Geology of the Marshall Quadrangle, Fauquier County, Virginia

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By Gilbert H. Espenshade

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GEOLOGY OF THE MARSHALL QUADRANGLE, FAUQUIER COUNTY, VIRGINIA

By Gilbert H. Espenshade

Abstract

The Marshall Metagranite, about 1 billion years old, is exposed in a small area of the Marshall quadrangle, Fauquier County, Virginia, and is overlain by the Fauquier Formation of Late Proterozoic age, consisting of metamorphosed conglomerate, arkose, siltstone, laminated shale, and dolomitic rock. Thickness of the Fauquier is estimated to range between 650 and 1,950 m. The succeeding Late Proterozoic Catoctin Formation consists mainly of metamorphosed basalt breccia and lava whose chemical compositions fall into two suites. The low-titanium suite, comprising the volcanic breccia zone in the lower part of the Catoctin, has a smaller content of TiO_2 and less iron and more MgO than the high-titanium suite, which consists of overlying volcanic breccia and lava. Total thickness of the Catoctin is conjectural but may be at least 3 km; thickness of the low-titanium breccia zone ranges between 220 and 1,000 m, and thickness of the high-titanium breccia zone ranges between 0 and 900 m. Thin, lenticular beds of arkosic quartzite and phyllite occur at several horizons within the Catoctin. All rock types are intruded by a multitude of Late Proterozoic metadiabase dikes, whose chemical composition is very similar to that of the high-titanium volcanic rocks. Many of these dikes were probably feeders to the basaltic volcanics of the Catoctin. The Fauquier sediments and the Catoctin basalts were deposited in a nonmarine environment under conditions of widespread crustal rifting accompanied by intrusion of swarms of diabase dikes. These events were precursory to the opening of the Iapetus Ocean at the end of the Proterozoic or start of the Paleozoic. Cambrian and Ordovician and possibly younger sedimentary rocks must have been deposited above the Catoctin, but no Paleozoic rocks now occur in the quadrangle. All the Proterozoic rocks, as well as the covering Paleozoic rocks, were strongly deformed by folds, faults, and pervasive foliation and were metamorphosed in

the greenschist facies during one or more Paleozoic orogenies; tectonic activity ended during the Allegheny orogeny of late Paleozoic time. Paleozoic orogeny produced the Blue Ridge anticlinorium, a long, major uplift that extends across the states of Virginia and Maryland into southern Pennsylvania; the Marshall quadrangle is on the eastern flank of the anticlinorium. Seismic surveys elsewhere in the Blue Ridge anticlinorium indicate that its core of Middle Proterozoic plutonic rocks is detached from its roots and the entire complex uplift thrust westward over Paleozoic strata. The Culpeper basin of nonmetamorphosed Triassic and Jurassic rocks is a few kilometers east of the quadrangle. Diabase dikes of Triassic and Jurassic age intrude the rocks of the Culpeper basin as well as the Proterozoic rocks of the anticlinorium.

INTRODUCTION

Geologic mapping of the Marshall quadrangle and the adjacent Rectortown quadrangle in Fauquier and Loudoun Counties, Virginia, was begun in 1973 to determine the geologic characteristics of the Precambrian rocks of the region--granitic rocks of Middle Proterozoic age that are overlain by Late Proterozoic metasedimentary and metavolcanic rocks. Work in the Marshall quadrangle was completed in 1980; mapping of the Rectortown quadrangle is incomplete.

Geologists of the State of Virginia had previously mapped to the south (Furcron, 1939) and to the north (Parker, 1968) of the Marshall quadrangle and were mapping to the west (Lukert and Nuckols, 1976) and southwest (Lukert and Halladay, 1980) during the Marshall project. J. W. Clarke of the U.S. Geological Survey was mapping the geology of the Orlean quadrangle (just west of the Marshall quadrangle) during the same period and collaborated with me in a preliminary account of the geology of the area (Espenshade and Clarke, 1976). A study with B. A. Morgan III and David Gottfried of the U.S. Geological Survey of the chemistry of the Late Proterozoic basaltic volcanic rocks is in progress.

My studies have benefited from field and office consultations with most of the above geologists and with other colleagues of the U.S. Geological Survey. I thank J. W.

Clarke and N. M. Ratcliffe for their perceptive reviews of this paper.

GENERAL GEOLOGY

The Marshall quadrangle is on the eastern limb of the Blue Ridge anticlinorium, a major linear uplift that extends northeasterly across the States of Virginia and Maryland (fig. 1) and into southern Pennsylvania. The uplift is also known as the South Mountain anticlinorium in Maryland and Pennsylvania and was called the Catoctin Mountain-Blue Ridge anticlinorium by Jonas and Stose (1939). The irregular ridges and peaks of the Blue Ridge lie along the western side of the anticlinorium.

Middle Proterozoic plutonic rocks, mostly gneissic granitic rock and subordinate paragneiss, make up the core of the anticlinorium (Bloomer and Werner, 1955; Espenshade, 1970; Bartholomew and others, 1981; Force and Herz, 1982). Zircon ages of these rocks are mostly in the 1,000- to 1,150-million-year (m.y.) range, but some are as old as 1,800 m.y. (Tilton and others, 1960; Lukert and others, 1977; Bartholomew and others, 1981; Force and Herz, 1982). Some of these rocks are intruded by a group of Late Proterozoic granitic plutons that have yielded zircon ages of about 650 to 730 m.y. (Rankin, 1975; Lukert and Clarke, 1981; Lukert and Banks, 1982).

Metasedimentary and metavolcanic rocks of Late Proterozoic age overlie the plutonic rocks. In northern Virginia the metasedimentary rocks were mostly conglomerate, arkose, siltstone, and shale, originally, whose clastic components were largely derived from the older plutonic rocks. These metasedimentary rocks have been called the Swift Run, Fauquier, and Mechum River (Gooch, 1958) Formations at various localities. A thick sequence of metavolcanic rocks, the Catoctin Formation, lies above the Swift Run and Fauquier. Basalt flows are the dominant type of volcanic rock in the region, but basalt breccias are abundant in and near the Marshall quadrangle, and rhyolite is widespread farther north in Maryland and Pennsylvania. A zircon age of about 820 m.y. has been obtained from the rhyolite (Rankin and others, 1969); this age for the Catoctin is not compatible with geologic relations in northern Virginia, where a younger Proterozoic age is indicated, as is discussed in a later section. Swarms of diabase dikes, many

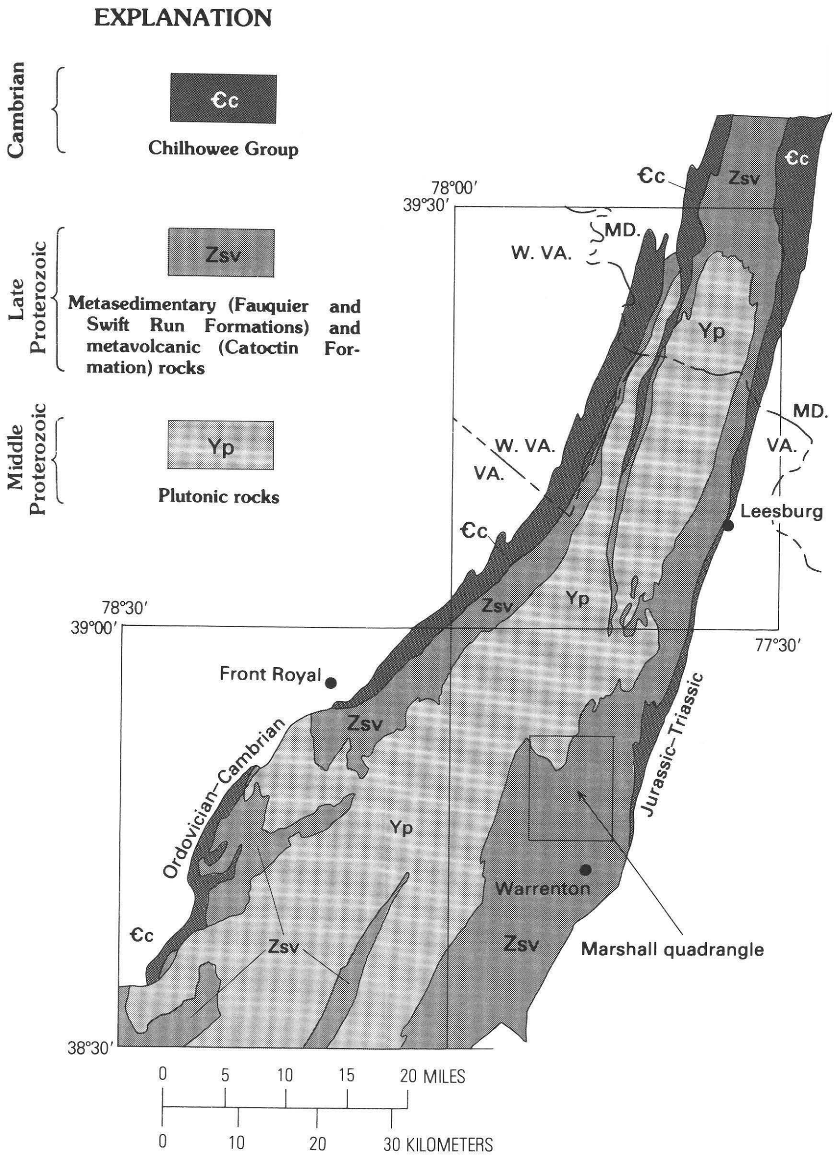

FIGURE 1.—Generalized geologic map of the northern part of the Blue Ridge anticlinorium showing location of the Marshall quadrangle.

of which were probably feeders to basalt flows, are intruded into the Proterozoic rocks.

Lower Cambrian quartzite and schist (Chilhowee Group) are above the Catoctin on both limbs of the anticlinorium and are succeeded in turn by Cambrian and Lower Ordovician carbonate and terrigenous sedimentary rocks along the western limb and on the eastern limb near Frederick, Maryland. However, along the eastern limb to the north and south of Frederick, the Chilhowee is in fault contact with the large basin of Triassic and Jurassic clastic sedimentary rocks that extends from near Culpeper, Virginia, north into Pennsylvania.

The Blue Ridge anticlinorium was formed in the Paleozoic during a period or periods of very strong, northwestward-directed deformation that ended in the Allegheny orogeny. All Precambrian rocks of the Marshall quadrangle and vicinity were metamorphosed in the greenschist facies during Paleozoic orogeny; plutonic rocks were strongly deformed by cataclasis. Regional geologic and seismic evidence suggests that the northern Blue Ridge anticlinorium may be unrooted and that Paleozoic sedimentary rocks may underlie the Precambrian rocks of the Marshall quadrangle at depths of 5 to 10 km.

MIDDLE PROTEROZOIC ROCKS

Marshall Metagranite

The Precambrian granitic rock that underlies the northwestern part of the Marshall quadrangle (pl. 1) is mostly fine-grained, dark gray, gneissic granite (Streckeisen, 1973) whose dominant minerals are quartz, plagioclase, and potassium feldspar; epidote, sericite, and fine-grained biotite are minor minerals (pl. 1, ref. locality 1). Chemical analysis of a sample from reference locality 1 is given in table 1. This type of granite was originally called the Marshall Granite by Jonas (Virginia Geological Survey, 1928) and is herein adopted as the Marshall Metagranite for use by the U.S. Geological Survey; it is widespread in the Orlean quadrangle to the west of the Marshall quadrangle (J.W. Clarke, personal communication, 1975) and also in the Rectortown quadrangle to the north of Marshall. Medium- to coarse-grained granite that has bluish-gray quartz, plagioclase, megacrysts of potassium feldspar, and considerable biotite occurs in a vaguely defined, elongated area just east of Marshall (pl. 1, ref. locality 2); this granite is mapped as a variety of the Marshall, although it is not certain that it is genetically related.

TABLE 1.—*Chemical analysis of Marshall Metagranite from the Marshall quadrangle, Virginia*

[Sample collected by J. W. Clarke from large outcrop (behind old school building) about 210 m N. 30° E. from BM 682, Marshall, Virginia (pl. 1, ref. locality 1). Analysis done in the laboratories of the U.S. Geological Survey by method as described under "single solution" (Shapiro, 1975). Field no. Ma; laboratory no. W186820; H. Smith, analyst]

Component	Percent
SiO_2	70.9
Al_2O_3	15.2
Fe_2O_3	1.4
FeO	1.0
MgO	0.82
CaO	1.1
Na_2O	4.6
K_2O	3.7
H_2O^+	.76
H_2O^-	.10
TiO_2	.29
P_2O_5	.17
MnO	.01
CO_2	.02
Sum	100

Zircons from a sample of Marshall Metagranite collected by M. T. Lukert from reference locality 1 were analyzed in the laboratories of the U.S. Geological Survey and yielded a $^{207}Pb/^{206}Pb$ age of 1,010 m.y.; the lead-uranium ages are slightly discordant (T.W. Stern, written communication, 1976).

The Marshall was intensely deformed and metamorphosed at biotite grade in the greenschist facies during the Paleozoic orogeny. Irregularly spaced cataclastic foliation was widely developed, some original minerals were recrystallized, and new minerals were formed. Much of the quartz was recrystallized to irregular mosaics of fine-grained quartz. Potassium feldspars were flattened, and plagioclase was pervasively saussuritized to sericite and epidote; these two alteration minerals also occur in thin veinlets that cut potassium feldspar and quartz. Fine-grained biotite is commonly associated with, and is evidently contemporaneous with, sericite and epidote. The rock is best called metagranite because of the thorough low-grade metamorphism.

