MARYLAND GEOLOGICAL SURVEY

Kenneth N. Weaver, Director

GUIDEBOOK NO. 4

THE PIEDMONT CRYSTALLINE ROCKS

AT

BEAR ISLAND, POTOMAC RIVER, MARYLAND

by

George W. Fisher
Dept. of Earth and Planetary Sciences
Johns Hopkins University
Baltimore, Md. 21218

A GUIDEBOOK PREPARED FOR THE 1971 ANNUAL MEETING

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GEOLOGICAL SOCIETY OF AMERICA

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Introduction

The Maryland Piedmont is underlain by a thick sequence of metamorphosed sedimentary and volcanic rocks, the Glenarm Series, mantling an 1100 my-old basement complex, the Baltimore Gneiss (Table 1). The principal stratigraphic unit in the Glenarm Series, the Wissahickon Formation, has been subdivided into five mappable facies on the basis of inferred original lithology (Table 1). The rocks along the Potomac River at Bear Island Provide outstanding exposures of the pelitic schist facies and the metagraywacke facies, which have been studied by numerous authors (Cloos and Anderson, 1950; Fisher, 1963; Reed and Jolly, 1963; Hopson, 1964; Reed and Reed, 1967; Reed, Marvin and Magnum, 1970; and Fisher, 1970a). Because they have been so intensively studied, these rocks have played a central role in current interpretations of Piedmont geology.

Age and Regional Setting of the Glenarm Series

The age and stratigraphic position of the Glenarm Series have been debated at length in the literature. Hopson (1964) reviewed the evolution of early ideas, and concluded from available radiometric dates that the Glenarm Series was probably late Precambrian, a northeastern extension of the turbidite sequence represented by the Ocoee Series in the Southern Appalachians and the Lynchburg Formation in central Virginia. However, several lines of reasoning suggest to me that at least part of the Glenarm is Cambrian, and should be correlated with the basal Cambrian clastic rocks found along the Blue Ridge (the Chilhowee Series):

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

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).

1) A new zircon date from metarhyolite in the Catoctin Formation, which lies between the Lynchburg and the Chilhowee, indicates an age of 820 my (Rankin and others, 1969).

2) Other new zircon dates suggest an age of roughly 550 my for volcanic rocks in the Glenarm Series in the northeastern Maryland Piedmont (Tilton and others, 1970; Higgins, personal communication, 1970). These dates are discordant, and subject to some uncertainty, but it seems very unlikely that they can be older than the 820 my-old Catoctin.

3) Facies changes within the lowermost unit of the Glenarm Series, the Setters Formation, suggest a transition to rocks of the Chilhowee Series in southern Pennsylvania (Fisher, 1971).

4) Mapping I have just completed in the western part of the Maryland Piedmont indicates an east-to-west facies change from phyllites of the Wissahickon Formation to phyllites probably belonging to the Chilhowee Series.

5) The stratigraphy of the Glenarm Series is remarkably like that of the rocks along strike in the New York City area, now known to be early Paleozoic (Hall, 1968; and Ratcliff and Knowles, 1969).

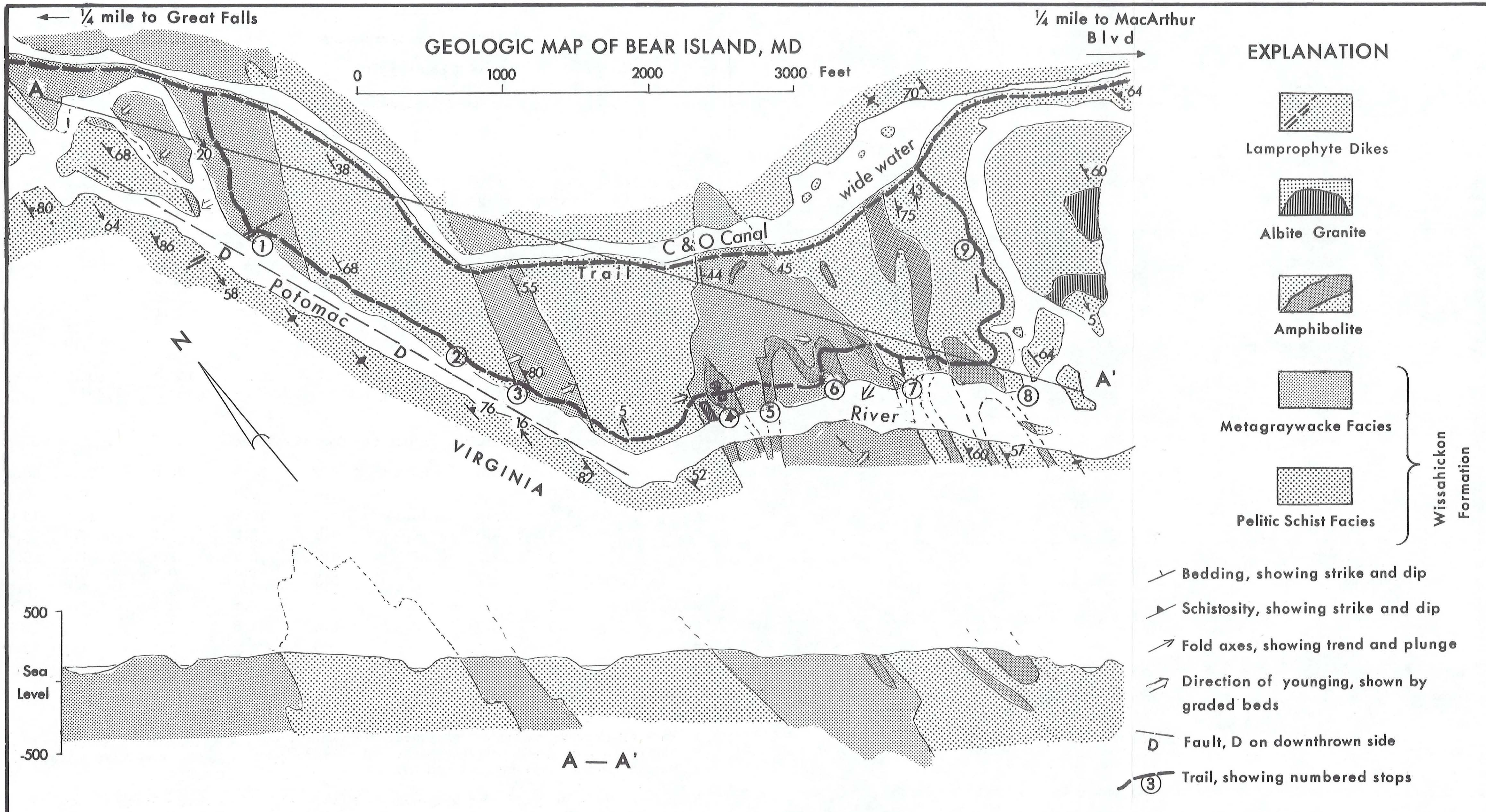
These relations raise important questions about how the different parts of the Glenarm Series fit together. If all of the above interpretations are correct in detail, Piedmont structure and stratigraphy must be much more complicated than commonly assumed (but *see* Rodgers, 1970, p. 190). Despite the remaining uncertainties, the evidence cited suggests to me that much of the Glenarm Series is equivalent to the early Paleozoic Appalachian section.

