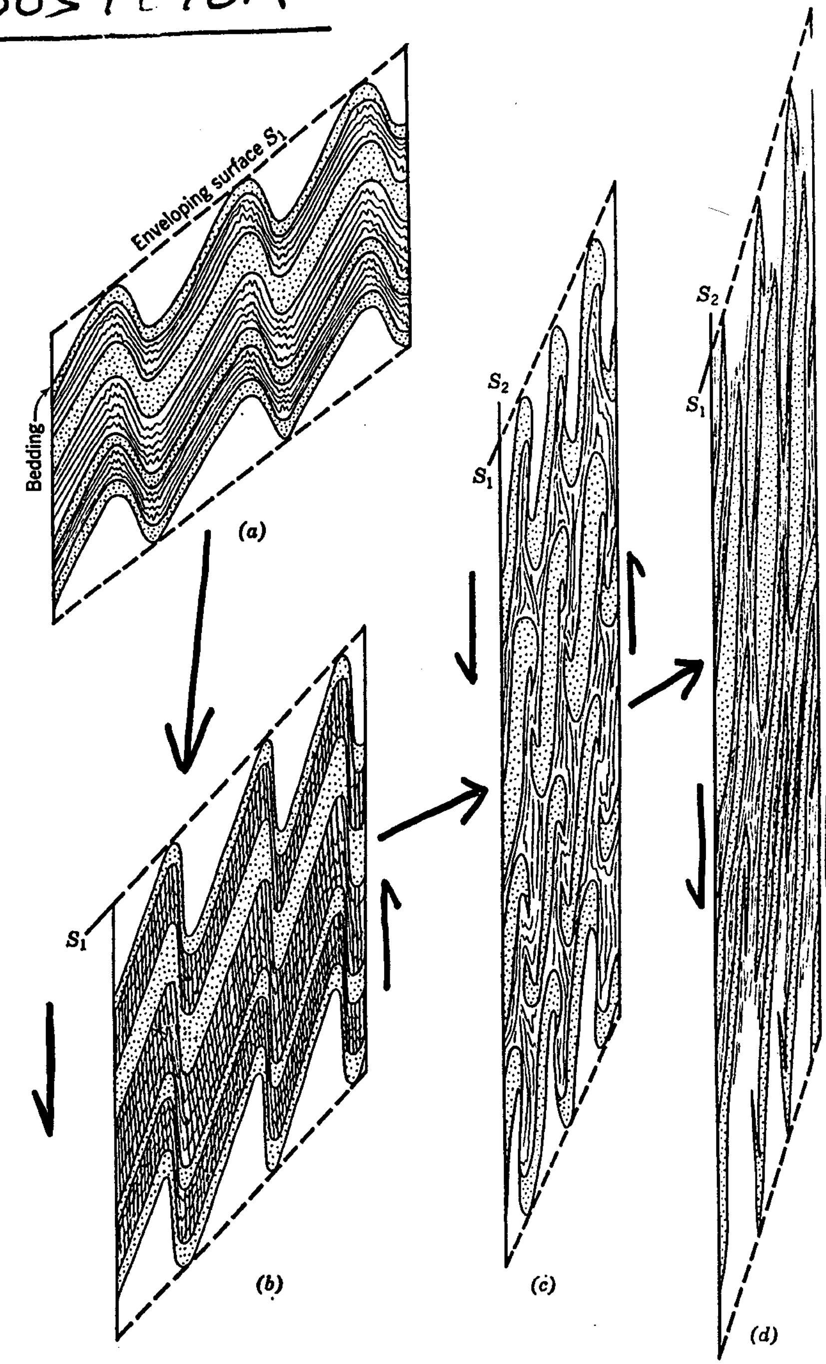


Fig. 4-11. Sequence of transposition of bedding S_1 into a foliation S_2.

- Check out the schistosity at the hinges of the fishhook folds, and see whether it wraps around the hinge, or cuts through it. Draw your findings here:

- If the schistosity wraps the fold noses, the schistosity is of an earlier generation than the folding. If it cuts through the hinges parallel to the axial surface, it's the same generation as the folding. Sum up everything, and assign the fishhook folds to a generation number: F-1, -2, -3, or -4. What's your critical evidence?