An inconspicuous, compositional layering is present in the Marshall at a few places that is cut discordantly by the Paleozoic foliation. This layering must be Middle Proterozoic in age and may represent a metamorphic event of that age or may be flow layering formed during intrusion of the granite.

The Marshall Metagranite is well exposed at many places except in the area east and southeast of Marshall. Distinctive soils that are unlike those of the arkosic rocks of the Fauquier are developed on the metagranite (Petro and others, 1956). These soil varieties consist of yellowish-brown to brown, micaceous silt clay loam, gritty clay loam, loam, and sandy loam.

LATE PROTEROZOIC ROCKS

Fauquier Formation

General features

Most of the Fauquier Formation is arkosic in nature and is composed largely of detrital material that was derived from the older granitic terrane. Size of the detritus decreases progressively from the lower part to the top of the Fauquier. The lower part of the formation consists of coarse meta-arkose and also thin, lenticular beds of meta-arkosic conglomerate near the base. The upper part of the Fauquier is mainly alternating beds of fine-grained meta-arkose and metasiltstone, except for the uppermost beds, which form a persistent horizon of very fine grained, thinly laminated metashale or metarhythmite and thin beds of dolomitic rock and meta-arkose.

The Fauquier Formation was deposited unconformably upon the plutonic basement because (1) the Fauquier rests upon granitic basement rocks everywhere and is not intruded by those granitic basement rocks, and (2) much of the Fauquier is made up of granitic detritus whose composition is similar to the granitic rocks. However, this unconformity now appears to be disrupted by faulting throughout the Marshall quadrangle and vicinity (see section on structural geology). Estimates of the total thickness of the Fauquier in the Marshall quadrangle give a range of 650 to 1,950 m (table 2). This wide range may be due partly to original variations in thickness and partly to faulting or folding; a more reliable estimate of formation thickness is not possible on the basis of present information.

TABLE 2.—*Lithologic units of the Fauquier Formation*

Unit	Estimated range of thickness (meters)
Metarhythmite, including thin beds of dolomitic rock and meta-arkose	50–150
Fine-grained meta-arkose and metasiltstone	300–700
Meta-arkose and thin beds of metaconglomerate	300–1,100
(Base)	
Total	650–1,950

Meta-arkose and metaconglomerate

The meta-arkose which makes up the lower part of the formation is dark gray and is composed of medium to coarse particles (1-4 mm in diameter) of quartz, feldspar, and granite, accompanied by a few percent of biotite and sericite. Crossbedding is common (fig. 2). The unit is well exposed from near Old Tavern northeast to the northern edge of the quadrangle. In this interval, thin, lenticular beds of metaconglomerate (1-2 m thick) occur near the basal contact of the Fauquier; pebbles and cobbles, as large as 12 cm across, of white to bluish quartz and granite are common. The metaconglomerate near the basal contact of the Fauquier becomes much coarser farther to the northeast. Granite cobbles as large as 25 cm in diameter occur in the Rectortown quadrangle at a locality about 5 km northeast of the Marshall quadrangle; about 15 km farther

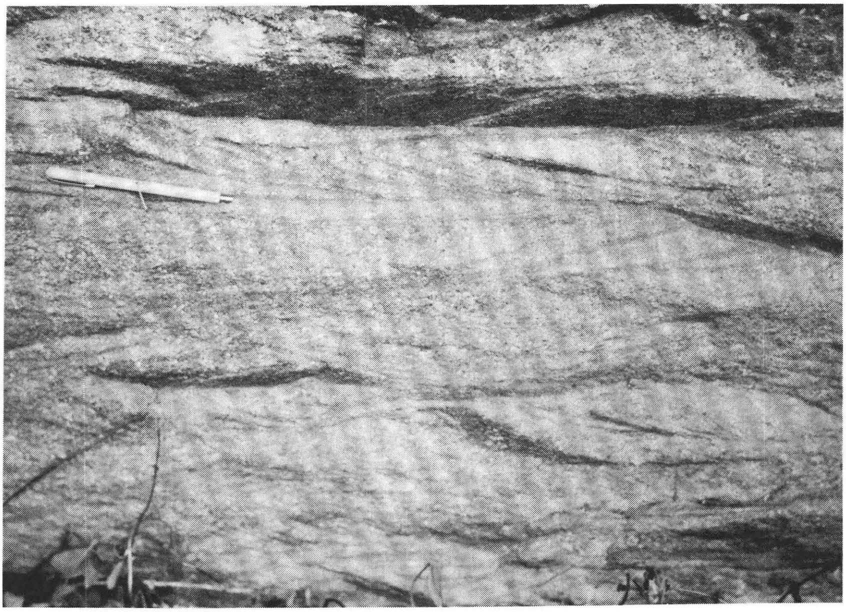

FIGURE 2.—Crossbedded arkose in lower part of Fauquier Formation. Object is 12 cm long. On lane to BM 668 at ref. locality 23, about 2,650 ft (810 m) S. 68° E. of Brookes Corner.

northeast, along Goose Creek in the Lincoln quadrangle, granite boulders about 50 cm in diameter are present in conglomerate (Parker, 1968). Thickness of this lower unit of the Fauquier (meta-arkose and metaconglomerate) is estimated to range from about 300 m near Old Tavern to 1,100 m at the northern edge of the quadrangle.

Meta-arkose and metasiltstone

The fine-grained meta-arkose and metasiltstone that make up most of the upper part of the Fauquier consist of dark gray, fine-grained arkose beds, 5 to 45 cm thick, that alternate with siltstone beds, 1 to 12 cm thick. Sedimentary features, such as graded bedding, crossbedding, channeling, and slate chips are present. Principal mineral constituents are quartz, feldspar, and sericite; chlorite is abundant in some rock, and biotite in others; magnetite, pyrite, and epidote are present in small amounts. This unit is very well exposed in the drainage basins of Carter and Horner Runs in the western part of the quadrangle. To the northeast of Old

Tavern exposures of these lithologies are poor, and fine-grained meta-arkose is the usual variety, rather than the cyclic alternation of fine-grained meta-arkose and metasiltstone. A distinctive conglomerate, containing fragments of quartzite and red shale, as well as cobbles of quartz and granite, occurs in this unit in small areas in the northwestern part of the quadrangle (pl. 1, ref. locality 6). Thickness of this member of the Fauquier is estimated to range from about 300 m near Old Tavern to about 700 m at the northern edge of the quadrangle.

Metarhythmite and dolomitic rock

The topmost unit of the Fauquier is mainly very fine grained, thinly laminated metarhythmite, which also contains lenses of dolomitic rock and meta-arkose at and near the top. The metarhythmite is composed of pairs of silty layers (light tan-gray) and micaceous layers (dark gray to dark blue-gray); a pair of layers is generally 0.2 to 0.8 mm thick, but a few are as thick as 5 to 10 mm (pl. 1, ref. localities 7 and 8). Major minerals are sericite and silt-sized quartz grains; chlorite or biotite, and magnetite are commonly present. Thiesmeyer (1939) described these rocks as "varved slates" whose sediments were probably deposited in freshwater lakes, possibly under conditions of alpine glaciation, although he found no direct evidence of glaciation. The metarhythmite beds appear to be thickest southwest of Old Tavern; their estimated thickness (calculated from map widths and bedding dips of the unit) ranges from 50 to about 150 m.

Lenses of dolomitic rocks are present in the upper part of, or above, the rhythmite sequence; these range from nearly pure, fine-grained, white dolomitic marble, to gray or blue siliceous dolomite, to dolomitic arkose (pl. 1, ref. localities 13 and 14). In several exposures, the rock is composed of platy, dolomitic fragments and resembles an intraformational conglomerate. Dolomite, fine-grained quartz, and sericite are principal minerals; tremolite is present in some rocks. Most exposures of the dolomitic beds are southwest of Old Tavern; to the northeast of Old Tavern, marble was exposed over widths of a few meters near the upper contact of the Fauquier in an excavation for

Highway I-66, and dolomitic arkose was found in an excavation for a sewage pump beside Virginia Highway 55 just west of The Plains; both exposures were subsequently covered by construction material. It is possible that the dolomitic unit is continuous or nearly continuous at or near the top of the Fauquier. Thickness of the horizon is very difficult to judge because of the poor exposures but may be as much as 10 to 20 m in places. Drilling or trenching of the dolomitic zone to obtain more data on its lithology, continuity, thickness, and genesis would be desirable. Mack (1965) described the occurrences of dolomitic rock at this horizon from the Warrenton quadrangle northeast to near the Potomac River, a distance of about 60 km. However, he incorrectly assigned these beds to the younger Everona Limestone of Late Cambrian (?) age, which forms a belt farther east in the adjacent Piedmont Province.

Thin lenses of meta-arkose and metasiltstone occur in some places at the top of the Fauquier, apparently just beneath the base of the Catoctin. The largest lens of meta-arkose is near the southwestern corner of the quadrangle and has a maximum thickness of about 20 m and a length of more than 0.5 km. Similar meta-arkose is exposed over widths of 1 to 2 m several kilometers to the northeast. Near Old Tavern and The Plains equivalent beds are quartzitic and appear to be 1 or 2 m thick; they contain rounded quartz grains and resemble some quartzite in the lower part of the Catoctin.

Soils

The soils derived from the Fauquier Formation are distinct from those formed from the Catoctin Formation or from metagranite, and their distribution shown on the soil map of Fauquier County (Petro and others, 1956) corresponds very closely to the extent of the Fauquier Formation shown on the geologic map. Also, soils derived from the medium- to coarse-grained meta-arkose unit in the lower part of the Fauquier are mostly permeable, yellowish-brown sandy loam, whereas varieties of brown fine sandy loam and silt loam (some with considerable mica and clay) occur in the overlying fine-grained meta-arkose and metasiltstone unit in the upper Fauquier; here, too, the soil map reflects the geologic map rather well.

Regional stratigraphic relations

The Fauquier Formation was first described and named in the Warrenton 15-minute quadrangle, just south of the Marshall quadrangle, by Furcron (1939). However, he applied this name only to the upper part of the pre-Catoctin metasedimentary rock sequence; he considered that the meta-arkose and metaconglomerate units in the lower part of the sequence were younger than Catoctin, and he correlated them with the Loudoun Formation of Cambrian age. Furcron (1969) later recognized that this stratigraphic interpretation was incorrect, and he proposed the name Bunker Hill Formation (instead of Loudoun) for the meta-arkose unit, which is exposed along Virginia Highway 55 near Bunker Hill in the Marshall quadrangle. He stated that the Bunker Hill passed upwards into the Fauquier Formation, and he grouped the two formations, together with the Rockfish Conglomerate (occurring in central Virginia), as making up the Lynchburg Group, equivalent to the Lynchburg Gneiss of central Virginia. Espenshade and Clarke (1976) concluded that Furcron's revised nomenclature was difficult to use in the Marshall, Rectortown, and Orlean quadrangles and proposed that Fauquier be redefined to include all the Precambrian metasedimentary rocks of post-granite and pre-Catoctin age in the region and as thus redefined is herein adopted for use by the U.S. Geological Survey. The Fauquier Formation is at the same stratigraphic position as the Swift Run Formation, whose type locality is on the western limb of the Blue Ridge anticlinorium (Jonas and Stose, 1939) but lacks pyroclastic volcanic material which is said to occur at a few places in the Swift Run. Parker (1968) applied the name Swift Run to strata on both limbs of the anticlinorium about 20 km northeast of the Marshall quadrangle that are equivalent to the Fauquier as now defined. In Frederick County, Maryland, a short distance north of the Potomac River, discontinuous lenticular exposures of quartzite and tuffaceous slate between the plutonic rocks and the Catoctin have been called the Swift Run Tuff by Stose and Stose (1946).

Arkosic metasedimentary rocks, which were called the Mechum River metasedimentary rocks by Gooch (1958) and are very similar to and probably equivalent to the Fauquier and Swift Run, form a narrow belt that extends for about

100 km northeast along the center of the anticlinorium (Schwab, 1974). The northern end of this belt is in the Massies Corner quadrangle (Lukert and Halladay, 1980), about 16 km southwest of the southwestern corner of the Marshall quadrangle (fig. 1).

The Lynchburg Formation, whose type locality is along James River at Lynchburg, 185 km southwest of the Marshall quadrangle, rests upon plutonic basement overlain by greenstone of the Catoctin Formation and has been correlated with the Fauquier by Bloomer and Werner (1955), Furcron (1969), Brown (1970), and others. The Lynchburg is 3,000 to 4,000 m thick and consists of basal conglomerate and several hundred meters of thick-bedded arkose in the lower part that is overlain by a thick sequence of alternating beds of metagraywacke (biotite-quartz-feldspar gneiss) and metapelite (biotite-muscovite schist) accompanied by graphitic schist. Numerous bodies of amphibolite and hornblende gneiss and some bodies of ultramafic rock occur in the Lynchburg. Brown (1970) concluded that the Lynchburg is a deep-water, eugeosynclinal deposit, and he considered the Swift Run to be its thin northwestern edge. The Lynchburg in the area between its type locality and the Marshall quadrangle along the eastern side of the anticlinorium has been described by Nelson (1962) and Allen (1963). Further study of the entire belt of Fauquier and Lynchburg is needed to determine relations between the fluvial sediments of the Fauquier and the marine sediments of the Lynchburg.