Summary of the Geology of Bear Island

The principal lithologic units exposed on Bear Island are the metagraywacke and pelitic schist facies of the Wissahickon Formation, several concordant sheets of amphibolite, and small plugs and dikes of albite granite (Fig. 1).

The rocks of the metagraywacke facies are fine-grained mica-oligoclase-quartz gneisses, rhythmically interbedded with coarse-grained sillimanite-mica schists containing sericitized porphyroblasts of staurolite, kyanite and andalusite. The schists are locally permeated with quartz-albite exudation veinlets. The metagraywackes crop out in two distinct zones: a lower zone of thick-bedded, originally coarse-grained metagraywacke about 1000 feet thick on northern Bear Island; and an upper zone of thin-bedded metagraywacke about 2000 feet thick, which outlines a south-plunging syncline in the central part of the island. The two zones are separated by 1000 feet or more of pelitic schist.

Despite their metamorphism, the metagraywackes preserve the characteristic chemical composition of graywacke (Table 2), and numerous relict sedimentary structures: graded bedding, load casts, sedimentary lamination, slump features, and convolute bedding. These relict features, and the rhythmic interbedding of metamorphosed graywacke and shale clearly show that these rocks originated as turbidite deposits (Fisher, 1963, 1970a; Hopson, 1964). Judging from the thickness and areal extent of the metagraywackes in the Wissahickon, the depositional basin must have been large, deep, and presumably marine. The associated shales are inferred to be products of normal pelagic sedimentation because of their chemical composition and close association with the Wissahickon turbidites.



← 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

Table 2

Composition of Metagraywackes

From Hopson, 1964

Modal Analyses

	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.

The amphibolite occurs in sheets from 1 to nearly 100 feet thick, which form generally concordant sill-like masses within both pelitic schist and metagraywacke. Fisher (1963, 1970a) Reed and Jolly (1963) and Hopson (1964) all interpret these sheets as intrusive sills of diabase or gabbro on the basis of their chemical composition, coarse-grained relict texture, local cross-cutting contacts, and rare relict pigeonite (Reed and Jolly, 1963, p. H7). A few of the thinner layers may represent basaltic flows or tuffs, but this is unproven.

Unpublished radiometric determinations on zircon from amphibolite at the south-eastern tip of Bear Island give Pb^{207}/Pb^{206} age of 525 ± 60 my, or a concordia age of 550 my, assuming continuous diffusion (Steiger, personal communication, 1968).

The Wissahickon metasediments and amphibolites are both cut by numerous small aplitic to pegmatitic plugs and dikes of light-colored muscovite granite. The mineral assemblages in the margins of these bodies vary from biotite-oligoclase-quartz (chiefly in intrusions cutting amphibolite) to muscovite-albite-quartz (in rocks cutting pelitic schist). This variation appears to reflect metasomatic exchange with the wall rocks, chiefly influx of FeO, MgO and CaO from the amphibolite, and loss of K_2O to the pelitic schist.

The cores of the granite bodies are muscovite-microcline-albite-quartz granite, regardless of the chemistry of the adjacent wall rocks. Even the core rocks are not uniform in composition, however; they lie on a line between the granite minimum and average Wissahickon metasediments, suggesting that they owe their muscovite content to selective assimilation of the felsic constituents of Wissahickon schists (Fig. 2).

