Geology and Mineral Deposits of the Roseland District of Central Virginia

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By NORMAN HERZ *and* ERIC R. FORCE

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Relations among anorthosite, ferrodioritic rocks, and titanium-mineral deposits in Nelson and Amherst Counties in the Blue Ridge of Virginia

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GEOLOGY AND MINERAL DEPOSITS OF THE ROSELAND DISTRICT OF CENTRAL VIRGINIA

By NORMAN HERZ[1] and ERIC R. FORCE

ABSTRACT

The Roseland district of Nelson and Amherst Counties, Va., is centered on an intermontane basin along the southeastern margin of the Blue Ridge. The Grenville-age igneous rocks in this area are less altered than elsewhere in the Blue Ridge, and exposure is sufficient to map their relations. The district was formerly an important producer of titanium minerals and still contains over 5 percent of U.S. identified resources of those minerals. The valuable minerals, rutile and ilmenite, formed in two stages which largely correlate with anorthosite and ferrodiorite, respectively.

The oldest rocks (apparently pre-Grenville) are garnet-graphite-pyroxene-blue quartz granulites and quartz mangerites. Platy-textured leucocratic charnockites are associated with these rocks but are probably a younger neosome.

The Roseland Anorthosite (about 1,050 Ma) intrudes these older rocks as a largely concordant basal sheet. Crosscutting relations with country rock are abundant, however. The anorthosite consists of andesine-antiperthite megacrysts in a granulated oligoclase-potassium feldspar matrix. Its margins contain pyroxene and blue quartz megacrysts, probably as a result of high-temperature reaction between anorthosite melt and country rocks. The unusually alkalic nature of the anorthosite has led to unusual rutile mineralization in this contaminated marginal facies and its immediate country rocks, especially in swarms of anorthosite sills in mangeritic rocks forming the anorthosite roof along the eastern side of the body.

The Shaeffer Hollow Granite (about 990 Ma) is a coarse leucocratic blue quartz granite, porphyritic with tabular feldspars. It cuts granulite but is present largely as roof pendants and screens in the younger ferrodioritic plutons, except in a wide deformation zone where it appears to be the dominant protolith of mylonitic rocks.

The Roses Mill and Turkey Mountain ferrodiorite-charnockite plutons (about 970 Ma) together form a largely concordant upper intrusive sheet. Intrusive relations with older units, however, are abundant. These rocks have high ilmenite-apatite-(zircon) contents that reflect distinctively high values of Ti, P, Zr, Fe/Mg, and K/Si. Blue quartz is present only as abundant xenocrysts. Much of these plutons is isochemically altered to biotitic augen gneiss. Layered concordant impure nelsonite (ilmenite-apatite rock) is locally found along the bases of these plutons, and nelsonite forms discordant bodies in the immediately underlying country rock. These lithologies probably formed by liquid immiscibility. Nelsonites and ilmenite-rich ferrodiorite constitute the main ilmenite resources of the district.

The anorthosite and ferrodiorite-charnockite plutons are apparently not comagmatic but probably cogenetic. The anorthosite formed in a deeper crustal environment than ferrodiorite and probably was emplaced as a diapir into the higher crustal level.

In the northwestern side of the district are ferrodioritic charnockitic rocks of the Pedlar massif. They are about 1,040 m.y. old but are separated from all other units by a wide zone of deformation so that original relations are not known.

The Mobley Mountain Granite (about 650 Ma) is a fine- to medium-grained subsolvus two-mica granite with related aplites and pegmatites.

Grenville-age metamorphism of granulite and anorthosite units was of the pyroxene granulite facies. Two-pyroxene and oxygen isotope geothermometry suggest 800 °C and 8 kbar, with $P_{H_2O} < P_{total}$. Typical assemblages include blue quartz, perthitic to antiperthitic feldspars, orthopyroxene and clinopyroxene, garnet, graphite, rutile and ilmenite, and minor titanium-rich biotite and hornblende.

Lower amphibolite-facies metamorphism may have accompanied intrusion of the Mobley Mountain Granite in the latest Proterozoic. Greenschist metamorphism which accompanied Paleozoic deformation was selectively overprinted on higher grade rocks except in deformation zones where assemblages of chlorite, carbonate, epidote, and albite are pervasive.

The two major structures of the district are (1) the Roseland complex dome, cored by the anorthosite, which extends over 22 km in a northeast-southwest direction, and (2) a wide zone of mylonitic deformation along the northwest flank of the dome. Four periods of deformation are recognized in the area, and the last three correlate with the granulite-, amphibolite-, and greenschist-facies metamorphic episodes. The first two are seen only in the oldest rocks and consist of tight folds and related fabrics that are cut by younger units. The dome belongs to the third period and probably accompanied formation of a pre-Mobley Mountain foliation that dips steeply southeast in many units. The third period was also responsible for much movement in the mylonitic zone, though there is evidence of a later fourth period of deformation there.

INTRODUCTION

GENERAL GEOLOGIC AND ECONOMIC SETTING

The Roseland district is characterized by deposits of the titanium minerals ilmenite and rutile and by the rocks anorthosite and nelsonite, in a Proterozoic crystalline terrane in the Blue Ridge of Virginia. It is located in Nelson and Amherst Counties of central Virginia, about midway between Charlottesville and Lynchburg (fig. 1). The district is covered by four 7½-minute quadrangles: Piney River, Massies Mill, Arrington, and Horseshoe Mountain. Geologic mapping (pl. 1) was carried out of the entire Piney River quadrangle as well as a large part of Horseshoe Mountain, the southern part of Massies Mill, and the northwestern part of Arrington. The purpose of the study was to gain an understanding of the origin of titanium-mineral resources and to evaluate the district's titanium resources and resource potential, commonly said to be among the largest in the country.

Principal access to the area is provided by U.S. Highway 29 on the east side, U.S. Highway 60 in the southwest, State Highway 151 through the central part,

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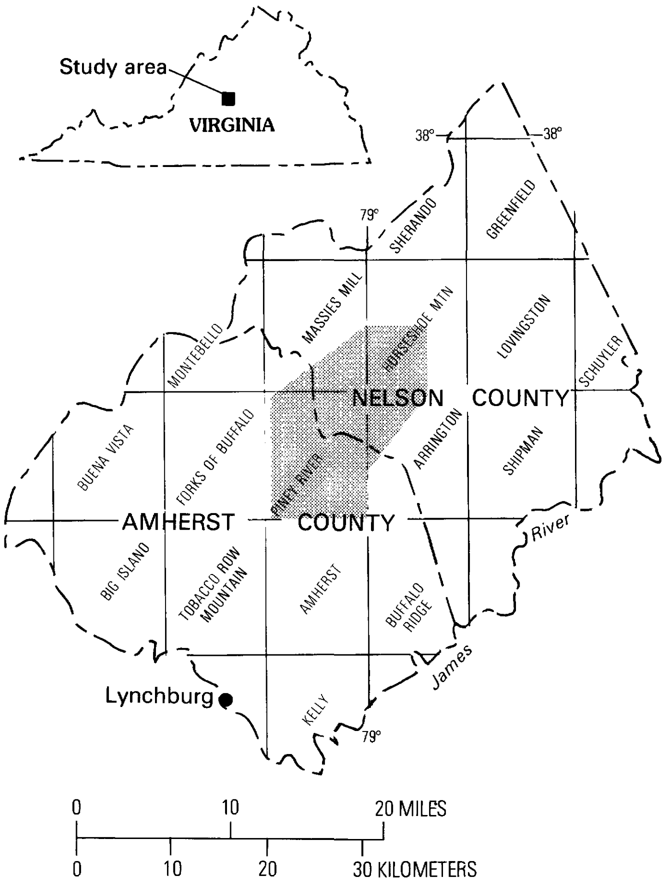


FIGURE 1.–Index map showing location of the study area (shaded). Within the grid, 7½-minute quadrangles are labeled.

and State Highway 776 in the western part. The Virginia Blue Ridge Railroad has its northern terminus at Piney River and connects with the Southern Railroad to the south at the James River. The land is mostly farmed on gentle slopes; the steep slopes are mostly forested.

Physiographically, the district is the border area of the Blue Ridge to the northwest and the Inner Piedmont to the southeast; geologically, however, it is within the Blue Ridge (Bloomer and Werner, 1955). The district is drained by the Buffalo, Tye, and Piney Rivers, which flow in a southeasterly direction to the James River. Elevations range from highs in the Blue Ridge of about 3,000 to 4,000 ft (910–1,220 m) in the George Washington National Forest in the Massies Mill and Horseshoe Mountain quadrangles to a low of about 520 ft (160 m) at the confluence of the Piney and Tye Rivers in the Arrington quadrangle. The relief is rugged in the Blue Ridge section and flat to rugged in the Piedmont, depending on the nature of the bedrock; anorthosite and granulite underlie flat terrane which forms the floor of an intermontane basin. Charnockites, augen gneisses, and granites form the surrounding more rugged terrain.