Catoctin Formation

General features

The Catoctin Formation in the Marshall quadrangle consists predominantly of two kinds of metabasalt breccia in the lower part of the formation that are succeeded by a great thickness of metabasalt flows. On the basis of their chemical composition, these volcanic rocks appear to represent two suites: one is relatively low in titanium and high in magnesium (restricted to the lower zone of metabasalt breccia) and the other is relatively high in titanium and low in magnesium (comprising the upper zone of metabasalt breccia, metabasalt flows, and metadiabase dikes). The lower zone of volcanic breccia, the low-titanium metabasalt breccia member, extends entirely across the quadrangle; it is especially thick in the Watery Mountains. The upper zone of breccia, the high-titanium metabasalt breccia member, is present mainly along the eastern side of the Watery Mountains; it is quite thick in the northern part of the mountains and becomes abruptly thinner and pinches out to the southwest and northeast. Both types of volcanic breccia are resistant to weathering and are exposed as large, rough ledges or cliffs, particularly along the western slope of the mountains. The higher and wider parts of the Watery Mountains correspond closely with the thickest parts of these two breccia zones. The low country and two ridges farther east are underlain mainly by metabasalt flows, which are generally less resistant to weathering than the volcanic breccias. Outcrops are fewer, and the cover of soil and underlying saprolite is much thicker in this terrane. Quartzite, quartz-muscovite schist, and phyllite occur in thin, discontinuous beds at several horizons in the volcanic sequence.

The geology of the northern part of the Blue Ridge anticlinorium was first mapped by Keith (1894), who concluded that some of the Catoctin metavolcanic rocks were intruded by the granitic rocks. This view prevailed for many years until Jonas and Stose (1939) and Stose and Stose (1946) demonstrated that the granitic rocks were older than the metabasalt flows and were intruded by numerous metadiabase dikes.

Low-titanium and high-titanium basaltic suites

This study has shown that the metabasalt rocks of the Catoctin Formation in the region belong to two distinct chemical suites. A low-titanium suite comprises a zone of metabasalt breccia and nonfragmental rock at or near the base of the Catoctin, and a high-titanium suite comprises an overlying zone of metabasalt breccia, a thick sequence of metabasalt flows, and the swarms of metadiabase dikes and sills.

Chemical analyses of varieties of metavolcanic rock and metadiabase from the Marshall quadrangle are given in table 3. The low-titanium suite is characterized by lower content of TiO_2, iron, K_2O, and P_2O_5, and higher content of MgO than the high-titanium suite. Locations of the samples are shown on plate 1. The samples of metabasalt breccia

TABLE 3.—*Chemical analyses of Catoctin metavolcanic rocks and related metadiabase from the Marshall quadrangle, Virginia*

[All analyses were done in the laboratories of the U.S. Geological Survey. FeO, H_2O^+, H_2O^-, and CO_2 were determined by method as described under "single solution" (Shapiro, 1975). All other determinations were by X-ray spectroscopy, except that Fe_2O_3 was calculated by subtracting iron present in FeO from total iron determined as Fe_2O_3. Z. A. Hamlin, P. P. Hearn, N. G. Skinner, H. Smith, and S. Wargo, analysts]

	Low-titanium suite			High-titanium suite							
	Metabasalt breccia and nonfragmental rock			Metabasalt breccia		Metabasalt				Metadiabase	
Field No.	EB124A	EB156	EB158	EB213	EB214	EB168	EB173	EB176	EB192	EB166	EB197
Lab No.	W197691	W195551	W195552	W210167	W210168	W197688	W197689	W197690	W201515	W201512	W201517
SiO_2	49.4	46.7	47.8	52.4	47.3	47.8	47.9	45.7	48.5	51.4	47.0
Al_2O_3	13.4	14.6	14.8	12.4	12.8	13.0	12.7	13.0	13.8	14.3	15.4
Fe_2O_3	3.1	3.5	2.8	8.3	5.6	3.2	3.1	5.7	6.4	2.4	4.6
FeO	5.2	6.6	7.3	5.0	8.6	10.6	11.0	9.6	6.7	9.4	7.6
MgO	9.4	10.7	10.0	4.8	9.6	5.6	5.4	6.0	5.9	4.6	5.6
CaO	14.9	11.5	10.3	9.1	6.8	10.1	10.4	9.1	9.51	7.99	11.2
Na_2O	1.4	2.0	2.0	3.6	3.4	1.4	1.9	2.4	3.2	3.0	1.9
K_2O	0.16	0.10	0.08	0.18	0.56	0.62	0.36	0.23	0.85	1.39	0.16
H_2O^+	1.1	2.9	3.1	1.1	3.3	2.3	1.9	2.8	1.88	2.12	2.7
H_2O^-	.12	.14	.14	.20	.12	.47	.20	.25	.17	0.15	.23
TiO_2	.43	.53	.62	2.3	2.3	2.98	3.15	3.68	2.07	2.95	2.49
P_2O_5	.08	.06	.08	.21	.26	.22	.27	.33	.21	.36	.22
MnO	.16	.15	.16	.13	.16	.21	.21	.22	.19	.17	.19
CO_2	.04	.01	.01	.01	.01	.01	.01	.03	.02	.02	.02
Sum	98.89	99.49	99.19	99.73	100.81	98.51	98.50	99.04	99.40	100.25	99.31

were taken from breccia fragments; the matrix to the fragments is mineralogically similar to the fragments.

The distinction between the two suites is readily apparent in a graph of MgO and TiO_2 content, which includes analyses of seven additional samples from nearby quadrangles (fig. 3). One of the two samples from the upper breccia zone falls outside the cluster of the two suites (sample EB214, table 3; fig. 3); the other sample (EB213) conforms to the high-titanium suite. The lava represented by sample EB214 had a high content of both TiO_2 and MgO, perhaps due to mixing of the two magma suites in some unknown manner.

One of the analyzed samples (table 3) represents rock that was somewhat altered subsequent to eruption. Sample EB213 has a SiO_2 content of 52.4 percent, which is probably a little higher than its original content, because very tiny amygdules and minute veinlets of quartz are evident in thin section; however, the secondary SiO_2 is probably less than 1 percent.

It appears that rocks of the low-titanium suite occur only at or near the base of the Catoctin in this region. The chemical composition of these rocks suggests that the parent magma of the earliest eruptions was not so far advanced in the differentiation process as the magmas which fed the younger breccias, the great thickness of younger flows, and the diabase dikes and sills. However, the samples analyzed in this study are all from the lower half of the Catoctin, and the chemical composition of the upper half of the Catoctin in this region has not been determined. Also, rhyolite is very abundant in the Catoctin farther north in the anticlinorium in Maryland and Pennsylvania, but it is not known whether any rhyolite occurs in the Catoctin to the east of the Marshall quadrangle.

Low-titanium metabasalt breccia member

The typical low-titanium metabasalt breccia is composed of blocky or angular fragments of fine-grained, medium gray-green rock in a fine-grained, generally schistose, matrix (fig. 4). Fragments generally range from about 1 to 20 cm long and have a maximum length of about 50 cm. Most fragments appear dense and textureless, although some fragments are finely laminated and some

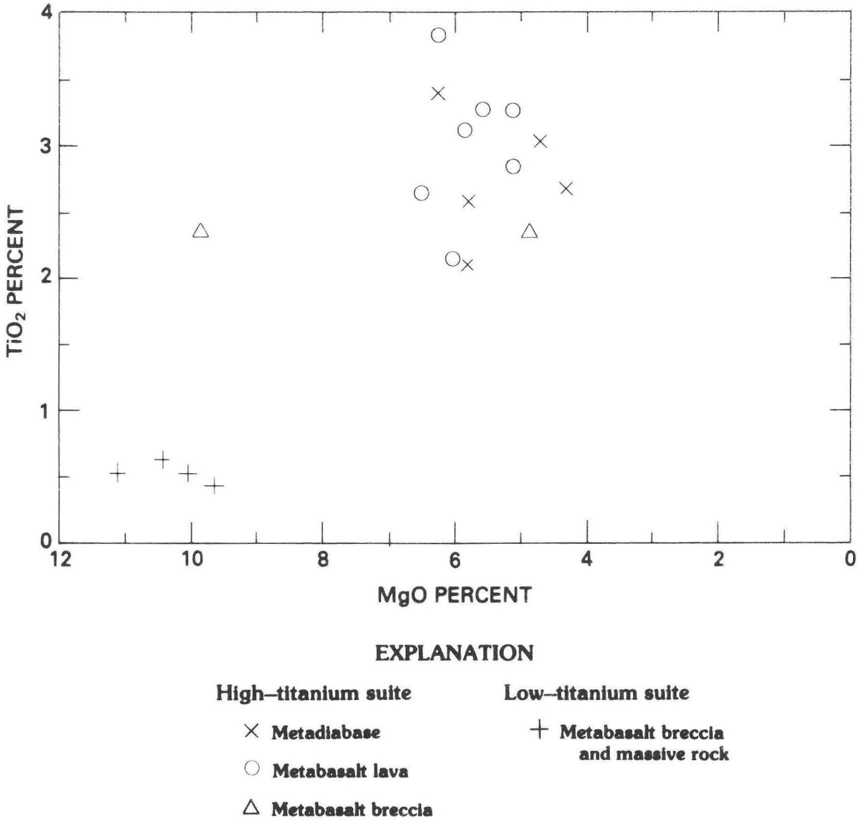

FIGURE 3.—MgO and TiO_2 content of metabasalt lava and breccia and metadiabase from the eastern side of the Blue Ridge anticlinorium in northern Virginia. Analyses recalculated to H_2O and CO_2 free. Quadrangles sampled and number of samples: Marshall (11), Rectortown (3), Jeffersonton (3), and Lincoln (1).

have trains of small amygdules. In places grains of white feldspar occur in small aggregates (a few millimeters across) or in networks of very irregular veinlike clusters. The individual aggregates might be interpreted as inclusions derived from granitic rocks or from arkosic rocks, but the cluster networks suggest hydrothermal or metamorphic origin. The breccia fragments are especially resistant to weathering and form rough, knobby surfaces on outcrops (pl. 1, ref. localities 11 and 12). Bedding is rarely evident but was found at one locality in the Watery Mountains; here beds, 25 to 60 cm thick, of fine-grained fragmental material are interlayered with typical breccia containing fragments

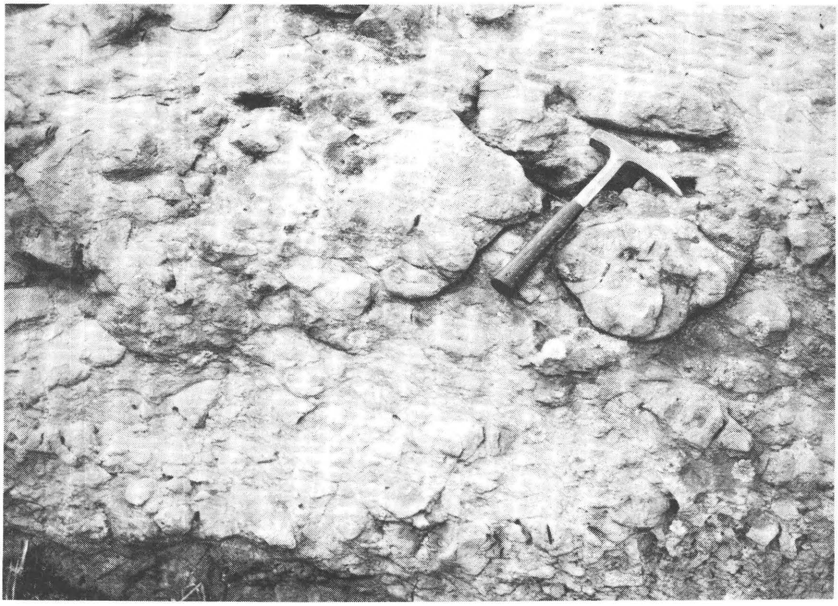

FIGURE 4.—Volcanic breccia in low-titanium metabasalt breccia member of Catoctin Formation. Ref. locality 11, about 2,700 ft (825 m) N. 65° E. of Old Tavern.

as large as 40 cm across (fig. 5). Pillow structure was found in a small exposure in the low-titanium breccia zone in the Watery Mountains about 0.55 km northwest of Prickly Pear Mountain (pl. 1, ref. locality 19). Nonfragmental rock, whose color and mineral and chemical composition are similar to those of the breccia, occurs in the lower part of the zone of breccia along the western side of the Watery Mountains where it is exposed across widths of 300 to 400 m in the stream valley east of Enon Church and in other large valleys (pl. 1, ref. locality 16). Both fragmental and nonfragmental rock are composed of fine-grained mixtures of amphibole (colorless to pale tan under crossed polarizers), epidote, chlorite, and albite; sphene and biotite are rare. Both varieties of rock have similar chemical composition.