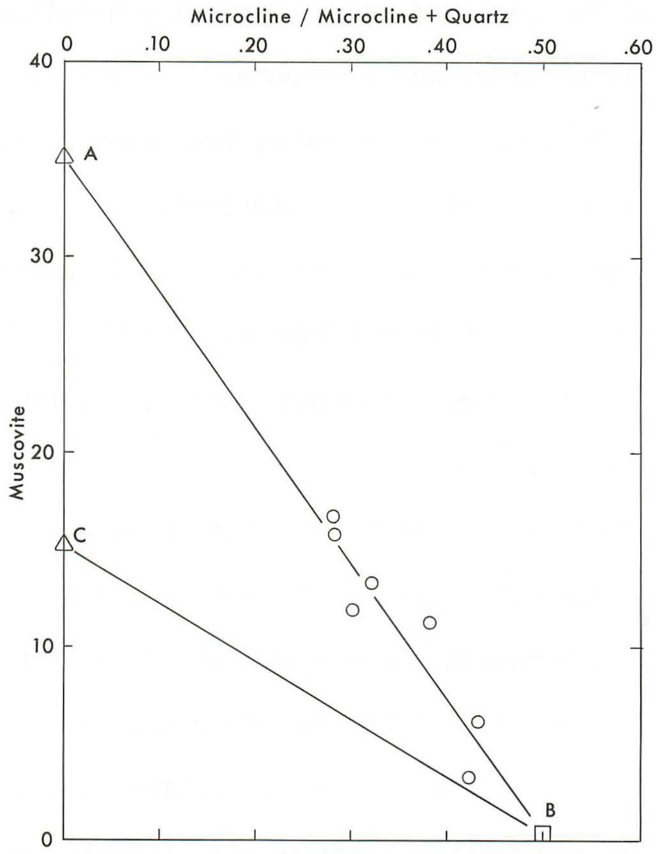


Fig. 2: Modal composition of the cores of granite bodies on Bear Island. A represents the average composition of Wissahickon metasediments; B represents the composition of the granite minimum in the system $KAlSi_3O_8$ - $NaAlSi_3O_8$ - SiO_2 - H_2O at 4000 bars P_{H_2O}, estimated from Tuttle and Bowen (1958) and James and Hamilton (1969); C represents the composition of a rock produced by the conversion of all microcline in B to muscovite, conserving Al_2O_3, and losing K_2O.

Between the north end of Bear Island and Great Falls, several dark green, fine grained dikes of lamprophyre intrude the Wissahickon metasediments (Fisher, 1963; Reed and others, 1970). The dikes contain strongly zoned phenocrysts of dark brown biotite set in a fine-grained matrix of microcline, albite, quartz, calcite, green chloritized biotite, and local spongy prisms of actinolite. K-Ar age determinations on biotite separated from two of these dikes by Reed and others (1970) give nearly identical ages of approximately 360 my (Late Devonian).

The youngest rocks on Bear Island are gold-bearing quartz veins emplaced along fault and shear zones which offset the lamprophyre dikes. During the past 100 years, 5000 ounces of gold, valued at more than $150,000.00 have been recovered from these veins, but no production has been reported since 1951 (Reed and Reed, 1967).

The tectonic structures in these rocks have been described by Cloos and Anderson (1950), Reed and Jolly (1963), and Fisher (1963, 1970a). They reflect at least three stages of folding and one of faulting (Table 3).

Little work has been done on the geomorphology of Bear Island, but the broad outlines of erosional history seem clear. Bear Island lies just downstream from Great Falls, which marks a major change in the form of the Potomac River, from a broad, shallow, generally placid river flowing in a wide valley above the falls, to a narrow, deep, swift river in a steep, rocky gorge below. Much of northern Bear Island is a bedrock terrace at roughly the same elevation as the present river bed above the falls. Many pot-holes on this terrace show that the river once flowed at this level, probably in earliest Pleistocene time. On southern Bear Island, the river appears to have occupied two channels: one on the site of the modern chan-

Table 3

Sequence of Events at Bear Island

Lithologic Units	Structures	Metamorphism
Deposition of graywacke and shale		
	Slump deformation of partly consolidated sediments (F_1)	Diagenesis
Intrusion of mafic sills (550 my)		
	Isoclinal folding (F_2) with schistosity (S_2) nearly parallel to bedding	Prograde
	Major folds (F_3) with crenulation cleavage (S_3) cutting S_1 and S_2	
Emplacement of granite bodies		Peak
	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	

nel, and the other on the present site of Widewater and the Chesapeake and Ohio Canal. At some later time, probably during periods of lowered sea level in Pleistocene time, the river cut rapidly into its bed, carving the gorge that extends from Great Falls to Washington, D.C. The present falls probably reflect the contrast in hardness between the unusually thick, resistant metagraywackes at Great Falls, and the crushed, brecciated rocks along the normal fault bounding northern Bear Island, immediately below the falls.

Acknowledgements

Some of the trail description and much of the botanical information in this guide is based on The River and The Rocks, a popular guide to the geology of Great Falls published by the U.S. Department of the Interior from material supplied by J. C. Reed, Jr., R. S. Sigafoos, W. L. Newman, C. B. Hunt, and myself.

Ernst Cloos, C. A. Hopson, J. C. Reed, Jr., Hans Eugster, D. L. Southwick, E. H. Hansen and many other geologists have contributed to my understanding of these rocks by discussions during previous field trips, and by criticism of various manuscripts on Piedmont rocks.

Trip Log

THIS TRIP CONSISTS OF A 2.4 MILE HIKE OVER EXTREMELY RUGGED TRAILS; IT SHOULD BE TAKEN ONLY BY THOSE IN GOOD PHYSICAL CONDITION WHO ARE EQUIPPED WITH STOUT, RUBBER SOLED HIKING BOOTS, AND WARM, RAIN-PROOF CLOTHING.

Assemble in the parking lot of the Shoreham Hotel at 8:00 am. Busses will drive 17.9 miles to the parking lot at Great Falls, Maryland via Connecticut Avenue, the Washington Beltway, and Maryland Rts. 190 and 189. Most of the route lies on the gently rolling Piedmont upland, underlain by metasediments of the Glenarm Series, and various igneous rocks.

Shortly after leaving the Washington Beltway, Route 190 passes several quarries in the diamictite facies of the Wissahickon Formation, probably an immense submarine slide deposit (the Sykesville Formation of Cloos and Cooke, 1953, and Hopson, 1964). The rock from these quarries is used extensively in the Washington area for building stone.

Just beyond the junction of Route 189 with MacArthur Boulevard, the remains of the mill at the Maryland mine can be seen through the trees on the left. The mine operated intermittently from about 1900 to 1940; from 1936 to 1940, it yielded about 2500 ounces of gold, valued at $90,000.00.

Mileage

0.00 Leave busses in parking lot, assemble at Great Falls Tavern Visiting Center.

The low dam which crosses the river at this point diverts water into an underground aqueduct for use by the District of Columbia and nearby suburbs.

The Chesapeake and Ohio Canal, beside the Visitor Center, runs from Cumberland, Maryland to Washington, D.C., a distance of 180 miles. Construction began in 1824, and the canal was opened to traffic in 1850; in 74 years of operation, 21 million tons of coal were brought down the canal from Cumberland. The canal locks are made of Triassic sandstone quarried near Seneca, Maryland, about nine miles upstream from Great Falls.