The Virginia Blue Ridge Complex of Brown (1958) is considered to be the basement in the region. It includes igneous rocks such as anorthosites, charnockites, mafic rocks, and granites as well as granulites and gneisses, all supposedly of Grenville age. The Complex is up to 32 km in width and extends some 500 km from central Maryland in the north, where it disappears under metamorphic rocks of Late Proterozoic age, southwestward through Virginia and into North Carolina. The gross structure of the Complex is considered to be an anticlinorium, but different rock sequences are said to form the two limbs (Conley, 1979, p. 123). In the study area, a large domal structure is present that may be part of this regional anticlinorium. An adjacent shear zone may decouple the limbs of this dome. Metamorphic foliation dipping steeply southeast is pervasive. The Complex is bounded to the southeast by rocks of the James River Synclinorium of Late Proterozoic and early Paleozoic(?) age. On the northwestern side, the Complex is thrust over rocks of Late Proterozoic and early Paleozoic age.

The Grenville-age rocks have been deformed repeatedly; Grenville deformation corresponds mostly to granulite facies metamorphism, later Proterozoic events to amphibolite facies metamorphism, and Paleozoic spaced (nonpenetrative) foliation is associated with thrusting and corresponds to local retrograding to greenschist facies.

The Roseland district has long been known as one of the world's most important sources of rutile and ilmenite, the principal ore minerals of titanium. Mining began here in 1878 for iron but was not successful because of the high titanium content in the ore (Watson and Taber, 1913, p. 47–50). Beginning early in this century, both rutile and ilmenite were mined when the true nature of the ores was better understood. The American Rutile Company, operating in Roseland, was soon supplying the entire world demand for rutile and continued operating until 1949 when competition from placer deposits on Australian beaches forced the operation to close down.

Saprolite[2] deposits of ilmenite were mined along the Piney River, starting in 1930, by the Vanadium Corporation of America (Fish, 1962, p. 5). American Cyanamid acquired the properties in 1944 to supply ilmenite for a new pigment plant at Piney River but ceased operating in 1971. At present, there are no active producers of titanium minerals in the district.

The rock types traditionally associated with deposits of titanium minerals are the anorthosite (rutile along its contact with older rocks) and nelsonite (ilmenite-apatite rock).

[2] "A general name for thoroughly decomposed, earthy, but untransported rock" (American Geological Institute, 1960, p. 255).

Anorthosite, consisting of relatively pure feldspar with little quartz, had been quarried for some years (until 1981) in the Piney River District by the International Minerals and Chemical Corporation. The mill product is called "aplite," and is used largely in the manufacture of container glass and glass wool insulation (Wells, 1976).

Other known mineral resources of the district include phosphate (Watson and Taber, 1913, p. 48-49) and kaolin (Lintner, 1942). Some development work has been done in the area, but no mining has been conducted for either commodity.

PREVIOUS GEOLOGICAL WORK

MAPPING AND STRATIGRAPHY

The first geologic mapping in the area was by Watson and Taber (1913) who described the principal rock types as (1) biotite-quartz monzonite gneiss and various schists, (2) syenite, previously called pegmatite, (3) gabbro, (4) nelsonite, and (5) diabase. The syenite, gabbro, and nelsonite were believed to be approximately contemporaneous and gradational. The term "syenite" was used in accordance with then-accepted nomenclature, but Watson and Taber (1913, p. 68) stated in a footnote that a better name would be "andesine anorthosite."

Jonas (1935) introduced the term "hypersthene granodiorite" for the unit that was later named the Pedlar Formation (Bloomer and Werner, 1955) on the northwest side of the district. Other lithologic units that were recognized and named include the Lovingston granite gneiss (Jonas, in Stose, 1928) and the Roseland Anorthosite (Ross, 1941).

Bloomer and Werner (1955) proposed a stratigraphy for this part of the Blue Ridge that became the standard for over two decades (table 1). They called the oldest unit, which was present only as elongate gneissic inclusions in younger rocks, the "basement complex gneiss." The oldest mappable unit of the basement complex was the Lovingston Formation gneiss and granite, which consisted principally of quartz, potassium-feldspar, plagioclase an_{30}, and biotite. The Lovingston gneiss was defined as having prominent porphyroblasts of potassium feldspar up to 4 in. (10 cm) in diameter; the included granitic facies tended to be equidimensional with grain aggregates about 1 cm in diameter. The Marshall Formation was the next major unit of the basement complex and graded into the Lovingston below and the Pedlar Formation above. The Marshall was mineralogically similar to the Lovingston but was distinguished from it by a lack of prominent porphyroblasts (augen) and a strong layering of quartzofeldspathic bands that averaged a few millimeters in width and were separated by folia of bleached and chloritized biotite. The Pedlar Formation consisted largely of hypersthene granodiorite and formed most of the basement complex northeast of Roanoke; it was both surrounded by and graded into the Marshall and Lovingston Formations. In addition to hypersthene granodiorite, the Pedlar included granitic, granodioritic, syenitic, quartz dioritic, anorthositic, and unakitic rocks. The Roseland Anorthosite was described as an oval body about 13 miles (21 km) long and 2.5 miles (4 km) wide in the middle of the basement complex, bordered by the Marshall Formation in the Piedmont and the Pedlar Formation in the Blue Ridge. This basement rock sequence was named the Virginia Blue Ridge Complex by Brown (1958) and is shown as such on the 1963 Geologic Map of Virginia (Calver and Hobbs, 1963).

In mapping immediately north of the Roseland district in the Greenfield and Sherando quadrangles, Bartholomew (1977) recognized some new units in the

TABLE 1.—*Lithologic units used by previous workers in the study area*

Watson and Taber, 1913	Jonas and Stose, 1939	Bloomer and Werner, 1955	Hillhouse, 1960
Diabase			Dolerite dikes
Nelsonite		Nelsonite	Nelsonite
Gabbro			Pegmatitic Anorthosite
Syenite (formerly pegmatite)	Anorthosite	Roseland Anorthosite	Border Gneiss
	Hypersthene granodiorite	Pedlar Formation	Hypersthene granodiorite, massive, layered and altered.
		Marshall Formation	Feldspathic gneiss Biotite pencil gneiss
Biotite-quartz monzonite gneiss	Lovingston granite gneiss	Lovingston Formation	Biotite aplitic gneiss Granitic gneiss Augen gneiss
		Basement complex gneiss	

Virginia Blue Ridge Complex and suggested several major revisions in the stratigraphy somewhat along the lines of the revisions we propose (table 2). He found that a 1- to 3-mile (2- to 5-km) zone of cataclastic rocks, the Rockfish Valley Fault and related deformation zone, separated two distinct massifs: the Lovingston to the east and the Pedlar to the west. The Lovingston massif consists of layered granulite gneiss, which was intruded first by the Lovingston Formation, a massive, coarse-grained biotite-bearing granitic gneiss, and subsequently by small bodies of massive charnockite. West of the fault, the Pedlar massif is made up of minor layered granulite gneiss and massive Pedlar Formation charnockite-suite rocks.

Preliminary accounts of the geology of the Roseland district by the authors are Herz (1969, 1984), Force and Herz (1982), and Herz and Force (1984).

ECONOMIC GEOLOGY

Watson and Taber's (1913) monographic study began the studies of titanium deposits in the district and is still a standard reference in studies of similar deposits throughout the world. They pointed out the association of rutile deposits with anorthosite (called syenite in their study) and documented the nelsonitic type of ilmenite deposit. They believed that the rutile and associated ilmenite were formed as primary minerals from the residual fluids of the anorthosite magma.

Ross (1941) continued with a good petrologic study of the titanium mineral deposits but thought that the mineralization occurred as a result of a hydrothermal process. Ross pointed out a close relationship of the anorthosite border to both rutile and nelsonite mineralization and assumed that the latest movements in the area were due to the anorthosite emplacement which occurred after its consolidation.

The 1940's and 1950's saw a continuation of the inconclusive debate of hydrothermal vs. magmatic origin for the nelsonites. Philpotts (1967), however, showed that liquids of iron-titanium oxide plus apatite composition form immiscible and eutectic mixtures at two-thirds oxides and one-third apatite with liquids of dioritic composition. Nelsonites have compositions similar to the eutectic ratio which suggests temperatures of formation of 850–1,000 °C. Kolker (1982) supported this model with a detailed petrographic study of nelsonites.