- Sum it all up and draw the fishhook folds, show axial surface trace(s), and give a stress-field and strain-field interpretation on your sketch.

THE EDGE OF THE LEDGE:

Exposed here is what appears to be a **granitic dike** in various stages of structural disarray.

- Describe the fold geometry: symmetric or asymmetric? upright or inclined? or recumbent? kink or buckle? axial surfaces parallel or not parallel?

- How do attitudes of fold axial surfaces compare to attitudes of neighboring schistosity?

DESCRIBE THE DIKE:

- Trace the dike into its unfolded portions. What is the attitude of the unfolded portions relations to schistosity?

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

- Why are the dike segments parallel to schistosity thin, and the folded parts perpendicular or at high angles to schistosity thick?

- Look inside the granite for individual grains that are aligned, i.e. look for a **mineral foliation** in the granite. Where in the dike is that alignment best developed? What might that mean?

- What is the mineral foliation parallel to? What could that mean about the timing of intrusion of the dike? relative to deformation?

- **KEY QUESTION**: Could the fishhook folds and the dike deformation both have originated in the same stress field? Do they indicate the same kind of strain? Defend your answer.

- IN SUMMARY: Which do you like better for the deformation here: shearing strain? or flattening strain?

<u>STOP 5:</u> ANDALUSITE KNOB

the rocks: pelitic schist, and Bear Island granite masses

features to look for:

- andalusite **<u>porphyroblasts</u>**: 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 **<u>prograde</u>** 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?

- <u>**migmatite**</u> is well-developed here.

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

<u>STOP 6:</u> 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.

<u>**EAST SIDE OF RIDGE**</u>:

- observe the <u>**boudinage**</u> in the high wall - what strain does it signify? What (probably) fold generation?

- Which is the most competent rock here? which is least competent?

<u>**CREST OF RIDGE AND OUT TO POINT**</u>:

- <u>**great**</u> 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.

- <u>**THE SCHIST**</u>:

  - interbedded pelitic schist and granular, psammitic gneiss. Original bedding is visible in places. Probably transposed, but still original bedding.

- **SEQUENCE OF DEFORMATION**: notice the **boudinage** of the psammitic layers, and the flow of pelitic layers to fill in the vacancies.

  But then look at the **tails** of the tension-gash material as it enters the pelitic layers: there must have been significant layer-parallel **shear** in the pelitic layers.

  What was the sequence of deformation here?

- Make a drawing of the boudinage-tails relationships, and indicate sense of shear.

- **COMPETENCE AND COMPETENCE CONTRAST, PART 1**: Which rock type in this situation has the higher competence? What do you base your answer on?

- What deformational evenT would you assign these structures to?

- **THE GRANITE:**

  - The granite occupies a swarm of cross-cutting, anastomosing dikes that become so concentrated that the resulting rock is actually a migmatite, mixed igneous and metamorphic rock. But this migmatite is an **injection migmatite**, in which the igneous material was not melted directly from these local rocks but came from somewhere else.

  - You can observe several generations of dikes, based on cross-cutting relationships.

- **THE FAULT:**

  - the far point is cut off from the mainland by a fault, running basically parallel to the river. What is the horizontal component of the net slip? dextral or sinistral?

WEST SIDE OF THE MAIN RIDGE:

- **THE AMPHIBOLITE:**

- cross over the crest of the ridge and encounter the **contact of the amphibolite.** Describe the orientation of the contact relative to layering and foliation in the adjacent pelitic schist. Is it concordant or discordant?

- Walk into the amphibolite, away from the contact, and observe the texture and grain size. The 5mm-cm size knubbly clots in the rock are relict outlines of pyroxene grains int he original gabbro.

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

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

  - How much deformation has this 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 the amphibolite fabric and grain size. What happens to the texture in the amphibolite as you approach the contact? Describe.

- What do you think this change represents? How could you explain it?

- What are the **relative age relationships** between schist/gneiss, amphibolite, and granite? Which is youngest, which is oldest? Which is most deformed? least deformed?