Cross the canal, and follow the towpath downstream (to the left).

0.46 The canal passes high above an intermittent channel of the Potomac. During periods of low water in fall and summer, this channel is nearly dry. But in spring floods it often fills to a depth of 40 feet.

0.55 Trail junction; turn right on trail marked with blue blazes along west side of Bear Island. The towpath continues straight ahead past a stop lock and diversionary dike 1.6 miles to Widewater and MacArthur Boulevard. The flood of March 1936 covered the trail to a depth of 10 to 15 feet at this point.

0.76 STOP 1 The trail crosses a narrow valley eroded along a set of three lamprophyre dikes intruding metagraywacke; turn right and follow valley 70 feet to outcrop at overlook.

The lamprophyre contains strongly-zoned phenocrysts of dark brown biotite set in a fine-grained matrix of albite, quartz, calcite, green chloritized biotite, and local spongy prisms of actinolite. K-Ar determinations on the biotite indicate an age of approximately 360 my (Reed and others, 1970).

The river here is entrenched along a normal fault, which accounts for the straight walls of the gorge at this point. Displacement along the fault can be determined from: 1) offset of the lamprohyre dikes -- the prominent clefts visible on the cliffs on the opposite bank mark the continuation of the dikes, offset 80 feet upstream; and 2) truncation of the large anticline in metagraywacke on northern Bear Island (Fig. 1) -- its failure to carry across the fault means that the opposite side must be downthrown by at least 1000 feet.

The gold-bearing quartz veins in the Great Falls area were emplaced in shear-zones which parallel this fault. Hence they are probably younger than the lamprophyre dikes, and could be as young as Triassic (Reed and Reed, 1967).

<u>Return to the trail and continue downstream (to the right).</u>

1.08 <u>STOP 2</u> For about 150 yards the trail winds about among ribs and knobs of quartzose mica schist with numerous large pot-holes. This bedrock bench is at about the same elevation as the present river bed above Great Falls, and marks the bed of the river prior to erosion of the present gorge.

This point also provides an excellent view of the straight-sided gorge cut along the normal fault. On the walls of the gorge, horizontal color bands produced by different species of lichen and chemical staining reflect different levels of flooding. Near the tops of the cliffs the rocks are rough, and covered with several species of lichen: Umbilicaria, Parmelia conspersa and Lecanora cinera. Floods reach these levels only rarely, perhaps every 10 to 20 years.

About 20 to 30 feet below the cliff edge is an irregular band of dark olive green moss, Grimmia laevigata. This zone is flooded about once every 2 years.

Below the moss, in a zone extending down to 10 or 20 feet above normal water level, the rocks have a yellowish cast due to yellow and orange lichens, Candelariella vitellina. This zone is flooded several times yearly.

The metallic purplish-black coating on the rocks just above normal water level consists of iron and manganese oxides.

1.21 STOP 3 Climb down to a small sandy beach in a cove on the upstream side of a rock jutting out into the river, several yards below the trail to the right.

On the highest part of the rock promontory are veined sillimanite-mica schists with some sericitized porphyroblasts of kyanite. In the saddle just south of the schist are typical coarse-grained, psammitic metagraywackes of the Wissahickon formation. The psammites appear more quartzose than unmetamorphosed graywackes, due to recrystallization of the fine-grained mud matrix of the original graywacke; but they clearly have the chemical composition of graywacke (Table 2). Several of the thicker beds preserve detrital grains of quartz and feldspar near their base. Many of the beds are graded, as shown by the upward diminution in both grain size and quartz content. Tops face downstream.

Some of the lamination in the psammite are inherited sedimentary structures. But in many places, the lamination cuts bedding and parallels the plane of flattening of crushed detrital grains, indicating that it must be a tectonic structure, probably S_2 (Table 3).

Return to the trail and continue downstream.

1.23 Trail crosses a small valley eroded along a fracture zone which parallels many of the nearby gold-bearing quartz veins. Rocks in the stream bed are heavily stained with iron, probably derived from sulfides precipitated along the fracture zone.

A little-used side trail to the left leads 0.2 miles to the C and O Canal.

Continue across the valley and up the cleft in the rock slabs on the opposite side of the valley; follow trail along bedrock terrace for about $\frac{1}{4}$ mile.

1.47 STOP 4 A prominent granite plug and several small granite dikes intrude amphibolite and metagraywacke.

The metagraywackes are best displayed on a rock bench jutting out into the river, opposite a high cliff on the far bank. East-facing graded beds show that these rocks are stratigraphically above those at stop 3, on the northwest limb of the large syncline on central Bear Island (Fig. 1).

Psammitic beds here are much thinner than those at stop 3, and are interbedded with a higher proportion of pelitic material. Several pelitic beds contain large, sericitized porphyroblasts of a bladed aluminum silicate, probably kyanite. Schistosity (S_2) is dominantly parallel to bedding, but locally parallels the axial planes of small isoclinal folds. Ptygmatically folded quartz veins show that the beds have been greatly thinned during folding.

The amphibolite has the chemical composition of diabase or gabbro (Table 4), and is composed of clusters of hornblende needles in equidimensional clots, surrounded by fine-grained andesine. The hornblende clots pseudomorph original pyroxene crystals, locally containing pigeonite relics (Reed and Jolly, 1963). The light-colored andesine surrounding the hornblende clots is finely granular, but locally the granules form patches of grains with uniform optical orientation, apparently ghosts of primary plagioclase laths. The overall texture of the amphibolite appears to mimic the original texture of the parent rock; the coarseness of this texture suggests that the body was an intrusive sill, not a flow.