In addition to studies of rutile and ilmenite deposits in unweathered rock, other works have shown that economic deposits of ilmenite have formed in saprolite (Fish, 1962) and that stream placer deposits of both rutile and ilmenite also have formed (Herz and others, 1970; Minard and others, 1976). The saprolite deposits are developed in anorthosite contact areas and on "diorite" (Fish, 1962) and are mostly unrelated to nelsonite dikes. Placer deposits appear to be derived from both anorthosite and its related rocks as well as from charnockites and high-grade granulitic metamorphic rocks of the Blue Ridge.

Hillhouse (1960) in an unpublished dissertation made estimates of titanium mineral resources with which we are in substantial agreement.

PROPOSED LITHOLOGIC UNITS

In the Roseland District, we used units generally similar to those described by Bartholomew (1977) (table 2). The oldest mappable unit includes banded granulites, mangerites, quartz mangerites, and associated leucocratic granite and charnockite.[3] Granulites are found largely on the southeast side of the district and typically contain garnet, orthopyroxenes and clinopyroxenes, blue quartz, perthitic feldspars, graphite, and sulfides.

Intrusive into these oldest rocks is the Roseland Anorthosite, a megacrystic andesine antiperthite rock having abundant blue quartz and pyroxene toward the border areas, where rutile also commonly occurs.

Shaeffer Hollow Granite, a coarse leucocratic granite, is the youngest body that contains primary blue quartz; in this district, the blue quartz serves as a guide in separating older from younger rocks.

These older units were deformed together and behaved as a country rock terrane during intrusion of the Roses Mill and Turkey Mountain plutons. The latter units together form the Roses Mill Plutonic Suite of Herz and Force (1984). The Roses Mill pluton occupies a large area in the eastern part of the district and consists of a ferrodiorite suite that includes charnockite and has locally been altered to biotitic granitoid augen gneiss. The Turkey Mountain plutons found in the southern and southwestern parts are closely related to the Roses Mill and consist of magnetic charnockite, also locally altered to augen gneiss, as well as layered dioritic rocks. Nelsonite cumulates are found especially at the bases of

[3] The charnockite suite of granitoid rocks typically has orthopyroxene, with or without clinopyroxene, as the principal mafic mineral, and perthitic or antiperthitic feldspars, and is commonly associated with anorthosite (deWaard, 1969). Chemical compositions are similar to igneous rocks of the normal granitic suite, the principal difference being the relatively low P_{H_2O} conditions of crystallization of the charnockites. We have followed the usage of others (for example, Martignole, 1975) and use the term "charnockite" as an analog of granite and the term "quartz mangerite" for granodiorite. Mangerite is used for quartz-poor rocks of quartz mangerite or charnockite composition. We use the term "charnockitic ferrodiorite" for quartz-bearing rocks with much primary orthopyroxene and with high Fe/Mg and K/Si ratios. Many associated rocks in the Roseland District were later metamorphosed under lower amphibolite or greenschist conditions and developed suites including biotite, uralitic hornblende, and epidote. We have retained the original igneous terms for these rocks. "Leucocharnockites" are locally lacking in pyroxene but have perthitic and antiperthitic feldspars; we consider them to be an analog to leucogranite but retain the term leucocharnockite to emphasize their close relation to the charnockite suite.

TABLE 2—*Terminology of this report and a modern study of an adjacent area for the Lovingston massif*
[n.a., not applicable]

Age (m.y.)	Era	Rock unit	Lithologies and key minerals (in parentheses)	Metamorphic and tectonic events and key minerals (in parentheses)	Units of Bartholomew (1977; 1981)
	Cenozoic	Surficial units	Gravels	n.a.	n.a.
	Mesozoic	Diabase	Diabase		Diabase
	Paleozoic	n.a.	Mylonite	DEFORMATION ZONE: Greenschist facies (chlorite, epidote, carbonate, sphene).	Rockfish Valley deformation zone.
650	Late Proterozoic	Mobley Mountain Granite.	Granite (colorless quartz, two-feldspars).	DEFORMATION ZONE: Lower amphibolite facies (biotite, garnet, sphene).	n.a.
	do.	Mafic dikes	n.a.	n.a.	Pyroxenites and mafic dikes
970	Middle Proterozoic (Grenville).	Roses Mill and Turkey Mountain plutons.	Ferrodiorite, charnockite, layered diorite, nelsonite (ilmenite, apatite, zircon, two-pyroxenes, colorless quartz, perthite).	Grenville granulite-facies metamorphism and anatexis (two-pyroxenes, garnet, blue quartz, perthite).	Massive charnockite and Lovingston Formation.
990	do.	Shaeffer Hollow Granite.	Leucocratic granite (perthite, blue quartz).		n.a.
1,050	do.	Roseland Anorthosite	Anorthosite (andesine antiperthite, blue quartz, rutile).		
	?	Banded granulites	Banded granulite gneiss and quartz mangerite.	?	Layered granulite gneiss

both plutons, and nelsonite veins are found in structurally lower units. Both plutons and the nelsonite contain ilmenite, apatite rich in rare earth elements, and zircon.

Across a wide northeast-trending mylonitic zone in the northwest part of the district is the Pedlar massif; because of the absence of good correlations across this zone, its relation to the other units is unknown. The similarity of ferrodioritic parts of the Pedlar in lithology and age suggests correlation to the Roses Mill pluton. All the above units form protoliths of rocks deformed in the northeast-trending mylonitic zone. The most abundant protoliths, apparently, are leucocratic charnockites.

Post-Grenville Proterozoic rocks include the Mobley Mountain Granite and the mafic dikes which may represent feeder dikes for the Catoctin Formation metabasalt flows that crop out to the west and to the east. Different mafic dikes appear to be both post- and pre-granite. Other mafic dikes, including ultramafics and lamprophyres, are also present but of unknown age and affiliation. The latest igneous event is taken to be the emplacement of diabase dikes of early Mesozoic age.

All these units are discussed in detail in subsequent sections.

FIELD WORK

Geologic mapping was done by Herz from 1965 to 1968 and by Herz and Force from 1977 to 1979. Mapping was aided by aeromagnetic maps and partial aeroradiometric coverage. Observations of soil color, saprolite properties, and float were used extensively along with bedrock exposures to construct a geologic map and cross section (pl. 1) showing the rock units and their structures. Numbered localities mentioned in the text and described in appendix 2 are also shown.

Two meteorological events helped to improve the accuracy of our geologic map of the district. First, Hurricane Camille in 1969 cleaned off many steep slopes on the north side of the district, elucidating relations especially within the Roses Mill pluton (fig. 2). Second, two exceptionally dry years allowed extensive streambed traversing; streambed exposures in the map area are excellent (fig. 3).

ACKNOWLEDGMENTS

We thank Katherine Wolf and Irene Harrell for help with the text. Robert Ayuso and Michael Foose were the

FIGURE 2.—Landslide scar on east side of the ridge north of Bryant Mountain. Hurricane Camille in 1969 caused hundreds of such slides in Nelson County. The resulting exposures of fresh rock are a foundation for our studies of the Roses Mill pluton.

technical reviewers. We also acknowledge the assistance given to the project by C. E. Craven, then chief geologist of American Cyanamid, Piney River, Va. The Virginia Division of Mineral Resources, through its former director, J. L. Calver, and its present director, R. C. Milici, also provided continuous support and encouragement. M. J. Bartholomew and others of the Virginia Division of Mineral Resources gave much of their time in support of the field mapping.

PRE-GRENVILLE AND GRENVILLE ROCKS

BANDED GRANULITES AND ASSOCIATED ROCKS

The lithology which defines the banded granulite map unit is finely banded granular to platy-textured leucocratic gneiss containing garnet, graphite, blue quartz, perthitic feldspar, and pyroxene (figs. 4, 5; locs. 1, 2). Mangeritic rocks, locally containing garnet and graphite and having slight to strong foliation, are also characteristic of the unit (locs. 3, 4).

Inseparable from the banded granulite map unit but probably present as an anatectic neosome in the above rocks are leucocratic blue quartz-perthite rocks (leucocharnockites) of characteristic platy texture (fig. 6). These rocks commonly form thin layers (locs. 4, 5; fig. 5) concordant to older granulites.

The granulite unit is in contact mostly on its structurally lower side with anorthosite. Abundant dikes and sills of anorthosite are found within the granulite and are most abundant near the anorthosite border, showing that most granulite lithologies are older than the anorthosite.

