Geology of the Harpers Ferry Quadrangle, Virginia, Maryland, and West Virginia

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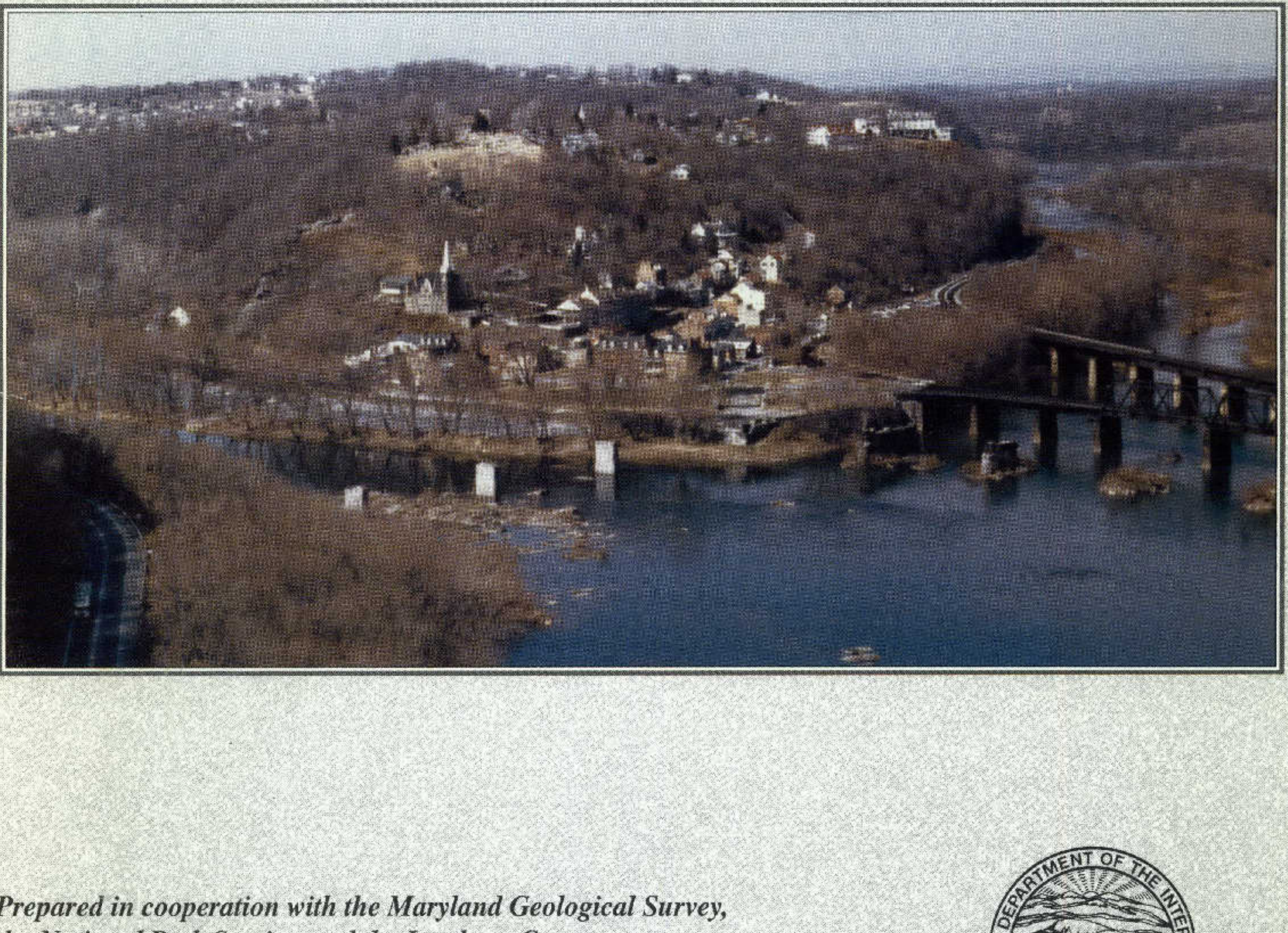

Prepared in cooperation with the Maryland Geological Survey,
the National Park Service, and the Loudoun County
Department of Environmental Resources

U.S. GEOLOGICAL SURVEY BULLETIN 2123

Cover: Looking west at Harpers Ferry, West Virginia, from the Loudoun Heights trail on Blue Ridge in Virginia. Photograph taken March 1989 by Scott Southworth.

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By Scott Southworth and David K. Brezinski

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Structure and stratigraphy of the Middle Proterozoic through Early Cambrian rocks of the complexly deformed Late Paleozoic Blue Ridge-South Mountain anticlinorium

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[Plate is in pocket]

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TABLES

METRIC CONVERSION FACTORS

Multiply	By	To obtain
	Length	
millimeter (mm)	0.0394	inch
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
	Volume	
cubic meter (m^3)	1.30795	cubic yard
	Temperature	
degree Celsius (°C)	1.8 and add 32	degree Fahrenheit (°F)

Geology of the Harpers Ferry Quadrangle, Virginia, Maryland, and West Virginia

By Scott Southworth[1] and David K. Brezinski[2]

ABSTRACT

The Harpers Ferry quadrangle covers a portion of the northeast-plunging Blue Ridge-South Mountain anticlinorium, a west-verging allochthonous fold complex of the late Paleozoic Alleghanian orogeny. The core of the anticlinorium consists of high-grade paragneisses and granitic gneisses that are related to the Grenville orogeny. These rocks are intruded by Late Proterozoic metadiabase and metarhyolite dikes and are unconformably overlain by Late Proterozoic metasedimentary rocks of the Swift Run Formation and metavolcanic rocks of the Catoctin Formation, which accumulated during continental rifting of Laurentia (native North America) that resulted in the opening of the Iapetus Ocean. Lower Cambrian metasedimentary rocks of the Loudoun, Weverton, Harpers, and Antietam Formations and carbonate rocks of the Tomstown Formation were deposited in the rift-to-drift transition as the early Paleozoic passive continental margin evolved.

The Short Hill fault is an early Paleozoic normal fault that was contractionally reactivated as a thrust fault and folded in the late Paleozoic. The Keedysville detachment is a folded thrust fault at the contact of the Antietam and Tomstown Formations. Late Paleozoic shear zones and thrust faults are common.

These rocks were deformed and metamorphosed to greenschist-facies during the formation of the anticlinorium. The Alleghanian deformation was accompanied by a main fold phase and a regional penetrative axial plane cleavage, which was followed by a minor fold phase with crenulation cleavage. Early Jurassic diabase dikes transected the anticlinorium during Mesozoic continental rifting that resulted in the opening of the Atlantic Ocean. Cenozoic deposits that overlie the bedrock include bedrock landslides, terraces, colluvium, and alluvium.

INTRODUCTION AND GEOLOGIC SETTING

The geology of the Harpers Ferry quadrangle was mapped in 1989 and 1990 under a cooperative agreement between the U.S. Geological Survey (USGS) and the Maryland Geological Survey. In Virginia, the mapping was part of a cooperative agreement between the USGS and the Loudoun County Department of Environmental Resources (Southworth, 1991a; Burton and others, 1992b; Southworth and others, in press).

The area is underlain by rocks of the northeast-plunging Blue Ridge-South Mountain anticlinorium, a late Paleozoic (Mississippian?) Alleghanian structure (fig. 1). Middle Proterozoic paragneisses and granitoids intruded by Late Proterozoic metadiabase and metarhyolite dikes and Jurassic diabase dikes underlie broad valleys in the areas and form the core of the anticlinorium. Late Proterozoic metasedimentary and metavolcanic rocks and Lower Cambrian metasedimentary rocks underlie the high ground of Blue Ridge-Elk Ridge and Short Hill-South Mountain where topographic relief ranges from 100 to 450 m (300 to 1,476 ft). The Short Hill fault transects the quadrangle and causes a repetition of the west limb of the anticlinorium. Alluvium is found along the Potomac and Shenandoah Rivers and all tributaries. Colluvium is abundant on the flanks of Blue Ridge-Elk Ridge and Short Hill-South Mountain.

The map area (pl. 1) includes the Harpers Ferry National Historical Park, and this report commemorates its 50th anniversary. A segment of the Appalachian Trail and the Chesapeake and Ohio Canal National Historical Park are also included on plate 1. Abundant trails on the mountains and along the Shenandoah and Potomac Rivers provide access to excellent exposures of bedrock.

Rocks of Late Proterozoic and Early Cambrian age in this quadrangle are heterogeneous, and some units pinch and swell abruptly. Postdepositional erosion (Jonas and Stose, 1939; Stose and Stose, 1949) and deposition on a paleotopographic surface (Nickelsen, 1956) have formed unconformities. Unconformities occurring in rocks of Late Proterozoic and Early Cambrian age reflect changes from the Iapetan rift to a passive continental margin (drift).

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[1] U.S. Geological Survey.

[2] Maryland Geological Survey.

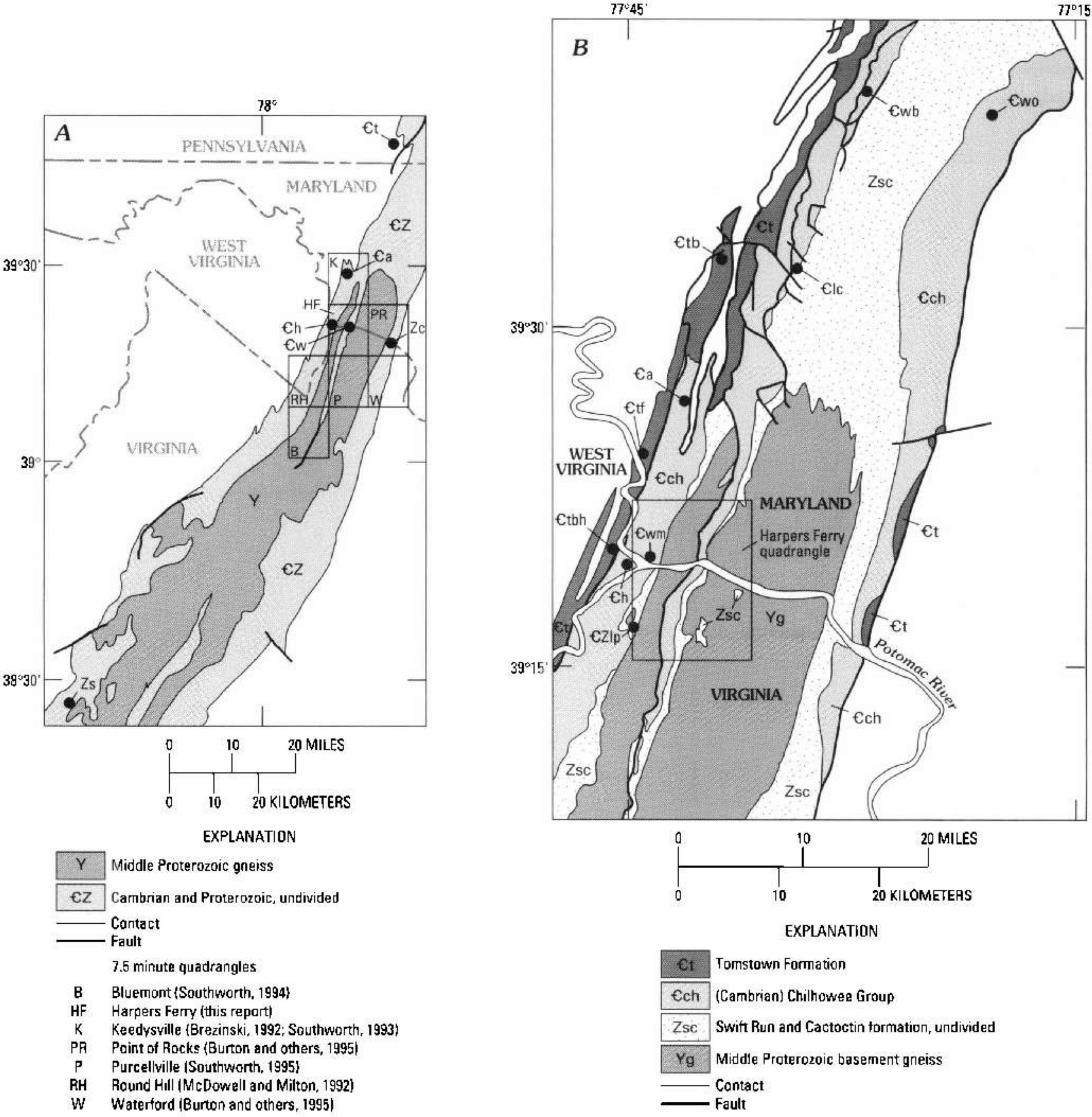


Figure 1. *A*, The location of the Harpers Ferry quadrangle and adjacent quadrangles within the Blue Ridge-South Mountain anticlinorium (patterned areas). Type localities (solid dots) of the Late Proterozoic and Lower Cambrian rocks are shown. *B*, Type localities (solid dots) of the members of the Weverton and Tomstown Formations (Brezinski, 1992). Symbols for type localities in *A* and *B* are €tb, Benevola Member; €tf, Fort Duncan Member; €tbh, Bolivar Heights Member; €a, Antietam Formation; €h, Harpers Formation; €w, Weverton Formation; €wo, Owens Creek Member; €wm, Maryland Heights Member; €wb, Buzzards Knob Member; €lc, Loudoun Formation, conglomerate; €Zlp, Loudoun Formation, phyllite; Zc, Catoctin Formation; Zs, Swift Run Formation.

Fluvial clastic sediments of the Late Proterozoic Swift Run Formation lie unconformably on Middle Proterozoic gneiss and mark the beginning of rifting of Laurentia, which formed the Iapetus Ocean (Rankin, 1976). Metadiabase and metarhyolite dikes and extrusive metabasalt of the overlying Catoctin Formation were emplaced during the main phase of continental rifting. Conglomerate of the Late Proterozoic and Lower Cambrian Loudoun Formation and conglomeratic quartzite of the Lower Cambrian Weverton Formation were deposited in the rift-to-drift transition. Tabular crossbedded quartzite of the Owens Creek Member (upper part) of the Weverton Formation comprises shoreface deposits of initial drift facies (Simpson and Eriksson, 1989). The drift regime was fully established during deposition of clastic rocks of the Lower Cambrian Harpers and Antietam Formations. Rocks of the Lower Cambrian Tomstown Formation were the first carbonate rocks deposited during initial phases of the evolving passive continental margin.

The area was first mapped by Keith (1894) at a scale of 1:125,000, and this map (pl. 1, scale 1:24,000) commemorates the centennial anniversary of his Harpers Ferry folio. Subsequent mapping was by Jonas and Stose (1939) and Cloos (1941) at a scale of 1:62,500, Nickelsen (1956) at a scale of 1:25,000, and Dean and others (1990) and Howard (1991) at a scale of 1:24,000.

Keith (1894) established the basic stratigraphic nomenclature for the stratified cover rocks that overlie the basement rocks, and the type localities of his Catoctin Schist, Weverton Sandstone, and Harpers Shale are within the map area (fig. 1*A*). Jonas and Stose (1939) and Stose and Stose (1946) subdivided Keith's (1894) Loudoun Formation into the Swift Run Tuff, Catoctin Metabasalt, and Loudoun Formation. The formational names of the Swift Run and Catoctin were revised by King (1950) and Bloomer and Bloomer (1947), respectively. Nickelsen (1956) considered the Swift Run and Catoctin Formations to be of Precambrian age; his Loudoun Formation, Weverton Quartzite, Harpers Formation, and Antietam Quartzite constituted the Chilhowee Group of Early Cambrian age. Recently, Brezinski (1992) described and named a tripartite subdivision for the Weverton Formation and subdivided the Tomstown Formation (Stose, 1906) into four members, (fig. 1*B*).

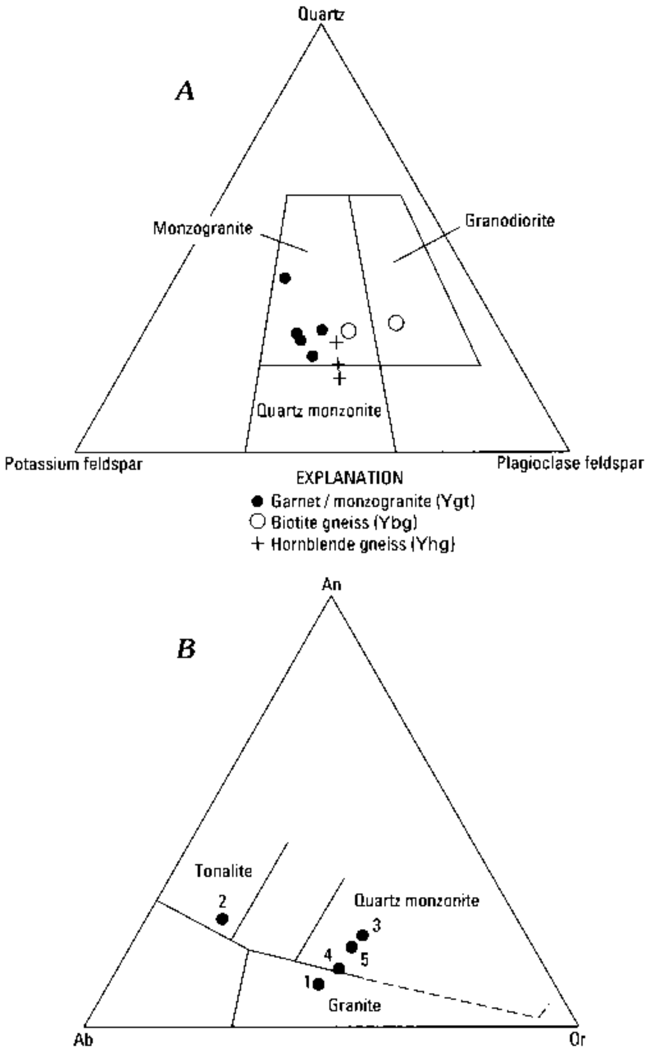


Figure 2. *A*, Quartz-alkali feldspar-plagioclase feldspar diagram (modified from Streckeisen, 1976) showing modal compositions of Middle Proterozoic rocks shown in table 1. Modes counted on Na-cobaltinitrate-stained rock slabs and thin sections. *B*, Normative feldspar plot (O'Connor, 1965) of Middle Proterozoic rocks in the Harpers Ferry quadrangle (numbers refer to samples in table 1).

MIDDLE PROTEROZOIC ROCKS

The oldest rocks in the quadrangle are paragneiss and intrusive granitoids. Four distinctive units were mapped: garnet graphite gneiss (paragneiss), hornblende gneiss, garnet monzogranite, and biotite gneiss. The intrusive granitoids (fig. 2, tables 1 and 2) have U/Pb ages that range from 1110 Ma to 1055±5 Ma (Aleinikoff and others, 1993) (fig. 3). Primary textures and minerals have been substantially altered by Paleozoic deformation and retrograde metamorphism.

GARNET GRAPHITE GNEISS

Garnet graphite gneiss (Yp) occurs as small bodies within the garnet monzogranite (Ygt) and biotite gneiss (Ybg) and is interpreted to be metasedimentary rock that predates the intrusive granitoids (Burton and Southworth, 1993). The rock is characterized by almandine and (or) clots of chlorite (retrograde after garnet), and specular flecks and books of graphite. The rock weathers to a distinctive dusky-

Table 1. Chemical analyses of rocks from the Harpers Ferry quadrangle, Virginia, Maryland, and West Virginia.

[Numbers 1–31 refer to chemical sample locations shown on plate 1. All analyses were done in the laboratories of the U.S. Geological Survey. Major elements determined by X-ray spectroscopy by D.F. Siems and J.E. Taggart. Minor and rare earth elements determined by instrumental neutron activation analysis by G.A. Wandless and J. Grossman. See Southworth 1991a for field and lab numbers of samples]

	Middle Proterozoic basement rocks					Late Proterozoic metadiabase dikes (Zmd)										Late Proterozoic metarhyolite dike (Zrd)
	Garnet monzogranite (Ygt)			Biotite gneiss (Ybg)	Hornblende gneiss (Yhg)											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	70.8	69.8	66.8	71.7	63.7	48.8	50.5	47.6	50.1	48.4	50.5	49.3	45.8	49.5	44.6	72.7
Al_2O_3	15.1	15.2	14.7	13.9	15.4	13.3	12.6	13.7	13.5	13.5	13.1	13.7	12.6	13.3	16.9	13.4
Fe_2O_3	.61	2.12	1.16	.96	4.39	3.44	4.86	3.76	2.6	2.86	3.23	3.77	3.84	14.9	6.1	1.18
FeO	1.8	1.1	3.1	1.4	0.95	9.6	9.4	9.4	10.0	10.4	9.7	8.3	11.5	—	5.0	1.3
MgO	.63	.39	1.0	.71	3.1	5.83	4.36	6.29	6.14	6.38	4.16	6.18	5.67	.96	4.96	.38
CaO	1.35	3.32	3.06	1.79	3.72	9.59	8.73	9.54	8.80	9.54	9.39	9.58	9.56	9.48	18.4	<.02
Na_2O	3.56	4.40	2.45	3.00	2.78	2.44	2.24	3.13	2.39	2.99	1.74	3.47	2.63	.83	.84	.75
K_2O	4.45	1.60	4.98	4.61	4.94	1.42	.83	.44	.45	.64	.49	.39	1.30	.38	.14	7.35
H_2O+	.60	.55	.84	.63	1.2	2.3	2.6	2.5	2.8	2.5	2.9	2.1	1.9	—	1.1	1.4
H_2O-	.07	.18	.11	.16	.03	.20	.35	.29	.24	.14	.10	.25	.13	—	.19	30
TiO_2	.26	.30	.73	.35	.93	2.47	2.80	2.29	2.30	2.23	2.74	1.92	3.99	.85	1.20	.36
P_2O_5	.10	.06	.19	.16	.28	.30	.35	.26	.28	.23	.52	.30	.53	.54	.17	06
MnO	.04	.05	.05	.03	.06	.20	.22	.19	.21	.22	.20	.20	.24	.20	.16	<.02
CO_2	<.01	<.01	.03	.01	.75	<.01	<.01	<.01	.07	<.01	.70	<.01	<.01	—	<.01	<.01
Total	99.38	99.08	99.2	99.41	99.09	99.9	99.85	99.4	99.88	100.04	99.47	99.47	99.7	96.94	99.7	99.23

red (5*R* 3/4, Goddard and others, 1948) soil that contains abundant graphite. The garnet graphite gneiss within the garnet monzogranite can be seen along Dutchman Creek. Fresh garnet graphite gneiss crops out within biotite gneiss near the Potomac River along Virginia State Route 287 (pl. 1, ref. loc. 1). Garnet graphite gneiss is also found to the east in the Waterford and Point of Rocks quadrangles (Burton and others, 1995), to the north in the Keedysville quadrangle (Southworth, 1993), and to the south in the Purcellville (Southworth, 1995) and Bluemont (Southworth, 1994) quadrangles. Garnet graphite gneiss in the southeastern corner of the map area mantles a large body of norite that is traced into the Purcellville (Southworth, 1995) and Waterford (Burton and others, 1995) quadrangles. Garnet graphite gneiss is lithologically similar to the Border Gneiss of Sinha and Bartholomew (1984) and the layered granulite gneiss in central Virginia that contains detrital zircons dated by $^{207}Pb/^{206}Pb$ method at 1800 Ma (Herz and Force, 1984).