Exposures are absent from much of the low-titanium breccia zone. Belts of no outcrop occur that are as much as several hundred meters wide, and it seems unlikely that resistant low-titanium metabasalt breccia lies beneath all these belts. Quite possibly, high-titanium metabasalt underlies some of this unexposed area and may actually be

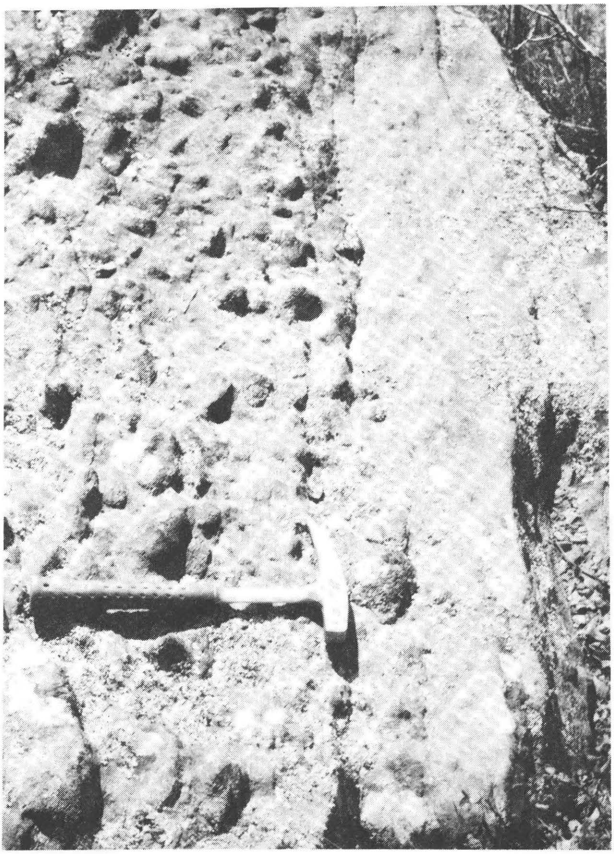

FIGURE 5.—Pavement exposure of beds of very coarse grained and fine-grained volcanic breccia in low-titanium metabasalt breccia member of Catoctin Formation. Ref. locality 18, about 3,900 ft (1,190 m) S. 17° W. of Rappahannock Mountain.

rather abundant in the zone of low-titanium metabasalt breccia. Note that a belt of high-titanium metabasalt does occur between two belts of low-titanium metabasalt breccia to the southwest and northeast of Old Tavern (pl. 1).

The trend and width of the main zone of low-titanium metabasalt breccia change abruptly at the northeast end of the Watery Mountains; the zone is much wider to the southwest than it is to the northeast. Estimates of the stratigraphic thickness of this breccia member are indefinite because of meager data on dip and bedding.

Thickness of the low-titanium metabasalt breccia member along Watery Mountains is estimated to be between 750 and 1,000 m; thickness northeast of the mountains is probably between 220 and 460 m.

The length of the low-titanium metabasalt breccia zone within the Marshall quadrangle is about 17 km. In the Warrenton 15-minute quadrangle to the southwest, volcanic breccia was mapped by Furcron (1939) for a distance of about 30 km; he named the breccia the Warrenton agglomerate member of the Catoctin. However, his Warrenton agglomerate probably includes both low-titanium and high-titanium metabasalt breccia, so Fucron's term is not applicable to the Marshall quadrangle. The low-titanium breccia has not been mapped geologically to the northeast of the Marshall quadrangle, but the soil map of Fauquier County (Petro and others, 1956) suggests that it extends, perhaps as intermittent occurrences, for at least 10 km to the northeast. Thus, the zone probably has a linear extent of at least 57 km.

High-titanium metabasalt breccia member

Another type of volcanic breccia lies above the low-titanium metabasalt breccia member along the eastern flank of the Watery Mountains. This breccia is composed of dark green, amygdular ellipsoids that range from about 5 to 40 cm in length in a matrix of dark green, dense angular fragments that are about 0.5 to 5 cm across (pl. 1, ref. localities 17 and 20). Abundant epidote commonly occurs in the matrix; quartz and epidote make up the amygdules of the ellipsoids. The large ellipsoids are probably volcanic bombs because they contain cores of small amygdular fragments (R. L. Smith, personal communication, 1980). Chemical analyses of samples of bombs from 2 localities (table 3, samples EB213 and EB214) show high titanium content like the metabasalt flows and the metadiabase dikes; several percent sphene are evident in thin section. This breccia is called the high-titanium metabasalt breccia member because of its relatively high content of TiO_2.

In many places there is an unexposed gap, 100 to 150 m wide, between the lowest exposures of the high-titanium metabasalt breccia and the highest exposure of the low-titanium metabasalt breccia. High-titanium metabasalt possibly underlies this gap, but on the map the two breccias are shown to be in contact except in the southern part of the map where high-titanium metabasalt does crop out between the two breccias. The upper contact of the high-titanium breccia is usually gradational, and either this type of breccia or finer-grained, epidotized breccia may alternate with nonfragmental metabasalt. The high-titanium metabasalt breccia member is thickest along a distance of 4 km near the north end of the Watery Mountains; its maximum thickness is estimated to be between 750 and 900 m.

Both types of breccia are composed almost entirely of basalt fragments that range widely in size. The breccias are pyroclastic deposits formed from lava erupted from volcanic vents or fissures. After examining exposures and polished specimens of the two types of metabasalt breccia and of nonfragmental low-titanium metabasalt, R. L. Smith (personal communication, 1980) concluded that the breccias appear to be a type of deposit known as an agglutinate. This is formed from the spatter of fountaining lava which produces hot plastic blobs and bombs that adhere together as they accumulate on the ground surface.

High-titanium metabasalt

Nonfragmental, fine-grained, dark gray-green schistose metabasalt is the dominant rock type above and east of the breccia zones; it also occurs at the base of the Catoctin beneath the low-titanium breccia zone to the northeast of Old Tavern and is possibly intercalated, but unexposed or poorly exposed, between breccia layers in both breccia zones. Its TiO_2 content is similar to that of the high-titanium breccia and the metadiabase and considerably higher than that of the low-titanium metabasalt breccia and associated nonfragmental rock, as shown in table 3. Principal minerals are actinolite, chlorite, epidote, and albite; several percent sphene, some opaques, and a little biotite are commonly present. Some metabasalt is amygdular, the amygdules typically being composed of quartz and epidote; chlorite is present in some amygdules. Thin zones of fine-grained volcanic breccia occur at some places. Irregular masses of epidosite as large as 2 m across are present at many places in the high-titanium metabasalt. High-titanium metabasalt weathers much more readily than do the breccias, and natural exposures of high-titanium metabasalt are much scarcer than exposures of breccia. In fact, metabasalt is very poorly exposed throughout the quadrangle; its presence is confirmed by its distinctive red clayey soil and saprolite, fragments of weathered metabasalt, scattered ledges of metabasalt, and abundant blocky pieces of epidotized metabasalt that are generally gathered into stone fences and rubble piles.

Metasedimentary rocks

Quartzite, quartz-muscovite schist, and phyllite occur in two, or possibly three, zones in the Catoctin Formation. The lowermost zone has been traced for about 4 km southwest of Old Tavern as a series of discontinuous lenses, which are generally no more than 5 m thick and about 100 m long. The northeastern half of this quartzite zone lies within high-titanium metabasalt whose contacts are fairly well determined, but the extent of metabasalt associated with the southwestern half of this quartzite zone is conjectural. Probable pillow lava occurs in a small exposure about 700 m northeast of the southwestern end of the zone (pl. 1, ref. locality 15).

The next higher metasedimentary zone is between 1 and 2 km southeast of the base of the main zone of high-titanium metabasalt and extends entirely across the quadrangle, a distance of about 15 km. Quartzite and phyllite occur in intermittent lenses that apparently are at three separate horizons within this zone, which is between 300 and 575 m wide. The quartzite lenses are as much as 15 m thick and 650 m long. Quartz in well-rounded bluish to gray grains, 1 to 3 mm in diameter, is the principal mineral; feldspar is less abundant than in arkosic beds of the Fauquier; carbonate occurs in some quartzite in the southwestern part of the quadrangle. Quartzite crops out as linear rows of low ledges at many places, but the beds are too thin to form significant ridges. Phyllite is exposed across widths of 50 m or so along some roads but rarely crops out naturally; it actually may be more abundant than quartzite in this zone.

Quartzite and quartz-muscovite schist occur in the Catoctin near the southeastern corner of the quadrangle, where they crop out as small lenses, about 2 to 7 m thick.

Probably there is a northeast-plunging anticline here, as suggested by the en-echelon pattern of lenses and by some bedding dips to the northwest and lineation plunges to the northeast. Exposures of other rocks are very scarce in this area; some soils here appear to be developed from metabasalt and some from metasedimentary rocks (Petro and others, 1956), and this place is designated on plate 1 as an area of intermixed metabasalt and metasedimentary rocks. Soils derived from metasedimentary rocks occur in a large surrounding area in the Thoroughfare Gap, Catlett, and Warrenton quadrangles. Possibly the parent metasedimentary rocks do not all belong to the Catoctin Formation; Furcron (1939) shows several large areas of his Fauquier and Loudoun Formations within the Catoctin in the Warrenton quadrangle geologic map adjacent to the southeastern part of the Marshall quadrangle.

Soils

Soils derived from high-titanium metabasalt are mostly silt loam, silty clay loam, and clay loam that are commonly friable and are yellowish brown, brown, reddish brown, or red in color. Soils derived from low-titanium metabasalt breccia in the rolling country northeast of Old Tavern are yellow, brown, to gray silt loam and silty clay loam that is commonly plastic when wet and tough when dry; this soil is mapped as the Myersville-Orange soil (formed from "agglomerate greenstone") by Petro and others (1956). Stony soils derived from colluvium prevail along the breccia zones in the Watery Mountains southwest of Old Tavern.

Thickness of the Catoctin Formation

The belt of Catoctin in and near the Marshall quadrangle, and at many other places on both limbs of the northern part of the Blue Ridge anticlinorium, has irregular outlines and variable widths which are probably due to one or more of the following factors: significant variations in the original thickness of the volcanic pile, variations in dip, repetition of beds by folding or faulting to form wide areas of Catoctin, or thinning of beds by shear on the anticlinoral limbs (Cloos, 1947) to form narrow areas. Because it is difficult to assess all these factors, estimates of thickness may be only rough approximations in many instances.

Despite these uncertainties, recent investigators of areas on the western limb of the anticlinorium have some degree of consistency in their estimates of the thickness of the Catoctin along a belt of about 160 km from the Sherando quadrangle northeast to the Ashby Gap quadrangle. Their thickness estimates are as follows:

Sherando quadrangle (Bartholomew, 1977)	760-1,220 m
Waynesboro East quadrangle (Gathright and others, 1977)	460-915 m
Greene and Madison Counties (Allen, 1963)	760 m
Luray area (Reed, 1955, 1969)	150-550+m
Linden quadrangle (Lukert and Nuckols, 1976)	580-790 m
Ashby Gap quadrangle (Gathright and Nystrom, 1974)	450-900 m

On the eastern limb of the anticlinorium variations of the width of the Catoctin belt, rather than thickness, are compared, because few estimates of thickness are available in the 190-km-long interval extending northeast from the southern corner of Albemarle County, Virginia, to Point of Rocks, Maryland. The belt is widest in and near the Marshall quadrangle. Widths are as follows:

Southern corner of Albemarle County, Virginia (Nelson, 1962)	1.5 km
Northeastern corner of Albemarle County (Nelson, 1962)	9.5 km
Warrenton quadrangle (Furcron, 1939)	(maximum) 11.5 km
Marshall and Thoroughfare Gap quadrangles (this study):	
Southern boundaries	12.7 km
Northern boundaries	7.0 km
Near Leesburg, Virginia (Toewe, 1966; Parker, 1968)	4.35 km
Near Point of Rocks, Maryland (Jonas and Stose, 1938)	1.5 km

The considerable width of the Catoctin belt in and near the Marshall quadrangle may reflect (1) great original thickness of the volcanic sequence here because of the eruption of large amounts of volcanic breccia and lava from nearby vents and (2) local widening of the belt by folding or faulting, as discussed in the section on structural geology. Because of the uncertainties about the nature of the folding and faulting in the Catoctin belt in the Marshall, Thoroughfare Gap, and Warrenton quadrangles, it is not possible to make a reliable estimate of the thickness of the Catoctin here; it may be greater than 3,000 m.

Metadiabase

Metadiabase dikes and sills intrude Marshall Metagranite and rocks of the Fauquier Formation at many places (pl. 1). A few metadiabase dikes were recognized in the Catoctin Formation because of texture or composition that differed from the surrounding volcanic rocks. Only a small number of the metadiabase intrusions are exposed naturally, because metadiabase usually weathers more readily than the enclosing rocks. This situation was revealed by excavations for U.S. Highway I-66 in the Marshall quadrangle and in a pipeline trench dug in 1974 across the northern part of the Rectortown quadrangle where many weathered dikes without surface expression were found. In a distance of 5.4 km of trench, thickness of the metadiabase dikes amounts to between 15 and 20 percent of the total distance; metagranite makes up the remainder. About 70 percent of the 181 dikes measured in the pipeline and highway excavations have trends between N. 10° E. and N. 35° E. (fig. 6). Most of the dikes range in thickness from 1 to 15 m and dip steeply eastward. The borders of some dikes are much finer grained than the interiors of the dikes. One of the thickest bodies of metadiabase is in the southwestern corner of the Marshall quadrangle (pl. 1, ref. locality 21); it is rather coarse grained and appears to be a gently dipping sill intruded along beds near the top of the Fauquier Formation.