As you continue along the trail, watch for lithology change, and holler when you pass back into schist. Consult the geologic map for location.

<u>STOP 7</u>: THE POND, AND PINE KNOB

MAPPING FOLDS, EARLY FOLDS AND LATE FOLDS, SUPERPOSED SCHISTOSITIES

We will spend considerable time here, if there's any time left.

- Stop and holler when you find amphibolite again along the trail.

- Follow the trail past the pond on the left. When the trail turns left, leave the trail and climb straight ahead.

- Examine the **<u>amphibolite</u>** here. Look for **<u>foliation</u>**, and for **<u>lineation in the plane of the foliation</u>**. 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 **<u>contact between amphibolite and schist</u>**. In the space below draw a sketch map of this little area, showing locations of schist and amphibolite, orientation of the contact, dip and strike symbols.

- Climb higher up the east face of the knob and look back to view a large

drag fold. The folded rock is gray metagraywacke, and it is surrounded by reddish-weathering pelitic schist.

- look in the hinge region for **foliations**, and determine whether any foliation **cuts through the nose** or **wraps around the nose**. Look for original bedding in the graywacke too. Make a sketch below of your findings:

- The logic about fold generations goes like this: the earliest tectonic foliation is assumed to be F-2. If foliation wraps around the fold nose, the fold is at least F-3 or later. If the foliation parallels the fold axial surface and cuts through the nose, the fold and the foliation are the same generation, and may well be F-2. If the graywacke contains layering that you decide is **not tectonic**, then layering is bedding, and is F-1 or even F-0.

  What generation do your data suggest this drag 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.

Return to the trail, and find the schist-amphibolite contact again. Follow that contact west toward the high knob (Pine Knob) ahead. Follow the contact wherever it goes. When you get to a point above the small swamp, stop, and take strike and dip of the contact, and the plunge of the mineral lineation in the amphibolite.

- The contact will go **around a fold nose**, at the base of Pine Knob. Locate that closure, and locate the axial surface. Look for foliation in the amphibolite at that point. Is there any? Take strike and dip.

- Look for aligned hornblende needles in the amphibolite, and determine the **plunge of the lineation** formed by those needles. Is the lineation in the plane of foliation here? Why or why not? What's that relation telling you? very important.

- How does the plunge of the lineation here compare to the plunge of the lineation farther back up the trail?

- Why is the lineation at different angle to foliation here than it was farther back up the trail?

- In the space below, draw a map of the relations between schist and amphibolite in this area. Show all the structural features we've examined here, including the drag fold, attitudes of foliation, attitudes of lineations, contacts. Draw it with the river at the bottom. Is the shear sense of the drag fold compatible with what you draw?

- What generation is this fold structure? What generation is the foliation? What generation is the lineation? Are they all the same generation?

Follow the schist-amphibolite contact off Pine Knob away from the river. Keep on that contact **wherever it goes**. This is the art of **mapping contacts**, a much-needed field-camp skill. Take a few attitudes along the way. Use the next page (blank) to draw your map on.

- If you find another hinge zone, look for lineations and determine plunge.

- You will find that the contact returns to the river. Follow it all the way if you can. Draw it on your map.

    - Is the fold a synform? or a syncline?

Return to Pine Knob. Climb to the saddle on the south side, where the trail turns left.

- Observe the closure of a similar fold showing **two sets of foliations**. The rock contains interbedded metagraywacke and pelitic schist. The metagraywackes show **graded layering**, and you can determine facing. The schist has encountered more layer-parallel shear than the graywacke. One foliation **wraps** around the hinge; it is best developed in the schists. The other foliation is weaker, and is developed only in schists in the hinge region.

    - Is the fold a syncline or a synform? Evidence?

    - Sketch the fold, and show the relations between bedding and the two foliations. Show axial surface. Which fold generations do you think are represented here?

- Scramble up the south side of the high knob to observe large **kyanite porphyroblasts** in the pelitic schist. Again, these crystal outlines are relicts; they do not contain kyanite now. The original kyanite was replaced by sillimanite (higher metamorphic grade, = prograde metamorphism), which was then replaced by muscovite (lower metamorphic grade, = **retrograde** metamorphism. Quite a history.