HORNBLENDE GNEISS

Hornblende gneiss (Yhg) is a massive, fine- to medium-grained melanocratic rock with 10 to 20 percent hornblende crystals that define a moderate to strong gneissic foliation. Hornblende gneiss has the composition of quartz monzonite (fig. 2) and contains crystals of hornblende, hypersthene(?), biotite, quartz, microcline, and plagioclase. Minor amounts of diorite and granite phases are seen locally. This dense rock is poorly exposed and underlies the southern half of Loudoun Valley and part of Pleasant Valley. The rock is retrograded to a distinctive "pink-green" potassium feldspar and chlorite gneiss where it occurs in a recumbent fold along with the cover rocks in the Purcell Knob structure (pl. 1, ref. loc. 2). Hornblende gneiss has been traced northward into the Keedysville quadrangle (Southworth, 1993) and southward into the Purcellville (Southworth, 1995) and Round Hill quadrangles (McDowell and Milton, 1992; Burton and others, 1992a), where it is restricted to the footwall block of the Short Hill fault. The massive hornblende gneiss that underlies the Purcell Knob synformal anticline has a preliminary U/Pb age of 1110 Ma (Aleinikoff and others, 1993) (chemical sample 5, table 1, and isotopic sample 6, fig. 3). The unit is lithologically similar to rocks of the Pedlar Formation (Gathright, 1976; Lukert and Nuckols, 1976) and the pyroxene granulite (Evans, 1991) in central Virginia.

GARNET MONZOGRANITE

Garnet monzogranite (Ygt) is a massive, leucocratic rock with as much as 5 percent almandine crystals that give the rock a distinctive spotted appearance (fig. 4). Garnet monzogranite, which is well exposed along the southern

Table 1. Chemical analyses of rocks from the Harpers Ferry quadrangle, Virginia, Maryland, and West Virginia—Continued.

	Late Proterozoic Catoctin Formation metabasalt (Zcm)					Early Jurassic diabase dikes (Jd)									
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
SiO_2........	47.9	49.7	47.0	46.2	50.8	50.2	50.4	50.4	50.6	56.0	53.3	48.1	47.6	47.4	47.4
Al_2O_3.....	18.3	14.3	14.4	16.0	15.1	15.3	15.2	15.2	15.2	15.2	17.0	15.6	14.6	14.6	14.8
Fe_2O_3.....	10.42	9.13	4.52	8.09	9.42	2.45	11.2	11.2	11.3	7.49	11.7	11.2	11.4	11.6	1.98
FeO.........	4.4	5.2	7.1	6.5	4.4	7.7	—	—	—	—	—	—	—	—	8.3
MgO.......	5.97	4.37	12.4	5.34	5.36	8.32	8.23	8.06	8.06	4.69	5.76	10.9	13.3	13.1	12.8
CaO........	.87	3.92	2.28	6.25	6.64	11.5	11.8	11.9	11.8	5.16	1.95	12.0	11.3	11.3	11.5
Na_2O......	5.99	1.92	2.60	4.02	1.22	1.86	1.87	1.96	1.98	3.63	5.09	1.60	1.46	1.48	1.46
K_2O........	1.04	2.62	.04	<.02	<.02	.72	.26	.25	.31	4.16	.13	.32	.31	.28	.29
H_2O+......	3.2	3.5	5.9	3.5	3.4	.92	—	—	—	—	—	—	—	—	.95
H_2O-.....	.21	.12	.31	.12	.25	.48	—	—	—	—	—	—	—	—	.35
TiO_2........	.97	3.10	2.23	3.17	2.53	.68	.68	.70	.72	.72	1.10	.29	.27	.27	.27
P_2O_5.......	.09	.40	.25	.60	.28	.10	.08	.08	.09	.28	.23	.07	.06	.07	.06
MnO.......	.28	.21	.34	.22	.20	.18	.18	.18	.18	.10	.15	.17	.18	.17	.17
CO_2........	<.01	1.2	.19	<.01	<.01	.02	—	—	—	—	—	—	—	—	.21
Total.....	99.65	99.69	99.56	100.04	99.63	100.43	99.9	99.93	100.24	97.42	96.41	100.25	100.48	100.27	100.54

Table 2. CIPW norms of Middle Proterozoic basement rocks in table 1.

[Numbers 1–5 refer to chemical sample locations shown on plate 1]

Mineral	Garnet monzogranite (Ygt)			Biotite gneiss (Ybg)	Hornblende gneiss (Yhg)
	1	2	3	4	5
Quartz	28.8	31.1	24.8	32.1	20.5
Orthoclase	26.6	9.62	30.0	27.6	29.8
Albite	30.5	37.9	21.1	25.7	24.0
Anorthite	6.06	16.3	14.0	7.88	12.1
Corundum	2.26	.367	.245	1.14	1.15
Hypersthene	4.09	.988	6.23	3.08	6.74
Magnetite	.866	2.89	1.70	1.39	1.40
Ilmenite	.500	.579	1.41	.674	1.81
Apatite	.240	.145	.458	.384	.678

bluff of Potomac River, contains xenoliths of garnet graphite gneiss. Garnet monzogranite has been traced northward into the Keedysville quadrangle (Southworth, 1993) and southward into the Purcellville quadrangle (Southworth, 1995). In the Bluemont quadrangle (Southworth, 1994), dikes and sills of the garnet monzogranite intrude a porphyroblastic granite. Garnet monzogranite at Potomac Wayside (pl. 1) has a U/Pb age of 1070 Ma (Aleinikoff and others, 1993) (chemical sample 1, isotopic sample 5, fig. 3). The rock locally has a greasy green lustre due to chloritized almandine. The unit has the modal composition of a monzogranite, but its normative composition ranges from granite to quartz monzonite (fig. 2); a tonalite dike (chemical sample 2) cuts the unit at the west end of Potomac Wayside. The garnet monzogranite is lithologically similar to the Old Rag Granite as mapped 50 km to the south by Lukert and Nuckols (1976).

BIOTITE GNEISS

Biotite gneiss (Ybg) has granite, granodiorite, and quartz monzonite phases (fig. 2) and is well exposed along the Potomac River. Biotite gneiss is thrust faulted on garnet monzogranite along the 1-km-wide Dutchman Creek shear zone. Biotite gneiss varies from potassium feldspar augen gneiss along the east boundary of the quadrangle to mylonite in the shear zone. The biotite gneiss has a strong, flat-lying gneissic foliation and contains xenoliths of massive garnet graphite gneiss along Virginia State Route 287 (pl. 1). The biotite gneiss has been traced eastward into the Waterford quadrangle (Burton and others, 1995) where it has a U/Pb age of 1055±5 Ma (Aleinikoff and others, 1993) (fig. 3). The biotite gneiss resembles the biotite granite gneiss mapped north of the Potomac River by Stose and Stose (1946) and is lithologically similar to the Lovingston Granite Gneiss of central Virginia.

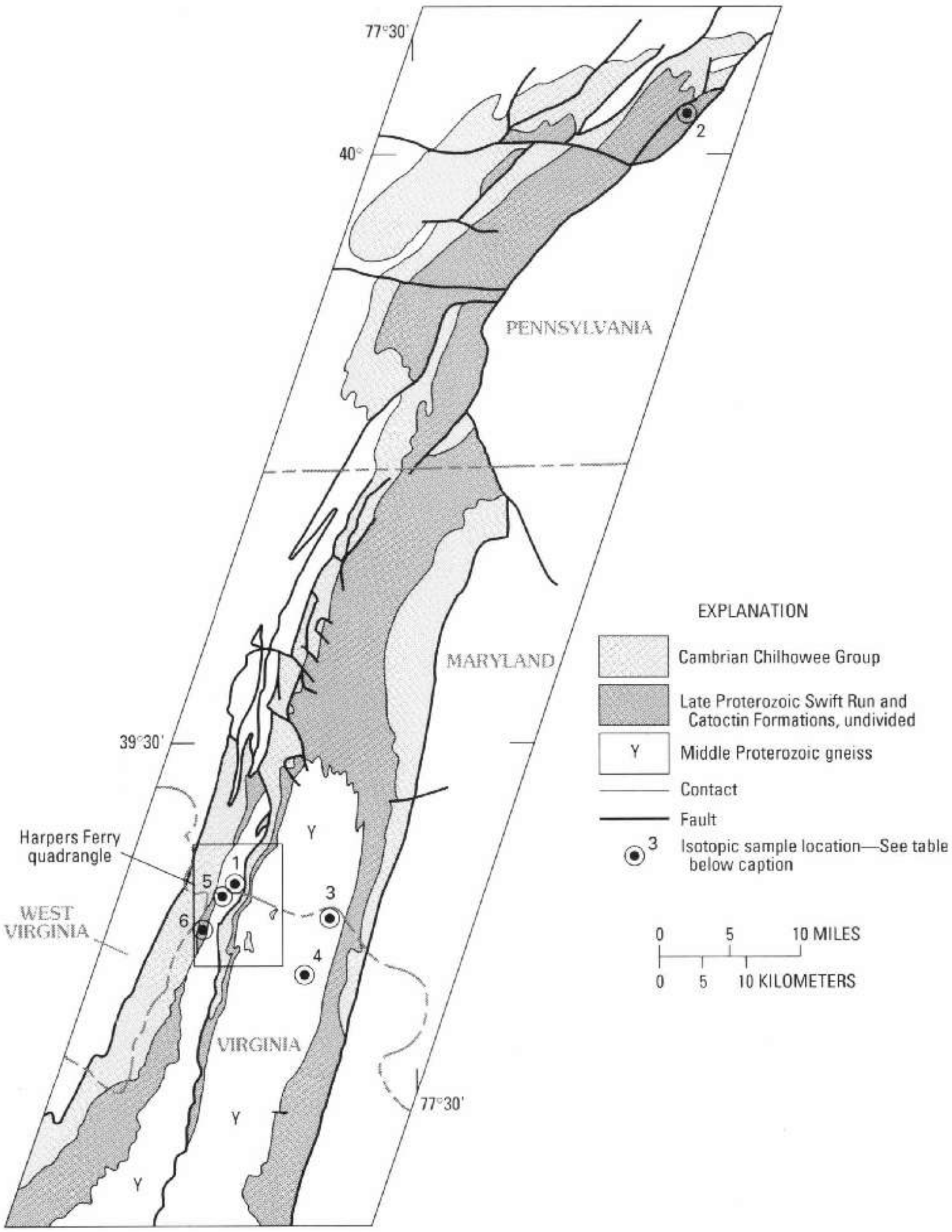


Figure 3. The locations of isotopically (radiometrically) dated rock units discussed in text.

Sample number	Rock unit	Age (Ma)	Age-dating technique	Reference
1	Jd	200	$^{40}Ar/^{39}Ar$	Kunk and others (1992).
2	Zcr	564 ± 9	U/Pb	Aleinikoff and others (1995).
3	Zrd	571.5 ± 4.7	U/Pb	Aleinikoff and others (1995).
4	Ybg	1055 ± 5	U/Pb	Aleinikoff and others (1993).
5	Ygt	1070	U/Pb	Aleinikoff and others (1993).
6	Yhg	1110	U/Pb	Aleinikoff and others (1993).

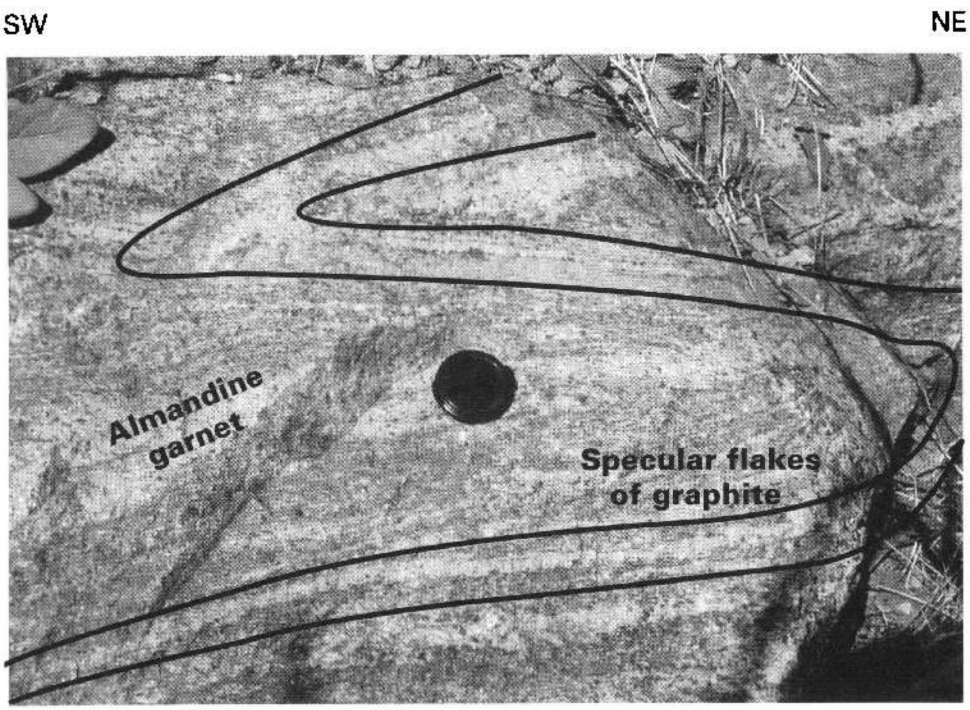


Figure 4. Garnet monzogranite (Ygt, 1070 Ma) showing gneissic foliation defining Grenvillian folds. Outcrop is along U.S. Route 340, northeast of Sandy Hook, Md., near the garnet graphite gneiss (Yp) (pl. 1). Specular flakes of graphite in this plutonic rock suggest that it assimilated the paragneiss. Lens cover is 5 cm in diameter.

LATE PROTEROZOIC ROCKS

SWIFT RUN FORMATION

Within the Swift Run Formation, sericitic quartzite and metasandstone (Zsq), quartz sericite schist (Zss), sericitic phyllite (Zsp), and marble (Zsm) are differentiated. Sericitic quartzite and metasandstone occur at the base of the formation. The unconformable basement contact is not exposed. Locally, paleoregolith of weathered basement rock occurs and can be seen north of Purcell Knob (pl. 1, ref. loc. 3). The paleoregolith retains the mineralogy of the parent gneiss, but grains are rounded, and clasts of phyllite are common. Outcrops of sericitic quartzite and metasandstone are as much as 10 m thick and contain cobbles and pebbles of vein quartz, siltstone, and iron-rich sandstone (fig. 5). These rocks are best seen from north of Purcell Knob (pl. 1, ref. loc. 4) to Loudoun Heights and along Maryland State Route 17.

Quartz sericite schist grades laterally into the sericitic metasandstone and often has a protomylonitic texture. The unit is best seen in the area of the Dutchman Creek and Mt. Olivet synclines (pl. 1, ref. loc. 5), where it is distinctively different in color and texture from outcrops at the base of Short Hill Mountain.

Sericitic phyllite interbedded with thin arkose and sandstone is above the sericitic quartzite at the Purcell Knob antiformal syncline (pl. 1, ref. loc. 6). Stratigraphic relations here are obscured by polyphase deformation.

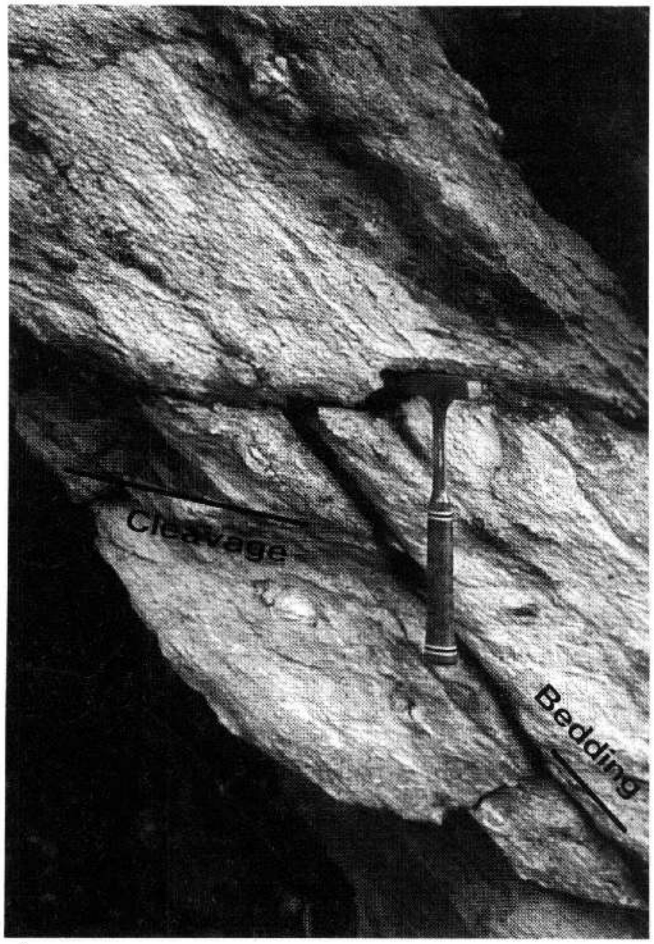
A lens of dolomitic marble less than 2 m thick marks the top of the Swift Run Formation at the Potomac River east of Short Hill Mountain. Volcaniclastic phyllite and metabasalt of the Catoctin Formation overlie the marble. Dolomitic marble is between the sericitic metasandstone and phyllite units on the limbs of the Purcell Knob antiformal syncline. The marble is found as tectonic boudin as much as 3 m thick and locally is mixed with the metasandstone. The marble is discontinuous and is interpreted to have been deposited in freshwater lakes (McDowell and Milton, 1992) rather than during a marine transgression as envisioned by Parker (1968).

The age of the Swift Run Formation is poorly constrained. It rests unconformably on the 1055±5 Ma biotite gneiss, and it underlies the Catoctin Formation. Metarhyolite of the Catoctin Formation has a U/Pb age of 564±9 Ma (Aleinikoff and others, 1995) (fig. 3).

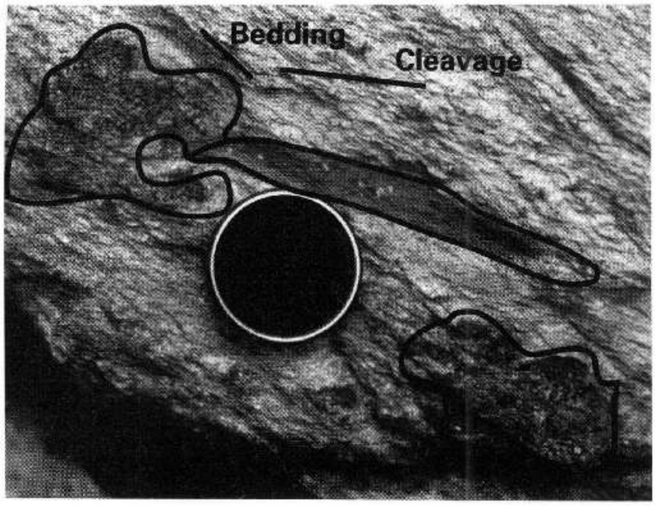
METADIABASE DIKES

Metadiabase dikes (Zmd) intrude the basement gneisses, and some also cut the Swift Run Formation. Because metadiabase dikes make up 50 percent of the basement core along the Potomac River (pl. 1, ref. loc. 7) Keith (1894) and Cloos (1951) incorrectly deduced that the granite intruded the metabasalt. The dike swarm was generated during rifting that led to continental breakup and opening of the Iapetus Ocean (Rankin, 1976). The distribution and density of dikes in this quadrangle indicate a highly extended continental crust.

The metadiabase dikes have long been interpreted as feeder dikes for the extrusive metabasalt of the Catoctin



A



B

Figure 5. Outcrop is on the east limb of the Purcell Knob fold (pl. 1). *A*, Sericitic quartzite of the Swift Run Formation (Zsq) showing beds, interpreted to be overturned, and cut by cleavage. Rock hammer is 28 cm long. *B*, Cobbles and pebbles of siltstone and iron-rich sandstone in the sericitic quartzite. Lens cover is 5 cm in diameter.

Formation (Stose and Stose, 1946), and similarities in chemical composition (table 1, figs. 6–8) support this concept. The metadiabase ranges from aphanitic (chemical sample 14, table 1) to porphyritic (chemical sample 15, table 1) in texture, which may result from both primary cooling history and Paleozoic deformation. Everywhere their strike and dip are parallel to the Paleozoic cleavage within them and to their contacts with the basement gneiss.

METARHYOLITE DIKES

A metarhyolite dike (Zrd) as much as 50 m wide and more than 14 km long intrudes the garnet monzogranite (Ygt) as well as the quartz sericite schist (Zss) of the Swift Run Formation east of Short Hill Mountain (pl. 1). This dike (chemical sample 16) can be traced south from the Potomac River into the Purcellville quadrangle (Southworth, 1995). Small metarhyolite dikes occur east of Potomac Wayside and in the extreme southeast corner of the map. The metarhyolite dikes are interpreted to be feeder dikes to rhyolite flows in the Catoctin Formation, and U/Pb data support this (Aleinikoff and others, 1995) (fig. 3). A metarhyolite dike (Zrd) to the east in the Point of Rocks quadrangle (Burton and others, 1995) has a U/Pb zircon age of 571.5±4.7 Ma (Aleinikoff and others, 1995) (fig. 3).

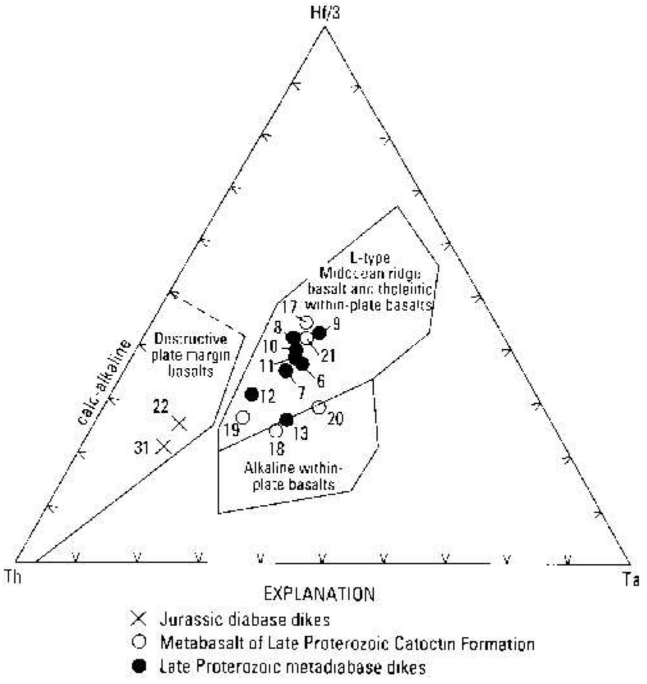


Figure 6. Hf/3-Th-Ta ternary diagram (after Wood, 1980) for tectonic setting of Late Proterozoic metadiabase dikes, extrusive metabasalt, and Jurassic diabase dikes. Numbers refer to table 1.