Most metadiabase is dark green and fine grained, although some has a medium-grained gabbroic texture. Principal minerals are actinolite, epidote, albite, and chlorite; relict augite is very rare. Chemical composition of metadiabase is similar to that of high-titanium metabasalt

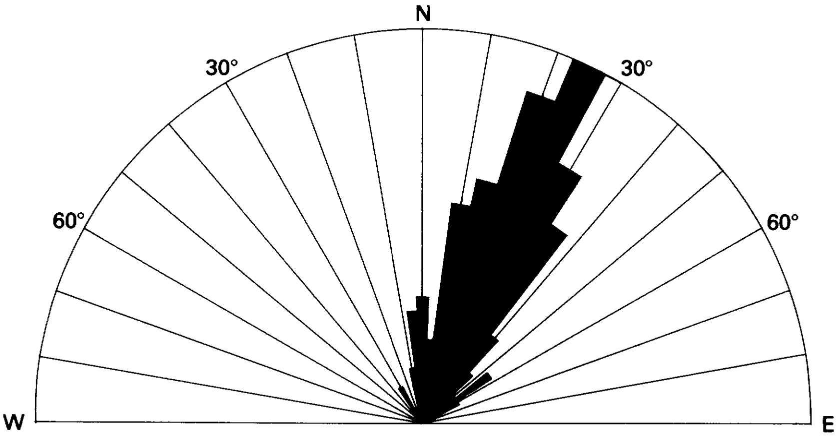

FIGURE 6.—Rose diagram of strike of 181 metadiabase dikes exposed in pipeline trench (167 dikes in distance of 5.4 km) and along U.S. Highway 50 (14 dikes in distance of 10 km) in the northern third of the Rectortown quadrangle, Loudoun and Fauquier Counties, Va.

(table 3, fig. 3), except for the high content of K_2O in sample EB166; probably some K_2O and also SiO_2 were introduced into this dike from adjacent granite during metamorphism. Many of the metadiabase dikes were probably feeders to Catoctin metabasalt flows.

Sedimentation, volcanism, and tectonic environment during Late Proterozoic time

The widespread nonmarine sedimentation, mafic volcanism, and dike intrusion just described probably were related events that occurred in an environment of strong crustal rifting. Current evidence for the age of these events is inconclusive but indicates that they happened near the close of the Precambrian in Late Proterozoic time, which was about 800 to 570 million years ago. Regional aspects of these matters follow.

The pre-Catoctin sedimentary rocks preserved on the flanks of the anticlinorium (the Fauquier Formation on the east and the Swift Run on the west) and in the belt along the middle of the uplift (the Mechum River Formation) all consist of similar lithologic types--mainly arkosic conglomerate and sandstone, siltstone, and shale. These appear to be largely of fluvial origin, although some thinly laminated shales may be lacustrine or estuarine; the thin horizon of dolomitic rock at the top of the Fauquier may be a shallow marine deposit. No fossils have been found in any of these rocks; further search for fossils in little-deformed dolomitic rock, thinly laminated shale, and siltstone is recommended. These three belts may be remnants of a once continuous blanket of sediments, or they may represent separate basins of deposition.

The Mechum River Formation, as described by Schwab (1974), is very similar to the Fauquier in lithology and upward decrease of grain size: both pass upward from basal conglomerate or coarse arkose through finer grained arkosic sandstone, siltstone, and mudstone. Thickness of the Mechum River ranges from about 450 to 900 m, compared to the range of 650 to 1,950 m for the Fauquier in the Marshall quadrangle; however, the top of the Mechum River is presumed to have been eroded because no volcanics overlie the formation. The Swift Run along the west side of the anticlinorium is much thinner, generally less than 60 m, and is missing altogether for short distances. In the Luray area, Reed (1955, 1969) included the sedimentary beds beneath the basaltic lavas as part of the Catoctin Formation, because these basal sediments are generally no more than 30 m thick and are lithologically similar to thin sedimentary beds that are interlayered with basalt flows. The Swift Run may thicken southward, for it is 0 to 120 m thick in the Vesuvius quadrangle (Werner, 1966) and 0 to 300 m in the Sherando quadrangle (Bartholomew, 1977). The Swift Run comprises mostly conglomerate, graywacke, arkosic sandstone, and slate but has subordinate amounts of tuffaceous material and thin basaltic flows at some places; basalt lies beneath Swift Run at a locality in the Sherando quadrangle (Bartholomew, 1977).

Sedimentary rocks of the Fauquier and Swift Run Formations underlie the Catoctin metabasalts so generally that many investigators have concluded that the volcanic sequence rests conformably upon the sedimentary sequence. Such is the relationship in the Marshall quadrangle and vicinity where the thin dolomitic horizon at the top of the Fauquier is present at many places for about 60 km northeast of Warrenton; little pre-Catoctin erosion could have occurred here. However, there are short intervals along both limbs of the anticlinorium where Catoctin metabasalt lies directly upon the granitic basement (Nickelsen, 1956; Werner, 1966; Parker, 1968; Lukert and Nuckols, 1976; Bartholomew, 1977). The absence of sediments below the Catoctin volcanics may be due to one of the following causes: local nondeposition of sediments, local erosion of sediments before Catoctin volcanism, or faulting to place the Catoctin directly upon the granitic rocks. On the nose of the anticlinorium there appear to be only small, widely separated lenses of Swift Run beneath the Catoctin (Stose and Stose, 1946). The fact that pre-Catoctin sedimentary rocks are scarcest on the nose of the anticlinorium, where the structure may be more complex than on the limbs, suggests that faulting, rather than nondeposition or erosion of sediments, is the most likely reason for the small amount of sediments on the fold nose. Indeed, Stose and Stose (1946) show several lenses of Swift Run to be located on faults. In conclusion, the evidence for a conformable succession from the Fauquier and Swift Run to the Catoctin is very strong.

Metavolcanic rocks of the Catoctin Formation extend along both limbs of the anticlinorium for more than 200 km southwest of the Potomac River (Virginia Division of Mineral Resources, 1963) and along the limbs and nose of the anticlinorium for about 100 km northeast of the Potomac (Maryland Geological Survey, 1968; Berg and others, 1980). In Virginia, the metavolcanic rocks are entirely metabasalt, with the exception of very minor amounts of metarhyolite tuff on the west limb of the anticlinorium (Gathright and Nystrom, 1974; Lukert and Nuckols, 1976) and quartz porphyry on the east limb near Oatlands (Keith, 1894). However, much metarhyolite occurs with metabasalt on the nose of the anticlinorium in Maryland, and metarhyolite predominates in Pennsylvania.

The basaltic rocks are mainly flows, except for the thick sequence of breccias on the east side of the anticlinorium near Marshall and Warrenton. Original features of the flows are especially well preserved on the west limb of the anticlinorium in the Luray area (Reed, 1955, 1969) where individual flows range from about 45 to 80 m in thickness; some flows are topped by zones of flow breccia (now schistose) that are as much as 6 m thick. Columnar jointing is commonly present; zones of amygdules are widespread. Several porphyritic flows in the Luray area contain abundant feldspar phenocrysts of distinctive nature; these flows can be readily traced from place to place. Thin beds of metasandstone and metashale or phyllite are interlayered with metabasalt throughout the northern part of the anticlinorium. The relief of the pre-Catoctin erosion surface was as much as 300 m locally.

A few chemical analyses of metabasalt flows and metadiabase dikes in the Luray area (Reed and Morgan, 1971) and the Linden and Flint Hill quadrangles (Lukert and Nuckols, 1976) on the west side of the anticlinorium suggest that their composition is similar to that of the high-titanium suite in the Marshall quadrangle and vicinity.

Reed (1955, 1969) has concluded that the Catoctin flows were plateau basalts erupted on land from fissures in the plutonic rocks of the basement, because of the floodlike character, presence of columnar jointing, areal extent of individual flows, the thin flow breccia zones, and the very thin interbeds of locally derived arkosic sediments. Furthermore, features characteristic of submarine eruption are absent, such as widespread pillow structure, bedded cherts, and much graywacke. Metabasalts on the east side of the anticlinorium also appear to have been erupted on land because of the thin beds of interlayered sediments (which are similar to the fluvial sediments of the Fauquier) and the insignificant amounts of pillow structure in the lavas; the pillow lavas found at two small exposures in the Marshall quadrangle were probably formed in very small bodies of water.

As already indicated, both the Fauquier and the Catoctin Formations appear to be thicker in and near the Marshall quadrangle than anywhere else in the northern part of the anticlinorium. This apparently greater thickness may be the result of repetition of beds of normal thickness by folding or faulting. On the other hand, unusually large amounts of sediments and volcanics may have been deposited in a local basin in the Marshall region. The existence of unusual structural and geomorphic conditions here in late Precambrian time is suggested by the very thick sequence of volcanic breccia near the base of the Catoctin in this region. These same conditions may also have caused a total accumulation of sediments and volcanics that was much thicker here than elsewhere.

The volume of lava (mostly basalt) erupted during Catoctin time was enormous, but because of burial by younger sediments, major structural complexities, and erosion, it is not possible to estimate the total volume reliably. The area of Catoctin Formation now exposed on the limbs and nose of the northern 300 km of the anticlinorium, plus the intervening area where the Catoctin has been eroded, assuming it was once a continuous sheet, amounts to about 7,500 km^2. If the average thickness of the volcanic sequence within this area had been 700 m (a figure compatible with thicknesses of the Catoctin reported from the west limb of the anticlinorium), the volume of lava in this part of the volcanic pile would have been about 5,250 km^3. The actual volume was doubtless far larger, because the volcanic sequence along much of the east limb of the anticlinorium was probably considerably thicker than 700 m and because the Catoctin extends downward to unknown depths on each limb of the anticlinorium. Thus, it is quite likely that the original volume of the Catoctin volcanics exceeded 10,000 km^3.

The eruption of this vast volume of basaltic lava was accompanied by the intrusion of swarms of diabase dikes, many of which must have been feeders for the flows. These mafic dikes are extremely abundant in pre-Catoctin rocks of the northern part of the Blue Ridge anticlinorium, but they are not always mentioned in geologic reports or shown on geologic maps. Greenstone dikes that intrude granitic rocks in the Luray area on the west flank of the anticlinorium are well described by Reed (1955, 1969) and shown on his geologic map. Some of these dikes are little deformed and display chilled borders, as well as columnar jointing normal to dike walls. Many writers describe two kinds of mafic dikes that intrude pre-Catoctin rocks: greenstone or metabasalt dikes, which are generally called feeder dikes to Catoctin volcanics, and amphibolite dikes, which some writers think are also Catoctin feeder dikes and others think are pre-Catoctin (Nelson, 1962; Allen, 1963; Bartholomew, 1977; Gathright and others, 1977). In the Warrenton quadrangle, Furcron (1939) describes metagabbro dikes of Catoctin age intruded into the Fauquier and greenstone dikes (which he says may be of Cambrian age) intruded into granitic rocks. No doubt he thought there were two generations of dikes because he then believed the granitic rocks to be younger than the Catoctin. Numerous Precambrian dikes are plotted on the geologic maps of the Linden and Flint Hill quadrangles (Lukert and Nuckols, 1976) and the Massies Corner quadrangle (Lukert and Halladay, 1980). Most of these dikes are described as amphibolite;

some are called greenstone or metabasalt; a few dikes are felsite. Age relations of the dikes in the Linden and Flint Hill quadrangles are said to be uncertain, although on the map explanation the amphibolite dikes are shown to be older than both the Catoctin Formation and the metabasalt dikes, the latter being called Catoctin feeder dikes. In the Massies Corner quadrangle, both metabasalt and amphibolite dikes are considered to be possible feeder dikes to the Catoctin volcanics; amphibolite dikes intrude rocks of the Mechum River Formation, which is probably correlative with the Fauquier. North of the Marshall area in Loudoun County, Virginia, metadiabase dikes are widespread in pre-Catoctin rocks, according to J. Howard (pers. commun., 1981). Farther north in Frederick County, Maryland, metadiabase dikes abound in basement rocks in the north-plunging core of the anticlinorium; the dikes are said to be syngenetic with the Catoctin (Stose and Stose, 1946).

The crustal rocks in the region that now makes up the northern part of the Blue Ridge anticlinorium were markedly distended by the dike intrusions, apparently by as much as 15 to 20 percent in places, as indicated by the total volume of dikes exposed in 5.4 km of pipeline trench. Crustal distension must have been about perpendicular to the dominant trend of the dikes, which is between north and northeast. The volume of mafic magma contained in the dike system was very large, but perhaps less than 10 percent of the volume of the overlying volcanic pile.

According to the concepts of plate tectonics (Dewey and Bird, 1970), the intrusion of swarms of mafic dikes accompanied by the subaerial eruption of floods of basaltic lava is the result of profound rifting that extends to deep magma sources within or beneath the continental crust. However, the earliest event may be rapid deposition of clastic sediments in fault basins that are formed before rifting has progressed downward to magma. Continued rifting followed by ascent of mafic magma may be a relatively short-lived event that subsides and dies out, or it may be the initial stage in the breakup of a continental crustal plate, which may be followed by the movement apart of plate fragments as oceanic crust is developed and spreads between the continental fragments.

Probably the clastic sediments of the Fauquier, Mechum River, and Swift Run Formations were deposited, the Catoctin volcanics erupted, and the diabase dike swarms emplaced in the early stages of this process before ocean spreading began. As already stated, there seems to be no unconformity between the sediments and volcanics; widespread subaerial basalt eruptions apparently began very suddenly, perhaps the result of extremely strong rifting that gave access to magma reservoirs.