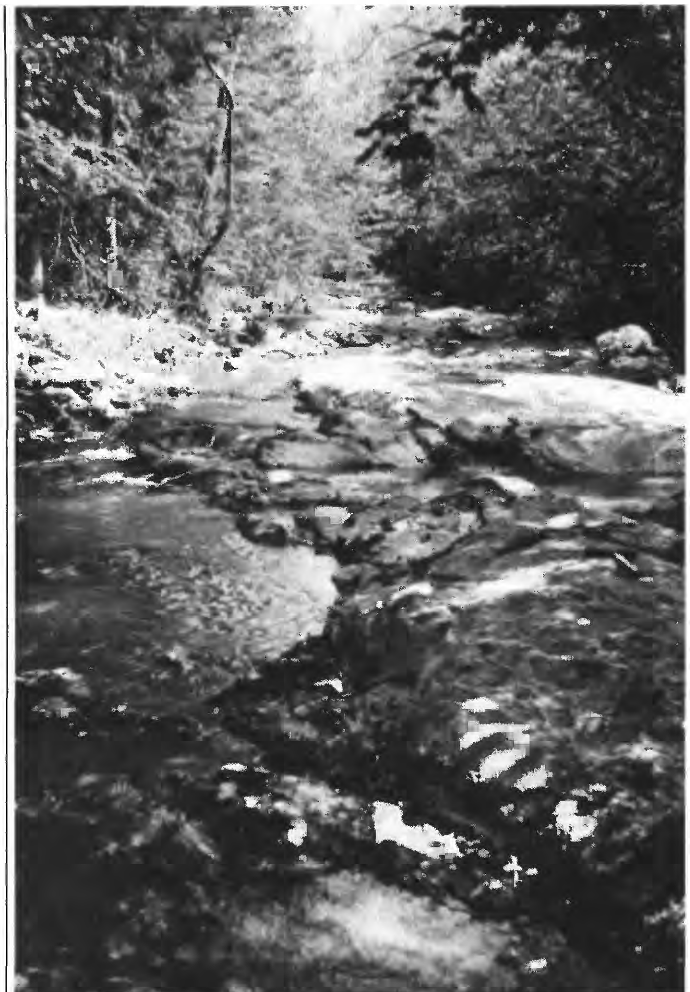


FIGURE 3.—Streambed exposures in Jennys Creek, locality 3 (shown on pl. 1 and described in app. 2). Such streambed exposures are a foundation for our studies of the relation between granulite, anorthosite, and Roses Mill units. Northward within the field of view, for example, slightly foliated quartz mangerite becomes strongly foliated then altered to a rutile-bearing assemblage. Small dikes of the Roses Mill pluton are also present. (See fig. 20.)

The structurally upper contact of the granulite is generally with Shaeffer Hollow Granite and with the augen gneiss facies of the Roses Mill and Turkey Mountain plutons. The contact is commonly faulted or even mylonitic, but numerous crosscutting relations show that the granulite is the oldest unit.

The granulite unit shows evidence of Grenville-age granulite-facies metamorphism throughout the map area. Lithologies are distinctive enough, however, that we can treat the unit as a lithologic rather than a

FIGURE 4.–Banding in granulite on Tye River, locality 11. Banding is formed here by alternation of lithologies rich and poor in pyroxene, now altered. At upper left is the finer margin of a large dike of Roses Mill pluton, which cuts banding.

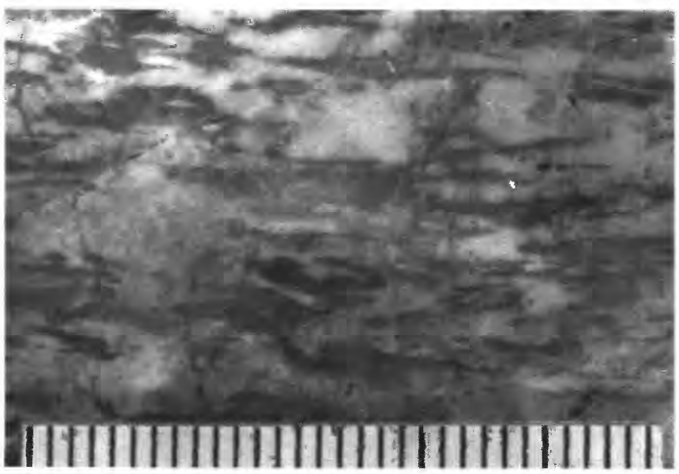


FIGURE 6.–Sawed hand specimen of platy-textured leucocharnockite with blue quartz (gray), feldspar (white), and minor ilmenite and rutile. Specimen from Piney River, locality 5. Millimeter scale.

metamorphic or tectonic unit. The deformational history of the granulite unit is complex but clearly consists of at least one phase that is missing from rocks of Roses Mill age or younger (fig. 7).

Individual lithologies within the banded granulite map unit could not be separated on plate 1. Well-exposed stream sections (locs. 1–5) and drill logs (see app. 1) show intervals of banded granulite typically 3 to 100 m thick, concordantly interlayered with quartz mangerites and mangerites 1 to over 100 m thick, with these rocks both concordantly interlayered and cut by leucocharnockite bodies 0.05 to 10 m wide. All these rocks are cut by younger units.

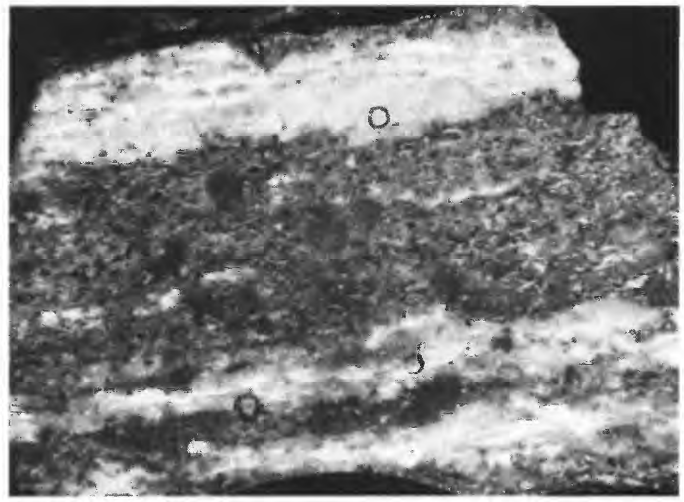


FIGURE 5.–Sawed hand specimen of banded granulite from Tye River, locality 1. Dark bands contain garnet, graphite (lustrous in this view), blue quartz, feldspar, uralite (after pyroxene), pyrrhotite, and rutile. Light bands are leucocharnockite containing blue quartz and altered feldspar with minor zircon (about 980 Ma in age). Quartz plates are mostly slightly strained rutilated single crystals. This banding is probably due to injection or partial melting. Small circles are around zircon grains. Field of view is 7 cm×4.5 cm.

FIGURE 7.–Isoclinal fold in garnetiferous banded granulite. Quartz-feldspar plates are here wrapped around fold; in probably older folds they are parallel to the axial plane.

Most outcrops of granulite show local Paleozoic deformation with attendant formation of retrograde minerals–clinozoisite, chlorite, carbonate, albite, sphene, and white mica.

BANDED GRANULITE GNEISSES

The lithology defining the banded granulite map unit is banded granulite gneiss. Impressive stream exposures

TABLE 3.—*Analyses of granulites, mangerites, and Shaeffer Hollow Granite*

[Analysts and methods (chemical) are as follows: Samples nos. 1,3,5–P. Elmore and colleagues, USGS, Reston, Va. (rapid rock analysis) and W.B. Crandell, USGS, Washington, D.C. (semiquantitative spectrographic); 2,6–G. J. Davis, University of Georgia (x-ray fluorescence); 4–F. Brown and colleagues, USGS, Reston, Va. (rapid rock analysis). ---, not detected.; P, present]