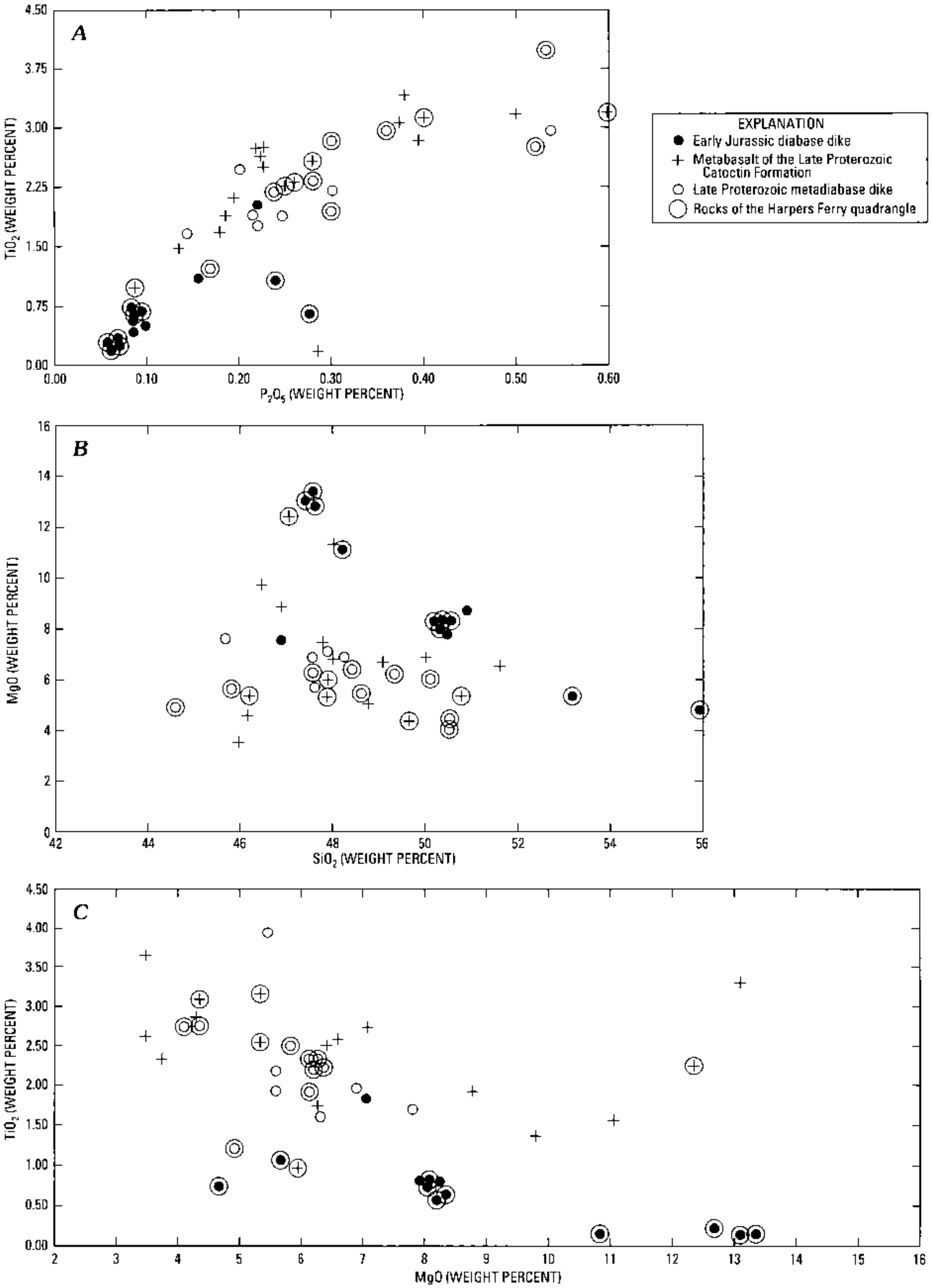


Figure 7. Variation diagrams for Late Proterozoic metadiabase dikes, metabasalt of the Late Proterozoic Catoctin Formation, and Early Jurassic diabase dikes. Circled symbols represent data on rocks of the Harpers Ferry quadrangle; other data are for rocks from other quadrangles. Data from table 1 and Southworth (1994; 1995). *A*, TiO_2 versus P_2O_5; *B*, MgO versus SiO_2; and *C*, TiO_2 versus MgO.

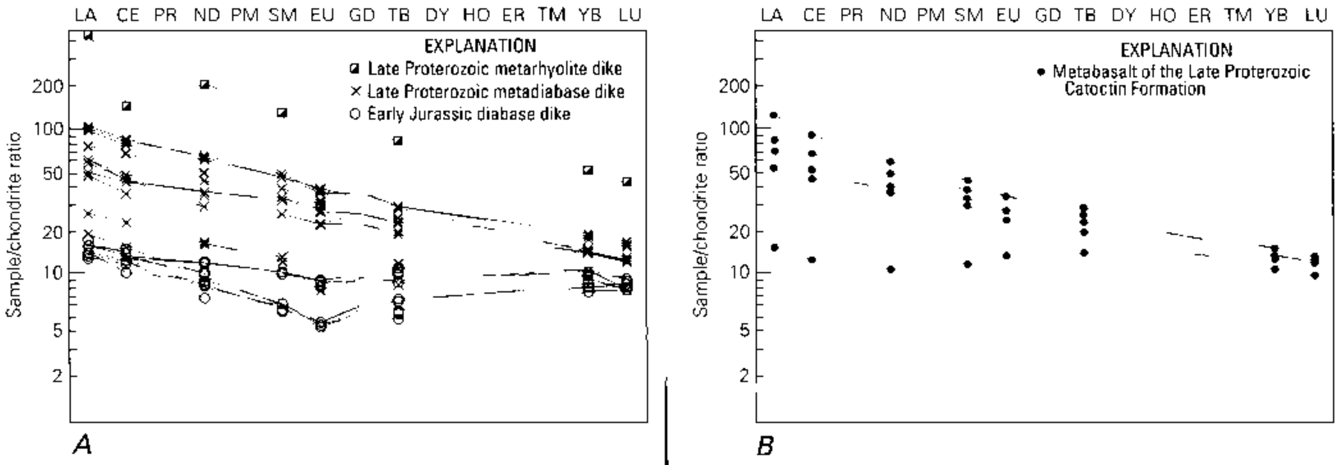


Figure 8. Chondrite-normalized, rare earth element (REE) plots of (*A*) Late Proterozoic metadiabase (10 samples) and metarhyolite (1 sample) dikes and Early Jurassic diabase dikes (10 samples) and (*B*) metabasalt (5 samples) of the Late Proterozoic Catoctin Formation. Table 1 shows major-oxide compositions of these samples.

CATOCTIN FORMATION

Tuffaceous metasedimentary rocks (Zct) and metabasalt (Zcm) constitute the Catoctin Formation. Tuffaceous metasedimentary rocks include phyllite, schist, mud-lump (rip-up) breccia (Reed, 1955), and thin-bedded metabasalt. Metabasalt includes massive to schistose metabasalt (greenstone) and agglomeratic metabasalt breccia that contains epidosite. The metabasalt unit is locally interlayered with metasedimentary rocks that were incorporated during deposition (Reed, 1955). Metabasalt of the Catoctin Formation in central Virginia has a Rb-Sr whole-rock and pyroxene age of 570±36 Ma (Badger and Sinha, 1988).

The Catoctin Formation is best exposed along the Potomac River at Short Hill Mountain. There, the lowermost part consists of tuffaceous phyllite and thin-bedded metabasalt that overlie marble (Zsm) of the Swift Run Formation. A 50-m section of the metabasalt consists of four belts of massive to schistose metabasalt, each ranging in thickness from 6 to 21 m. The metabasalt contains epidosite bodies, as much as 1 m in diameter, which are bounded on either side by mud-lump breccia and tuffaceous phyllite (fig. 9*A*) (pl. 1, ref. loc. 8). The belts of metabasalt are interpreted as flows (chemical samples 19 and 20, table 1). They form prominent ledges in the Potomac River but are absent north of the river for at least 2.5 km.

As much as 61 m of amygdaloidal, massive, aphanitic to schistose, metabasalt showing flow structures and columnar joints is exposed on Blue Ridge along the Loudoun Heights trail (chemical sample 18, table 1). Light-gray tuffaceous metarhyolite is interbedded with the metabasalt (fig. 9*B*). Tuffaceous metasedimentary rocks increase in abundance upward and are transitional with the phyllite of the Loudoun Formation (ꞒZlp) (pl. 1, ref. loc. 9).

PALEOZOIC ROCKS

CHILHOWEE GROUP

The Chilhowee Group consists of the Loudoun, Weverton, Harpers, and Antietam Formations. The stratigraphic relation between the Chilhowee Group and the underlying Late Proterozoic Catoctin Formation has been interpreted as either transitional (Nickelsen, 1956) or unconformable (King, 1950; Reed, 1955; Edmundson and Nunan, 1973; Gathright and Nystrom, 1974). Rounded clasts of red jasper and metabasalt (King, 1950; Reed, 1955; and Rader and Biggs, 1975) indicate a period of erosion between the two formations. Simpson and Sundberg (1987) identified Early Cambrian fossils, above a bed of metabasalt, in the Unicoi Formation in southwestern Virginia. The correlative rocks of the Chilhowee Group are interpreted to be a transgressive sequence of a rift-to-drift transitional regime.

LOUDOUN FORMATION

Two units occur in the Loudoun Formation: phyllite at the base (ꞒZlp) and coarse quartz pebble conglomerate (Ꞓlc) at the top. The base of the phyllite is placed at the top of the metabasalt and (or) tuffaceous metasedimentary rocks of the Catoctin Formation. The coarse pebble conglomerate occurs in discontinuous lenses.

Confusion about the use of the name Loudoun Formation has been persistent (Stose and Stose, 1946; Woodward, 1949; Bloomer and Werner, 1950; King, 1950; Cloos, 1951; Furcron, 1969) because it is largely indistinguishable from phyllites in the Swift Run and Catoctin Formations (Nickelsen, 1956). Phyllite in the Loudoun Formation is tuffaceous with elongated amygdules so it may be genetically

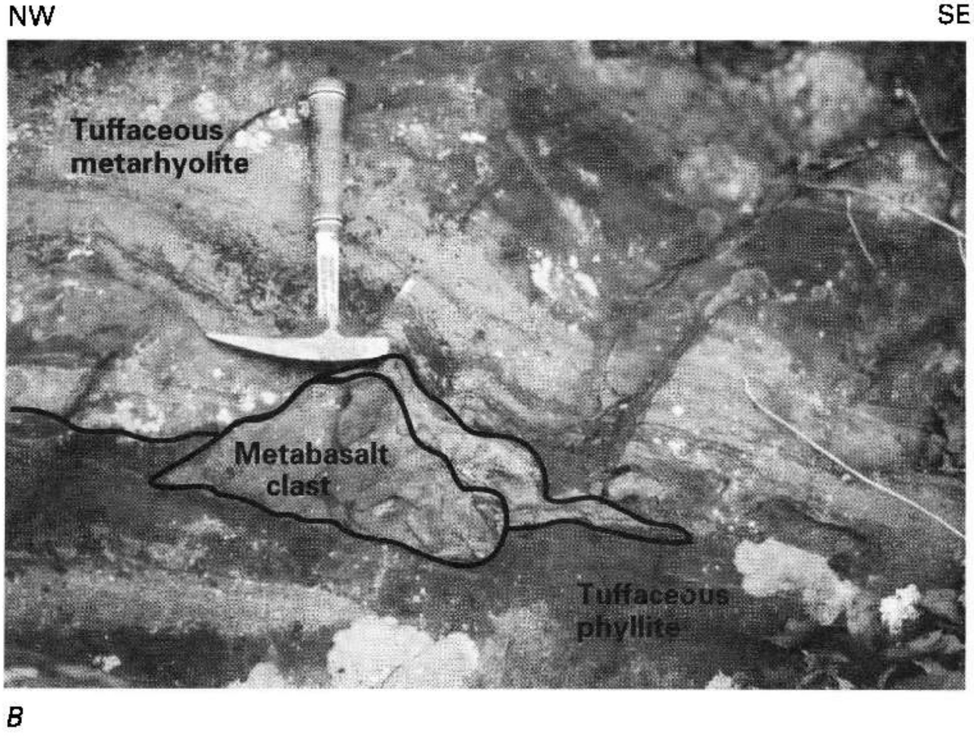


Figure 9. *A*, Metabasalt of the Catoctin Formation (Zcm) showing flows interpreted to be overturned, with epidosite bodies that are separated from schistose metabasalt by tuffaceous phyllite and mud-lump breccia (Zct) in recessive interval. Outcrop is along Potomac River at Short Hill Mountain (pl. 1). Stick just right of center is 1 m long. *B*, Clast of metabasalt and beds of tuffaceous metarhyolite interbedded with tuffaceous phyllite and metabasalt of the Catoctin Formation along the Loudoun Heights trail on the Blue Ridge (pl. 1). Rock hammer is 28 cm long.

related to Catoctin volcanism (Stose and Stose, 1946; King, 1950; Reed, 1955; Toewe, 1966; Gathright and Nystrom, 1974). The phyllite has been mapped previously as a unit within the Catoctin Formation, and the conglomerate as a unit within the lower member of the Weverton Formation (King, 1950; Reed, 1955; Freedman, 1967; Gathright and Nystrom, 1974; Rader and Biggs, 1975; Lukert and Nuckols, 1976; Southworth, 1991a).

PHYLLITE

Phyllite of the Loudoun Formation (€Zlp) is well exposed north of Purcell Knob on the limbs of inverted folds (pl. 1, ref. loc. 10). It is in sharp contact with the overlying conglomerate of the Loudoun or quartzites of the Buzzard Knob Member of the Weverton Formation. The phyllite is gray black and grades downward to light-olive gray and contains pale-red-purple lithic clasts (rhyolite?) in

Figure 10. Conglomerate (€lc) (right) and quartzite (€lc) (left) of the Loudoun Formation between phyllite of the Loudoun Formation (off photo to the left) and quartzite of the Weverton Formation (off photo to the right), north of Purcell Knob (pl. 1, ref. loc. 11). Head of rock hammer is 20 cm long.

a dusky-blue matrix. Medium- to light-gray phyllite contains pinkish-gray, very light gray, and pale-red-purple amygdules elongated in the slaty cleavage plane, which indicates a volcanic origin. Some of the black phyllite may be an iron-rich paleosol (Reed, 1955; Nickelsen, 1956). At the Loudoun Heights trail, approximately 10 m of phyllite containing very fine quartz pebbles is interbedded with thin layers of metabasalt. Phyllite of the Loudoun is not observed on the east side of Short Hill Mountain.

CONGLOMERATE

Conglomerate of the Loudoun Formation (€lc) is a lensoid, discontinuous, coarse, quartz-pebble conglomerate that may be channel fill of the Weverton Formation cut into the phyllite of the Loudoun. The contact with the phyllite is sharp, and the conglomerate contains rip-up clasts of the phyllite.

Conglomerate of the Loudoun Formation is best exposed north of Purcell Knob (pl. 1, ref. loc. 11) in vertical contact with the phyllite of the Loudoun and quartzite of the Buzzard Knob Member of the Weverton Formation. The quartz-pebble conglomerate contains rounded white and purple quartz clasts as large as 6 cm in diameter in a hematite-rich matrix. The conglomerate is arkosic, and some beds are cross stratified. A 1-m-thick, light-gray, massive cross-stratified quartzite lies between the conglomerate and the phyllite at one locality (fig. 10).

On the Loudoun Heights trail, coarse pebbles to small cobbles of rounded to subrounded quartz and red jasper occur at the base of the Buzzard Knob Member of the Weverton Formation. No conglomerate is observed on the east side of Short Hill Mountain, but it is present on South Mountain, Md., approximately 8 km north of the map area.

WEVERTON FORMATION

The Weverton Formation has traditionally been divided into informal lower, middle, and upper members (Nickelsen, 1956; McDowell and Milton, 1992). The type locality is located along U.S. Route 340 near Weverton, Md. (pl. 1 and fig. 11). Brezinski (1992) named these members the Buzzard Knob, Maryland Heights, and Owens Creek Members, respectively (fig. 1*B*). The Buzzard Knob Member consists of quartzite interbedded with metasiltstone. In places, this lower member is transitional with the conglomerate of the Loudoun Formation. Where the conglomerate is absent, the base of the Weverton may be unconformable on the phyllite of the Loudoun or the Catoctin Formation. The Maryland Heights Member consists of quartzite, metasiltstone, and metagraywacke. The Owens Creek Member consists of pebble conglomerate, quartzite, and metasiltstone and grades into the thin-bedded metasiltstone, arkose, and fine pebble conglomerate of the overlying Harpers Formation.

Rocks of the Weverton Formation are interpreted as alluvial sediments (Schwab, 1986) deposited at the base of a marine transgressive sequence and reflect a change from a volcaniclastic to a predominately fluvial environment; paleocurrent directions suggest a source from the west (Whitaker, 1955). Individually, the Buzzard Knob, Maryland Heights, and Owens Creek Members are fining-upward sequences, but the Owens Creek Member is coarser

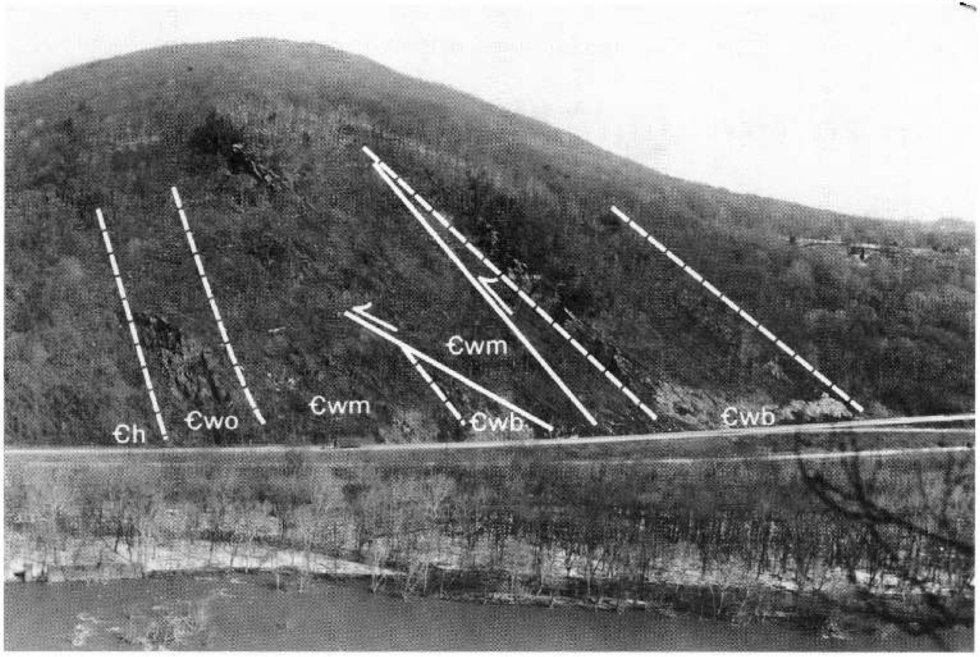


Figure 11. Type locality of the Weverton Formation along U.S. Route 340 and the Potomac River, east of Weverton, Md. Section is overturned and dips to the southeast (right). Ꞓwb, Ꞓwm, and Ꞓwo are the Buzzard Knob, Maryland Heights, and Owens Creek Members, respectively, of the Weverton Formation. Ꞓh, Harpers Formation.

and more poorly sorted than the Buzzard Knob and Maryland Heights Members.

BUZZARD KNOB MEMBER

The Buzzard Knob Member (Ꞓwb) consists of two well-sorted, crossbedded, mature quartzite beds that are separated by and interbedded with light-colored sandy metasiltstone. The Buzzard Knob Member is best seen at the type locality of the Weverton Formation (Weverton Cliffs); (pl. 1, ref. loc. 12) (figs. 11 and 12*B*). At Purcell Knob, the Buzzard Knob Member is arkosic and rests unconformably on hornblende gneiss (Yhg). Stose and Stose (1949) recognized this relation and interpreted doming and erosion between the time of deposition of the Catoctin and Weverton Formations.

MARYLAND HEIGHTS MEMBER

The Maryland Heights Member (Ꞓwm) consists of interbedded, dark-greenish-gray metasiltstone and metagraywacke with dusky-blue to greenish-gray, very coarse grained to granular quartzite. The dark metasiltstone is similar in appearance to metasiltstones in the lower part of the Harpers Formation (King, 1950) and has in the past been confused with it (Woodward, 1949). Quartzite beds vary from 5 to 10 m in thickness and are well exposed at Weverton Cliffs (fig. 11) as well as at the type section of the member (pl. 1, ref. loc. 13) along the railroad tracks at Blue Ridge-Elk Ridge (fig. 12*A*). The Maryland Heights Member is transitional with the underlying Buzzard Knob Member and overlying Owens Creek Member and is often mapped on the basis of a swale between the topographic ledge of the adjacent quartzite beds.

OWENS CREEK MEMBER

The Owens Creek Member (Ꞓwo) is a diagnostic "gun-metal blue" (Nickelsen, 1956) to green-gray coarse-grained sandstone to pebble conglomerate. The Owens Creek Member can be seen on Short Hill Mountain where upright and overturned sections are preserved in the Hillsboro syncline, in the cliffs of Maryland Heights (fig. 12*A*), and the Weverton Cliffs (fig. 11). The Owens Creek Member is more poorly sorted than the Buzzard Knob and Maryland Heights Members and contains pebbles of blue and red quartz, magnetite, opaque minerals, and blue-green phyllite clasts, 0.5 to 15 cm long, that give it a dark blue color. At the base of the Owens Creek Member is 4 m of clean gray-green conglomeratic quartzite. More than 8 m of gun-metal blue pebble conglomerate grades upward into 20 m of green-gray pebble conglomerate at the top. A total section of 27 to 32 m is in agreement with the 23 to 39 m measured by Nickelsen (1956). Exposures on Blue Ridge at the Potomac River gorge are so deformed by folding and cleavage that the member on Chimney Rock (local usage) was interpreted by Woodward (1949) to be part of the Harpers Formation.