A wide range of discussions and models has been presented to portray the evolution of the Appalachian mountain system by plate tectonics processes. Wilson (1966) suggested that in the period between the late Precambrian and the end of the Middle Ordovician, "an open ocean existed in approximately, but not precisely, the same location as the present North Atlantic." He called this ocean the "proto-Atlantic"; it has since been named "Iapetus." Wilson thought that the ocean basin began to close in the Late Ordovician and that the crustal plates eventually collided to form the Appalachian mountain system. Similar models based on these concepts have since been put forth by other geologists for the southern Appalachians. Brown (1973) proposed that the Mechum River and Catoctin Formations originated during continental rifting in the late Precambrian before a period of ocean opening; Schwab (1974) also suggested such a tectonic environment for the Mechum River sediments. Odom and Fullagar (1973) and Rankin (1972, 1975, 1976) have discussed the relations of late Precambrian sedimentation and igneous activity to continental rifting, and the subsequent stages in the evolution of the Appalachian orogen. Although basalt eruptions were widespread, rhyolite was erupted in only two regions of the Blue Ridge province: the South Mountain area of Pennsylvania and Maryland, and the Mount Rogers-Grandfather Mountain areas of Virginia and North Carolina. Rankin (1976) pointed out that these rhyolitic centers are situated at salients in the trend of the mountain system and suggested that these salients represented the intersection of three rift valleys ("triple junctions") where structural conditions were created that favored the eruption of rhyolites, as well as the intrusion of granites of similar composition.

Geologic relations that resemble those of the Blue Ridge anticlinorium exist at the northeastern end of the Appalachians in the Long Range of western Newfoundland and nearby in Labrador where Precambrian basement rocks are intruded by swarms of diabase dikes and are overlain by basalts and clastic sedimentary rocks of late Precambrian or early Paleozoic age (Strong and Williams, 1972; Strong, 1974). The authors point out that chemical compositions of the flows and dikes are very similar to those of the Catoctin metabasalts and associated dikes. They interpret the Newfoundland basalts to be plateau basalts that were formed along with the diabase dikes in a period of continental rifting early in the evolution of the Appalachian mountain system. Very similar conditions of rifting, clastic sedimentation, and mafic volcanism and mafic dike intrusion evidently prevailed in the regions of the Blue Ridge and the Long Range as precursors to opening of the Iapetus Ocean farther east.

These events in the Blue Ridge terrane occurred before deposition of the widespread clastic sediments of the Chilhowee Group (Lower Cambrian?), but radiometric ages of pre-Chilhowee rhyolites and granites of similar composition have a broad time span. The oldest age comes from zircons from five samples of felsite or rhyolite (one from the Catoctin in Pennsylvania, two from the Mount Rogers Formation in southwestern Virginia, and two from the Grandfather Mountain Formation in northwestern North Carolina), which yielded discordant uranium-lead ages that suggest an original age of 820 million years (Rankin and others, 1969). Uranium-lead data for zircons from two granite plutons in the Mount Rogers-Grandfather Mountain region (Davis and others, 1962) are also very close to the discordia chord for the rhyolites. This type of granite has distinctive chemical characteristics similar to those of the rhyolites and is peralkaline in places. The granite is thought to be the intrusive equivalent of the rhyolite and to be about the same age; together they make up the Crossnore plutonic-volcanic group (Rankin and others, 1969; Rankin and others, 1973; Rankin, 1975).

All other pertinent radiometric ages come from samples of granite, either from plutons of Crossnore-type granite in the Mount Rogers-Grandfather Mountain region or from granites of similar composition, called the Robertson River Formation by Allen (1965), that occur in plutons in northern Virginia. The following ages of Crossnore-type granite have been reported by Odom and Fullagar (1982): a nearly concordant zircon age of 695 m.y. and rubidium-strontium whole rock isochron ages (samples from four plutons) that range from 706 to 646 m.y. Zircon samples of the Robertson River in northern Virginia have yielded these radiometric ages: a discordant uranium-lead age (four samples) of 730 m.y. (Lukert and Halladay, 1980; Lukert and Banks, 1982); a nearly concordant uranium-lead age of zircon (one sample) of 700 m.y. (Lukert and Clarke, 1981; Clarke, 1982); and a $^{207}Pb/^{206}Pb$ age of zircon (one sample) of about 650 m.y. (Rankin, 1975).

In northern Virginia, granite of the Robertson River Formation appears to be older than the Fauquier and Catoctin because the Fauquier contains pebbles and cobbles of granite that resembles the granite of the Robertson River Formation (Clarke, 1976; Lukert and Halladay, 1980) and because amphibolite or metabasalt dikes (Catoctin feeders?) intrude granite of the Robertson River (Lukert and Halladay, 1980; Lukert and Clarke, 1981). Therefore, the basalts of the Catoctin, and presumably the associated rhyolites also, are probably no older than 700 m.y. and may be somewhat younger. Odom and Fullagar (1982) conclude that opening of the Iapetus Ocean occurred between 690 and 570 m.y. ago. Further investigation is needed of the age of the rhyolite of the Catoctin, the granitic pebbles and cobbles within the Fauquier and Mechum River, and the mafic dikes that intrude the Robertson River.

MESOZOIC ROCKS

Triassic and Jurassic Systems

Diabase

Diabase of Triassic and Jurassic age occurs in a large northwest-trending dike in the southeastern quarter of the quadrangle. The dike may split into several thin dikes southeast of Pignut Mountain, as suggested northwest of the mountain by occurrences of small blocks of diabase at localities to the south, southwest, and northwest of The Plains, as well as at the north-central edge of the quadrangle. Diabase was found at one point near the southwestern corner of the quadrangle. Dikes are typically marked by residual cobbles and boulders of diabase; outcrops are rare. Dominant minerals of the diabase are plagioclase, augite, and olivine; small amounts of uralite, biotite, and opaque minerals are present. Texture ranges from dense to medium grained (about 2 mm).

CENOZOIC ROCKS

Quaternary System

Alluvium and bottom-land colluvium

Stream alluvium and bottom-land colluvium, which essentially are fine materials that have been eroded from up-slope soils since farming began in the region, are grouped as a single map unit on plate 1. These areas correspond, with some modification, to the areas of recent alluvial and colluvial soils shown on the map of Petro and other (1956).

METAMORPHISM

The Marshall Metagranite (Middle Proterozoic age) and the Fauquier and Catoctin Formations (Late Proterozoic age) were all metamorphosed in the biotite grade of the greenschist facies during Paleozoic orogeny. Some pre-Fauquier rocks of the region were metamorphosed earlier during Middle Proterozoic time, as evidenced by the presence of garnet in granitic gneiss and granulite (Nickelsen, 1956; Lukert and Nuckols, 1976; Bartholomew, 1977). During Paleozoic metamorphism these garnets were partly retrograded to chlorite, but no garnet was formed in rocks of the Fauquier and Catoctin Formations in this part of the Blue Ridge anticlinorium; hence, garnet in pre-Fauquier rocks of this region seems to be definitely of Middle Proterozoic age.

No certain evidence for Middle Proterozoic metamorphism of the Marshall Metagranite has been found in the Marshall or Rectortown quadrangles; compositional layering seen at a few places in the Marshall could have been formed during intrusion of the granite, rather than by metamorphism. Garnetiferous, gneissic granulite occurs in a small area in granitic rocks that may be equivalent to the Marshall in the northwestern corner of the Rectortown quadrangle. This area has not been mapped in detail by me, but it seems probable that the garnetiferous granulite is an older mass of rock included in the granite; if so, the garnet may have been formed either before or during intrusion of the granite.

In the biotite-grade metamorphism of Paleozoic orogeny, the granitic rocks of the Marshall and Rectortown quadrangles were extensively saussuritized, mainly by replacement of plagioclase by sericite (fine-grained white mica) and epidote. Sericite was widely developed also in arkose, siltstone, and rhythmite; epidote was formed in arkosic rocks. Biotite was formed in small amounts in granitic rocks in clusters of tiny green to brown flakes; original biotite flakes were altered to unknown material containing a mesh of fine opaque material and small relics of biotite. Fine-grained biotite was formed also in arkose, siltstone, and rhythmite. Tremolite occurs in some siliceous dolomite. Magnetite octahedra are common, especially in metabasalt, metasiltstone, and metarhythmite; such magnetite is clearly of metamorphic origin, rather than detrital. Fine-grained mixtures of amphibole, chlorite, albite, and epidote characterize metamorphosed basalt, basalt breccia, and diabase; minute amounts of biotite occur in some of these rocks.

The most thorough study of the metamorphism of the Catoctin basalts has been in the Luray area on the western side of the anticlinorium by Reed and Morgan (1971). Sodium-rich greenstone, composed of albite-chlorite-epidote-actinolite-opaque ores-leucoxene and relict clinopyroxene, predominates. Associated with greenstone are irregular masses of epidosite, composed of quartz-epidote-actinolite; the epidosite is estimated to make up about one-third of the total. The calculated composition of combined greenstone and epidosite is nearly the same as the composition of probable feeder dikes of diabase intruded into basement rocks and is judged to approximate the original composition of the basalts. No epidosite occurs with the dikes. Sodium-rich greenstone and epidosite are thought to have been formed by fluids of high oxidation potential that circulated through a fissure system in the basalts either soon after eruption or during Paleozoic metamorphism.

White quartz is very common in the Marshall region in narrow veins, rarely more than a meter thick, in most rock types; veins of white quartz in the rocks of the Fauquier and Catoctin were probably formed during Paleozoic deformation and metamorphism. An earlier generation of vein quartz (Middle Proterozoic?) is indicated by abundant pebbles and cobbles of quartz, much of it blue-gray in color, in arkose and conglomerate of the Fauquier. An unusually large vein of this type of quartz in Marshall Metagranite underlies the knob with bench mark 751 feet just southwest of the town of Marshall; quartz lenses as much as 15 m wide occur for a distance of about 300 m along a trend of N. 70°E. This quartz is white in weathered outcrops but is blue gray in less weathered parts of the vein where exposed in highway excavations at the southwestern end of the knob.

In addition to the mineral changes, the rocks of the anticlinorium were strongly deformed during Paleozoic orogeny. Schistose foliation was widely developed in the sedimentary and volcanic rocks, accompanied by the formation of much sericite in the sedimentary rocks and by chlorite and fine amphibole in volcanic rocks. In granitic rocks, cataclastic features are prominent, particularly granulation of minerals and development of cataclastic foliation. Phyllonite, consisting of quartz-sericite schist, was formed from granite in extremely deformed zones several meters wide; feldspar was completely destroyed in phyllonite.

The history of Paleozoic metamorphism in this part of the Blue Ridge anticlinorium is not yet understood. Metamorphism and deformation clearly took place simultaneously under conditions of greenschist metamorphism, but when in the Paleozoic did this happen? Was the tectonism restricted to the Allegheny orogeny of the late Paleozoic when strata as young as Mississippian were folded and overridden by thrust sheets in the Valley and Ridge Province west of the Blue Ridge anticlinorium? Or did the Blue Ridge anticlinorium begin to form earlier during the Acadian or Taconic orogenies? If the latter, it appears that similar conditions of metamorphism and deformation prevailed, or were repeated, over a long interval in the Paleozoic, finally coming to an end during the Allegheny orogeny. Although metamorphism, folds, cleavage, and lineation appear to have been pre-faulting in the Front Royal area, Wickham (1972) was not able to date these events. In central Virginia, Bartholomew and others (1981) thought that metamorphism and deformation began in the middle Paleozoic and that postmetamorphic faulting was late Paleozoic.

STRUCTURAL GEOLOGY

Structural features of Middle Proterozoic age

The inconspicuous compositional layering in the Marshall Metagranite (pl. 1) is of Middle Proterozoic age because it is older than the Late Proterozoic metadiabase dikes. Detritus of layered plutonic rocks also occurs in conglomerate beds in the basal part of the Fauquier. Compositional layering is well developed and more prevalent in Middle Proterozoic rocks farther west and southwest in the Blue Ridge anticlinorium and is generally regarded as having been formed under conditions of granulite metamorphism about 1 billion years ago (Reed, 1955, 1969; Bartholomew, 1977; Bartholomew and others, 1981; Mitra and Lukert, 1982).

Structural features of Late Proterozoic age

The metadiabase dikes, which trend predominantly to the northeast (fig. 6), are the most evident structural features of Late Proterozoic age. As already noted, these swarms of dikes record a widespread event of strong crustal distension or rifting associated with Catoctin volcanism in the late Precambrian.

There is evidence for faulting within the Fauquier Formation just before the onset of mafic dike intrusion and volcanism. A fault zone, here called the Horner Run fault zone, appears to extend along the northwest-trending contact between the Fauquier and the Marshall Metagranite (pl. 1). This fault is required by the presence of the upper stratigraphic units of the Fauquier, especially the metarhythmite, in a shallow syncline along the contact with Marshall Metagranite (pl. 1, ref. locality 7). The position of the metarhythmite is clearly anomalous. In contrast, the lowest unit (meta-arkose) of the Fauquier occurs along the northeast-trending contact between the Fauquier and the Marshall. Along the southeasterly projection of the Horner Run fault zone into the Fauquier, upper and lower units of the Fauquier are exposed near each other (about 200 m apart) just southeast of the salient of Marshall Metagranite. However, no exposures exist near the fault projection for about 1,200 m farther southeast, and the relations in this interval shown on the geologic map (pl. 1) are conjectural.