Sample number	1	2	3	4	5	6
Major elements, in weight percent						
SiO_2	80.0	79.71	74.4	64.3	64.3	62.24
Al_2O_3	11.2	10.96	14.7	13.0	16.2	16.89
Fe_2O_3	1.0	([a])	.15	1.9	1.9	([a])
FeO	.36	2.30	.12	7.5	5.2	5.79
MgO	.23	.41	.07	2.9	3.0	1.19
CaO	.89	2.30	1.2	1.7	1.9	3.26
Na_2O	4.4	2.77	3.9	1.1	2.2	3.35
K_2O	.94	.68	4.2	2.5	2.4	3.30
H_2O^-	.05	.41	.15	.21	.22	1.13
H_2O^+	.60		.50	1.1	1.1	
TiO_2	.17	.23	.04	1.7	.64	.87
P_2O_5	.06	.03	.00	.55	.08	.25
MnO	.00	.07	.00	.19	.14	.07
CO_2	<.05	---	<.05	.02	<.05	---
F	---	---	---	.04	---	---
Total	99.9	99.87	99.4	98.7	99.3	98.34
Normative minerals, in weight percent						
Q	48.75	54.45	32.97	37.58	30.75	19.64
or	5.55	4.02	24.81	14.77	14.18	19.50
an+ab	41.23	34.65	38.93	13.91	27.51	42.89
C	1.47	1.56	1.56	6.80	6.72	2.48
hy	.57	3.42	.20	16.97	14.65	8.30
ap	.14	.07	---	1.30	.19	.59
il	.32	.44	.08	3.23	1.22	1.65
mt	.67	.93	.22	2.75	2.76	2.33
hm	.54	---	---	---	---	---
fr	---	---	---	.03	---	--
cc	---	---	---	.05	---	---

Sample number	1	2	3	4	5	6
Calculated mineral compositions						
en (%)	100.0	30.0	85.0	42.6	51.0	35.7
an (%)	9.7	32.4	15.3	33.1	32.4	33.9
or:ab:an	11.9	10.4	38.9	51.5	34.0	31.3
	:79.5	:60.6	:51.7	:32.5	:44.6	:45.4
	:8.6	:29.0	:9.3	:16.0	:21.4	:23.3
Trace elements, in parts per million						
Ba	500	322	200	---	1,000	1,269
Be	---	---	3	---	---	---
Ce	---	22	---	---	150	---
Co	3	4	---	---	7	14
Cr	---	---	---	---	100	---
Cu	30	---	3	---	70	---
Ga	7	---	15	---	10	---
La	---	11	---	---	100	7
Mo	---	0.5	---	---	7	0.4
Nb	---	0.2	---	---	10	15
Nd	---	---	---	---	---	---
Ni	---	---	---	---	<.3	---
Pb	20	1	20	---	10	23
Rb	---	7.2	---	---	---	91
Sc	---	---	---	---	20	---
Sr	100	218	50	---	150	392
V	7	18	---	---	150	68
Y	---	---	10	---	50	---
Yb	---	---	1	---	5	---
Zr	---	654	100	---	200	335

Modal analyses, in volume percent

Sample number	1	2	7	8	9	10	11	12	13
Quartz	9.2	61.7	42.6	9.2	10.9	18.4	---	18.2	9.1
Plagioclase	[b]18.8	[b]24.7	[f]40.6	[b]49.8	[c]42.3	[b]23.8	35.8	16.8	[h]28.7
Potassium feldspar	---	---	---	[g]22.4	9.1	8.8	---	48.0	[g]29.5
Orthopyroxene	6.8	---	---	6.6	---	---	---	---	---
Clinopyroxene	10.0	---	---	5.6	---	---	---	---	---
Hornblende	10.6	[c]2.7	---	[c]4.0	---	8.8	[c]20.5	---	[c]29.4
Biotite	---	1.4	.1	.7	8.3	2.0	18.8	4.6	---
Ilmenite	[e]1.9	---	---	---	2.4	---	[d]1.5	---	[d]2.5
Apatite	.6	---	---	.2	---	---	P	.7	.4
Garnet	15.3	---	---	---	---	---	2.5	---	---
Clinozoisite	5.6	4.9	1.0	---	7.1	19.0	17.2	5.4	---
Chlorite	10.2	---	---	---	---	---	---	1.0	---
Muscovite	19.6	4.3	11.7	---	---	18.4	---	3.4	---
Sphene	.6	---	.6	---	2.6	[i].7	.5	.9	---
Hematite	---	---	2.6	---	---	---	---	.7	---
Magnetite	---	.3	---	[k]1.4	---	---	[d]3.3	---	---
Rutile	---	---	---	---	8.5	([j])	([j])	---	---
Zircon	---	---	---	---	---	---	---	.2	---

[a] All Fe reported as FeO.
[b] Largely andesine antiperthite, an_{30}.
[c] Uralite.
[d] Rimmed by sphene and (or) biotite.
[e] Garnet rim.
[f] Antiperthitic, clinozoisite-filled.
[g] Perthitic.
[h] an_{30}.
[i] Includes ilmenite cores.
[j] Included with ilmenite.
[k] Included some ilmenite.

FIGURE 8.—Foliated banded granulite from Allen Creek, locality 2. Compositional layering, shown mostly by variations in garnet abundance, may be bedding; foliation parallel to pencil is younger.

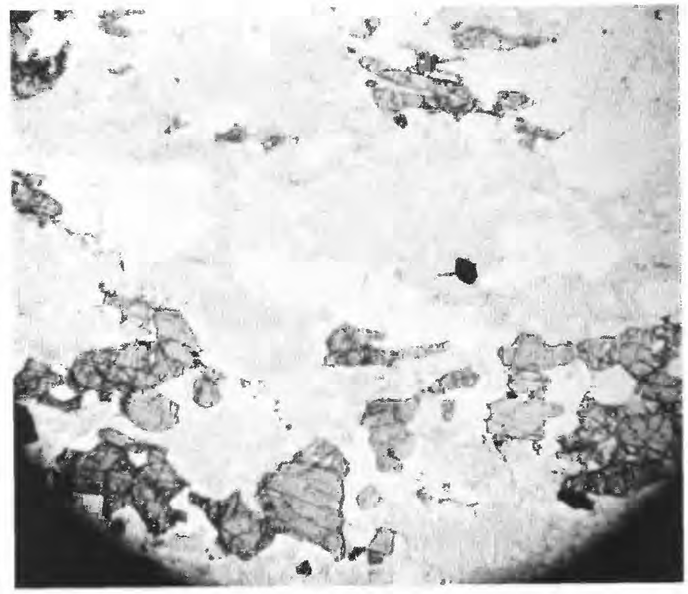


FIGURE 9.—Photomicrograph of two pyroxene-mesoperthite-blue quartz-ilmenite banded granulite. Blue quartz is unstrained and contains unstrained rutile needles. Plane light, potassium-feldspar-stained. Field of view is 5 mm.

of banded granulite gneisses exist (locs. 1 and 2 are proposed as references) but units could not be traced, and the lithology could not be separated as a map unit. The granulite gneisses locally are interlayered (conformably) with quartz mangerites described below. (See also app. 1.)

The term granulite can be applied to these rocks both in the metamorphic grade sense and in the sense of a granular-textured metamorphic rock. We believe them to be metasedimentary and volcanic in origin, the evidence being their mineralogy (abundant garnet and graphite) and the presence of prominent compositional banding (fig. 8; loc. 2).

Chemical and modal analyses of some banded granulite gneisses are shown in table 3. The prograde metamorphic assemblage is blue quartz, perthitic feldspars, garnet, two pyroxenes, pyrrhotite, rutile and (or) ilmenite, graphite, and apatite (fig. 9). The high compositional variability in the unit causes most rocks to contain only parts of the assemblage. Reddish-brown biotite and amphibole may be original phases locally. Secondary minerals include greenish biotite, actinolitic amphibole, white mica, epidote minerals, sphene, and chlorite.

Blue quartz forms as much as 65 percent of some granulites and is equant to platy (figs. 5, 9). In rocks without evidence of late deformation, platy quartz is little strained and consists of large single crystals. Rutile needles in the quartz show no evidence of strain.