HARPERS FORMATION

The Harpers Formation (Ꞓh) is a sequence of phyllitic metasiltstone interbedded with meta-arkose and pebble con-

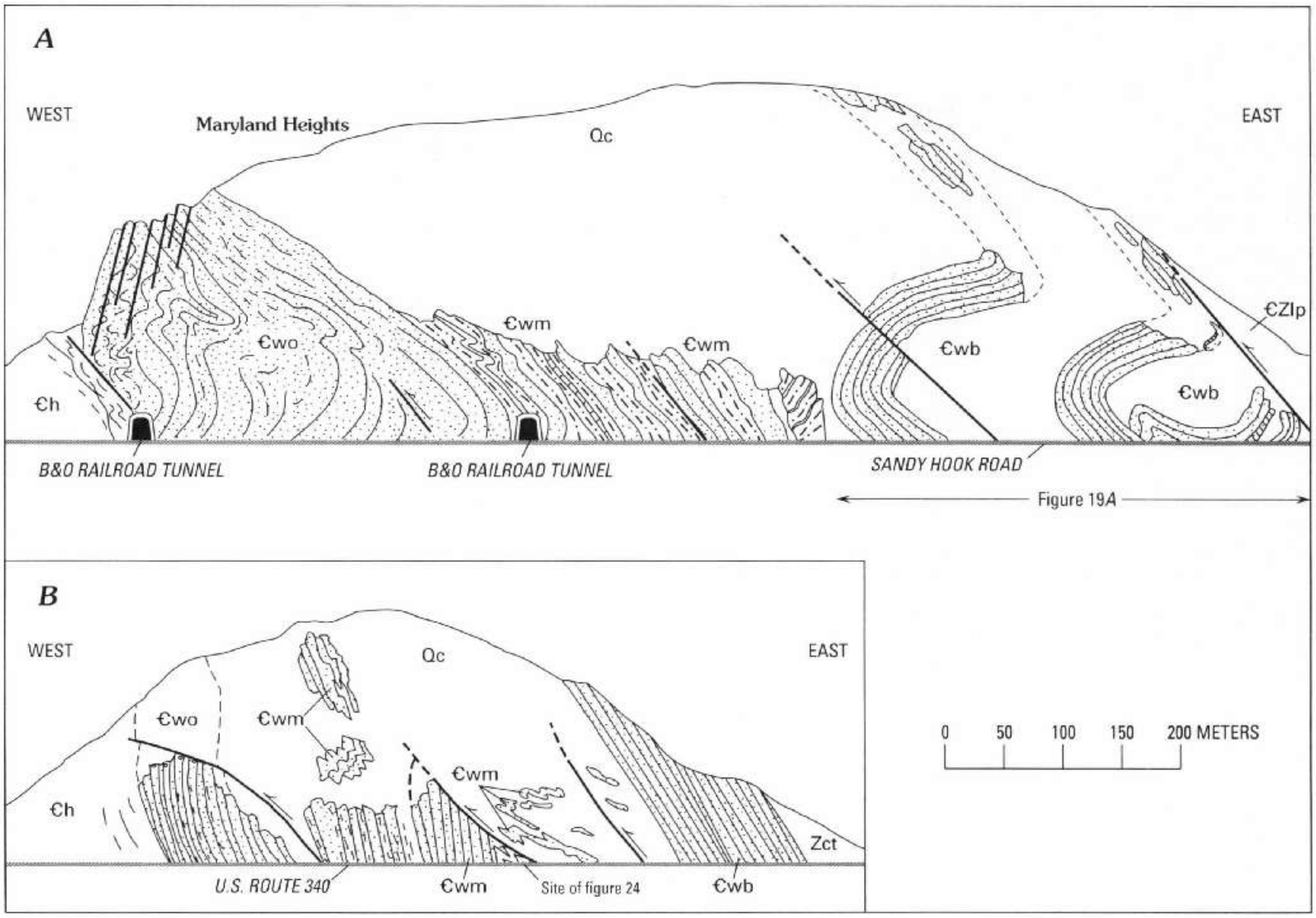


Figure 12. Diagrammatic sketches showing stratigraphy and structure of the Weverton Formation at the Maryland Heights section, *A*, at the south end of Elk Ridge and at Weverton Cliffs, *B*, at the southern terminus of South Mountain, Md. (pl. 1). Zct, tuffaceous metasedimentary rocks; Zcm, metabasalt of Catoctin Formation; Ꞓwb, Ꞓwm, and Ꞓwo are Buzzard Knob, Maryland Heights, and Owens Creek Members, respectively, of the Weverton Formation; Ꞓh, Harpers Formation; Qc, colluvium.

glomerate at the base and ferruginous, magnetite-rich sandstones (Ꞓhq; pl. 1, ref. loc. 14) in the upper part. *Skolithos* tubes (trace fossil) are interpreted to suggest that the Harpers Formation was deposited in marine environments of the transgressive Chilhowee Group (Simpson and Eriksson, 1989).

Strongly developed cleavage typically obscures bedding in outcrops of the Harpers Formation. Bedding-cleavage relations can be seen along the Shenandoah River near the type locality and along the Potomac River on the Sandy Hook Road. Within the Harpers Ferry National Historical Park, the stairs to "Jefferson's rock" are excavated along cleavage and bedding planes. Deformation is less intense west of the thrust fault near the U.S. Route 340 bridge at Bolivar, W.Va., where bedforms occur in light-gray sandstone and metasiltstone. Metasiltstone of the Harpers Formation is phyllonitic in the immediate upper plate of the Short Hill fault near Weverton, Md. Calcareous and sandy metasiltstones, magnetite-rich arkose, thin-bedded metasandstones and a 1-m-thick, dark greenish-gray fine pebble conglomerate are exposed on Short Hill-South Mountain along the Potomac River gorge.

ANTIETAM FORMATION

The Antietam Formation is gradational with the underlying Harpers Formation. The lowermost strata consists of thin (2 to 6 cm) very light gray quartzites with numerous *Skolithos* burrows interbedded with green-gray, sandy metasiltstone. Higher within the formation, the Antietam is characterized by bioturbated, very light gray, medium-bedded, well-sorted, fine- to medium-grained sandstone. The uppermost lithologies are composed of medium-gray, calcareous, crossbedded, coarse-grained sandstone. These rocks are exposed near Dargan, Md. (pl. 1, ref. loc. 15).

TOMSTOWN FORMATION

The Tomstown Formation is the youngest Paleozoic unit exposed in the map area (pl. 1). Brezinski (1992) sub-

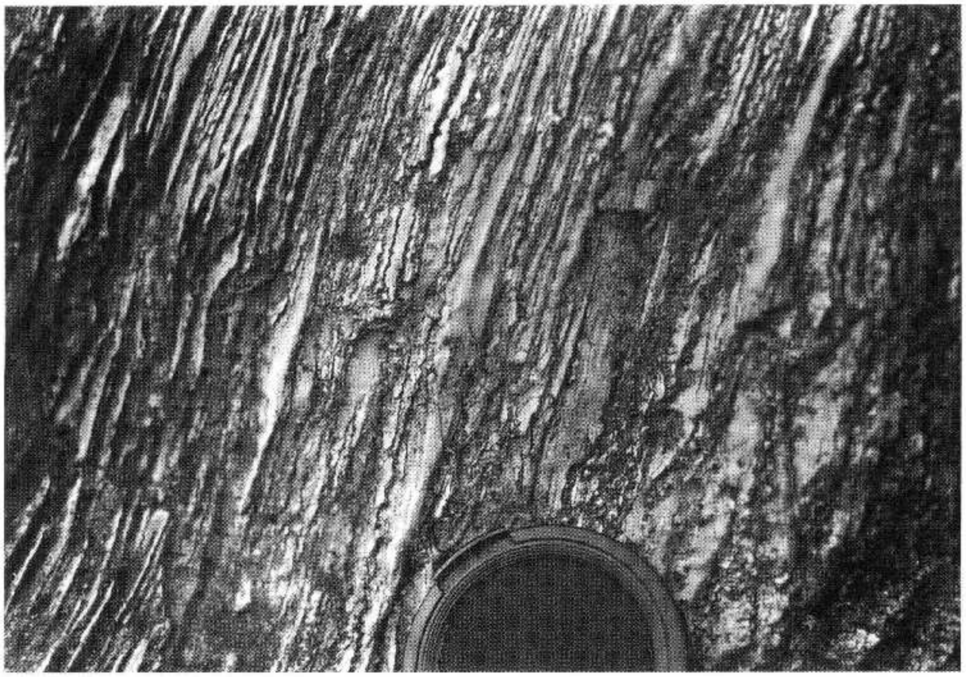


Figure 13. Mylonitic marble of the Keedysville marble bed of the Bolivar Heights Member of the Tomstown Formation along the CSX railroad tracks west of Bolivar, West Virginia, in the Charles Town quadrangle. Mylonitic foliation is parallel to transposed beds. The Antietam Formation is to the left. Lens cover is 5 cm in diameter.

divided the Tomstown into the Bolivar Heights, Fort Duncan, Benevola, and Dargan Members (in ascending order); the latter is not exposed in the Harpers Ferry quadrangle (fig. 1*B*). Carbonate rocks of the Tomstown Formation are indicators that the passive or trailing continental margin was established (Read, 1989). The vertical sequence of lithologies from the Bolivar Heights Member to the Benevola Member suggests that changes from shallow carbonate shelf to deep shelf to bank edge carbonate sand shoal had occurred. The Dargan Member was deposited during shallowing into more peritidal type environments.

BOLIVAR HEIGHTS MEMBER

The Bolivar Heights Member (Ꞓtbh) is characterized by thin-bedded, dark-gray, fine-grained limestone with tan, wispy, and rounded dolomitic burrows (pl. 1, ref. loc. 16). Bioturbation becomes more prevalent upsection. At the base of the formation is a 15-m-thick interval of very light gray to tan mylonitic marble that Brezinski (1992, p. 25) termed the Keedysville marble bed (fig. 13). Brezinski and others (1992) proposed that this marble occurs in a stratigraphically restricted fault zone that can be traced for more than 100 km from Berryville, Va., northward into south-central Pennsylvania.

FORT DUNCAN MEMBER

The Fort Duncan Member (Ꞓtf) is a 70-m-thick interval of dark-gray, burrow-mottled, thick bedded dolomite (pl. 1, ref. loc. 17). The contact with the underlying Bolivar Heights Member is sharp and likely erosional in origin. The cone-shaped fossil *Salterella* occurs throughout this member. This member is equivalent to the Vintage Dolomite of the Conestoga Valley of Pennsylvania both in stratigraphic position and lithologic character. Facies analysis suggests that the Fort Duncan Member was deposited in the deepest water deposits of the Lower Cambrian of the western Blue Ridge cover rocks.

BENEVOLA MEMBER

The Benevola Member (Ꞓtb) consists of approximately 25 m of very thick bedded to massive, light-gray sugary dolomite. Faint crossbedding is common. The lower contact is gradational with the underlying bioturbated dolomites of the Fort Duncan Member and can usually be placed where burrows are no longer evident. The purity and massive nature of this member make it a favored lithology for quarrying, such as near Millville, W. Va., in the adjacent Charles Town quadrangle.

JURASSIC DIABASE DIKES

Near-vertical, northwest- and north-trending diabase dikes of Early Jurassic age were emplaced during the extensional event that led to the opening of the Atlantic Ocean. The diabase is fine to coarse grained, massive, dense, and composed of plagioclase, augite, olivine, and quartz. These dikes occur along northwest and north-northeast strikes, and in north-northwest-striking, right-stepping en echelon trends. An $^{40}Ar/^{39}Ar$ radiometric date of 200 Ma (Kunk and others, 1992) was obtained from the 4.5-m-wide granophyric diabase dike on the B&O railroad cut along the Potomac River (chemical samples 23–26, table 1, and isotopic sample 1, fig. 3). Two of the diabase dikes cut the Short Hill fault.

METAMORPHISM

Middle Proterozoic rocks contain hornblende, hypersthene, almandine, red biotite, rod and bleb perthite, blue quartz, and sphene, which indicate upper amphibolite- to granulite-facies metamorphism during the Middle Proterozoic Grenville orogeny. The hornblende gneiss (Yhg, chemical sample 5, table 1, and isotopic sample 6, fig. 3) yields a $^{40}Ar/^{39}Ar$ hornblende cooling age of 945 Ma (Kunk and others, 1993). During the late Paleozoic Alleghanian orogeny, the gneisses, along with their cover rocks, were metamorphosed to greenschist facies. This retrograde event saussuritized the plagioclase and chloritized the amphibole, pyroxene, garnet, and biotite.

Deformation in the Blue Ridge-South Mountain anticlinorium occurred under greenschist-facies conditions at about 350°C and 3.5 kbar pressure, corresponding to an overburden of 10.6 km (Elliott, 1973). Muscovite in cleavage on the east limb of the anticlinorium in the adjacent Point of Rocks quadrangle has yielded an $^{40}Ar/^{39}Ar$ cooling age of 340 Ma (Burton and others, 1992b; Kunk and others, 1993).

Late Proterozoic to Lower Cambrian metasedimentary and metavolcanic rocks contain mineral assemblages that are stable at greenschist-facies conditions. Albite, chlorite, and magnetite are found in all of these rocks; actinolite and epidote are abundant in metabasalt, and sericite is abundant in the aluminosilicate-rich rocks. Epidosite is most common in metabasalt flows (Reed and Morgan, 1971) but is also found in metadiabase dikes as a result of circulating fluids (Espenshade, 1986).

White quartz veins are common in all units. The Purcell Knob antiformal syncline exposes isoclinally folded quartz veins in phyllite of the Swift Run Formation. The White Rock thrust fault is parallel to bedding in the Weverton Formation and is marked by brecciated blocks of quartzite that float in a matrix of vein quartz. Abundant residual blocks and boulders of white vein quartz are common in areas underlain by garnet monzogranite, yet they are rarely seen in outcrop.

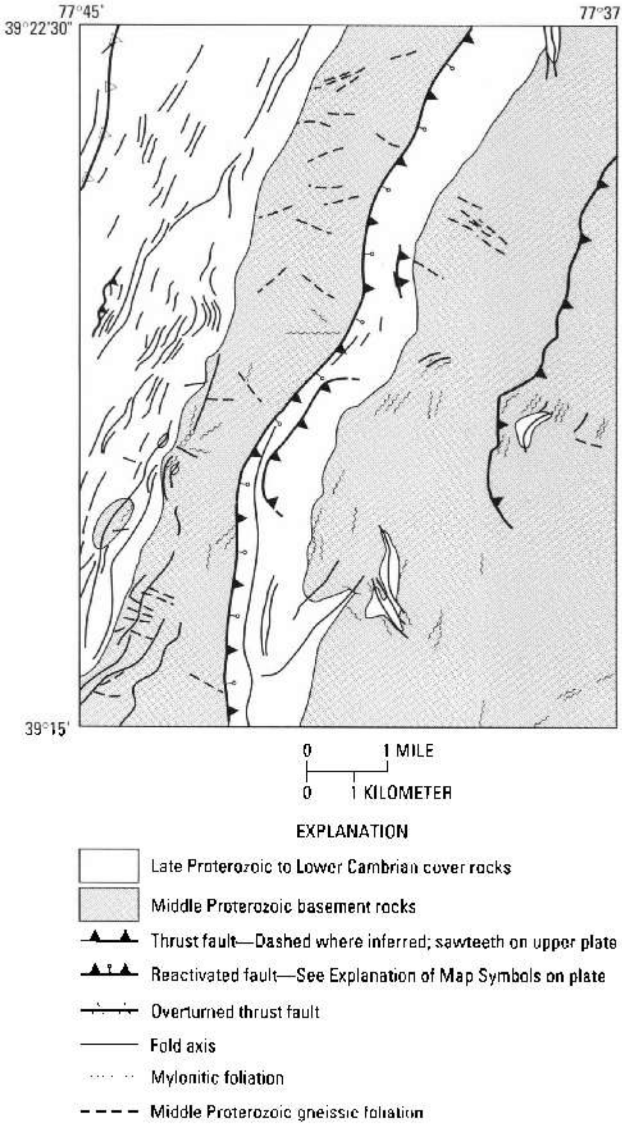


Figure 14. Generalized tectonic map of the Harpers Ferry quadrangle, highlighting major faults, folds, and foliations.

STRUCTURAL GEOLOGY

The Harpers Ferry quadrangle covers the western half of the Blue Ridge-South Mountain anticlinorium, a fault-bend fold that is overturned to the northwest, plunges gently to the northeast, and is allochthonous above one or more blind thrust faults (Harris, 1979; Mitra and Elliott, 1980; Mitra, 1987). Structural elements are complex and include gneissic foliation, mylonitic and phyllonitic foliation, bedding, three types of cleavage, lineations, joints, at least three orders of folds, and multiple generations of faults (fig. 14).

GNEISSIC FOLIATION

Gneissic foliations in the Middle Proterozoic rocks are planar zones of dark- and light-colored minerals in leucocratic and melanocratic layers that range from 1 cm to 0.5 m thick. The dark minerals include hornblende, hypersthene, almandine, biotite, and opaque minerals. The light-colored minerals are quartz, plagioclase, and alkali feldspar. The compositional foliation formed under upper amphibolite- to granulite-facies metamorphism during the Grenville orogeny (Kunk and others, 1993). Gneissic foliation is best developed and ubiquitous in the hornblende gneiss and is locally in the garnet graphite gneiss, garnet monzogranite (see fig. 4), and biotite gneiss. Steeply dipping gneissic foliation in the hornblende gneiss in Loudoun Valley reverses attitude over short distances and indicates significant folding of this unit. Gneissic foliation in the garnet monzogranite and biotite gneiss is nearly flat lying along the bluffs of the Potomac River east of Short Hill Mountain (fig. 15*A*).

MYLONITIC AND PHYLLONITIC FOLIATION

The deformed basement gneisses commonly have textures ranging from protomylonite to ultramylonite (Higgins, 1971). Mylonitic foliation is marked by planar aggregates of sericite, chlorite, and fine-grained recrystallized quartz in the otherwise massive gneiss. Microscopically, the mylonitic foliation shows evidence of grain-size reduction and dynamic recrystallization. Mylonitic foliation is best developed in the biotite gneiss and is rarely present in massive hornblende gneiss. Most mylonite zones are no wider than several meters and most are less than 20 cm wide. The Bolivar Heights Member of the Tomstown Formation is locally a mylonitic marble (fig. 13) as the result of detachment from the underlying Antietam Formation.

The largest zone of mylonitic foliation is the 1-km-wide Dutchman Creek shear zone. More than seven discrete mylonite zones, ranging from 0.5 to 3 m wide, define the shear zone along the Potomac River and Dutchman Creek. The rocks are predominantly ultramylonite and blastomylonite. Mylonitized gneiss closely resembles rocks of the Swift Run Formation (Keith, 1894; Stose and Stose, 1946; Nickelsen, 1956). Sense-of-shear indicators of asymmetric porphyroclastic augen, fractured books of feldspar, pressure shadows of quartz, sericite "fish," and shear band cleavage consistently show east-over-west thrust motion. The biotite gneiss (Ybg) grades into augen gneiss that, in turn, grades into mylonite as the shear zone is approached from the east. Poles to mylonitic foliation in the shear zone (fig. 15*A*) shows that it is coplanar with cleavage.

Phyllonitic foliation is recognized as platy, lustrous phyllosilicate-rich rocks that exhibit anastomosing cleavage. Outcrops of phyllonitic foliation were found only along the Short Hill fault in the Harpers Formation along U.S. Route 340. Phyllonitic foliation also occurs in metadiabase dikes in outcrop, as well as drill core, immediately north of the Potomac River. The phyllonitic foliation has microscopic mica "fish" and asymmetric buttons in hand specimen.

BEDDING

Bedding was recognized in most Late Proterozoic and Lower Cambrian rocks. Graded beds and crossbeds occur in the Weverton Formation and are locally present in the Swift Run Formation. Bedding is more difficult to discern in the Harpers Formation and is very difficult to find in phyllite and schist of the Swift Run and Catoctin Formations. Igneous flow structures occur locally in metabasalt of the Catoctin Formation. Bedding can be traced consistently along strike in the Weverton Formation on Short Hill-South Mountain. Elsewhere, bedding attitude changes over short distances and suggest significant folding.

Crossbeds in the Weverton Formation on Short Hill-South Mountain show that bedding is overturned in 93 percent of the observations (fig. 15*B*). West-dipping beds are upright fold limbs near the "Radio Facilities." The cluster of poles show the homoclinal nature of the strata that underlie the ridge. Approximately 72 percent of the observations of the Weverton Formation were overturned. Here, the strata are complexly folded, and the poles to bedding are shown with fold axes (fig. 15*B*).

CLEAVAGE

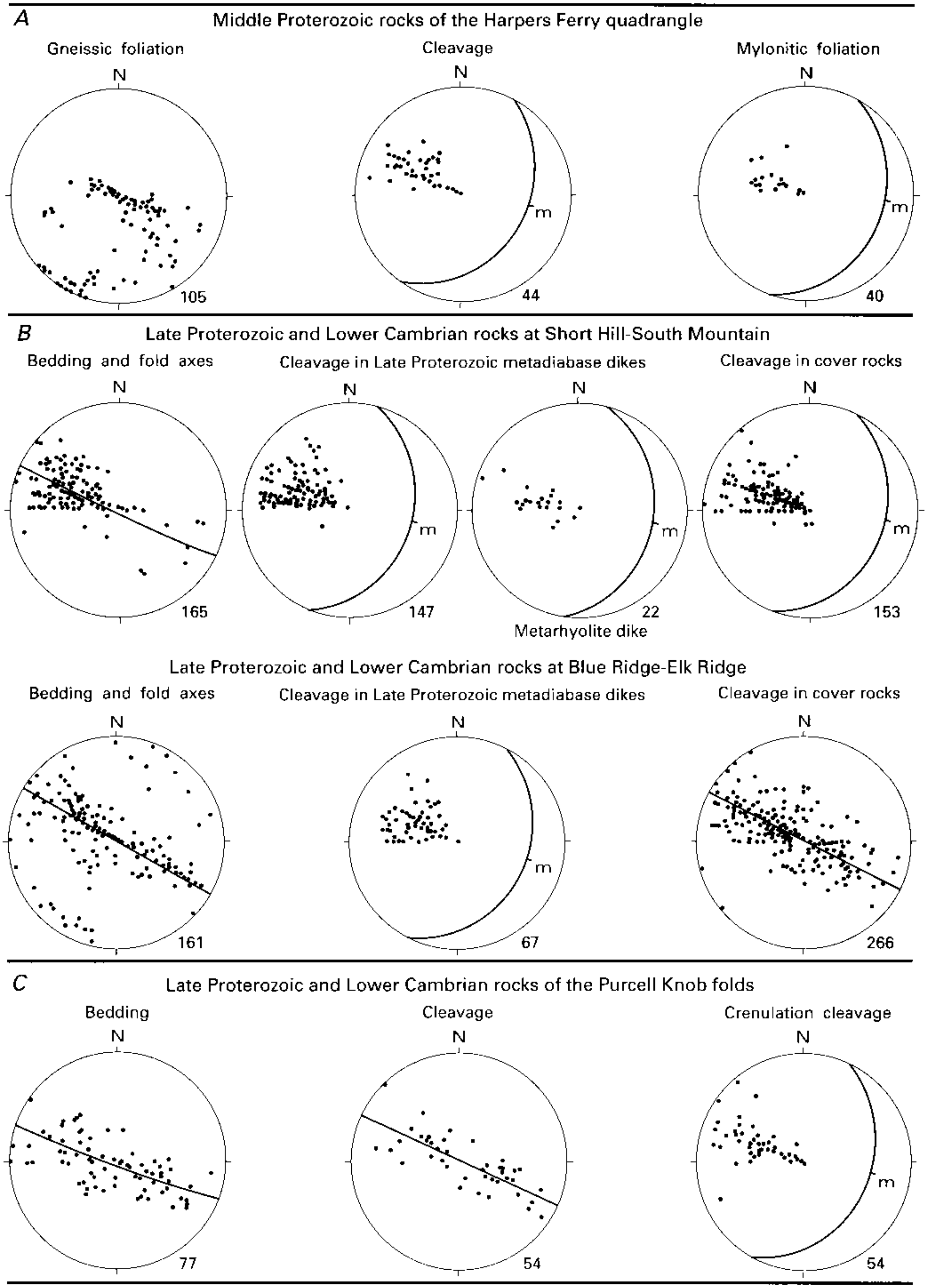
All Middle Proterozoic through Lower Cambrian rocks in this area have a penetrative cleavage and a consistent southeast dip. This trend, first identified as the South Mountain cleavage by Cloos (1947; 1951), is approximately axial planar to the Blue Ridge-South Mountain anticlinorium. It is a planar fabric characterized by the parallel alignment of the greenschist-facies minerals chlorite, quartz, sericite, magnetite, epidote, and actinolite. The cleavage is continuous into both slaty and schistose textures depending on the scale of layering and the rock competence. Cleavage in the gneiss, dikes, and cover rocks is coplanar and supports other field evidence that the basement and cover rocks were deformed together (fig. 15*B*).