STOP 8:

THE NORTH SYNCLINE: F-1 FOLDS

TECTONIC VS. NON-TECTONIC STRUCTURES - THE IMPLICATIONS OF COMPETENCE CONTRAST

Return to the area in the hinge region of the syncline you mapped just north of Pine Knob. In this region the strain is weak, and much original bedding and pre-tectonic features are exposed here. The plan is to wander around the area, 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 on 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, and contains porphyroblasts and other galactic debris. The metagraywackes are light colored, buff to gray to white.

The graded bedding developed in turbidites on the ocean floor. Originally, the graded bedding was both **size** grading and **compositional** grading: coarse-grained to fine-grained (what we normally think of as graded bedding), and also graywacke 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.

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

COMPETENCE AND COMPETENCE CONTRAST, PART 2:

As you look around, keep competence in mind, and don't be surprised if things seem out of whack with your current thinking (because they are).

- 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 extreme ductility. Sketch some of these relationships.

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. They are consistent with many experiments, very 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: remember at stop 6, at South Point, the grain 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?

- Cite or draw some examples.

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

These appearances are real; the metagraywacke actually was less competent than the schist. **In these particular situations**. Metagraywacke is normally more competent than schist, but here in this setting it wasn't. Why? What was different about this setting to cause this **competence inversion**?

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

- Can you imagine a time, or a setting, in the history of the rocks that might have allowed for each rock to have a radically different competence from its present competence? What might that have been?

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

- How does sediment pass from incompetent sediment to competent rock?

- Is there any stage along that sediment-rock evolution during which the competence contrast could be **reversed**?

- 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 the widespread shear strain in the pelitic schists here?

STOP 9: BEAR ISLAND GRANITE

Find the trail again, and proceed up-river (NW). 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?

- 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:

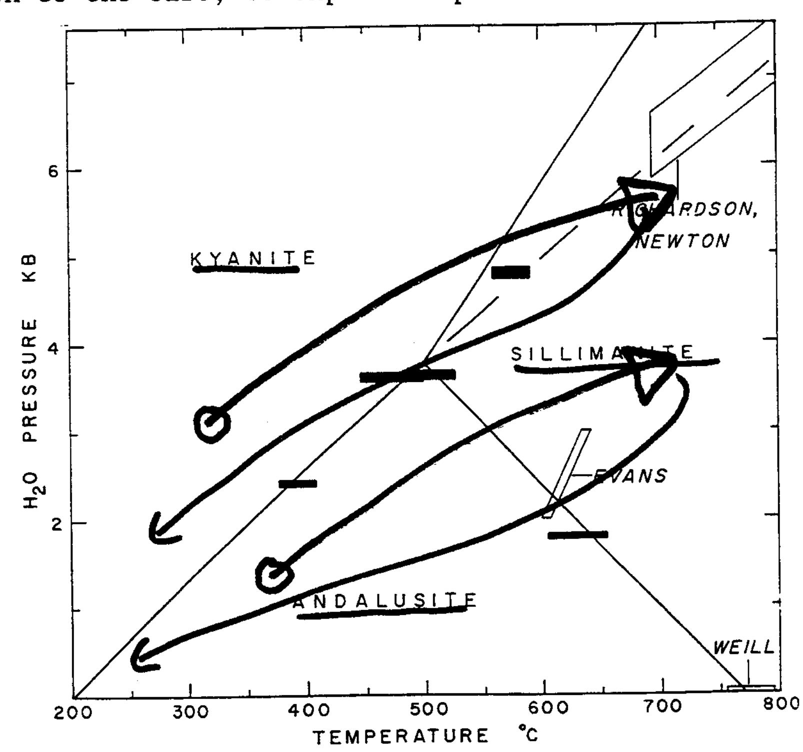
On eastern Bear Island, the prograde metamorphism created andalusite first, then sillimanite replacing the andalusite. The metamorphism may have followed some path in pressure-temperature space similar to line A on the stability diagram below.

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 and 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.

All rocks regardless of prograde evolution path underwent a second, lower-grade, **retrograde** metamorphism at P and T conditions where muscovite and quartz are the stable forms 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 or 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.