TABLE 3.—Continued

SAMPLE DESCRIPTIONS AND LOCATIONS (CHEMICALLY ANALYZED SAMPLES SHOWN ON PL. 1)

SAMPLE NO. 1. Massive quartzo-feldspathic leucocharnockite, poorly foliated, Allen Creek, near Roses Mill contact, Piney River quadrangle.
2. Thinly layered blue-quartz plagioclase leucocharnockite, some uralitic amphiboles. Piney River at Route 151, near anorthosite contact, Piney River quadrangle.
3. Blue-quartz feldspathic granite (Shaeffer Hollow), cataclastic, strongly lineated, elongate, banded felsic minerals. 0.75 km southwest of Harewood Cemetery, Piney River quadrangle.
4. Layered granulite, Tye River, locality 1.
5. Layered garnet granulite, Allen Creek, near anorthosite border, locality 2.
6. Layered granulite, rockslide east side of Mars Knob, Horseshoe Mountain quadrangle.
7. Massive felsic granulite gneiss interlayered with sample no. 5.
8. Mangerite from drill core, American Cyanamid Co., 28 m deep, Taylor property 100–200 m north of Roseland Rutile Quarry. Zoned antiperthitic andesine, reactions between pyroxene-plagioclase, pyroxene-magnetite yield amphibole; biotite between plagioclase-magnetite. Near locality 15.
9. Well-layered granulite, felsic layers to 1 cm, average 1–5 mm, biotite-epidote mats replace pyroxene. Tye River north of Route 56, Arrington quadrangle.
10. Layered granulite gneiss, uralitic amphibole replaces pyroxene, feldspar to 1 cm, east of Bryant on Route 672, Horseshoe Mountain quadrangle.
11. Mafic phase at anorthosite border, well foliated, pyroxenes replaced by fibrous amphibole, Allen Creek, Piney River quadrangle.
12. Shaeffer Hollow Granite, pink and white, foliated potassium feldspar porphyroblasts, inclusion filled, to 2 cm, plagioclase slightly saussuritized. Rockslide west side Bryant Mountain, Arrington quadrangle.
13. Shaeffer Hollow Granite xenolith in Roses Mill, elongate feldspar phenocrysts, west slope Bryant Mountain, locality 8.

Feldspars constitute as much as 70 percent of these rocks and range from perthitic potassium-feldspar through mesoperthite (fig. 9) to antiperthitic andesine (an_{30-40}). The larger feldspars typically contain equant inclusions of blue quartz.

Garnet forms as much as 50 percent of some granulites (fig. 7) and locally is as coarse as 5 cm. Coarse flake graphite constitutes as much as 5 percent of some rocks at locality 1.

Pyroxenes together constitute as much as 25 percent, and two pyroxenes are locally present. Many banded granulites, however, only contain pseudomorphs of alteration products after pyroxene.

Pyrrhotite and subsidiary pyrite form as much as 8 percent of some granulites, as at the northeast end of the section at locality 1. Some granulites are apparently rendered magnetic because of abundant pyrrhotite.

Ilmenite is the normal oxide mineral of the banded gneisses. Under some circumstances, such as proximity to leucocharnockite or anorthosite dikes, rutile may be present with or without ilmenite. Ilmenite is homogeneous in polished sections, and rutile forms separate grains or very coarse intergrowths. Rutile is rimmed by ilmenite at locality 1 and elsewhere is commonly rimmed by retrograde sphene. Ilmenite and rutile together form as much as 12 percent of some granulites.

QUARTZ MANGERITIC AND OTHER MANGERITIC ROCKS

Slightly to well-foliated rocks of a mangeritic or quartz mangeritic composition associated with the granulites are mostly of igneous origin. Rocks intermediate in character between mangerites and granulites occur (fig. 9). Mangerites, that is quartz-poor orthopyroxene-plagioclase rocks, are most abundant (locs. 3–5) nearer the contact with the anorthosite. These rocks were probably largely shallow sills, but some may also be flows and volcaniclastics now interlayered with the banded granulites. They commonly contain ilmenite or, locally, rutile. Textures are typically hypidiomorphic-granular; a layering of coarse-grained elongate pyroxenes and feldspars is locally present, permitting a cumulate origin for some layers. Myrmekitic or graphic intergrowths of feldspar and quartz are developed in some rocks, and in many rocks large pyroxenes poikilitically enclose all other minerals including quartz.

The rocks differ in their relative amounts of mafic and felsic minerals. The most common type is poor in quartz and potassium feldspar; plagioclase, commonly a sodic antiperthitic andesine, ranges from about 15 to 70 percent. The plagioclase grains are mostly equant, 0.5 to about 1 mm in diameter, and may show kink banding and zoning. Orthopyroxenes and subsidiary clinopyroxenes vary from about 10 to 30 modal percent and are uralitized to varying degrees. They are locally tabular and commonly aligned in bands. Deep-brown biotite with rutile needles and brown hornblende may also be present. Coarse pale garnet, formed as an apparent reaction between pyroxene and plagioclase, constitutes as much as 30 percent of some rocks. Oxide minerals include separate magnetite and ilmenite grains, commonly surrounded by reaction rims of sphene, brown biotite, or garnet or any combination of these minerals. Oxides form as much as 5 percent of the rock. Rutile is present instead of or in addition to ilmenite where mangerite is near anorthosite. Apatite varies directly with the oxide mineral content, from trace amounts to about 2 percent. Graphite is commonly present in these rocks; diffusion of carbon from the granulites may be responsible, or graphite-bearing mangerites may be metamorphosed volcaniclastics. Pyrrhotite is also present. Common alteration products include green biotite, green amphibole, chlorite, white mica, and epidote-clinozoisite.

In more felsic varieties, poikilitic perthitic potassium feldspar, up to 5 mm, is seen. Rounded quartz grains form abundant inclusions; outside the feldspar, they tend to have irregular shapes, generally elongate, and occur with abundant included rutile needles (fig. 9). Plagioclase occurs either as large grains, locally antiperthitic, of sodic andesine composition, or as smaller, twinned oligoclase-andesine. Myrmekitic or graphic intergrowth of feldspar and quartz is common. Plagioclase varies from about 10 to 50 percent, potassium feldspar 20 to 35 percent, and quartz 8 to 24 percent. Pyroxenes have locally developed coronas of amphiboles or amphibole plus biotite; with advanced alteration, the pyroxenes are replaced by mats of chlorite and colorless amphibole. Feldspars are commonly also altered in varying degrees to white mica and clinozoisite.

ORIGIN OF THE GRANULITE UNIT

The field relations and the compositions of lithologies comprising the banded granulite map unit suggest that it represents a sequence of sedimentary, volcanic to subvolcanic, and volcaniclastic rocks metamorphosed to granulite grade and partially melted, thus obscuring original features.

We believe that, in general, rock compositions have remained similar through metamorphism except where partial fusion has caused the formation of anatectites. Studies elsewhere have shown that several systematic small changes in composition occur at such high metamorphic grades. (See, for example, Sighinolfi, 1969, with K-Rb ratios.) Herz (1984) discusses trace-element changes in granulites in the study area.

A test of the original nature of the protoliths in such high grade rocks was proposed by Shaw (1972). He distinguished igneous from sedimentary origins on the basis of a discriminant function involving the major elements Si, Fe, Mg, Ca, Na, and K. Ames (1981) found that some well-layered granulites from Roseland showed negative (sedimentary) values of −0.81 and −1.51 as well as positive (igneous) values of 1.00, 2.82, and 6.07. This finding suggests that the granulites are of both sedimentary and igneous origin and represent a mixed sequence of volcanics and sediments.

The age of the granulite is indeterminate. It must be older than 1,050 m.y. because it is cut by anorthosite. Zircons from a leucocratic neosome in granulite however, yielded an age of 980 Ma, an age which represents anatexis and (or) metamorphism. Details of the age determinations are discussed later in this report.

STRATIGRAPHIC EQUIVALENCE

Bloomer and Werner (1955) were seemingly unaware of a contiguous terrane of pre-Lovingston, pre-anorthosite rocks. However, the granulite unit probably correlates with their unmapped Basement Complex gneiss unit which they (and we) recognize as xenoliths in younger intrusive rocks. Our contiguous granulite terrane was mapped by Bloomer and Werner as Marshall Formation on the basis of the presence of banding and the absence of large augen. They also mapped large areas of other rocks in the northwestern part of the area as Marshall Formation; these rocks show mylonitic banding and granulated augen and are unrelated to the granulite unit.

LEUCOCRATIC CHARNOCKITES AND ASSOCIATED ROCKS

Platy blue quartz-feldspar rocks (fig. 6) are common throughout the granulite map unit but cannot be mapped separately. Most commonly they form concordant bodies (locs. 4–6) though some are discordant. They appear to grade continuously in grain size and mineralogy into bodies we call anorthosite dikes (as at loc. 7). Leucocharnockite is also present as fine layers of injection or anatectic origin in banded granulite (fig. 5). Rutile is common in leucocharnockite and in adjacent host rocks.

Blue quartz forms 10 to 65 percent of the rock as nearly unstrained aggregates or even single crystals in plates commonly about 3 cm long (fig. 6). Rutile needles, which are undeformed and commonly have a discernible hexagonal orientation, are present in quartz grains. The significance of these features is discussed under "Metamorphism."

Feldspar is antiperthitic andesine (an_{30}) or oligoclase 25 to 45 percent of the rock, and perthite 0 to 10 percent. Larger grains of andesine antiperthite may contain blue quartz inclusions. Accessory minerals are rutile, ilmenite, biotite, pyroxene, and zircon (which is 980 m.y. old at loc. 1). Commonly, alteration to clinozoisite and white mica is advanced.