MIDDLE PROTEROZOIC ROCKS

Cleavage that formed during Paleozoic deformation cuts the gneissic foliation and is marked by biotite, sericite, chlorite, and recrystallized quartz in thin ductile-deformation zones (Mitra, 1978). The cleavage in the basement rocks is coplanar to cleavage in the cover rocks (fig. 15*B*). Both contain the same greenschist-facies mineral assemblages with the exception of biotite.

LATE PROTEROZOIC AND LOWER CAMBRIAN ROCKS

Slaty cleavage is best developed in fine-grained phyllite and schist of the Swift Run, Catoctin, and Harpers Formations, where it is the dominant structural element because bedding is largely transposed. Slaty cleavage is less well developed in quartzite of the Weverton Formation. Cleavage surfaces have a shiny luster because of sericite and chlorite crystals. Quartz grains are elongated and flattened in the cleavage plane. The Late Proterozoic and


A
Middle Proterozoic rocks of the Harpers Ferry quadrangle
Gneissic foliation
N
105
Cleavage
N
m
44
Mylonitic foliation
N
m
40
B
Late Proterozoic and Lower Cambrian rocks at Short Hill-South Mountain
Bedding and fold axes
N
165
Cleavage in Late Proterozoic metadiabase dikes
N
m
147
N
m
22
Metarhyolite dike
Cleavage in cover rocks
N
m
153
Late Proterozoic and Lower Cambrian rocks at Blue Ridge-Elk Ridge
Bedding and fold axes
N
161
Cleavage in Late Proterozoic metadiabase dikes
N
m
67
Cleavage in cover rocks
N
266
C
Late Proterozoic and Lower Cambrian rocks of the Purcell Knob folds
Bedding
N
77
Cleavage
N
54
Crenulation cleavage
N
m
54

Lower Cambrian rocks in this area have a strong penetrative southeast-dipping cleavage. In the Purcell Knob folds, however, cleavage dips northwest and is cut at a high angle by southeast-dipping crenulation cleavage (fig. 15*C*). Elsewhere, the cleavage is highly variable in orientation, both along and across strike, as the result of folding after the cleavage formed.

LATE PROTEROZOIC DIKES

Metadiabase dikes cut the gneissic foliation at a high angle, but they generally parallel the Paleozoic cleavage and mylonitic foliation of their host (fig. 15*B*). Cleavage in the dike rocks (fig. 15*B*) is parallel to the contacts and dips southeastward, coplanar to the South Mountain cleavage. Dikes that deviate from a southeast dip are associated with shear zones and the Purcell Knob inverted folds. Some dikes show boudinage and pinch-and-swell structure near contacts with basement rocks. The metadiabase is phyllonitic near the contact, and intrafolial folds occur in the plane of cleavage. During Paleozoic deformation, the dikes acted as shear zones in the basement rocks. Regional variations in the strike and dip of dikes are interpreted to reflect Paleozoic folds of the basement rocks.

CRENULATION CLEAVAGE

Crenulation cleavage is a discontinuous, spaced, zonal, and discrete cleavage (Gray, 1979). The crenulation cleavage is axial planar to F_2 folds that fold the cleavage and F_1 folds. Insoluble residues concentrated in the laminae suggest that it is a pressure solution cleavage (Gray, 1979). At the Purcell Knob inverted folds, crenulation cleavage uniformly dips to the southeast (fig. 15*C*) and approximately parallels the regional cleavage. Where crenulation cleavage is well developed, the slaty cleavage shows intrafolial folds and transposed compositional layering in the slaty cleavage plane. Crenulation cleavage is best developed along Blue Ridge-Elk Ridge (fig. 16) and is found locally to the north in the Keedysville quadrangle (Southworth, 1993), to the south in the Round Hill quadrangle (McDowell and Milton, 1992; Southworth and others, in press), and to the east in the Point of Rocks quadrangle (Burton and others, 1995).

SHEAR BAND CLEAVAGE

Shear band cleavage (White and others, 1986) is recognized only in rocks along the Short Hill fault where it cuts phyllonitic foliation in the Harpers Formation along U.S. Route 340 (fig. 17). Asymmetry of nearly horizontal shear bands with phyllonitic foliation shows consistent east-over-west motion. Dextral kinks fold the shear bands (Southworth, 1993).

LINEATIONS

Hornblende, garnet, biotite, and chlorite, elongated down the foliation and cleavage planes, are best seen in pavement outcrops of hornblende gneiss (Yhg) in Loudoun Valley. The lineations consistently plunge southeast to northwest. The Paleozoic cleavage is marked with down-dip lineations of elongated quartz, mica, lithic fragments, vesicles, and amygdules (Cloos, 1971).

JOINTS

Both open and quartz-filled annealed joints are common in all rocks of the quadrangle. Systematic joints are most abundant in quartzite of the Weverton Formation, and they are interpreted to be cross (northwest-strike), longitudinal (northeast-strike), and oblique joints formed during folding. The joints are spaced at a minimum of 1 cm apart. Joints are less common in the phyllite and schist. Joints are important conduits for ground water because cleavage planes have little open space. Investigations for ground water should employ a detailed, site-specific analysis of joints because regional compilations (Southworth, 1990, 1991a) give only a random distribution.

FOLDS

Blue Ridge-South Mountain anticlinorium is a first-order fold. Blue Ridge-Elk Ridge and Short Hill-South Mountain are overturned west limbs of second-order folds that are separated by the Short Hill fault. Blue Ridge-Elk Ridge defines a tectonite front (Mitra, 1987) where deformation in the cover rocks is much more extreme than in cover rocks that underlie Short Hill-South Mountain.

At least two different styles of folds are recognized: (1) F_1 isoclinal folds having axial plane cleavage and (2) F_2 inclined folds having axial plane crenulation cleavage. The F_1 and F_2 folds plunge gently to the northeast and southwest. The type locality of the fold phases is the Purcell Knob inverted folds. First mapped by Nickelsen (1956), the Purcell Knob inverted folds are complex, refolded folds that include rocks from the Middle Proterozoic hornblende gneiss through the Weverton Formation. An antiformal syn-

← **Figure 15.** Lower hemisphere equal-area projections of structural elements. *A*, Poles to gneissic foliation, cleavage, and mylonitic foliation in Middle Proterozoic rocks in the Harpers Ferry quadrangle. *B*, Poles to bedding and cleavage in Late Proterozoic and Lower Cambrian rocks from domains east (Short Hill-South Mountain) and west (Blue Ridge-Elk Ridge) of the Short Hill fault. *C*, Poles to bedding, cleavage, and crenulation cleavage of the Purcell Knob folds.

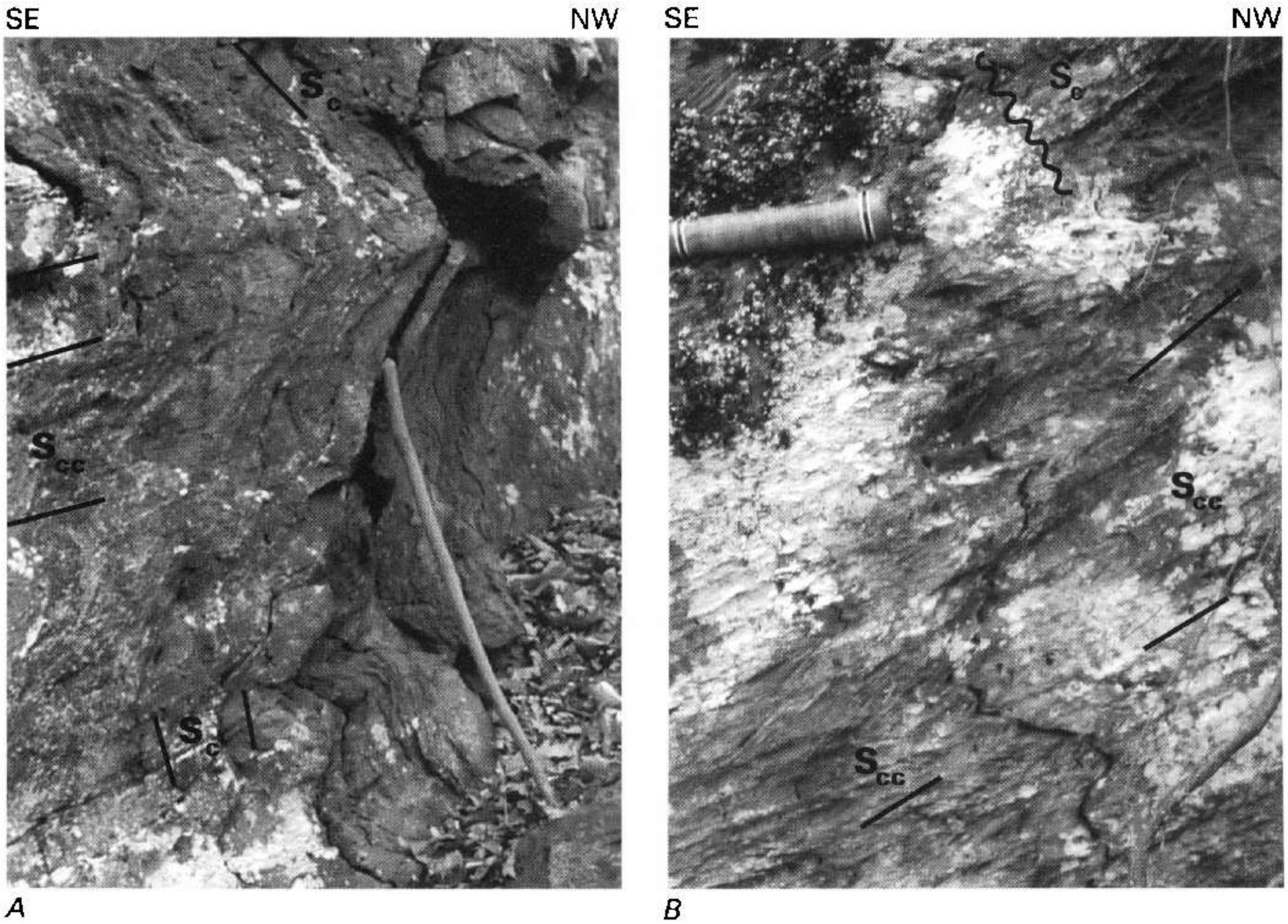


Figure 16. First-generation axial planar cleavage (S_c) cut by crenulation cleavage (S_{cc}) in metabasalt of the Catoctin Formation near Loudoun Heights Trail on Blue Ridge. *A*, Stick is 1 m long. *B*, Rock hammer handle is 15 cm long.

cline, a synformal anticline, and several inverted parasitic folds show that the basement is folded with the cover rocks. Younger rocks and cleavage dip westward beneath older rocks and are cut by crenulation cleavage that dips eastward. Westward-inclined F_2 antiforms and synforms exhibiting axial plane crenulation cleavage are superimposed on the F_1 isoclinal folds and cleavage (fig. 18). The crests of the F_2 folds rise and fall along strike.

A culmination of the antiformal syncline exposes metabasalt of the Catoctin Formation (chemical sample 17, table 1) beneath the Swift Run Formation. The rocks are thickened in fold hinges and thinned on inverted limbs, which is consistent with supratenuous folds of passive flow. Deformation of the hornblende gneiss (Yhg) in the synformal anticline is heterogeneous. Mylonitic foliation occurs at the contact with the cover rocks on the inverted limb, but the gneiss is massive in the core of the anticline. This style of folding is unique to the Blue Ridge-South Mountain anticlinorium (Nickelsen, 1956; Elliott, 1970). However, nappe-like recumbent folds of cover rocks can be traced southward into the Round Hill quadrangle (McDowell and Milton, 1992) and northward into the Keedysville quadrangle (Southworth, 1993). The orientation of foliations in the metadiabase dikes and basement gneiss in Loudoun Valley suggests that the Purcell Knob folds continue north to at least the Potomac River.

Short Hill Mountain is underlain by the second-order Hillsboro syncline. This isoclinal syncline is overturned to the northwest and is cored by rocks of the Harpers Formation. The overturned east limb shows monoclines of local third and fourth-order parasitic folds. The Hillsboro syncline can be traced southward for 21 km where it is cored by rocks of the Catoctin Formation (Southworth, 1994; 1995).

The Weverton Formation is intensely folded on Blue Ridge-Elk Ridge (figs. 12, 14, and 15*B*). Mesoscopic and macroscopic folds are overturned to the northwest, are disharmonic, and have similar fold geometry, (that is, thickened crests and thinned limbs). Second- and third-order,

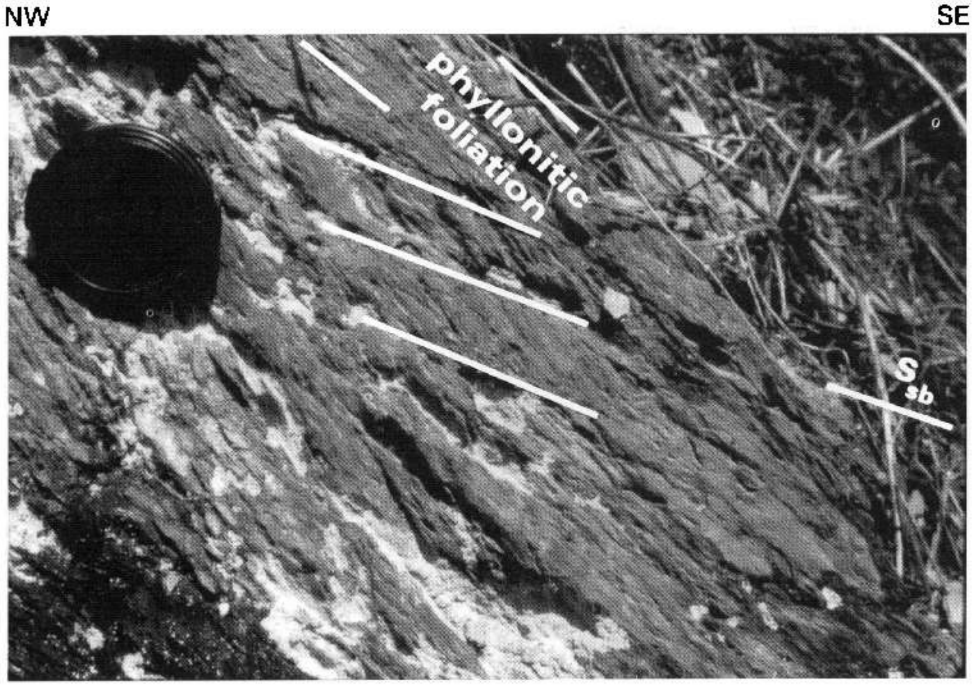


Figure 17. Shear band cleavage (Ssb) cutting phyllonitic foliation with east-over-west asymmetry in rocks of the Harpers Formation (Ꞓh) along U.S. Route 340 in the hanging wall of the Short Hill fault. Lens cover is 5 cm in diameter.

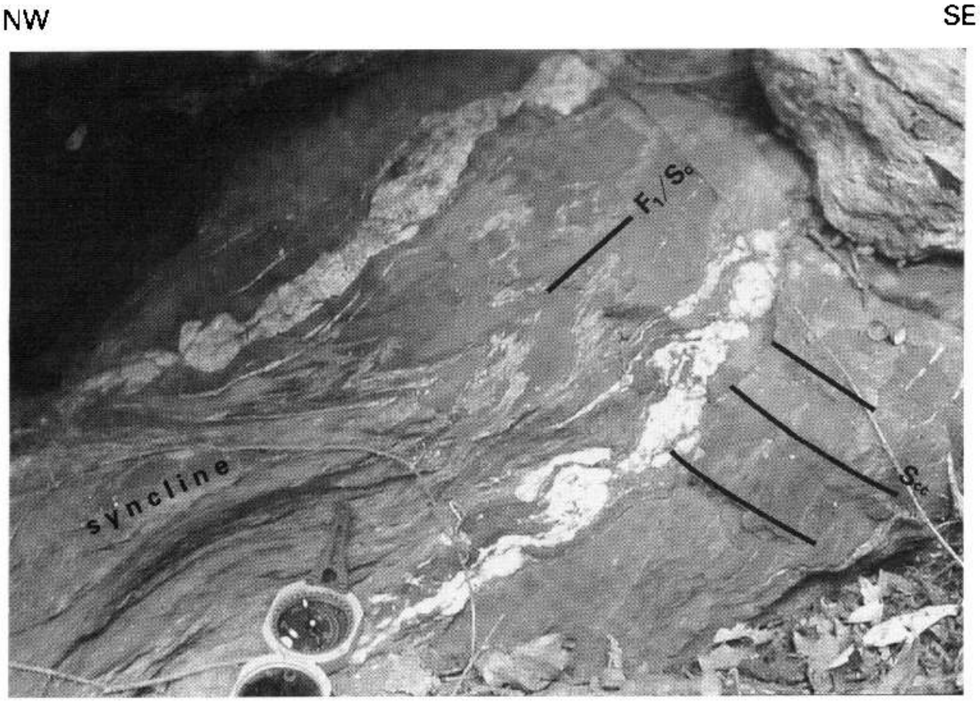


Figure 18. F_1 isoclinal syncline, facing downward to the west, and axial planar cleavage (S_c) that is cut by southeast-dipping crenulation cleavage (S_{cc}). This outcrop of phyllite of the Swift Run Formation (**Zsp**) is near reference locality 6 (pl. 1) of the Purcell Knob antiformal syncline. Brunton compass shown for scale.

asymmetric, similar folds have wavelengths of 1 to 100 m and plunge gently northeast or southwest. Two large recumbent folds exposed along the Potomac River plunge 10° southwest (figs. 12 and 19). Parasitic folds on these larger structures have extremely thickened strata produced by folding on Blue Ridge. Slickenlines, stretched quartz veins, and boudinage plunge down the dip of the bedding and indicate flexural slip folding. Several anticlines, synclines, and antiformal synclines in the Harpers Formation are recognized by cleavage fans and bedding and cleavage relations along the north bank of the Shenandoah River in the Harpers Ferry National Historical Park (fig. 20).

Two synclines in quartz sericite schist of the Swift Run Formation (**Zss**) are located east of Short Hill Mountain.

Figure 19. *A*, Recumbent anticlines of quartzite of the Buzzard Knob Member of the Weverton Formation (Ꞓwb) exposed on Elk Ridge north of the Potomac River (foreground) and illustrated in fig. 12*A*. *B*, Southwest-plunging overturned anticline in the Potomac River is the anticline seen on the left in fig. 19*A*. Width of the river is approximately 300 m.

The synclines are short and probably shallow. The Dutchman Creek syncline is in the upper plate of a shear zone. The Mt. Olivet syncline has a complex outcrop pattern that suggests refolded folds.

FAULTS

The Short Hill fault, the Dutchman Creek shear zone, the White Rock thrust fault, the Keedysville detachment, and several small thrust faults and normal faults are recognized in the map area (pl. 1). The Short Hill fault was interpreted by Cloos (1951) and Nickelsen (1956) to be a down-to-the-east Triassic normal fault. Field relations along the Short Hill fault reveal younger-on-older rocks typical of extensional faults, but contractional kinematic indicators show east-over-west motion (Southworth, 1993). Drilling of the Short Hill fault (October 1990, south of Weverton, Md., along the Keep Tryst Road; fig. 21) revealed phyllonitic

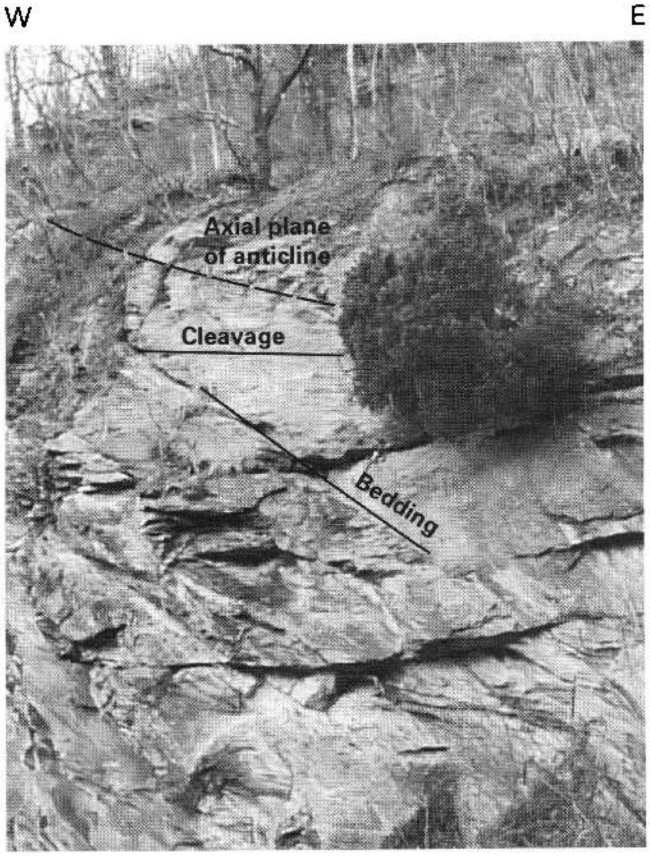


Figure 20. Overturned anticline in the Harpers Formation (€h) showing bedding and cleavage relations in the Harpers Ferry National Historical Park along the Shenandoah River (pl. 1). Height of outcrop is approximately 15 m.

metasiltstone of the Harpers Formation in fault contact with a phyllonitic Late Proterozoic metadiabase dike intruded into Middle Proterozoic garnet monzogranite. The attitude of the southeast-dipping fault was determined to be approximately 35°, but excavations along U.S. Route 340 show that the dip of the fault changes from 8° to 40° over short distances. Microstructures of the core show shear band cleavage that cuts phyllonitic foliation with an east-over-west sense of motion. The fault plane is parallel to the phyllonitic foliation but anastomoses along the shear bands. These foliations are cut by later northwest-dipping dextral kink bands. On the basis of these data, Southworth (1991a and b) interpreted the Short Hill fault as a thrust.

Brezinski and others (1991) and Campbell and others (1992) interpreted the Short Hill fault at the Potomac River to be the "South Mountain fault," which is part of a late-stage, linear, en echelon fault system that extends to Pennsylvania. Brezinski (1992) considers this strand of the South Mountain fault to be coincident with the Rohrersville fault (fig. 22), which he interprets to be an early Paleozoic normal fault. The South Mountain fault, the Rohrersville fault, and the Eakles Mill fault of Brezinski (1992) are younger-on-older faults that are interpreted by Southworth (1993) to be the continuations of the Short Hill fault. Brezinski's (1992) South Mountain fault (north of Rohrersville) and Sans Mar fault are interpreted by Southworth (1993) to be late thrust faults that splay from the Short Hill fault. These thrust faults imbricated the hanging-wall strata of the Short Hill fault during Late Paleozoic contractional reactivation.