In the lower part of the Catoctin, the horizon of quartzite lenses extends without break across the fault trend. Hence, it appears that the age of the Horner Run fault zone was late- or post-Fauquier, before deposition of the lower quartzite horizon of the Catoctin and probably earlier than the lowest basalt breccia zone in the Catoctin. The location of the vents or fissures from which the breccias were extruded is unknown but may have been structurally related to the Horner Run fault zone because the very thick part of the high-titanium metabasalt breccia zone lies just southwest of the projection of the fault zone and the low-titanium metabasalt breccia zone is considerably thicker to the southwest of the fault zone projection than to the northeast (pl. 1).

The Horner Run fault zone is presumed to have been a normal fault having steep southwesterly dip and downthrow on the southwest side of the fault zone (fig. 7). It is possible that widespread normal faulting also took place earlier to produce a terrane of mountain ranges and fault basins in which the coarse arkosic detritus of the lower Fauquier was deposited. However, no evidence for such faults has been found.

Additional evidence for a fault zone along the northwest-trending contact of the Marshall Metagranite and the Fauquier is the presence of tectonic breccia in the Marshall, composed of rounded to subangular granite fragments as large as 10 cm across in a fine-grained matrix, in a zone 600 to 800 m wide east of the contact (pl. 1, ref. localities 4 and 10). Granite exposures that are farther than 800 m from the contact show little or no breccia. Although the wide zone of brecciated granitic rock is adjacent to the supposed fault, it is not known whether the breccia is Proterozoic or Paleozoic in age. Neither does the breccia give any information about movement direction in the fault zone.

There are several features that appear to contradict the concept of a simple normal fault of late Fauquier age. The very irregular northwesterly trend of the Fauquier-Marshall contact and the suggestion of low dips of the contact at places where the contact is sharply indented (pl. 1) are difficult to visualize as being the result of normal faulting. Possibly renewed movement in and near the fault zone during the Paleozoic orogeny may have made the

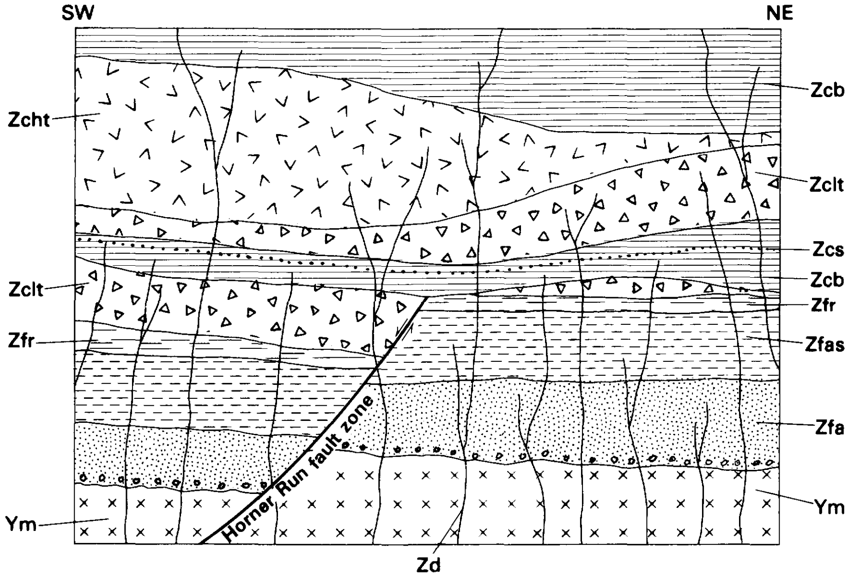

FIGURE 7.—Section looking northwest along the Horner Run fault zone showing possible geologic relations in early Catoctin time. Southwest of the fault zone normal faulting has produced a basin that was filled with low-titanium basalt breccia before deposition of the horizon of thin quartzite lenses in the lowermost high-titanium basalt lavas. Symbols are those used in plate 1.

original fault contact more irregular. Normal faulting of considerable displacement in a relatively brief time period, as depicted in fig. 7, would probably result in rapid erosion and deposition of coarse detritus in the metarhythmite unit of the upper Fauquier. Although such detritus is not evident near the fault in the large unexposed area along the southerly projection of the Horner Run fault zone, meta-arkose does occur in thin lenses within or at the top of the metarhythmite both to the southwest and to the northeast of the fault zone (pl. 1).

Structural features of Paleozoic age

Comprehensive studies in the Blue Ridge anticlinorium of Paleozoic structural features and their history were begun by the pioneer work of Cloos (1947) in Maryland and later extended to areas in Virginia by him and his students (Whitaker, 1955; Reed, 1955; Nickelsen, 1956; Cloos, 1971; and Wickham, 1972). Other studies have also contributed significantly to our understanding of the Paleozoic tectonic features and history in the northern part of the anticlinorium (see particularly King, 1950; Gathright and others, 1977; Bartholomew, 1977; Mitra, 1979; Bartholomew and others, 1981; and Mitra and Lukert, 1982).

The northern part of the Blue Ridge anticlinorium is an asymmetric, complex fold whose western limb dips more steeply than the eastern limb. Tight, northeasterly trending folds in the stratified rocks are overturned or recumbent at many places, especially on the western limb; fold axes usually plunge at low angles. Cleavage and lineation are well developed in Proterozoic plutonic rocks and in Proterozoic and Paleozoic stratified rocks. Cleavage occurs in rocks as young as Devonian in the Massanutten syncline, 10 to 15 km west of exposed Proterozoic rocks (Mitra and Lukert, 1982). These features form a very uniform structural pattern throughout a large region. Cleavage strikes northeast and dips southeast; lineation consists of streaks, elongated mineral grains, amygdules, pebbles, and ooids which plunge down the cleavage plane.

Cloos (1947) concluded that the anticlinorium is a huge shear fold in which major northwestward movement had occurred by means of laminar flow along parallel cleavage planes. Other workers have mapped thrust faults that trend northeast and transverse faults in both stratified and plutonic rocks. Recent studies have found northeast-trending zones of ductile deformation, shear, and mylonitization in the plutonic rocks (Gathright and others, 1977; Bartholomew, 1977; Mitra, 1979; Bartholomew and others, 1981; and Mitra and Lukert, 1982). These features suggest that much of the movement in the plutonic rocks of the anticlinorium core was localized in discrete zones instead of being distributed along cleavage planes. Cloos did not become aware of these important displacement zones within the plutonic core because his studies were mainly in the overlying stratified rocks.

The most conspicuous Paleozoic structural feature in the Marshall quadrangle, seen in nearly every exposure of Proterozoic rocks, is a pervasive foliation (called cleavage by many works in the region) that strikes northeast and dips southeast.

Folds are best developed in the western belt of Fauquier extending southwest from the Horner Run fault zone. Here bedding dips gently in various directions in patterns that suggest randomly oriented, low-amplitude folds; foliation strikes uniformly northeast and dips southeast (pl. 1, ref. locality 9). On the other hand, in the eastern belt of Fauquier, which is parallel to the northeast-trending contact with the Marshall Metagranite, bedding and foliation are essentially parallel, and no folds are evident. South-plunging fold axes and lineations are very common in metabasalt of the Catoctin in an area of several square kilometers near Airlie; such strong lineation is rare elsewhere in the quadrangle. Several kilometers east of Airlie, a northeast-plunging anticlinal fold in the Catoctin is suggested by en-echelon distribution of thin lenses of micaceous quartzite, some of which dip northwest and have north-plunging lineation. Larger folds in the Catoctin, as well as faults, are suggested by the sinuous, easterly trending course of the base of the Catoctin in the Warrenton 15-minute quadrangle and also by the sizable belts of sedimentary rock in the Catoctin, as shown on the geologic map of Furcron (1939) and the soil map of Petro and others (1956); these possible folds or faults may extend into the region around Airlie and the southeastern part of the quadrangle.

Widespread cataclasis accompanied the development of cataclastic foliation in granitic rocks during Paleozoic orogeny. Shear zones or phyllonite zones, composed of sericite and quartz and having widths of several meters, were formed locally; these zones trend about parallel to foliation (pl. 1, ref. locality 3). Other structural features in granitic rocks include northwest-trending, biotite-filled veinlets (pl. 1). Biotite-filled veinlets are typically about 1 mm thick, are spaced several centimeters apart, have varying northwesterly trends, and commonly intersect to form a network; the veinlets are widespread in granitic rock. Biotite is accompanied by quartz, sericite, and epidote in the veinlets; all these minerals are the youngest generation of metamorphic minerals in the granitic rock. Breccia commonly occurs with the northwest-trending veinlets in elongated zones a few centimeters wide. Left-lateral displacement of 5 to 10 cm is evident along veinlets at a few localities (pl. 1, ref. locality 5). Northwest-trending veinlets, filled with epidote, do occur in metabasalt but are much less common than the veinlets in granite.

As pointed out above, the wide zone of tectonic breccia adjacent to the east side of the Horner Run fault zone may be either Late Proterozoic or Paleozoic in age. In a large exposure of brecciated Marshall Metagranite near the west edge of the quadrangle, many fragments are lenticular and elongated parallel to regional foliation (fig. 8). This parallelism in trends suggests that at this locality both breccia and foliation are of the same age, being Paleozoic.

Breccia and vein networks in granitic rocks have been described recently from the plutonic terrane a few tens of kilometers southwest of the Marshall quadrangle. Mitra (1979) shows two very detailed maps of large exposures where ductile deformation zones form patterns that are very similar to the networks of northeasterly shears and northwesterly veinlets occurring in the Marshall and Rectortown quadrangles. In the Massies Corner quadrangle in the northern part of the area studied by Mitra, ductile deformation zones in granite, as well as breccias along faults and shear zones in granitic rocks, have been described by Lukert and Halladay (1980).

Along the northwestern limb of the anticlinorium, Cloos (1971) and Wickham (1972) have described northwest-trending "slickensided surfaces" (Cloos) and "lineated fractures" (Wickham) that are about perpendicular to cleavage in granitic rocks and the Catoctin Formation. These surfaces may be similar to the northwest-trending veinlets in granite of the Marshall and Rectortown quadrangles which range considerably in their bearing but also show movement transverse to the trend of the anticlinorium.

Northwestward-directed faulting probably took place during the Paleozoic along the Horner fault zone, along the unconformable basal contact of the Fauquier Formation, and possibly along contacts between other rock units that had marked differences in competence. Evidence for Paleozoic movement along the Horner Run fault zone consists of the folded Fauquier beds in a sizable area southwest of the fault zone and the complete absence of folds northeast of the fault zone. This contrast in Paleozoic deformation patterns points to a discontinuity of movement on either side of the fault zone. The randomly oriented folds southwest of the Horner Run fault zone may have formed above a detachment in the basal Fauquier or above unknown faults in the underlying basement rocks. To the northeast of the fault zone, a thrust fault along the basal contact of the

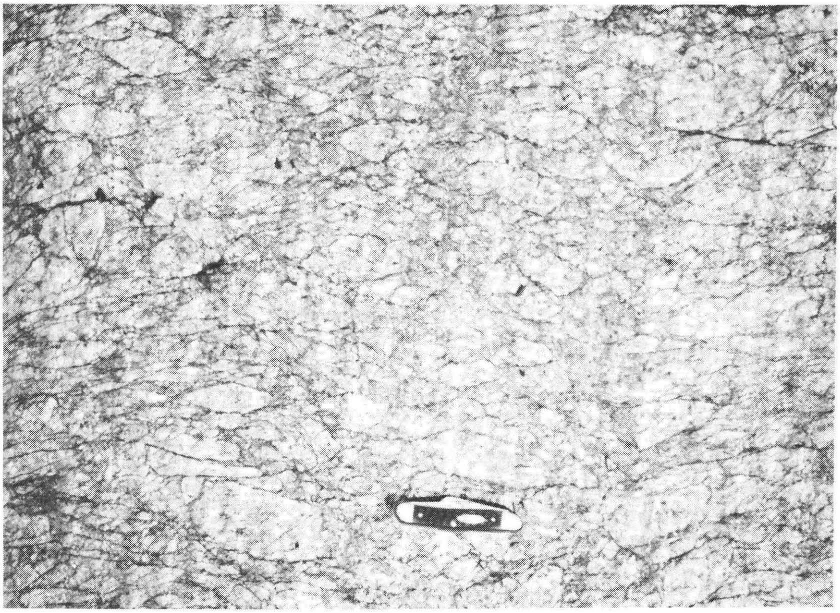

FIGURE 8.—Tectonic breccia in Marshall Metagranite. Knife is 9 cm long. Reference locality 22, between Virginia Highway 55 and U.S. Highway I–66, about 650 ft (200 m) east of west edge of Marshall quadrangle.

Fauquier is suggested by the presence of strongly sheared granitic and arkosic rocks at many places near the contact. Presumed Paleozoic movement is shown somewhat diagrammatically in the sections of plate 1.

An unusual type of closely spaced sheeting in siltstone of the upper part of the Fauquier is exposed very near the Horner Run fault zone about 2,075 m west of Old Tavern (fig. 9). The sheeting was probably formed parallel to bedding by Paleozoic movement in the fault zone. A genetic relation between the sheeting and the fault zone is suggested because similar sheeted siltstone has not been found at any other place in the quadrangle.