ROSELAND ANORTHOSITE

The Roseland Anorthosite, in the core of an elongate dome that comprises the basic structural element of the district, underlies the central part of the area. It is 14.4 km long in a northeast-southwest direction, 1.5 to 3.2 km wide, and covers about 35 km^2 in total outcrop area. It had earlier been referred to as a pegmatite, syenite, or albitite before Ross (1941) established the rock as an anorthosite. The rock is made up of andesine antiperthite in large broken megacrysts 10 to 20 cm in diameter; the megacrysts are separated by granulated zones of finer grained oligoclase, 0.1 to 2 mm in diameter, with minor microcline and quartz. Original megacrysts were 1 m or longer as judged by exposures in outcrops where broken fragments appear to have similar orientations, suggesting a larger original grain size (loc. 10, Allen Creek, Piney River quadrangle). The granulated areas are partially a product of protoclasis and partially of finer groundmass. Border facies of the anorthosite are similarly coarse grained but are more quartz mangeritic in composition and are rich in blue quartz and pyroxene megacrysts as well as rutile and ilmenite. The age of the Roseland Anorthosite is reported as 1,045 Ma by Pettingill and Sinha (1984).

Anorthosites are widely distributed in terranes of Grenville age throughout the world, but there is still no general agreement on their genesis or even their classification. (See, for example, Middlemost, 1970; Berrangé, 1965.) Since the Roseland type is so restricted in occurrence, it has not been discussed in recent review articles on anorthosite, with only one exception (Isachsen, 1969). In classifying terrestrial anorthosites, most authors follow Buddington (1961, p. 422) who set up two groups: (1) a Bushveld type where anorthosite was part of a differentiated stratiform sheet and (2) an Adirondack massif type where the anorthosite was nonstratiform and comprised large domical plutonic masses. The Roseland Anorthosite is a massif type.

Anderson and Morin (1969) further subdivided massif anorthosites into a labradorite type with an_{63-45} or $_{2-3}$ megacrysts and an andesine type with $an_{48-23}or_{6-25}$ megacrysts that are characteristically antiperthitic. The labradorite type also typically contains either hypersthene or olivine as well as augite, magnetite, and ilmenite; has contact relations with country rock that are difficult to interpret; and can have external forms of varied shapes. The andesine type anorthosite contains hypersthene and hemo-ilmenite, is distinctly intrusive into country rock, and is domical in shape.

Although the Roseland Anorthosite is an andesine type by the classification of Anderson and Morin (1969), it also contains abundant potassium feldspar and quartz, both modal and normative, a composition not characteristic of other massif anorthosites. Comparing chemical compositions (tables 4, 5), it is clear that the average Roseland type has more SiO_2 and Na_2O and more than double the K_2O content of the average massif anorthosite. The term alkalic anorthosite thus appears appropriate to describe the Roseland type anorthosite (Herz, 1969). Other alkalic anorthosites are found at Pluma Hidalgo in Oaxaca, Mexico (Paulson, 1964), and St. Urbain, Quebec (Mawdsley, 1927). At St. Urbain, Mawdsley (1927) and Dymek (1980) described the K_2O-rich andesine anorthosite as comprising the bulk of the body but in the central part of the massif as crosscutting a labradorite anorthosite. Our observations in the Pluma Hidalgo district indicate that the regional Toltepec anorthosite is highly altered except in swarms of sills along its roof, and that it everywhere contains quartz. Rutile and hemo-ilmenite are found in all three alkalic anorthosites; rutile occurrences in anorthosites appear to be restricted to the alkalic varieties.

PETROGRAPHY

The Roseland Anorthosite samples show two distinct petrographic features: Light-bluish-gray areas comprised of andesine antiperthite megacrysts and cream to white granulated areas. An electron microprobe analysis of the antiperthite host shows a composition of $an_{30.7}ab_{68.5}or_{0.8}$ and of the potassium feldspar lamellae, $an_{1.1}ab_{6.1}or_{92.8}$. Structurally, the exsolution lamellae are maximum microcline (of Wright, 1968). Bulk chemical analyses of the andesine megacrysts (table 2 of Ross, 1941) show a composition of $or_{25.1}ab_{51.0}an_{23.4}$ $celsian_{0.5}$, or, calculated as only plagioclase, $an_{31.5}$. Feldspar compositions calculated from whole-rock norms vary $or_{14-21}ab_{51-59}an_{27-28}$ (table 4).

Granulated white areas which fill in between the bluish andesine antiperthite megacrysts consist of a feldspar aggregate varying in grain size from very fine (0.01 mm) to medium (about 2 mm) in diameter. The feldspars include microcline, antiperthitic andesine, and oligoclase-albite. Many grains show kink banding, in addition to twinning, and grain boundaries are ragged. Patchy replacement by clinozoisite is common.

Rutilated quartz, generally deep blue in color, is seen throughout the anorthosite as a common accessory, but it is most common along its margins where mafic minerals are present. In the least granulated rocks, rutilated quartz is present as coarse graphic intergrowths with feldspar; in more granulated rocks it appears as irregular blebs and masses or veinlets.

Ross (1941, p. 11) reported the primary pyroxene to be clinohypersthene, with an inclined extinction $Z \wedge C = 440$. We could not confirm this but found abundant orthopyroxene with a faint pink pleochroism and parallel extinction occurring in stringers or as rectangular aggregates that averaged 10 cm in diameter but commonly were as large as 70 cm. Chemical analysis shows a composition of $en_{55.2}fs_{40.8}wo_{4.0}$ (Ross, 1941, p. 11). In some specimens the pyroxene, apparent in hand specimen, is replaced by colorless amphiboles including actinolite and anthophyllite. Biotite, ilmenite, rutile, and apatite are also found within mafic aggregates, and rutile is disseminated along the eastern border area of the Roseland Anorthosite.

FIELD RELATIONS

Anorthosite dikes in older rocks are common, as are xenoliths of anorthosite in younger rocks. Anorthosite dikes cut banded granulite at localities 7 and 11 and mangerite at localities 12, 13, and 14 (figs. 10, 11). Swarms of anorthosite sills and dikes occur in some places as near Allen Creek, and these are the loci of important rutile resources. Appendix 1 contains logs of several drill holes penetrating areas of anorthosite dike swarms. The feldspar in dikes of relatively pure anorthosite is oligoclase (an_{20-25}) that is medium to fine grained and locally antiperthitic. Thus it correlates more closely with the granulated portions of normal anorthosite than with the feldspar megacrysts.

MARGINAL IMPURE FACIES

The margins of the anorthosite body typically contain much more pyroxene, quartz, and rutile than the interior; all the minerals are coarse grained (fig. 12; locs. 5, 15). Even the anorthosite dikes and sills may have this texture (fig. 11), which is probably the result of the high-temperature interaction of anorthosite magma with the chemical constituents of mangeritic country rock, resulting in coarse mangerite from which some iron has been stripped (leaving behind rutile). The texture may in part also result from accumulation of early-formed crystals on the margins of an anorthosite magma chamber during emplacement. This facies of anorthosite could not be mapped separately.

EMPLACEMENT FEATURES.

Mylonites developed from anorthosite are common. A wide zone of deformed sericitic anorthosite is exposed in

TABLE 4.—*Composition of Roseland Anorthosite*

[___, not analyzed or not detected. Figures may not add to totals shown due to independent rounding. Analysts and methods are as follows: P. Elmore and colleagues, USGS, Reston, Va. (rapid rock analysis) amd W. B. Crandell, USGS, Washington, D.C. (semiquantitative spectrographic)]

Sample number	1	2	3
Major elements, in weight percent			
SiO_2	60.1	60.7	61.3
TiO_2	.14	.15	.15
Al_2O^3	24.0	23.3	23.4
Fe_2O_3	.26	.39	.23
FeO	.20	.24	.20
MgO	.08	.02	.30
CaO	5.1	5.0	5.0
Na_2O	5.3	5.3	6.2
K_2O	3.2	3.1	2.1
P_2O_5	.07	.08	.08
MnO	.02	.02	.02
H_2O^-	.15	.16	.06
H_2O^+	.67	.77	.65
Total	99.3	99.2	99.7
Normative minerals, in weight percent			
Qz	6.20	7.52	6.30
or	18.91	18.32	12.41
ab+an	69.66	69.10	76.71
C	2.72	2.33	2.04
hy	.20	.05	.75
ap	.17	.19	.20
il	.27	.29	.29
mt	.30	.40	.28
hm	.05	.11	.04
Total	98.47	98.30	98.98
Calculated mineral compositions			
an (percent)	35.7	35.1	31.7
or:ab:an	21.4:50.6:28.0	21.0:51.3:27.8	13.9:58.8:27.2
Minor elements, reported in parts per million to nearest factor of 1.5			
Ba	1,500	1,000	1,000
Cu	20	30	3
Ga	15	15	13
Pb	30	15	___
Sr	1,000	1,000	1,000
Y	___	___	7
Zr	___	___	20
Be	___	___	<1

SAMPLE DESCRIPTIONS AND LOCATIONS (CHEMICALLY ANALYZED SAMPLES SHOWN ON PL. 1)

SAMPLE NO. 1. Massive anorthosite near granulite contact, splotchy blue-gray and white, closely veined by thin blue veins and patchy blue areas with needle-like clinozoisite crystals, rock largely coarse, granular antiperthitic andesine and finer grained, intergranular oligoclase, quartz blue and rutilated. Allen Creek, Piney River quadrangle.