The granite plug has a core of coarse-grained pegmatite containing microcline, albite (An_1), quartz, some muscovite, and very minor spessartite; it is surrounded by an aplitic margin containing 5 to 6 percent biotite, oligoclase (An 10-15) and greatly reduced amounts of microcline (Fig. 3a). These differences appear to reflect interaction between the amphibolite and the magma that produced the

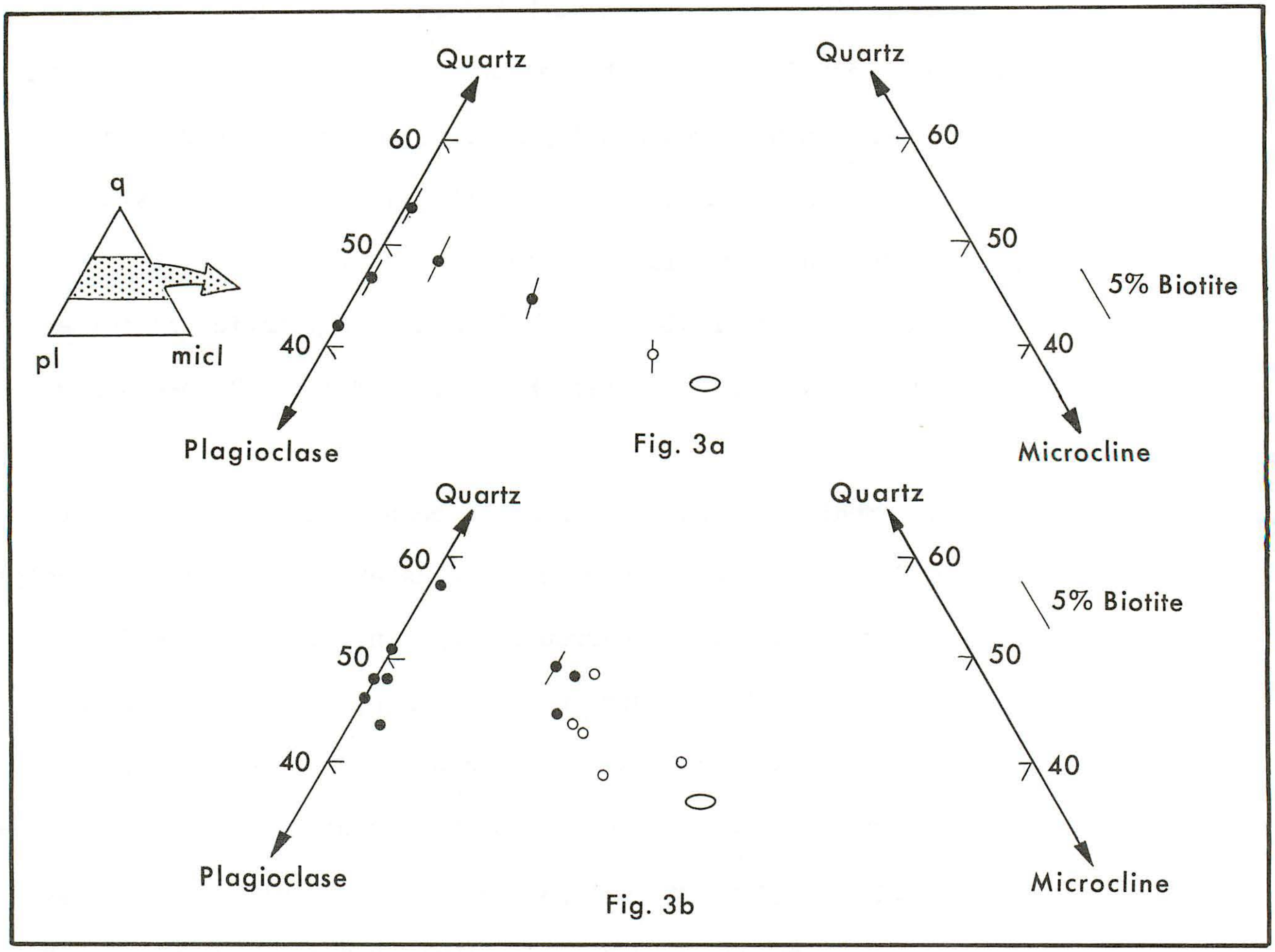


Fig. 3: a, Modal compositions of granitic rocks intruding amphibolites on Bear Island; solid circles represent rocks in the margins of intrusions, open circles the cores of the intrusions, and the oval represents the composition of the granite minimum in the systems $KAlSi_3O_8$ - $NaAlSi_3O_8$ - SiO_2 - H_2O at bars P_{H_2O}, estimated from Tuttle and Bowen (1958) and James and Hamilton (1969). The length of the bar through each point is proportional to the biotite content.

b, Modal compositions of granitic rocks intruding pelitic schists and metagraywackes on Bear Island; symbols are the same as in Fig. 3a.

Table 4

Composition of amphibolite (M55)
from central Bear Island, Md.,
near stop 4.

Chemical Analysis*

SiO_2	47.03
TiO_2	3.10
Al_2O_3	17.03
Fe_2O_3	4.00
FeO	11.23
MgO	3.91
MnO	0.23
CaO	9.10
Na_2O	1.66
K_2O	0.54
H_2O^+	1.74
H_2O^-	0.11
CO_2	0.20
P_2O_5	0.10
ZrO_2	0.02
	100.00

Norm

qz	7.15
or	3.19
ab	14.05
an	37.40
wo	2.59
en	9.76
fs	12.45
mt	5.80
il	5.90
ap	0.16
cal	0.15
	98.90

Modal Analysis

hornblende	55.2
plagioclase	22.5
epidote	10.0
magnetite	6.2
quartz	3.4
biotite	1.7
chlorite	0.5
apatite	0.5
zircon	t
sphene	t
hematite	t
allanite	t
	100.0

points counted 1,800

plagioclase: An

t = present in trace amounts.

* Hopson, 1964, p. 146.

core: FeO and MgO diffused into the magma and reacted with microcline to form biotite; CaO diffused inward, and reacted with albite to form oligoclase. Near the granite, hornblende in the amphibolite is bluish, and partly altered to biotite, suggesting that Na_2O and K_2O may have diffused from the granite into the amphibolite.

Continue along the trail across the amphibolite sill, over a low ridge of metagraywacke, and into the small, sandy valley beyond. In the valley, turn right, and scramble over the rocks for a few yards to the large bench of metagraywacke jutting out into the river.