The Short Hill fault has been traced for more than 60 km northward from a shear zone in Middle Proterozoic gneiss in Fauquier County, Va. (Howard, 1991; Southworth, 1993; 1994), to the west side of Elk Ridge in Maryland where Lower and Middle(?) Cambrian rocks overlie Lower Cambrian rocks (Brezinski, 1992; Southworth, 1993). Near Rohrersville, Md., the Short Hill fault is folded and transected by pressure solution crenulation cleavage similar to that in the Purcell Knob inverted folds (Southworth, 1993). The Short Hill fault is interpreted to be an early Paleozoic normal fault that was reactivated by contraction in the Alleghanian orogeny (Wojtal, 1989; Brezinski, 1992; Southworth, 1993).

The Dutchman Creek shear zone is a 1-km-wide fault zone that places mylonitic biotite gneiss (Ybg) on garnet monzogranite (Ygt). Kinematic indicators in the mylonitic foliation show east-over-west motion. However, the structural level and preservation of quartz sericite schist (Zss) of the Swift Run Formation in the hanging wall of the Dutchman Creek syncline may be the result of an early normal fault. Similar to the Short Hill fault, the Dutchman Creek shear zone may be a reactivated early extensional fault.

The White Rock thrust fault is interpreted to be a detachment structure that involves quartzite of the Maryland Heights Member of the Weverton Formation on the crest of Short Hill Mountain. The thrust fault is marked by a zone of cataclastic vein quartz as much as 10 m thick. In places, foliated quartz cataclasite constitutes 80 percent of the fault zone in which 0.25- to 0.5-m-thick slabs of quartzite breccia float in a white quartz matrix (fig. 23) (pl. 1, ref. loc. 18). South of White Rock, the east slope of Short Hill Mountain is underlain by colluvial blocks of similar deformed vein quartz. This area is interpreted to be the sole of a bedding-parallel detachment in the Buzzards Knob Member (€wb) of the Weverton Formation.

The Keedysville detachment is marked by aerially extensive mylonitic marble near the base of the Bolivar Heights Member of the Tomstown Formation (Brezinski, 1992). The mylonitic marble, which Brezinski termed the Keedysville marble bed, is very light gray, to white, with streaks of tan dolomite, ranges in thickness from 3 to 15 m, and has a pervasive east-west oriented stretching lineation (fig. 13). Overlying the marble, 25 to 35 m of mylonitized limestone exhibits asymmetric shear indicators that suggest a top-to-the-northwest sense of movement. Marble has been folded along with adjacent strata indicating that it originated prior to major folding episodes. The Keedysville marble bed has, at present, been traced from Berryville, Va., northward into Franklin County, Pa., a distance of more

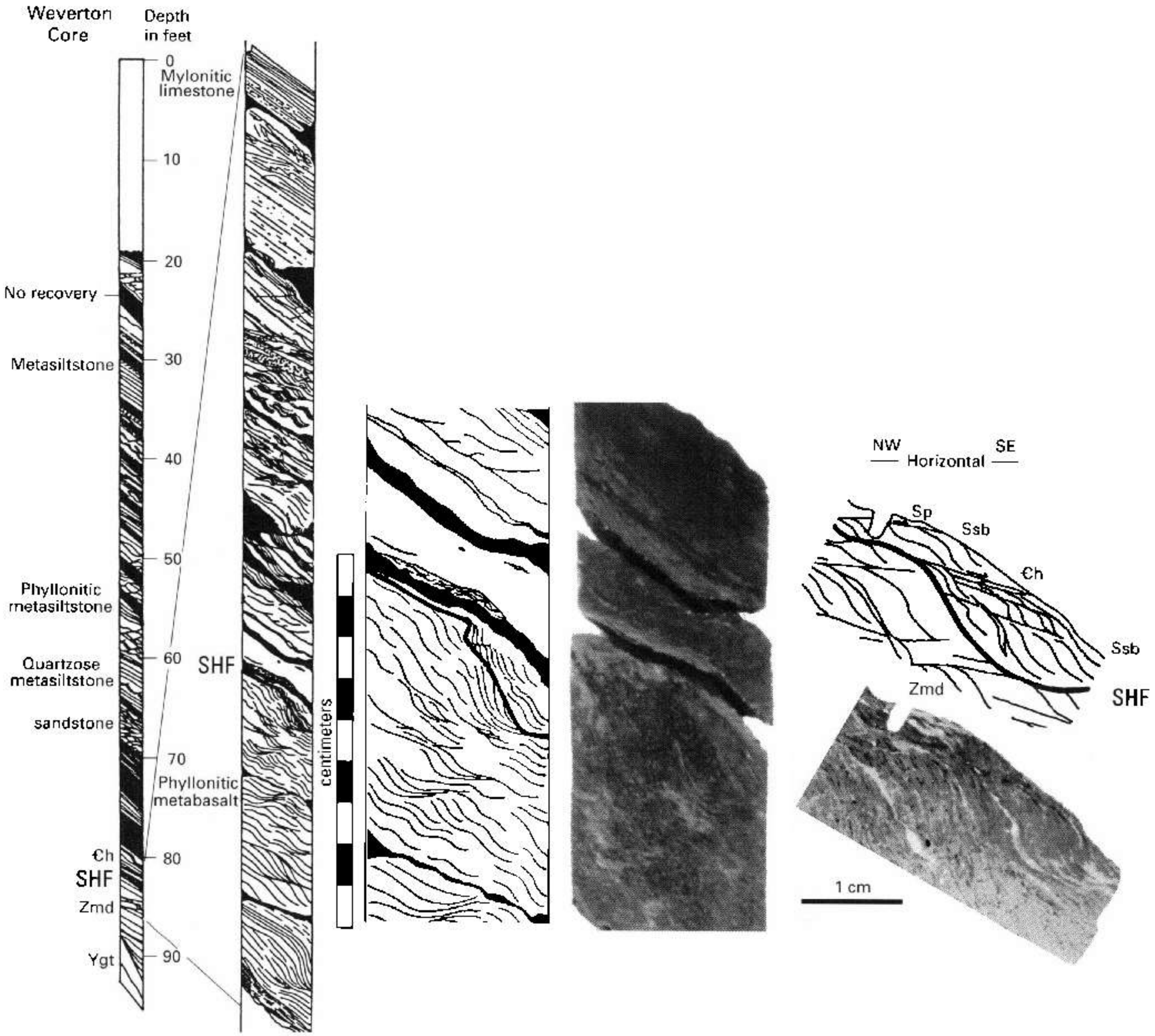


Figure 21. Structural maps and photograph of drill core and photomicrograph of the plane of the Short Hill fault (SHF). Sp, phyllonitic foliation; Ssb, shear band cleavage; Ꞓh, Harpers Formation; Zmd, metadiabase dike.

than 100 km. The Keedysville marble bed is interpreted to be a bedding-parallel detachment that decoupled the overlying carbonate rocks from underlying siliciclastic rocks of the Chilhowee Group. Since the mylonitic rock is folded with the adjacent Blue Ridge cover sequence, detachment predated the major folding episodes that produced the Blue Ridge-South Mountain anticlinorium.

Intraformational thrust faults in the Weverton Formation are exposed at Blue Ridge-Elk Ridge and Weverton Cliffs north of the Potomac River (figs. 11 and 12). One of the thrust faults at Weverton Cliffs has indeterminate displacement but truncates isoclinal folds in the footwall (fig. 24).

Highly cleaved phyllite of the Harpers Formation is interpreted to be in thrust contact with right-side-up metasiltstone of the Harpers Formation within the Harpers Ferry National Historical Park. Where recognized, bedding in the Harpers Formation to the east is nearly horizontal to inverted (Lessing and others, 1991). The thrust fault is intraformational with indeterminate displacement and is interpreted to be a late fault that is partly responsible for the wide outcrop pattern of the Harpers Formation.

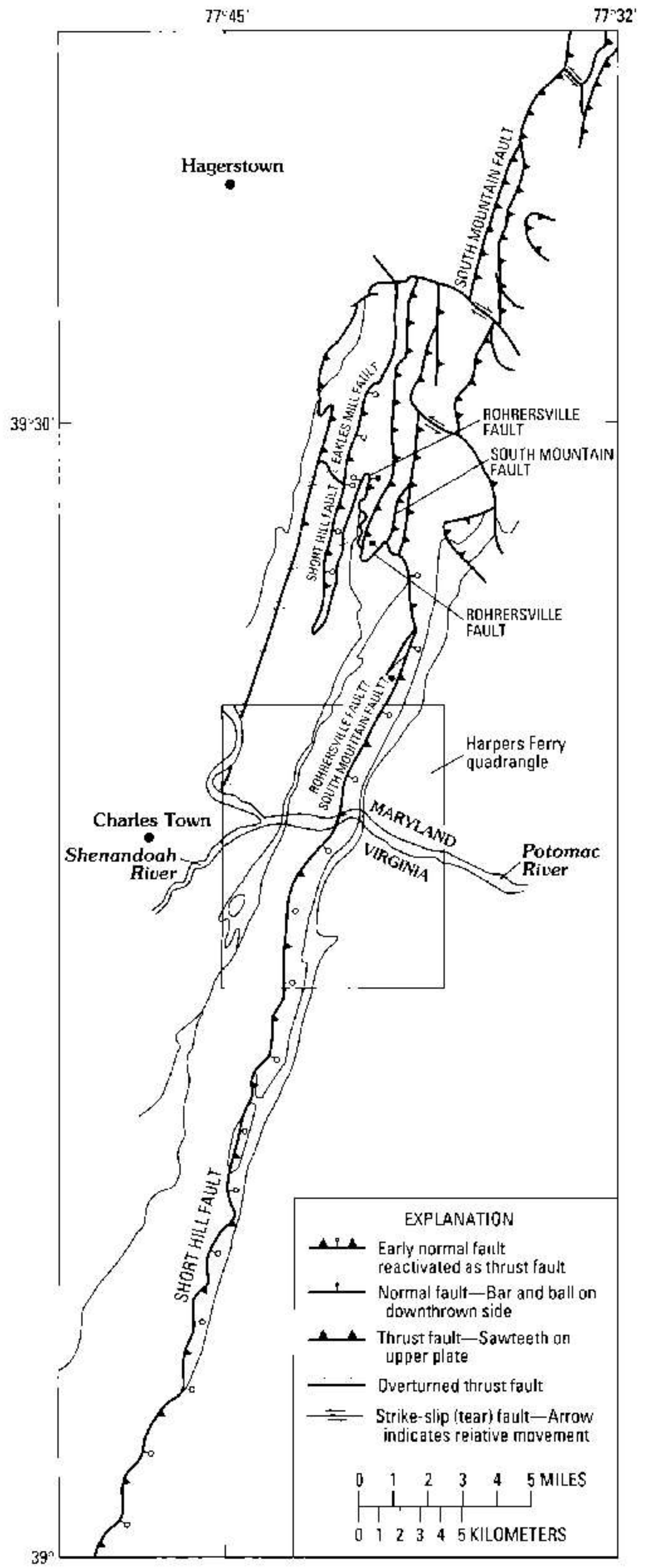


Figure 22. Structural map showing the relation of the Short Hill fault (Southworth, 1993) to faults mapped by Brezinski in Maryland. The Eakles Mill and Rohrersville faults were mapped by Brezinski (1992), and the South Mountain fault was mapped by Brezinski and others (1991) and Brezinski (1992).

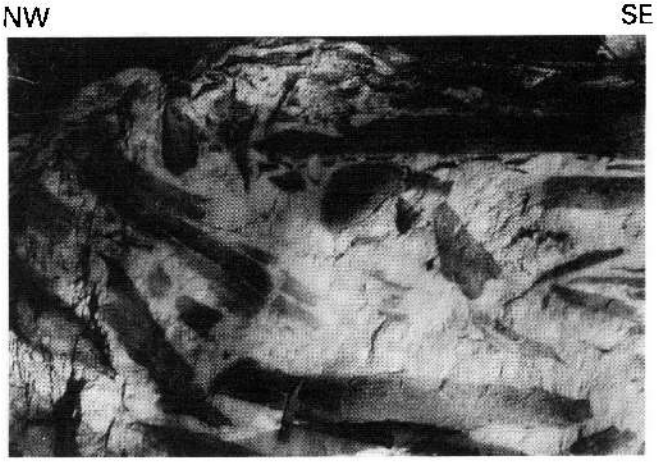


Figure 23. Blocks of quartzite of the Weverton Formation (Ꞓwb) (dark) in matrix of vein quartz along the White Rock thrust fault near reference locality 18 (pl. 1). Rock hammer at lower center is 28 cm long.

Northwest-trending, steep, northeast-dipping shear zones in garnet monzogranite along Potomac Wayside are interpreted to be normal faults. The phyllonitic to pseudotachylytic fault rock has the chemistry of a Jurassic diabase dike (chemical sample 25, table 1).

West of Potomac Wayside, a northwest-striking vertical fault in the Weverton Formation with slickenside striations raking 35° to 40° southeast is parallel to the normal faults and shear zones along the B&O tracks and may indicate minor oblique faulting along the Potomac River gorge.

TECTONIC HISTORY

The geology of the Harpers Ferry quadrangle records a diverse tectonic history of orogenies followed by episodes of rifting (table 3). Stratigraphy, structure, and metamorphism of the rocks represent several Wilson cycles of opening and closing ocean basins (Wilson, 1966) (fig. 25).

MIDDLE PROTEROZOIC

The oldest rocks are a suite of paragneisses that were assimilated by granitoid plutons during the Grenville orogeny. Isotopic data of granitoids in the region show that the plutonism lasted from 1144 to 1058 Ma (table 3). Rod and bleb perthite, almandine, hypersthene, hornblende, red biotite, and blue quartz in the gneissic foliation of these rocks record granulite-facies metamorphism that has a hornblende cooling age of 920 Ma (Kunk and others, 1993). These rocks show compositional and metamorphic layering (gneissic foliation) of granulite-facies mineralogy that often strikes northwest, parallel to unit contacts.

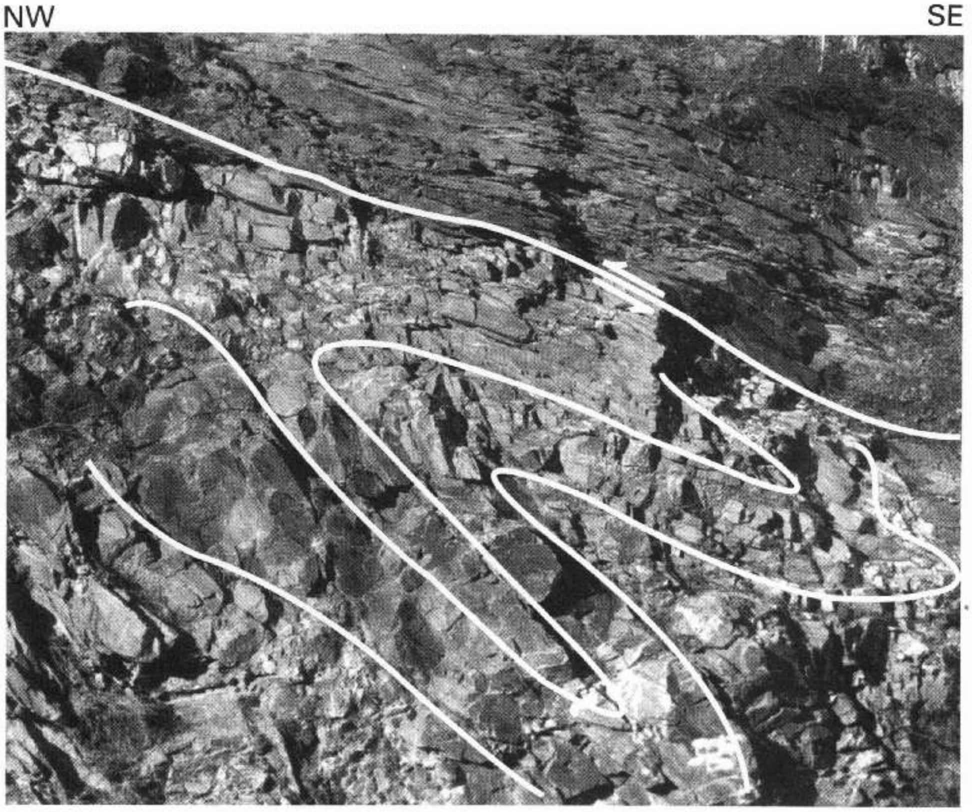


Figure 24. Intraformational thrust fault in the Maryland Heights Member of the Weverton Formation (Ꞓwm) showing tight to isoclinal folds in the footwall. Outcrop along Route U.S. 340 at Weverton Cliffs. Folded quartzite bed (highlighted) is approximately 1 m thick. Photograph is illustrated in fig. 12*B*.

LATE PROTEROZOIC

The Grenville orogeny was followed by a long period of Late Proterozoic extension. The Robertson River Igneous Suite (Tollo and others, 1991), found 14 km to the southwest, is the largest anorogenic pluton in the central Appalachian Blue Ridge province. The peralkaline granites indicate a period of incipient continental rifting that lasted from 730 to 700 Ma (Tollo and Aleinikoff, 1992).

Late Proterozoic metasedimentary rocks of the Swift Run Formation were deposited unconformably on an irregular surface of basement granitoids. They are correlative with rocks of the Fauquier (Espenshade, 1986) and Mechum River Formations (Gooch, 1958), as well as with rocks of the Lynchburg Group (Wehr, 1985). Exposures of the Fauquier Formation and Lynchburg Group are restricted to the east limb of the Blue Ridge-South Mountain anticlinorium and are interpreted to be shallow-water marine facies of a restricted basin (Conley, 1989). The Mechum River Formation occupies a long, linear synclinorium along the axial region of the anticlinorium that has been interpreted to be a Late Proterozoic graben (Gooch, 1958; Schwab, 1986). Fault bounded outliers of the Mechum River Formation can be traced to rocks of the Fauquier Formation of the east limb.

Late Proterozoic normal faults that were active during sedimentation of the Fauquier Formation have been recognized by Espenshade (1986) and Kline and others (1991) to the south. These high-angle faults strike northwest and offset the basement-cover contact. Cataclastic breccia (Espenshade, 1986) and extensional shear fabrics (Kline and others, 1991) are found in the Marshall Metagranite of the footwall. Elsewhere, clasts of granitoids in the basal Fauquier Formation have a greenschist-facies fabric that Kline and others (1991) and Kline (1991) interpret to be the result of Late Proterozoic extension.

The Middle Proterozoic and Late Proterozoic granitoids and Late Proterozoic metasedimentary rocks are intruded by hundreds of metadiabase dikes and some metarhyolite dikes. The metabasalt dikes are part of a major dike swarm that extends the entire length of the Appalachian orogenic belt and are related to the extensional event that preceded Iapetus rifting (Ratcliffe, 1987). They have also long been interpreted to be feeder dikes to the metavolcanic rocks of the Catoctin Formation that yield ages of 570 to 565 Ma (table 3) for the main phase of continental rifting (Rankin, 1976).

PALEOZOIC

The metavolcanic rocks of the continental rifting are overlain by a fining-upward sequence of sedimentary rocks that record a marine-transgression of the newly formed Iapetus Ocean. Rocks of the Lower Cambrian Chilhowee

Table 3. Geochronology and tectonic history of the Blue Ridge-South Mountain anticlinorium, northern Virginia and southern Maryland.

Epoch/Period/Era	Age (Ma)	Unit	Petrology	Tectonic event	Dating technique	Reference
Early Jurassic	200	Dikes	Diabase	Late-stage continental rifting	Ar/Ar hornblende	Kunk and others, 1992.
Mississippian	340			Greenschist-facies cleavage Alleghanian orogeny	Ar/Ar muscovite	Burton and others, 1992b. Kunk and others, 1993.
Early Cambrian		Tomstown Formation	Dolomite	Passive margin		
		Antietam Formation	Sandstone			
		Harpers Formation	Siltstone	Rift to passive margin transition		
		Weverton Formation	Quartzite			
		Loudoun Formation	Conglomerate, phyllite			
Late Proterozoic	570–565	Catoctin Formation	Metabasalt, metarhyolite	Continental rifting	Rb/Sr pyroxene	Badger and Sinha, 1988.
		Dikes	Metadiabase, metarhyolite	Continental rifting	U/Pb	Aleinikoff and others, 1995.
		Swift Run Formation	Metasedimentary rocks	Alluviation during continental rifting		
	730–700	Robertson River Igneous Suite	Granitoids	Anorogenic pluton of incipient rift	U/Pb	Tollo and Aleinikoff, 1992.
Middle Proterozoic	1000–920	Diorite		Cooling age of granulite-grade Grenville metamorphism	Ar/Ar hornblende	Kunk and others, 1993.
	1058	Leucocratic metagranite			U/Pb	Aleinikoff and others, 1993.
	1060	Charnockite	Diorite, monzonite		Pb/Pb	Herz and Force, 1984.
	1070	Garnet monzogranite		Plutonism of Grenville orogeny	U/Pb	Aleinikoff and others, 1993.
	1110	Hornblende gneiss	Quartz monzonite		U/Pb	Aleinikoff and others, 1993.
	1127±7	Biotite granite			U/Pb	Aleinikoff and others, 1993.
	1092–1139	Granite gneiss			U/Pb	Aleinikoff and others, 1993.
	1144	Porphyroblastic granite gneiss			U/Pb	Aleinikoff and others, 1993
	1800	Paragneiss	Gneiss, schist, quartzite, and phyllonite		Pb/Pb	Herz and Force, 1984.

Group represent the transition from rift to passive continental margin, beginning with conglomerate of the Loudoun Formation and quartzites of the Weverton Formation and ending with carbonate rocks of the Tomstown Formation. These rocks form the base of the Paleozoic Appalachian basin.

The Paleozoic tectonic history of the Appalachian orogen is complex (Hatcher, 1989), and the timing of events affecting the Blue Ridge-South Mountain anticlinorium remains an enigma (Rankin and others, 1989). The Short Hill fault provides evidence of extensional faulting that postdates Early to Middle(?) Cambrian deposition of carbonate rocks, but the tectonic setting is unclear (Southworth, 1993). There is strong evidence of Early and Middle Ordovician (480 to 420 Ma) deformation and metamorphism of the Taconic orogeny along the hinterland of the Appalachians, but evidence for this is lacking in the immediate region (Drake and others, 1989). The Taconic orogeny is thought to be the first major compressive event caused by one stage of the closing of the Iapetus ocean. The Middle Devonian Acadian orogeny of the northern Appalachian and Piedmont provinces was another compressional event during closing of the Iapetus Ocean (Hatcher, 1989), but deformation of this orogeny has not been documented in this region either. The Iapetus Ocean finally closed with the continental collision of North America and Africa during the late Paleozoic Alleghanian orogeny. The Alleghanian orogeny lasted from the Late Mississippian until the Late Permian (340 to 250 Ma) (Hatcher, 1989).