The probability of both Precambrian and Paleozoic movement along the Horner Run fault zone suggests that Precambrian and Paleozoic movement may have occurred along other transverse faults in the Blue Ridge anticlinorium, such as the west-trending Front Royal fault about 10 km west of the quadrangle (Wickham, 1972; Rader and Biggs, 1975; Lukert and Nuckols, 1976) and the

FIGURE 9.—Closely spaced sheeting in siltstone in upper part of Fauquier Formation. It was probably formed parallel to bedding by Paleozoic movement in the Horner Run fault zone. Pen is 13 cm long. Photo taken about 375 ft (115 m) upstream from ref. locality 10.

northwest-trending Ashby Gap fault about 15 km northwest of the quadrangle (Gathright and Nystrom, 1974).

The Blue Ridge anticlinorium in North Carolina and southwestern Virginia has long been known to be composed of a complex of great thrust sheets of Precambrian plutonic and stratified rocks. However, the structural nature of the anticlinorium in northern Virginia, Maryland, and Pennsylvania is not so clear from surface geologic patterns, and controversy has existed as to whether the plutonic core was rooted or not. Gwinn (1970) analyzed the structure of the folded Paleozoic rocks to the northwest of the South Mountain (Blue Ridge) anticlinorium in south-central Pennsylvania and estimated that Cambrian rocks on the northwest flank of the anticlinorium had been transported more than 80 km northwestward. He concluded that this great amount of shortening of the Paleozoic stratified rocks could be associated either with an allochthonous (detached) core of the anticlinorium (if the detachment zone passed beneath the core) or with a rooted core (if the detachment zone passed above the core). Persuasive arguments for an allochthonous anticlinorium have been given by Root (1970, 1973) for south-central Pennsylvania and by Harris (1979) for northern Virginia. Mitra (1979) has suggested that the large thrusts mapped by him in the plutonic core pass downward into a sole thrust; he concluded that about 58 km of shortening of the plutonic basement has resulted from movement along ductile deformation zones and along major thrust zones. If so, Mitra's 58 km of basement shortening would be added to Gwinn's 80 km of shortening in Paleozoic strata to give a total shortening for this part of the Appalachian system of at least 138 km during the Paleozoic orogeny.

Dennison (1976) has proposed that gravity tectonics was a very important process early in the Allegheny orogeny. All the Paleozoic formations in the present folded and faulted Valley and Ridge Province are pictured as being the original cover of the Blue Ridge Province, which slid westward along a decollement in the incompetent Rome Formation as the anticlinorium rose, probably early in the Permian. He thinks that the orogeny closed with erosion of the denuded source area and westward thrusting of the anticlinorium over the gravity-slumped strata.

Recent seismic surveys in the southern Appalachians have shown the presence of deep horizontal reflecting layers beneath the Blue Ridge and Piedmont geologic provinces that have been interpreted to be flat Paleozoic strata beneath an allochthonous cover of metamorphosed Precambrian and Paleozoic rocks (Cook and others, 1979; Harris and Bayer, 1979). A similar situation may well exist in the northern Blue Ridge anticlinorium, although it has not been demonstrated by geologic features exposed at the surface. Thus, Paleozoic strata that are exposed 25 km and more northwest of the Marshall quadrangle may extend southeastward at depths of 5 to 10 km beneath the Precambrian rocks of the quadrangle.

As pointed out in the section on metamorphism, the history of Paleozoic orogeny in the northern Blue Ridge anticlinorium is not clear. Deformation must have ended during the Allegheny orogeny in the late Paleozoic when Mississippian strata were involved in thrust faulting in the Valley and Ridge Province to the west. However, the time of the early stages of orogeny is uncertain. Wickham (1972) found in the Front Royal area that metamorphism, folds, cleavage, and lineation were all pre-faulting, but he could not determine whether there had been a single, continuous orogenic event or a series of several tectonic episodes. Therefore, he did not assign an age to the tectonism. Bartholomew and others (1981) concluded that in central Virginia, orogeny probably began in the middle Paleozoic. They infer that significant displacement along the Rockfish Valley ductile deformation zone (a zone of mylonitic rock, 1 to 10 km wide) occurred between Middle Ordovician and Devonian time; postmetamorphic faulting was late Paleozoic. No evidence was found in the Marshall and Rectortown quadrangles to date the orogeny.

Structural features of Mesozoic age

The youngest structural features known in the Marshall quadrangle are the northwest-trending diabase dikes of Triassic and Jurassic age. A diabase dike with similar trend also intrudes Triassic and Jurassic strata of the Culpeper basin a few kilometers to the southeast in the Catlett quadrangle (Lee, 1980). Triassic and Jurassic faults associated with the Culpeper basin could pass into the Marshall quadrangle, but they have not been recognized. It is not known whether movement during the Triassic and Jurassic has occurred along older faults in the Marshall quadrangle.

GEOLOGIC HISTORY

The geologic history of the region is summarized in table 4. A few matters not previously discussed or given in table 4 follow.

The thickness of the cover of Late Proterozoic and early Paleozoic stratified rocks certainly had some effect upon the nature of deformation and grade of metamorphism during Paleozoic orogeny. However, an estimate of that thickness is most difficult because of the intense Paleozoic deformation, the profound erosion of the region, and the

TABLE 4.—*Outline of the geologic history of the northern Blue Ridge anticlinorium*

Geologic time	Geologic events	Tectonic conditions
Present to Middle Jurassic	Erosion and removal of much of the cover of stratified rock from the Blue Ridge anticlinorium to expose large areas of Proterozoic plutonic rocks. No record of important deformation.	North American plate moves westward as Atlantic Ocean widens. Minor crustal activity.
Early Jurassic to Late Triassic	Tholeiitic magma intruded as diabase dikes and sills and extruded as thin basalt flows interbedded with Jurassic sediments in Culpeper basin east of Blue Ridge anticlinorium.	Crustal rifting extends to magma source in mantle. Atlantic Ocean starts to open.
	Normal faulting and vertical movement cause relative uplift of Blue Ridge anticlinorium and downwarp of Culpeper basin to east. Erosion of Blue Ridge terrane is accelerated and continental arkosic sediments are deposited in basins. Possible reactivation of Proterozoic and Paleozoic faults.	Crustal rifting; a precursory event to opening of Atlantic Ocean.
Late Triassic to Early Permian	Erosion of lofty mountain chain formed by Blue Ridge anticlinorium.	Tectonic activity declines.

TABLE 4.—*Outline of the geologic history of the northern Blue Ridge anticlinorium*—Continued

Geologic time	Geologic events	Tectonic conditions
Early Permian to Middle Ordovician	Intense westward-directed deformation in greenschist metamorphic environment starts at undetermined time, perhaps during Taconic or Acadian orogenies, and ends during Allegheny orogeny in Permian. Late Proterozoic and early Paleozoic stratified rocks are tightly folded, pervasively foliated, sliced by thrust faults, and metamorphosed at low grade. Middle and late Proterozoic plutonic rocks are thoroughly cataclasized, foliated, cut by ductile deformation zones and thrust faults, and metamorphosed at low grade. Proterozoic faults possibly reactivated. A great sheet of plutonic rocks was probably sliced off the basement and with its stratified cover transported westward over Paleozoic sedimentary rocks for many kilometers to form the Blue Ridge anticlinorium.	Major period of deformation and metamorphism during late stages of closure of Iapetus Ocean.
Early Ordovician to Late Proterozoic (?)	Slow subsidence of continental margin. Deposition of thick section of marine carbonate sediments, and lesser amounts of fine terrigenous sediments, on continental shelf, preceded by deposition of the basal clastic sequence, mainly the Chilhowee Group.	Long period of crustal quiescence begins as Iapetus Ocean widens.

TABLE 4.—*Outline of the geologic history of the northern Blue Ridge anticlinorium*—Continued

Geologic time	Geologic events	Tectonic conditions
Late Proterozoic	Deposition of Catoctin Formation: Start of basaltic volcanism by extrusion of low-titanium breccias and flows from local vents. Accelerated extrusion of great volume of high-titanium tholeiitic basalt, probably fed by vast number of high-titanium tholeiitic dikes, which accompanied crustal distension of 15 to 20 percent in places. Rhyolitic volcanics are extruded in Maryland and Pennsylvania. Intermittent deposition of thin beds of sandstone and shale (sediments derived from erosion of Fauquier Formation?) accompanied by minor faulting?	Crustal rifting extends to magma source in mantle. Iapetus Ocean starts to open?
	Last stage of deposition of Fauquier Formation: Local normal faulting to form Horner Run fault zone and possibly other faults. Minor rejuvenation of topographic relief and deposition of thin beds of arkose at top of Fauquier.	Renewed crustal rifting.

TABLE 4.—*Outline of the geologic history of the northern Blue Ridge anticlinorium*—Continued

Geologic time	Geologic events	Tectonic conditions
	Later stage of deposition of Fauquier Formation: Sediments become progressively finer grained, starting with fine-grained arkose and siltstone, and culminating in finely laminated shale (rhythmite) and dolomitic rock.	Brief period of crustal quiescence.
	Early stage of deposition of Fauquier Formation: Coarse to very coarse grained arkosic sediments probably deposited in basins created by normal faulting; sediments are derived from rapid erosion of plutonic terrane.	Crustal rifting precursory to opening of Iapetus Ocean.
Late and Middle Proterozoic	Long period of erosion to expose deep-seated rocks. Intrusion of granite of Robertson River Formation (at shallow levels?).	Minor crustal activity.
Middle Proterozoic	Formation of plutonic, igneous, and metamorphic rocks: Marshall Metagranite, Lovingston Granite Gneiss, Flint Hill Gneiss, and Pedlar Formation of Bloomer and Werner (1955).	Complex orogenic processes.

covering of the eastern limb of the anticlinorium nearly everywhere by the fault basins of Triassic and Jurassic strata. Root (1973) has estimated that the maximum thickness of Paleozoic sedimentary cover on the South Mountain part of the anticlinorium in Pennsylvania may have been about 14,500 m. The thickness of Late Proterozoic sedimentary and volcanic rocks beneath the Paleozoic strata may have been several thousand meters. Thus, it is likely that the Middle Proterozoic plutonic rocks of the northern part of the Blue Ridge anticlinorium were covered by a thickness of 5 to 15 km of sedimentary and volcanic strata before Paleozoic orogeny.

There is the problem, too, of how this stratified cover behaved during orogeny. Dennison (1976) has suggested that much of the cover slid westward by gravity along a decollement in the Rome Formation as the anticlinorium rose early in the Allegheny orogeny. I am skeptical that gravity tectonics occurred on such a grand scale as this. If it had, it seems likely that blocks of pre-Rome strata (such as the Chilhowee and Catoctin) would also have slid westward to be preserved somewhere in the Valley and Ridge province in Virginia; fault blocks of these older units are unknown.

Another aspect of the geologic history that deserves emphasis is the close similarity between the tectonic environment and related sedimentation and igneous activity of the Late Proterozoic and the Triassic and Jurassic Periods. During both times large-scale crustal rifting apparently occurred that culminated in the formation of spreading oceanic crust. In both terranes, nonmarine arkosic sediments, ranging from conglomerate to siltstone, were deposited, and late in the tectonic event basaltic magma was intruded as dikes and sills and reached the surface as lavas and breccias. These similarities have been noted earlier by Brown (1973) and by Schwab (1974). It is remarkable that two such very similar tectonic events happened in the same region of the earth some 400 to 500 million years apart.

MINERAL RESOURCES

In the past, many of the different kinds of rock in the quadrangle have been used for a variety of purposes, but no exploitation has taken place recently. Rock cleared from fields was used to build numerous stone fences. Quartzite and epidotized metabasalt from the Catoctin and arkose from the Fauquier have been used in construction of buildings. The Episcopal Church in Upperville, built with quartzite obtained from beds in the Catoctin just south of the southwestern part of the quadrangle, is an especially handsome building. Some small quarries in metagranite and metabasalt were operated, probably mostly for road metal. The dolomitic unit of the Fauquier was quarried at several places in the 19th century for agricultural lime, and it was also quarried on a larger scale for crushed stone at a place along Goose Creek, about 18 km northeast of the quadrangle (Mack, 1965; Parker, 1968). Roofing slate of rather poor quality was once obtained from beds of the Fauquier in the Warrenton area (Furcron, 1939), but no slate of suitable quality has been found in the Marshall quadrangle. It is doubtful that important mineral resources exist in the Precambrian rocks of the Marshall quadrangle.

RADIOACTIVITY

The rocks in the Marshall quadrangle and vicinity have a wide range in natural gamma radioactivity (Neuschel, 1965). The basaltic volcanic rocks of the Catoctin Formation have the lowest gamma values of any lithologic type of the region and underlie a belt of markedly low aeroradioactivity. On the other hand, the granitic rocks and the Fauquier Formation underlie a belt of higher aeroradioactivity whose gamma values are several times those of the Catoctin. The highest gamma values shown on Neuschel's map in this region are about 5 to 10 km north of The Plains and also in several belts in granitic rock to the east and west of Marshall.

During the field studies, scintillometer traverses along roads in the Rectortown quadrangle in the area to the north of The Plains found that the granitic rocks and meta-arkose in the Fauquier had similar ranges of radioactivity; values of about 1.5 to 3 times local background occur at a few places over widths of a meter or two in both types of rock. Source of the radioactivity was not determined. Radioactivity anomalies in the Massies Corner quadrangle (southwest of the Marshall quadrangle) are associated with local concentrations of thorium in augen-bearing gneiss (Lukert and Halladay, 1980).

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