1.53 STOP 5 Pelitic layers interbedded with metagraywackes in the tilted slab at the northeast corner of this bench are segmented into small brick-like slabs, with psammitic "mortar" squeezed into the cracks between the slabs. These psammitic beds appear to have been more ductile than the pelitic beds, the reverse of the competency relationship usually observed in tectonically deformed rocks. On this basis, Hopson (1964, p. 91) concluded that this deformation must have occurred while the rocks were still soft, prior to complete lithification. The disrupted zone along the right-hand edge of the slab may also be a soft-sediment deformation feature.

An amphibolite sill exposed along the western edge of the bedrock bench has been broken into a number of slabs about 4 feet thick and 15 feet long. The slabs are scattered about in a well-defined zone which can be traced up the cleft in the cliff and inland across the low ridge of metagraywacke. Each contains a strong schistosity and lineation, sharply truncated by psammitic and schistose pelitic rocks, squeezed into the break between slabs. Therefore break-up of the amphibolite must post-date the schistosity and lineation, and must be tectonic.

The metagraywackes here contain numerous biotite-muscovite segregations, surrounded by "bleached" zones virtually free of mica. The ingredients for the biotite and muscovite were clearly derived from the surrounding felsic rind, probably by diffusion of ions through an intergranular pore fluid. Diffusion probably resulted from local activity gradients reflecting differences between the mineral assemblage in the dark core and that in the felsic rind (Fisher, 1970b). The elongation of the segregations parallel to schistosity and small cross-cutting fractures implies that diffusion was more effective in those directions.

<u>Return to the trail and continue downstream over a low ridge of metagraywacke and up a cleft in the prominent hill beyond to an outcrop of folded metagraywacke in a small level area on the northeast flank of the hill. The outcrop has a small blue number 8 painted on it.</u>

1.61 <u>STOP 6</u> This locality is an excellent place to study the relationships between two of the principal fold generations on Bear Island.

The trail crosses the nose of a large, south-plunging F_3 anticline, outlined by an amphibolite sill in the sinuous valley in the woods just to the northeast (Fig. 4). The rocky knob visible through the trees beyond the valley is underlain by metagraywackes stratigraphically beneath the amphibolite. The main schistosity in the amphibolite (S_2) wraps around the nose of the fold, parallel to the contact with the overlying metagraywackes; these relations are well exposed on the overhanging ledge just beneath this outcrop. β axes, produced by intersection of measured attitudes of the contact plunge steeply south, parallel to the hornblende lineation in the amphibolite (Fig. 5). Most of the large folds on Bear Island, including the major syncline outlined by the metagraywackes on central Bear Island (Fig. 1), are F_3 folds.

Many of the minor folds in the metagraywackes along the trail at this point are F_3 folds. S_2 schistosity wraps around fold crests and is cut by incipient S_3 axial plane schistosity. Fold axes plunge steeply south, parallel to the axis of the large fold outlined by the amphibolite (Fig. 5).

A few of the minor folds, however, are F_2 folds; they have S_2 parallel to their axial planes, and axes which plunge eastward down the schistosity, at a high angle to the F_3 fold axes (Fig. 4). An excellent example can be seen by following the trail a few yards down the hill, into the marshy area underlain by amphibolite, then turning left and scrambling up a small cleft in the metagraywackes beneath the amphibolite (Fig. 6). No large-

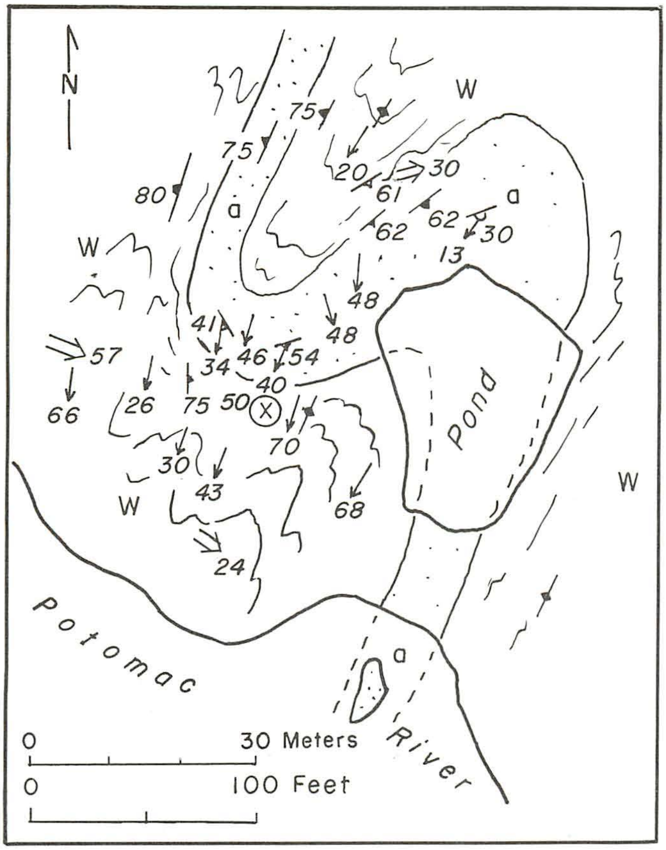


Fig. 4: Amphibolite sill (a) and Wissahickon metagraywacke (w) in F_3 anticline, with minor F_2 folds (double arrows), F_3 folds and lineation in amphibolite (single arrows), S_2 (open symbols) and S_3 (solid symbols). Central Bear Island. X equals Stop 8.