The Blue Ridge-South Mountain anticlinorium has long been interpreted to be an Alleghanian structure because the South Mountain cleavage, which is geometrically associated with it (Cloos, 1951), can be traced westward through rocks as young as Devonian (Mitra and Elliott, 1980). Since cleavage and folds of only one episode of deformation are recognized, Mitra and Elliott (1980) concluded that thrusting, folding, and cleavage were coeval. In general, cleavage on the east limb of the Blue Ridge-South Mountain anticlinorium is steeper than on the west limb, so cleavage fans with respect to the anticlinorium (Cloos, 1951; Mitra and Elliott, 1980). Local and regional variations in the orientation of the South Mountain cleavage have been related to later folding (Cloos, 1951; Nickelsen, 1956; Mitra and Elliott, 1980; Onasch, 1986; Mitra, 1987), the position of different order structures (Mitra, 1987), movement along the North Mountain fault above its foot-

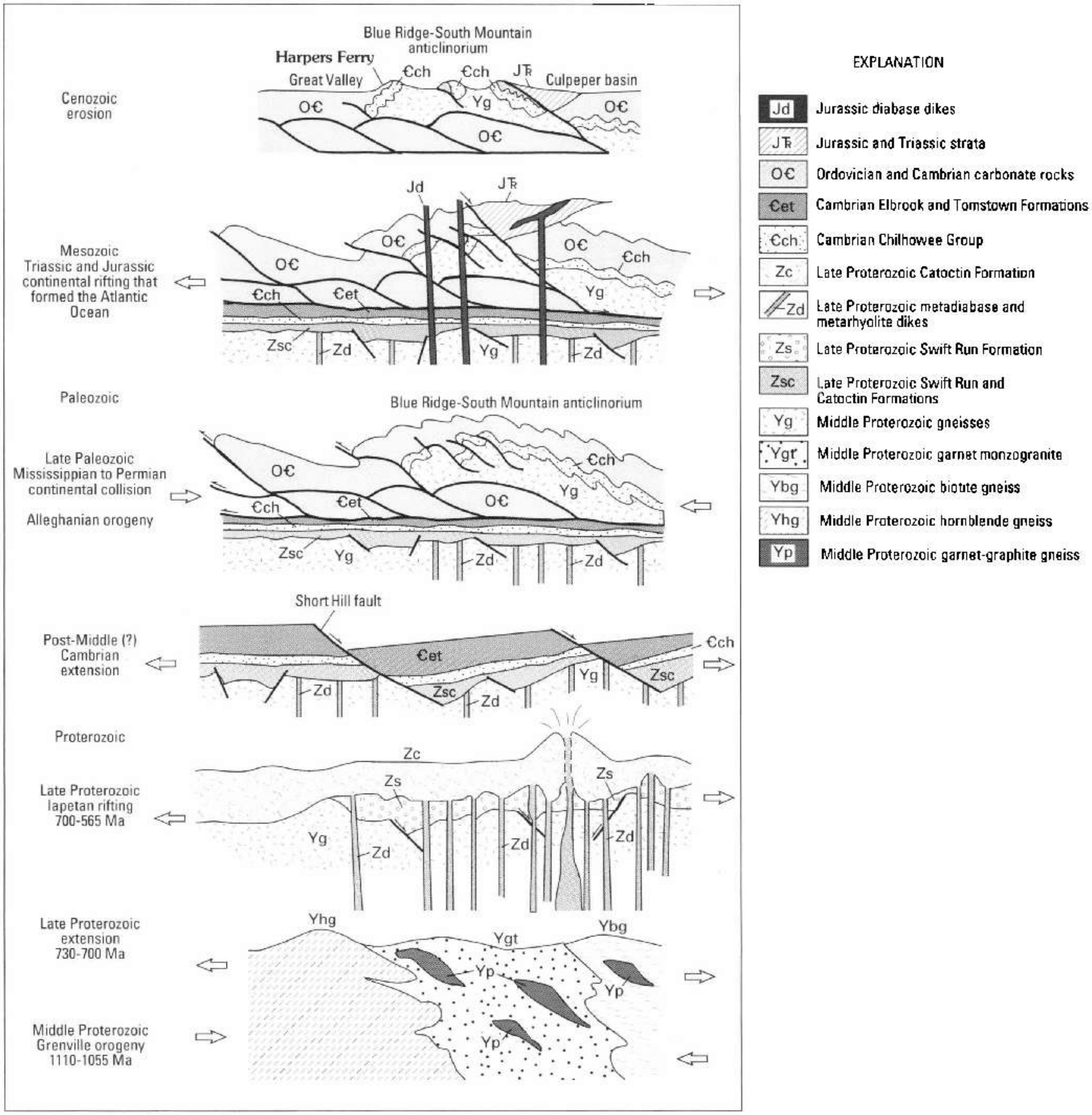


Figure 25. Diagrammatic sketches showing Middle Proterozoic to Cenozoic tectonic history of the Blue Ridge-South Mountain anticlinorium near Harpers Ferry, W.Va.

wall tectonic ramp (Mitra, 1987), and doming by antiformal duplex in the footwall of the Blue Ridge thrust sheet (Southworth, 1993).

The timing of deformation in the Blue Ridge-South Mountain anticlinorium can be determined only by its relation to stratigraphy and metamorphism (Drake and others, 1989). Evans (1991) and Bartholomew and others (1991) suggest that Taconian greenschist-facies foliation was simply transported during Alleghanian deformation and is parallel with Alleghanian cleavage that affected rocks of the foreland. Isotopic dating of muscovite in cleavage in the east limb of the Blue Ridge-South Mountain anticlinorium in this region shows a cooling age of 340 Ma with complex spectra (Burton and others, 1992b; Kunk and others, 1993).

MESOZOIC

The Alleghanian orogeny was followed by extension that led to the opening of the Atlantic Ocean in the Mesozoic. The continental rifting produced isolated half grabens of terrigenous sediments along Paleozoic faults (Root, 1989) on and across the east limb of the Blue Ridge. Syn- and postfaulting sedimentary and igneous rocks that dip to the west across the basins demonstrate listric normal motion along the main border faults. Later extension is shown by swarms of diabase dikes that cut across the basin into the Harpers Ferry quadrangle.

CENOZOIC

A new Wilson cycle began with the Cenozoic deposition of the Coastal Plain strata eroded from the uplifting Blue Ridge-South Mountain anticlinorium. High angle reverse faults that place Lower Cambrian(?) rocks on Cretaceous and Pleistocene strata in the Piedmont and Coastal Plain Provinces demonstrate an active compressive state of stress due to current plate motion (Prowell, 1989).

QUATERNARY BEDROCK LANDSLIDES

Gravitational sag, or sackungen (Zischinsky, 1969), occurs along the east slope of Short Hill Mountain. A 0.5-km-long by 100-m-wide sackungen of quartzite of the Buzzard Knob Member (Ꞓwb) of the Weverton Formation occurs west of the intersection of Virginia State Routes 758 and 852 (pl. 1, ref. loc. 19). The gap exposes 10 to 13 m of northwest-dipping right-side-up quartzite on top of southeast-dipping overturned quartzite, which forms the dip slope west of the gap and a continuous dip slope near the contact with the Catoctin Formation. The leading edge of the sackungen can be traced continuously from end to end; the strike of west-dipping upright beds forms an arc above a linear northeast-striking belt of overturned beds on the dip slope.

A spring in the gap at the sackungen discharges more than 200,000 gallons per day for the Brunswick, Md., municipal water supply (Southworth, 1990). A causal relation between ground water impediment by a diabase dike and increased pore pressure along bedding and joint planes may have initiated the sackungen.

A sackungen is interpreted along the sole of a bedding-parallel thrust fault southeast of White Rock. Quartzite of the Buzzard Knob Member of the Weverton Formation is displaced eastward over a continuous strike belt of the Swift Run and Catoctin Formations that forms the hogback ridge. This area is locally known as the "sand pit," and a 61-m-deep water well in quartzite saprolite discharges more than 75 gallons per minute (Brutus Cooper, Loudoun County Department of Environmental Resources, oral commun., 1990).

A rock block slump of the Catoctin Formation occurs at the end of Virginia State Route 852 near the Potomac River. Approximately 25,000 m^3 of phyllite and metabasalt moved 20 m down slope. West-dipping slaty cleaved rock is exposed at the toe; detachment was along cleavage parallel to the slope. Hemlock trees growing on the rock block slump suggest that the block has been stable for more than a century.

A small landslide immediately north of U.S. Route 340 on the east side of South Mountain lies at the contact of Catoctin Formation and Weverton Formation. The landslide is composed predominantly of colluvium of quartzite and weathered phyllite and is active during wet periods.

SURFICIAL GEOLOGY

Three surficial units were mapped: undifferentiated alluvium and fine colluvial debris (Qal), colluvium (Qc), and alluvial terrace deposits (Qt). Topographic relief and surface-water runoff play an important role in the depositional processes and resultant landforms of these units. Depositional processes include fluvial transport (alluvium), debris flow (debris), as well as gravity and freeze-thaw processes (colluvium). These units are spatially distributed from upper to lower slopes, and each has a characteristic landform (Jacobson and others, 1990). The alluvium and fine colluvial debris underlie sinuous flood plains along creeks and rivers. Alluvial terraces and fine colluvial debris from side slopes are transitional with alluvium and are included with it on the map. Large areas of coarse cobbles, boulders, and blocks of quartzite and metabasalt are shown (by overprint pattern) as colluvium on Blue Ridge-Elk Ridge and Short Hill-South Mountain. The colluvium is concentrated in hillslope depressions as boulder streams, boulder fields (fig. 26), and talus, but virtually all of the mountainous areas are mantled by thin colluvium. Coarse cobbles, boulders, and blocks of quartzite that were transported by colluvial processes are found as debris fans and debris terraces along the Potomac River at Blue Ridge and Short Hill Mountain. The tops of these debris deposits are terraced, which suggests modification by fluvial reworking.

High alluvial terraces of the Potomac River are preserved in Maryland and West Virginia. Well-rounded cobbles, boulders, and small blocks of quartzite exist along the north bank as much as 30 m above the Potomac River.

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Figure 26. Colluvium (Qc) of quartzite of the Weverton Formation forms boulder fields on the lower slope where boulder streams coalesce. Black dog in center is 0.5 m high.

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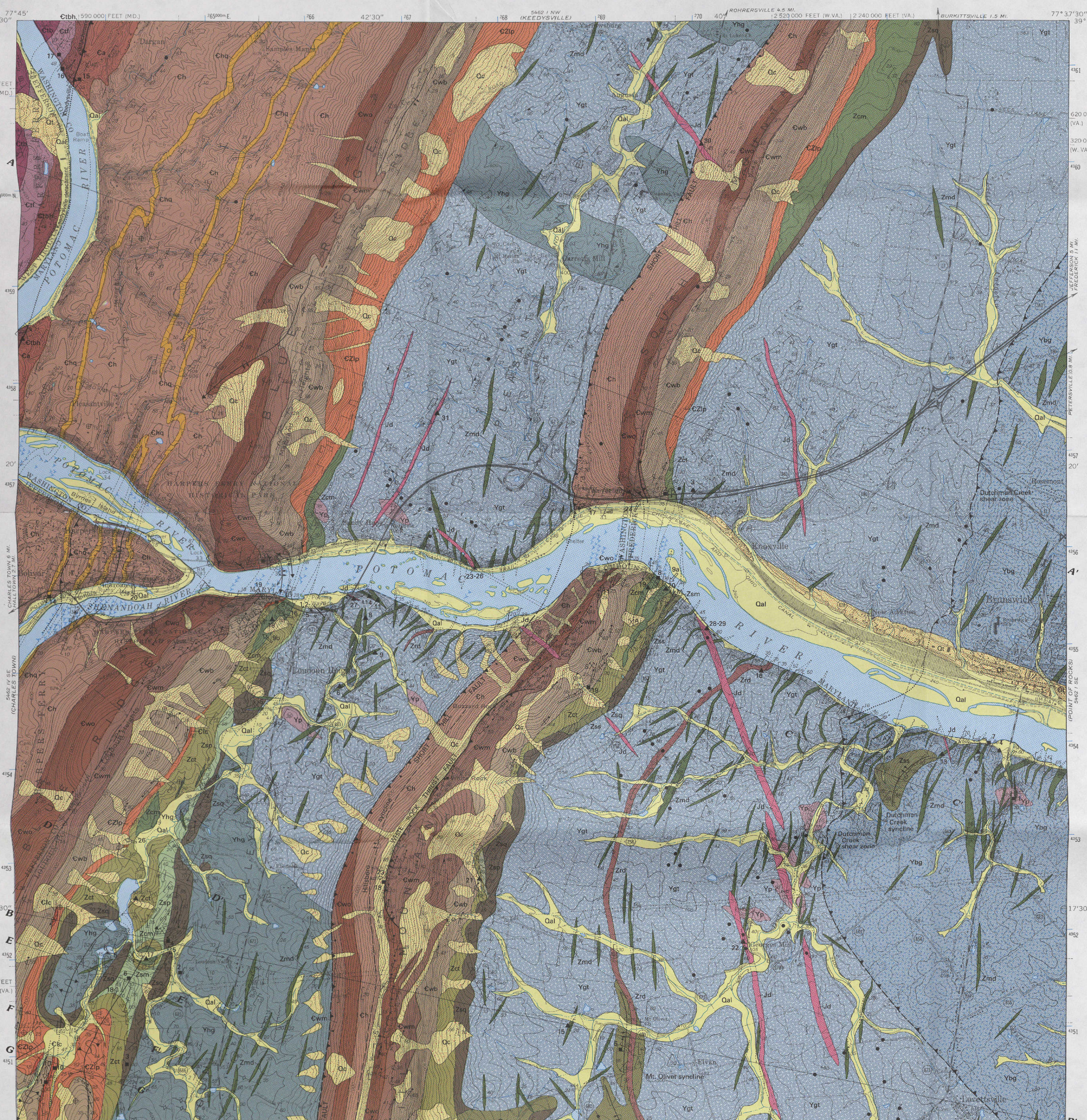
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

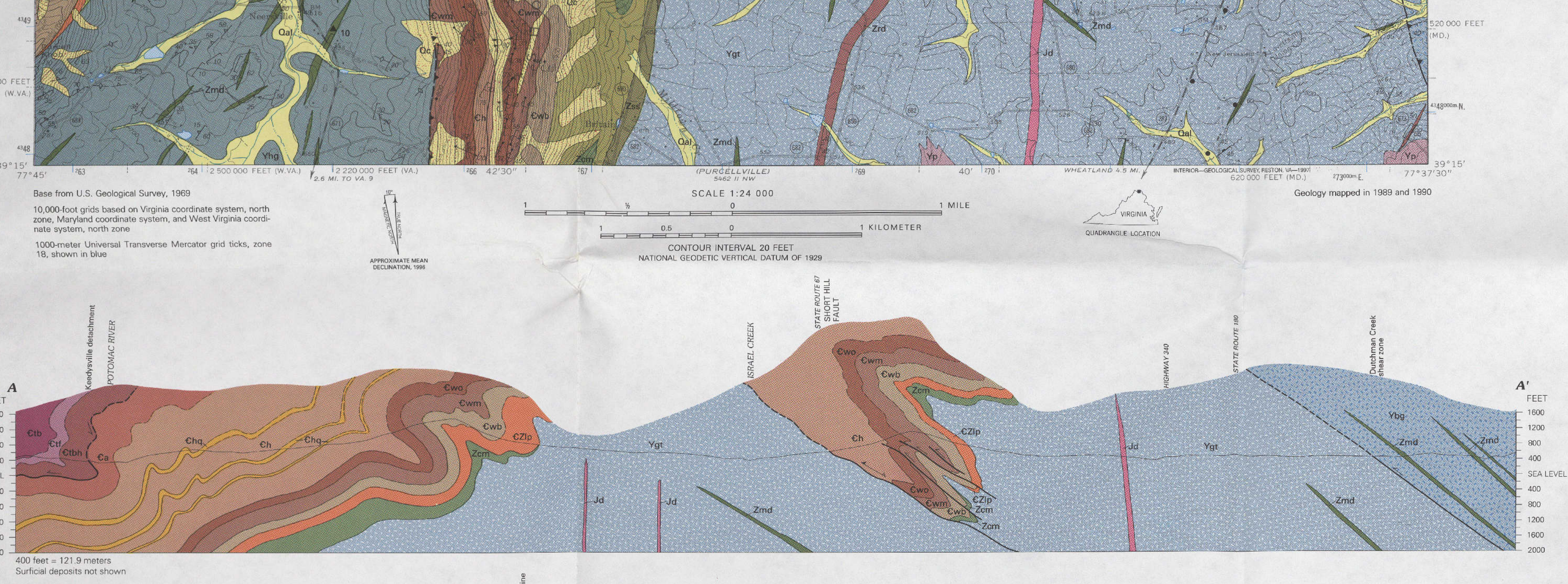
BULLETIN 2123
PLATE 1



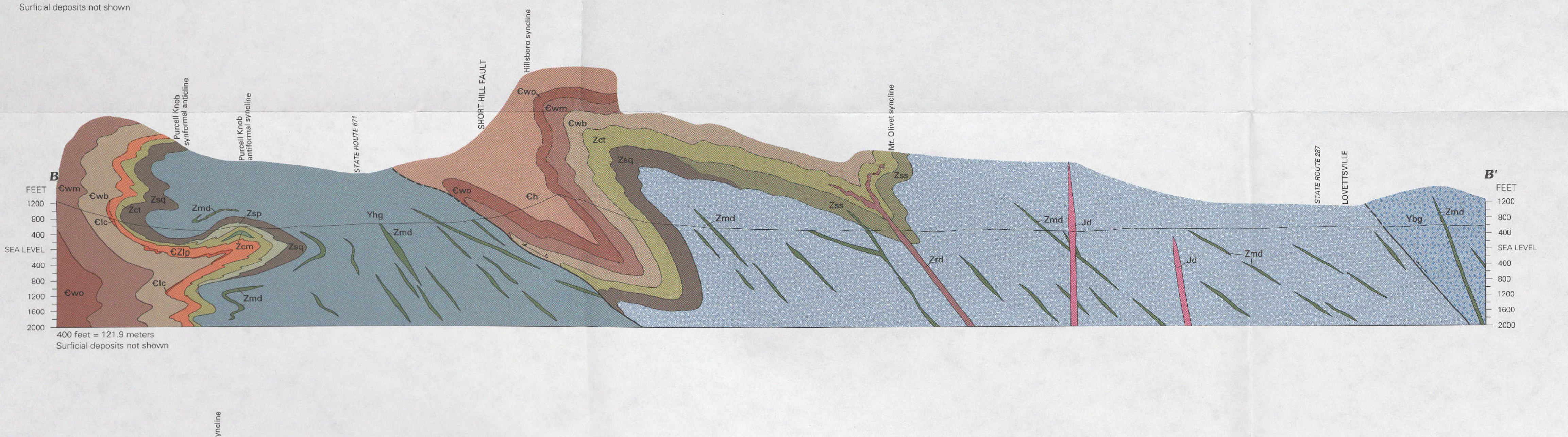
Base from U.S. Geological Survey, 1969
10,000-foot grids based on Virginia coordinate system, north zone, Maryland coordinate system, and West Virginia coordinate system, north zone
1000-meter Universal Transverse Mercator grid ticks, zone 18, shown in blue

SCALE 1:24 000
CONTOUR INTERVAL 20 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

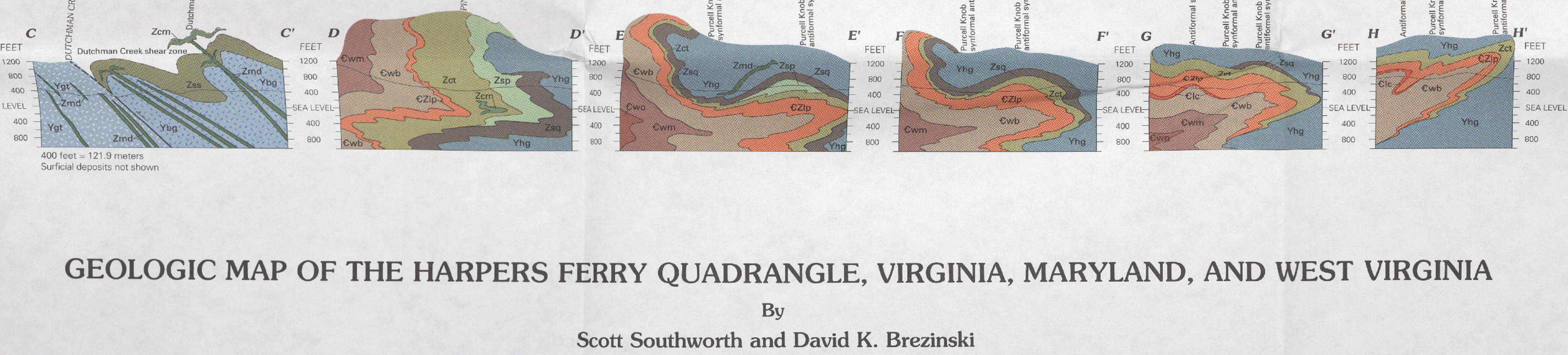
Geology mapped in 1988 and 1990



400 feet = 121.9 meters
Surficial deposits not shown



400 feet = 121.9 meters
Surficial deposits not shown



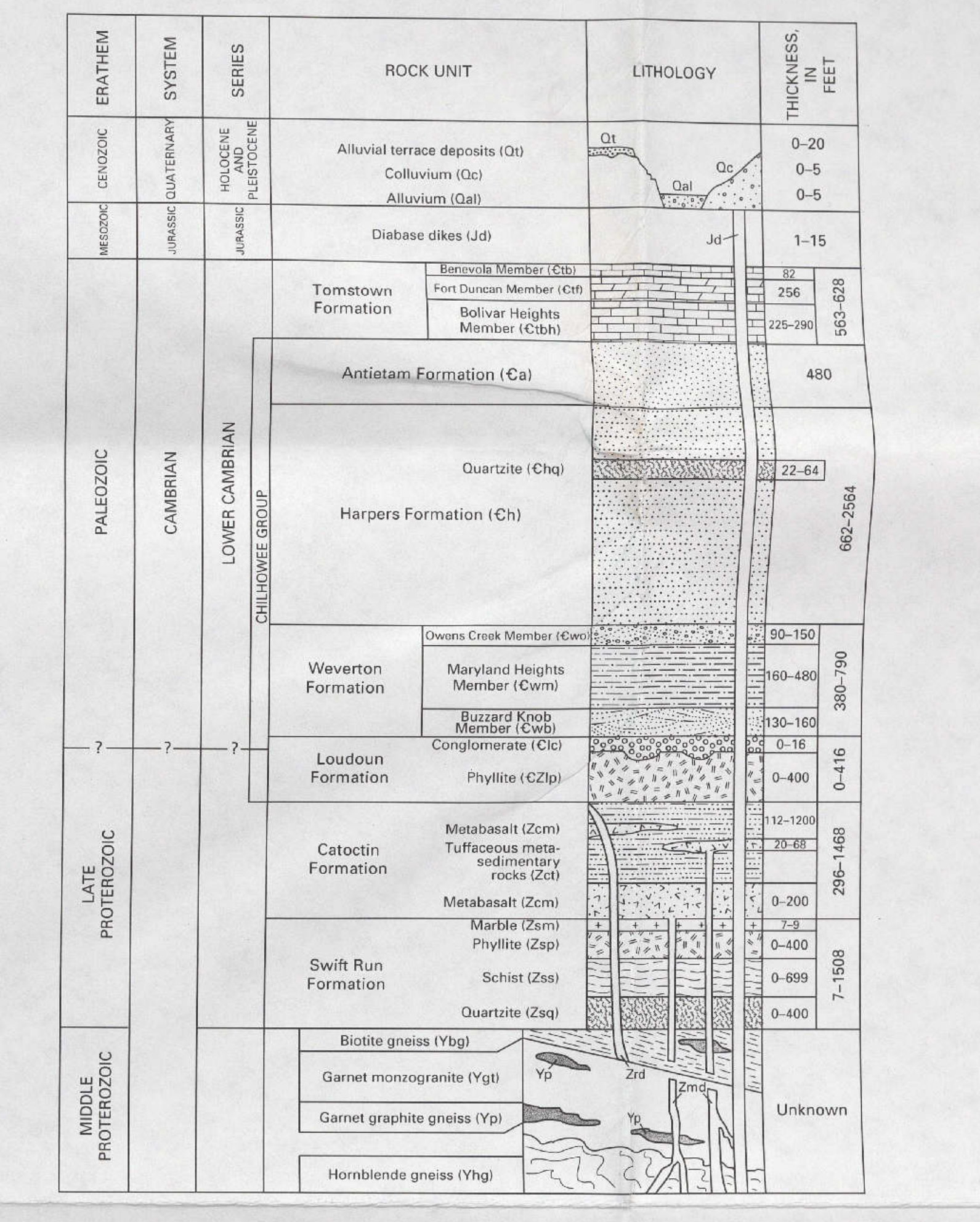
400 feet = 121.9 meters
Surficial deposits not shown