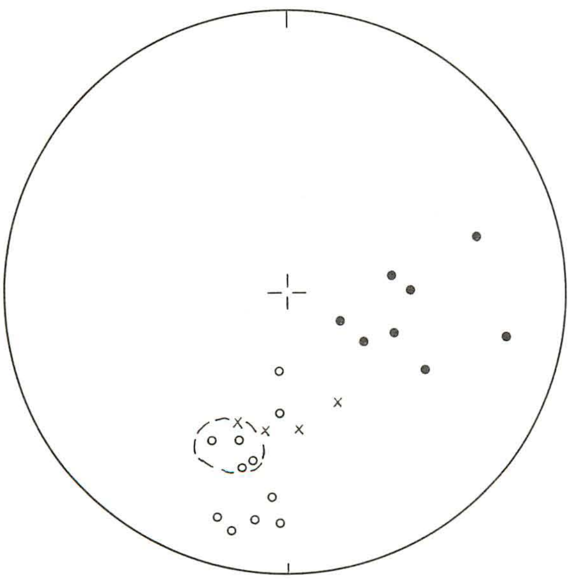


Fig. 5: Stereographic projection of structures in the area of Fig. 4; F_3 axes in metagraywackes (o) parallel hornblende lineations in the amphibolite (x) and β axes for the contact between the amphibolite and the metagraywacke (all intersections enclosed by dashed line). Orientations of F_2 axes (o) are markedly different.

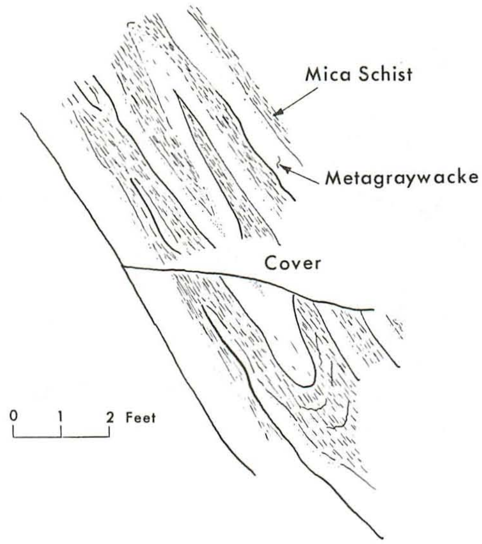


Fig. 6: Isoclinal F_2 fold, seen in a section nearly perpendicular to the fold axis (azimuth 75°, plunge 30° NE). S_2 schistosity parallels the axial plane of the fold, and cuts bedding (S_1) at the crest of the fold. Sketched from photograph. Central Bear Island.

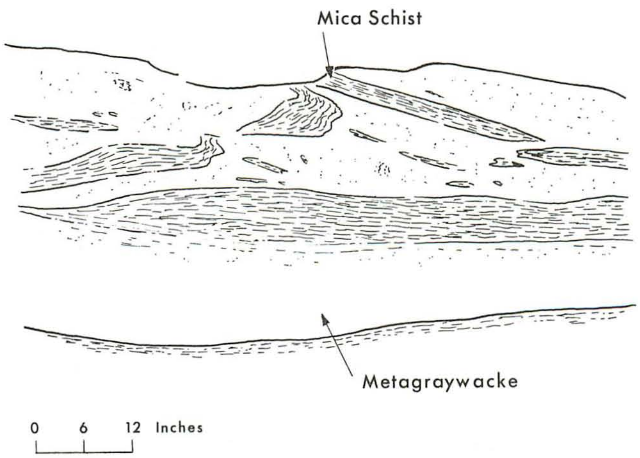


Fig. 7: Disrupted bed at Stop 7, showing slabs of pelitic schist (s) engulfed in a structureless matrix of metagraywacke (m). Sketched from photograph.

scale F_2 folds have yet been found in the rocks along the Potomac, perhaps because they are so strongly assymetrical that they cause no discernable repetition of the stratigraphy.

Development of S_2 parallel to axial planes of the F_2 folds, and in the amphibolite, shows that much of the S_2 schistosity is a tectonic structure, not a mimetic schistosity.

Continue along the blue-blazed trail to plank bridge over a small stream, a few yards below the point where the trail first joins the stream. Unmarked side trail to left leads 0.18 mile to C and O Canal.

1.76 Before crossing the stream, follow an unmarked side trail to the right through the trees diagonally away from the stream. Continue over some rock slabs to an open, rocky area, then follow along the strike of the rocks for about 50 yards to a prominent rocky knob near the Potomac, just downstream from a small amphibolite body.

STOP 7 A bed showing internal disruption by slumping is well exposed on the up-stream side of the knob, about three feet from the contact with the amphibolite (Fig. 7). The bed contains contorted slabs of mica schist scattered about in a soupy, structureless matrix of metagraywacke. This bed can be followed along strike for 40 feet or so; everywhere the bed is wildly disrupted internally, but the beds above and below are undisturbed. The style of the deformation, its restriction to a single bed, and the ductility of the psammitic material relative to the pelitic slabs all suggest that this deformation occurred while the sediments were still soft, prior to complete lithification (Hopson, 1964, p. 91).

Note, however, that the disrupted slabs contain a weak schistosity (S_2) parallel to bedding. If the bedding was folded prior to metamorphism, this schistosity must be mimetic, following the original bedding plane fissility. Although it appears likely that S_2 schistosity in some rocks formed mimetically, while S_2 in other rocks formed tectonically (as at stop 6), the two types are extremely difficult to distinguish in many cases.

Note that the beds here face northwest. This outcrop is near the southeast margin of the large syncline outlined by the metagraywackes on central Bear Island (Fig. 1).

Return across the rocks to the plank bridge over the stream; cross the stream and follow the blue-blazed trail straight ahead over a low rock ledge; do not follow the side trails which parallel the stream. Pass through a small clearing to a low rocky ridge stretching to the right.

1.93 The main trail turns sharply left in a small sandy valley immediately beyond a rocky ridge; turn off the trail and follow the ridge to the right, to a ledge with a view of a prominent rocky peninsula jutting into the river, just downstream from a large amphibolite body. Scramble down onto the peninsula (during periods of high water this outcrop may be inaccessible).

STOP 8 This peninsula provides excellent exposures of the granite dikes and their interaction with both pelitic schists and amphibolites.