GEOLOGIC MAP OF THE HARPERS FERRY QUADRANGLE, VIRGINIA, MARYLAND, AND WEST VIRGINIA

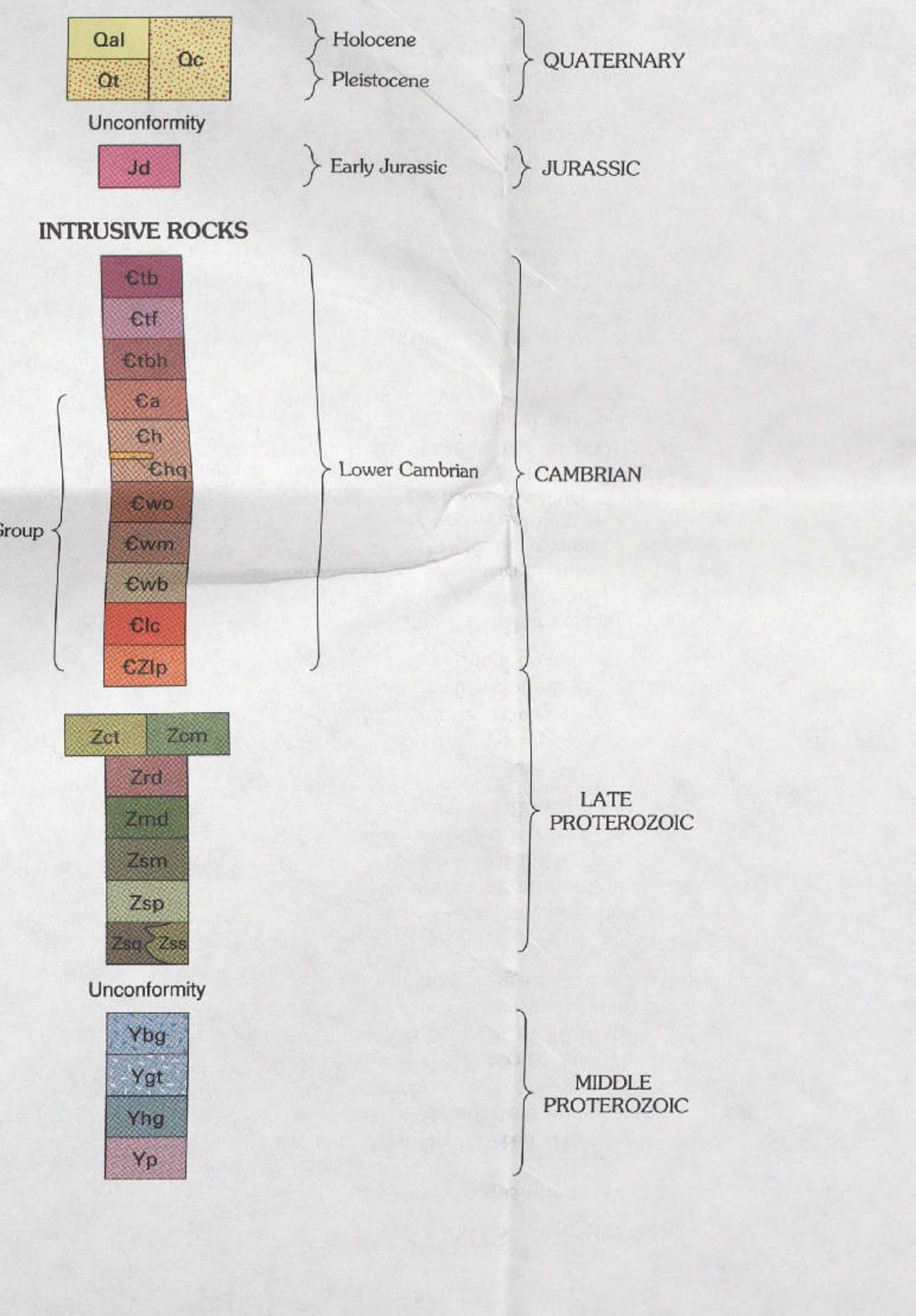
By

Scott Southworth and David K. Brezinski

1996



CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Color designations, in parentheses, are from Goddard and others (1948)

Qal **Alluvium and fine colluvial debris, undifferentiated (Holocene)**—Clay, sand, pebbles, gravel, cobbles, and minor boulders underlying sinuous flood plains along Piney Run, Dutchman Creek, Milltown Creek, Israel Creek, and Little Catoctin Creek and the Potomac and Shenandoah Rivers. Includes alluvial terrace deposits as much as 20 ft above stream channels. Fine colluvial debris from slopes is transitional with alluvium. Sediments are well sorted and are found in fining-upward sequences as much as 20 ft thick

Qc **Colluvium (Holocene and Pleistocene)**—Coarse cobbles, boulders, and large blocks of predominantly quartzite and minor amounts of metabasalt that were transported by gravity, debris flow, and freeze-thaw processes. Abundant on mountain slopes. Includes boulder streams, boulder fields, and talus. Coarse colluvium is concentrated in hillslope depressions and hollows

Qt **Alluvial terrace deposits (Pleistocene)**—Very poorly sorted clay, sand, pebbles, gravel, and boulders from 30 ft to as much as 100 ft above the Potomac River. Clasts are moderately well rounded to well rounded; some quartzite boulders are greater than 5 ft in diameter

Jd **Diabase dikes (Early Jurassic)**—Dark-gray (*N*3), fine-grained to porphyritic diabase composed of quartz, olivine, augite, and plagioclase; weathers to moderate yellowish-brown (10*YR* 5/4). Includes three geochemical types: high-titanium quartz normative, low-titanium quartz normative, and olivine normative. Subvertical linear bodies as much as 330 ft thick are discontinuous and sometimes en echelon. Residual cobbles and boulders are shown as solid dots where trend of dike is unknown. Dike along the Potomac River has a $^{40}\mathrm{Ar}/^{39}\mathrm{Ar}$ age of 200 Ma (Kunk and others, 1992) (sample 1, fig. 3). Ten chemical analyses (samples 22–31) are shown in table 1

Tomstown Formation (Lower Cambrian) (Stose, 1906)

Єtb Benevola Member (Brezinski, 1992)—Yellowish-gray (5*Y* 8/1) to very light gray (*N*8), and white (*N*9), massive, pure, saccharoidal dolomite. Thickness is 82 ft

Єtf Fort Duncan Member (Brezinski, 1992)—Medium-dark-gray (*N*4) to grayish-black (*N*2), medium-bedded, pervasively bioturbated dolomite with very light gray (*N*8) to white (*N*9) sparry dolomite void fillings. Thickness is 256 ft

Єtbh Bolivar Heights Member (Brezinski, 1992)—Medium-dark-gray (*N*4), dark-gray (*N*3) to brownish-black (5*YR* 2/1) thick- to thin-bedded, locally nodular-bedded limestone, containing olive-gray (5*Y* 4/1) to olive-black (5*Y* 2/1), locally anastomosing, burrows. Basal 45 ft is a pinkish-gray (5*Y* 8/1) to light-gray (*N*7) laminated marble. Thickness ranges from 226 to 289 ft

CHILHOWEE GROUP

Єa **Antietam Formation (Lower Cambrian) (Keith, 1894)**—Very light gray (*N*8) to yellowish-gray (5*Y* 7/2) quartzite and dark-greenish-gray (5*G* 4/1) phyllitic metasiltstone that contains *Skolithos* tubes (Nickelsen, 1956). The base is gradational downward into the Harpers Formation. The top is gradational upward into the Bolivar Heights Member of the Tomstown Formation and, locally, is a fault zone. Thickness is estimated at 480 ft

Єh **Єhq** **Harpers Formation (Lower Cambrian) (Keith, 1894; King, 1950)**—Predominantly dark-greenish-gray (5*G* 4/1) to brownish-gray (5*YR* 4/1), laminated to massively bedded, highly cleaved, phyllitic metasiltstone; bedding is obscure. Meta-arkose, sandy metasiltstone, fine pebble conglomerate, magnetite-rich metasiltstone, and calcareous metasiltstone are found locally from the base to middle part of unit. Locally contains fine-grained, thin-bedded, dark-greenish-gray (5*G* 4/1), 22- to 64-ft-thick metasandstone (Єhq) interbedded with metasiltstone. Base is locally sharp but transitional with underlying quartz-pebble conglomeratic quartzite of Owens Creek Member of the Weverton Formation. Top is not exposed in map area. Thickness ranges from about 600 to 900 ft on Short Hill-South Mountain and is 2,500 ft on Blue Ridge and Elk Ridge

Weverton Formation (Lower Cambrian) (Keith, 1894; King, 1950)

Єwo Owens Creek Member (Brezinski, 1992)—Dusky-blue (5*PB* 3/2) to dark-gray (*N*3) quartz-pebble conglomerate and greenish-gray (5*G* 6/1) quartz-pebble conglomeratic quartzite, metasiltstone, and interbedded quartzite. Poorly sorted, medium to thick bedded, graded, and crossbedded. Contains local accumulations of magnetite, heavy minerals, red jasper, red quartz, and phyllite clasts. Pebbles commonly are 0.4 in. in diameter. Top of unit is a sharp contact occurring at top of quartz-pebble conglomeratic quartzite; bottom of unit is gradational with the metasiltstone of the Maryland Heights Member. Thickness is 105 ft on Short Hill-South Mountain and 90 to 150 ft on Blue Ridge-Elk Ridge

Єwm Maryland Heights Member (Brezinski, 1992)—Interbedded, dark-greenish-gray (5*GY* 4/1) metasiltstone and dusky-blue (5*PB* 3/2) to greenish-gray (5*G* 6/1), very coarse grained to granular quartzite. Quartzite beds vary from 16 to 32 ft in thickness. Total thickness ranges from 160 to 480 ft

Єwb Buzzard Knob Member (Brezinski, 1992)—Light-gray (*N*7) to medium-light-gray (*N*6), medium- to fine-grained, well-sorted, graded, and crossbedded quartzite. Massive to thick bedded at base and top. Middle part is thin bedded and contains light-gray (*N*7) phyllitic metagraywacke and metasiltstone. Lower part is locally arkosic and overlies conglomerate and phyllite of the Loudoun Formation, metabasalt of the Catoctin Formation, or locally, hornblende gneiss. Total thickness ranges from 130 to 160 ft

Loudoun Formation (Late Proterozoic? and Lower Cambrian) (Stose and Stose, 1946)

Єlc Conglomerate (Lower Cambrian)—Small cobble to very coarse pebble conglomerate of rounded to subrounded white, blue, and red quartz, gneiss, red jasper, and variegated phyllite in grayish-black (*N*2), hematite-rich siltstone matrix. Pebbles commonly are 0.4 to 0.8 in. in diameter but are as large as 2.4 in. Contains local beds of fine pebble conglomerate and graded, crossbedded quartzite. At most places this unit is in sharp contact with underlying phyllite; at other places, contact is gradational. Unit is podiform and discontinuous and may be local channel fill. Unit has a maximum thickness of 16 ft and is restricted to Blue Ridge

ЄZlp Phyllite (Late Proterozoic? and Lower Cambrian?)—Consists of gray-black (*N*2), light-olive-gray (5*Y* 6/1) to light-gray (*N*7), fine-grained phyllite containing tuffaceous clasts and elongated amygdules. Top is a sharp, possibly unconformable, contact with overlying conglomerate of the Loudoun. Base is transitional with tuffaceous metasedimentary rocks of the Catoctin Formation (Zct). Unit contains very fine pebbles of quartz that increase in number upward. Ranges in thickness from 0 to 400 ft, but commonly is less than 200 ft

Catoctin Formation (Late Proterozoic) (Keith, 1894; Bloomer and Bloomer, 1947)

Zcm Metabasalt—Dark-greenish-gray (5*G* 4/1) to medium-bluish-gray (5*B* 5/1), fine-grained to aphanitic, massive to schistose metabasalt (greenstone) composed of actinolite, chlorite, epidote, quartz, and albite. Includes amygdaloidal metabasalt and agglomeratic metabasalt breccia that contains epidosite. Epidosite bodies as much as 3 ft in diameter are present locally. Locally interlayered with tuffaceous metasedimentary rocks unit (Zct). Individual flows range in thickness from 20 to 68 ft, but unit ranges from 0 to 164 ft on Short Hill Mountain and 0 to 200 ft on Blue Ridge. Five chemical analyses (samples 17–21) are shown in table 1

Zct Tuffaceous metasedimentary rocks—Pink-gray (5*YR* 8/1), medium-light-gray (*N*6), light-brownish-gray (5*YR* 6/1), and medium-black-gray (*N*4) tuffaceous phyllite and schist, mud-lump breccia, and dark-greenish-gray (5G 4/1), thin-bedded metabasalt. Light-greenish-gray (5GY 8/1) metarhyolite tuff is locally present. Unit is locally interlayered with the metabasalt unit (Zcm). Top grades into the overlying phyllite of the Loudoun Formation (ЄZlp). Unit is generally covered but is well exposed adjacent to massive metabasalt. Outcrop width suggests a *maximum thickness of 1,200 ft on Short Hill Mountain and 499 ft on Blue Ridge. More than 112 ft crops out in and along the Potomac River at Short Hill Mountain*

Zrd ***Metarhyolite dikes (Late Proterozoic)****—Light-gray (N7) to medium-light-gray (N6), fine-grained to aphanitic metarhyolite that contains grayish-yellow (5Y 8/4) potassium feldspar phenocrysts. A 164-ft-wide dike intrudes basement gneiss and the Swift Run Formation. Medium-gray (N5) to medium-dark-gray (N4) tuffaceous metarhyolite containing quartz-filled amygdules and light-gray (N7) fragments of metarhyolite as much as 2 in long is found as float adjacent to dike along Potomac River.* One chemical analysis (sample 16) is shown in table 1

Zmd **Metadiabase dikes (Late Proterozoic)**—Dark-greenish-gray (5*G* 4/1), medium-grained to aphanitic metadiabase composed of actinolite, chlorite, epidote, and albite. Dikes range in thickness from 0.4 in to 164 ft. In places, metadiabase is coarse grained to porphyritic and commonly has masses of epidosite. Common in basement rocks and less abundant in the Swift Run Formation. Compositionally similar to the metabasalt of the Catoctin Formation (Zcm). Ten chemical analyses (samples 6–15) are shown in table 1

Swift Run Formation (Late Proterozoic) (Jonas and Stose, 1939; King, 1950)

Zsm Marble—Pinkish-gray (5*YR* 8/1) and yellowish-gray (5*Y* 8/1) to light-brownish-gray (5*YR* 6/1), fine-grained, dolomitic marble found as 7- to 9-ft-thick discontinuous pods at or near the top of formation

Zsp Sericitic phyllite—Variegated, sericitic phyllite interbedded with thin, discontinuous beds of dark-gray (*N*3) to light-olive-gray (5*Y* 6/1) arkose and sandstone. Restricted to Purcell Knob antiformal syncline where intense deformation has tectonically mixed the lithologies with quartz veins and some metabasalt dikes. Base of unit is top of sericitic metasandstone. Top of unit is transitional with overlying tuffaceous metasedimentary rocks (Zct) of the Catoctin Formation. Thickness ranges from 0 to 400 ft

Zss Quartz sericite schist—Light-gray (*N*7), pale-olive (10*Y* 6/2), and dusky-yellow (5*Y* 6/4) to moderate-yellowish-brown (10*YR* 5/4) quartz sericite schist and pale-olive (10*Y* 6/2) fine pebble conglomerate that contains rounded to subrounded white and blue quartz pebbles, abundant sericite, and sparse chlorite. Quartz sericite schist may be either a fining-upward sequence above metasandstone or a product of deformation; bedding was not recognized. Thickness ranges from 0 to 298 ft on Blue Ridge to more than 699 ft in synclines east of Short Hill Mountain

Zsq Sericitic quartzite and metasandstone—Pinkish-gray (5*YR* 8/1), yellowish-gray (5*Y* 8/1), light-greenish-gray (5*GY* 8/1), medium-gray (*N*5), and light-olive-gray (5*Y* 6/10) to greenish-gray (6*GY* 6/1), sericite-rich, very coarse to medium-grained quartzite and metasandstone that contains rounded quartz cobbles as much as 4 in. in diameter. Also includes sericite-rich, matrix-supported or clast-supported, rounded, coarse quartz-pebble conglomerate. Graded beds and crossbeds are common as are elongate phyllite clasts as much as 3 in. in length. Unit unconformably overlies Middle Proterozoic basement gneiss and grades laterally into quartz sericite schist (Zss). Paleoregolith of weathered gneiss locally forms the base. Thickness ranges from 0 to 400 ft, but most outcrops are 33 ft wide

Ybg **Biotite gneiss (Middle Proterozoic)**—Medium-light-gray (*N*6) to light-olive-gray (5*Y* 6/1), equigranular, biotite-bearing gneiss that contains light-brown (5*YR* 6/4), porphyroblastic to porphyroclastic feldspar augen as much as 2 in long. Unit is mylonitized in the Dutchman Creek shear zone. Unit has compositional phases of granodiorite and granite and contains about 41 to 50 percent plagioclase, 30 percent quartz, 20 to 30 *percent potassium feldspar, and as much as 10 percent biotite. Unit has a U/Pb upper intercept age of 1055±5 Ma (Aleinikoff and others, 1993). One chemical analysis (sample 4) is shown in table 1*

Ygt **Garnet monzogranite (Middle Proterozoic)**—*Very coarse to medium-*grained, equigranular to granoblastic, almandine-bearing leucocratic monzogranite. Typically massive, but locally is gneissic and mylonitized. Contains very light gray (N8) to light-gray (N7) feldspar with medium-gray (N5) quartz as much as 0.2 in. in diameter and dusky-red (5R 3/4), euhedral to anhedral almandine garnet as much as 0.2 in. in diameter. Garnet can be highly fractured with lineated blebs of chlorite and sericite. Composed of quartz, microperthite, microcline, myrmekite, albite (An$_{10}$), oligoclase (An$_{20-30}$), andesine (An$_{40-50}$), and symplectic biotite and minor amounts of chlorite, illmenite, zircon, sphene, epidote, leucoxene, and clinozoisite. Modal composition ranges from 35 to 40 percent potassium feldspar, 28 to 32 percent plagioclase feldspar, and 28 to 29 percent quartz; almandine garnet makes up 2 to 5 percent of unit. Unit has a U/Pb upper intercept age of 1070 Ma (Aleinikoff and others, 1993) (sample 5, fig. 3). Three chemical analyses (samples 1–3) are shown in table 1

Yhg **Hornblende gneiss (Middle Proterozoic)**—Medium-light-gray (*N*6) to medium-gray (*N*5), equigranular to granoblastic, hornblende-bearing gneiss with quartz monzonite and granite phases. Usually massive to well foliated, but granite phase is compositionally layered with augen. Composed of 36 to 49 percent perthite and microperthite, 27 to 45 percent saussuritized plagioclase (oligoclase, An$_{15-30}$), 18 to 27 percent quartz, less than 10 percent orthopyroxene (possibly hypersthene) and biotite, 10 to 20 percent hornblende in crystals 0.2 to 0.4 in long, and minor amounts of epidote, sericite, titanite, and opaque minerals. Unit has a preliminary U/Pb upper intercept age of 1110 Ma (Aleinikoff and others, 1993) (sample 6, fig. 3). One chemical analysis (sample 5) is shown in table 1

Yp **Garnet graphite gneiss (Middle Proterozoic?)**—Light-brown (5*YR* 6/4) to moderate-brown (5*YR* 4/4) garnet graphite gneiss composed of 25 percent quartz, 20 percent chlorite (clots), 20 percent saussuritized plagioclase, 10 to 20 percent graphite (flecks and books), and 10 percent almandine. *Produces a distinctive rusty, brick-red soil. Origin of these rocks is uncertain, but they are interpreted to be metasedimentary rocks that were assimilated by the granitoids*

EXPLANATION OF MAP SYMBOLS

Contact—Approximately located; dashed where inferred; dotted where concealed

Mylonite and cataclasite zone—Showing strike of mylonitic foliation

FAULT

Thrust fault—Approximately located; dashed where inferred; dotted where concealed. Sawteeth on upper plate

Overturned thrust fault—Dotted where concealed. Sawteeth on upper plate and teeth show direction of dip

Normal fault—Ball and bar on downthrown block

Reactivated fault—Dashed where inferred; dotted where concealed. Ball and bar on downthrown block of early normal fault and sawteeth on upper plate of later thrust fault. In cross section, open arrow shows early motion and solid arrow shows late motion

FOLDS

Overturned anticline—Dashed where approximately located; dotted where concealed. Showing trace of axial surface, direction of dip of limbs, and, where known, direction of plunge

Synformal anticline—Dotted where concealed. Showing trace of axial surface and direction of plunge

Overturned syncline—Dashed where approximately located; dotted where concealed. Showing trace of axial surface, direction of dip of limbs, and, where known, direction of plunge

Antiformal syncline—Dotted where concealed. Showing trace of axial surface and direction of plunge

Minor anticline*—Showing bearing and plunge of axis*

PLANAR FEATURES

(May be combined with each other or with linear features)

Strike and dip of bed—Ball indicates top of bed known from sedimentary structures

21 Inclined
78 Overturned
46 Rotated more than 180°
Vertical
⊕ Horizontal
Horizontal and inverted

Strike and dip of gneissic foliation in Middle Proterozoic rocks

36 Inclined
Vertical

Strike and dip of cleavage

20 Inclined
Vertical
Horizontal

32 **Strike and dip of crenulation cleavage**

12 **Strike and dip of shear band cleavage**

Strike and dip of joint

25 Inclined
Vertical

Bedrock landslide (Schultz and Southworth, 1989)—Hachures on escarpment; arrow shows direction of downslope movement

Sackungen (gravitational sag)
Rock block slump

LINEAR FEATURE

(May be combined with planar features)

10 **Bearing and plunge of mineral lineation**

OTHER FEATURES

S **Quarry**—S, sandstone or quartzite; M, marble; F, hematite; A, gold

● **Jurassic diabase boulder**

3▲ **Geochemical sample locality**—Number refers to table 1

5△ **Isotopic (age date) sample locality**—Location of samples 1, 5, and 6 are shown; see text figure 3 for location of samples 2, 3, and 4

6■ **Reference locality**—See text for discussion

Drill core hole

4 **Location of photograph cited in text showing perspective and figure number**

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