The pelitic rocks here are sillimanite-mica schists permeated with quartz-albite veinlets which give the rocks a migmatitic aspect. The felsic veinlets almost certainly did not form by the partial melting of these rocks, because rocks of this composition should produce a melt rich in microcline, and the veinlets contain none. They were probably precipitated from an intergranular pore fluid, but the source of the quartz and albite is not clear. Probably most of the felsic material was locally derived, and the mica-rich layers enclosing the veinlets represent the mafic residuum of this segregation process. But some of the quartz and albite may have been added metasomatically by the nearby granite dikes.

There are two granite dikes on the peninsula: a small, hook-shaped one near the center of the peninsula and a large dike (really a series of en echelon dikes) near the water's edge. The small hook-shaped dike has a core of coarse muscovite-microcline-albite-quartz pegmatite, surrounded by a fine-grained margin of muscovite-albite-quartz aplite.

Most of the large dike near the water's edge is muscovite-albite-quartz aplite similar to the margin of the smaller dike. It contains little or no microcline, and no obvious pegmatitic core.

Muscovite-albite-quartz aplites of this type are restricted to intrusions cutting the pelitic rocks, whereas biotite-oligoclase-quartz aplites of the type found in the plug at stop 4 occur almost exclusively in intrusives cutting amphibolite. Clearly, therefore, the aplites must have formed by interaction between the original muscovite-microcline-albite quartz magma and the local wall rocks (Fig. 3). In the granites cutting pelites, this interaction appears to have involved the breakdown of microcline in the magma to form muscovite with loss of K_2O to the wall rocks, driven by the incompatibility of sillimanite in the wall rocks and microcline in the intrusion.

Where the large dike near the water's edge passes into the amphibolite, it changes from a single dike several feet thick to a mass of intersecting veinlets a few inches thick. Adjacent to the veinlets, hornblende in the amphibolite is extensively altered to biotite, and epidote is widely developed. The veinlets are composed of oligoclase, quartz and rare biotite.

Return along the ridge to the blue-blazed trail, and follow it to the northeast.

Trail continues up a steep hill, down into the valley beyond, and up again; just before descending once again, the trail passes to the right of a low ledge extending diagonally away from the trail.

2.09 STOP 9 On the top of this ledge, the pelitic rocks contain many stubby crystals of andalusite, partially altered to sillimanite, and now largely pseudomorphed by fine aggregates of sericite. Andalusite partially altered to sillimanite is common at this end of the island, while at the north end of the island only bladed crystals of kyanite altered to sillimanite have been found. It appears as if the rocks at this end of the island must have entered the sillimanite field from the andalusite field, while the rocks farther north entered the sillimanite field from the kyanite field. If so, the rocks in the center of the island must have passed close to the triple point in the system Al_2SiO_5, about 5000 bars pressure, and 650°C (Fig. 8). The presence of muscovite and quartz in the sillimanite-bearing rocks reinforces this conclusion, and further requires that the partial pressure of water must have been nearly equal to the total pressure (Fig. 8).

Return to the trail and continue north.

2.19 The trail emerges on the towpath of the C and O Canal at Widewater. Turn left and follow the towpath 1.55 miles to the Visitors Center at Great Falls. MacArthur Boulevard can be reached by following the towpath 0.51 miles to the right.

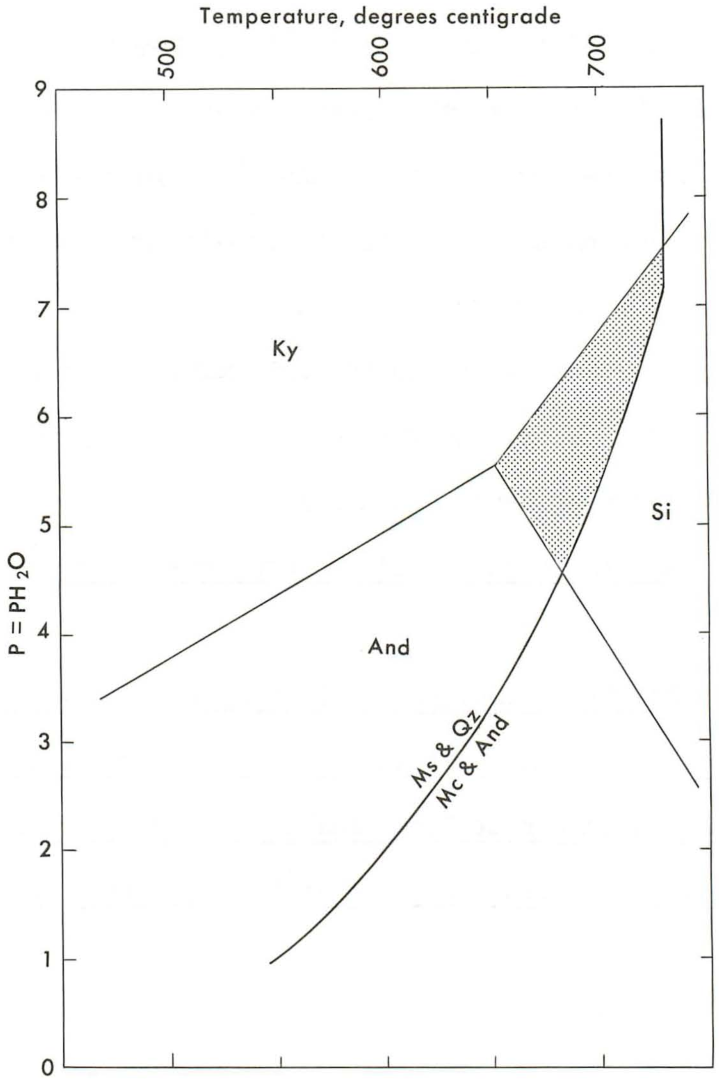


Fig. 8: Conditions near the peak of metamorphism at Bear Island (stippled), inferred from the stability of andalusite (and), kyanite (ky) and sillimanite (si) from Richardson and others (1969); and from the stability of muscovite (ms), quartz (qz), and microcline (mc), from Evans, 1965. (Pressure shown in kilobars.)

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