2. Massive anorthosite, similar to (1). Buffalo Quarry, Piney River quadrangle.

3. Anorthosite mill product, IMC "aplite" plant, locality 17.

the Tye River section through the core of the anorthosite (loc. 16), at the northeast end of the body, and similar zones at the southwest end suggest that the terminations of the anorthosite body are largely tectonic. Smaller ultramylonite zones in anorthosite are exposed at locality 17. The deformation is probably Paleozoic in

TABLE 5.—*Anorthosite analyses compared*

[Figures are weight percent. Col. 1=World average, anorthosite in layered complexes (Nockolds, 1954); col. 2=World average, anorthosite massifs (Nockolds, 1954); col. 3=Roseland anorthosite, average of four analyses (table 4; Watson and Taber, 1913)]

Column	1	2	3
SiO_2	50.0	54.5	60.4
TiO_2	.14	.52	.15
Al_2O_3	28.9	25.7	23.6
Fe_2O_3	.80	.83	.29
FeO	1.43	1.46	.21
MgO	.84	.83	.13
CaO	14.0	9.62	5.0
Na_2O	2.73	4.66	5.6
K_2O	.42	1.06	2.8
P_2O_5	.21	.11	.08
H_2O	.55	.63	.79

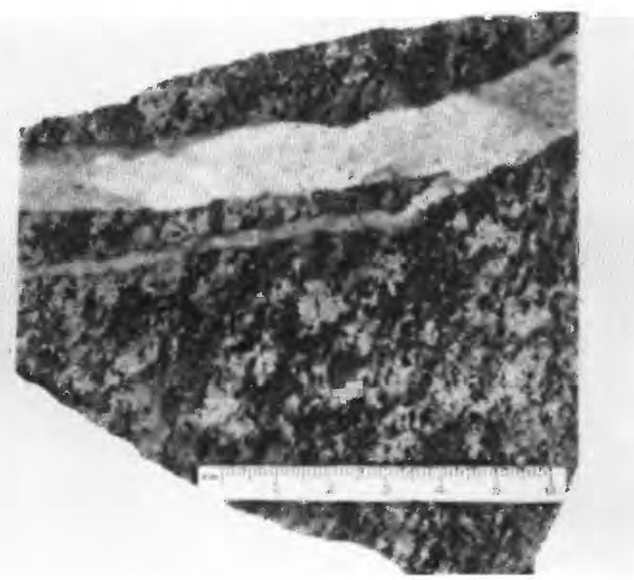


FIGURE 10.—Anorthosite dikelet cuts quartz mangerite at locality 12. Anorthosite here is monomineralic plagioclase with composition an_{25}. These dikes contain rutile.

large part judging from the low metamorphic grade of the secondary minerals. Some mylonitization probably accompanied anorthosite emplacement, as anorthosites elsewhere that show no younger deformation commonly show mylonitization related to diapiric emplacement (Martignole and Schrijver, 1970). A later section discusses possible diapirism of the Roseland Anorthosite.

SHAEFFER HOLLOW GRANITE

Leucocratic rocks with tabular feldspars and locally with recognizable igneous textures occur in the northern part of the map area, mostly as screens or roof pendants between Roses Mill intrusive sheets. These rocks, which we refer to as the Shaeffer Hollow Granite after the

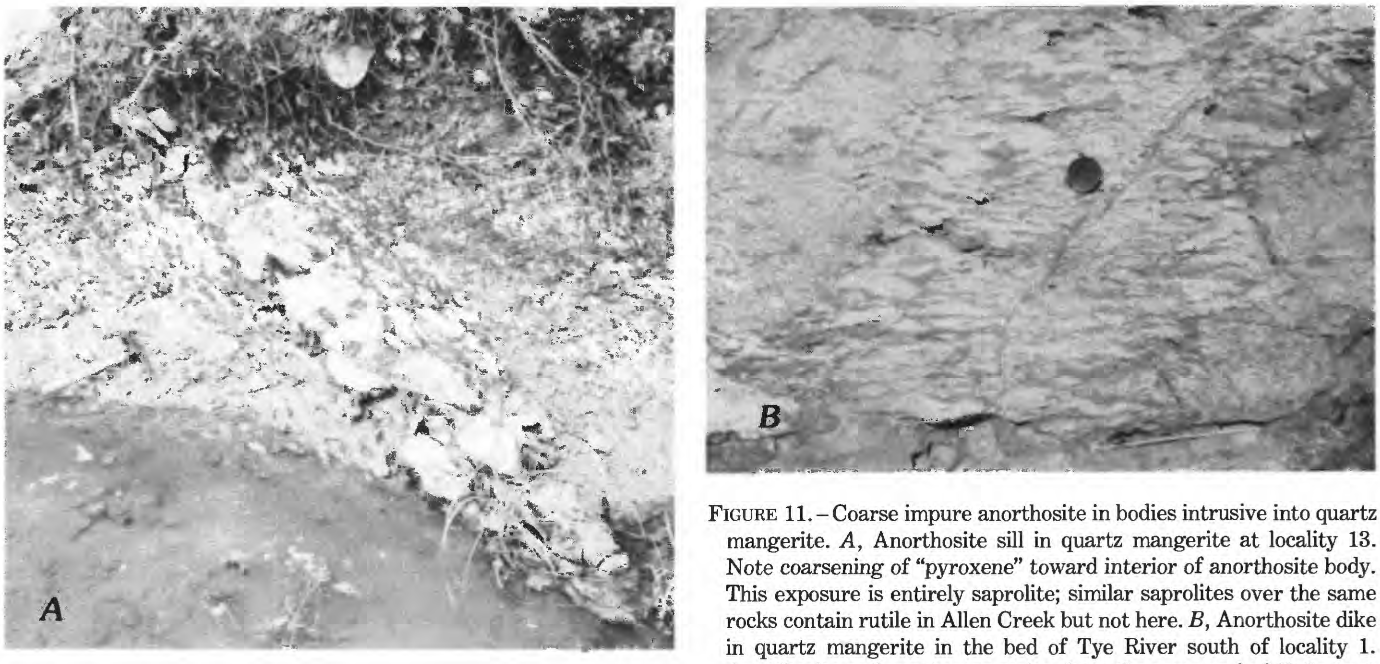


FIGURE 11. – Coarse impure anorthosite in bodies intrusive into quartz mangerite. *A*, Anorthosite sill in quartz mangerite at locality 13. Note coarsening of "pyroxene" toward interior of anorthosite body. This exposure is entirely saprolite; similar saprolites over the same rocks contain rutile in Allen Creek but not here. *B*, Anorthosite dike in quartz mangerite in the bed of Tye River south of locality 1. Anorthosite and quartz mangerite share the same early foliation not shown by nearby nelsonite. Lens cap is 3.3 cm.

FIGURE 12. – Coarse-grained anorthosite with pyroxene, blue quartz, and finer rutile from a margin of the anorthosite body in the bed of Piney River, at locality 5.

FIGURE 13. – Ptygmatically folded Shaeffer Hollow Granite with tabular feldspars, cut by Roses Mill dikes, one of which is sheared and boudinaged (loc. 9).

large outcrop area in Shaeffer Hollow (Horseshoe Mountain quadrangle), are pre-Roses Mill ferrodiorite as they form xenoliths in Roses Mill. The granite is post-granulite; it contains granulite xenoliths (both at loc. 8). Elsewhere the unit contains Roses Mill dikes (loc. 9; fig. 13).

The unit has tabular feldspar phenocrysts, commonly 2 to 5 cm in length, where it is least altered (fig. 14). These phenocrysts become augen where the rocks have been altered and deformed. Even the least altered exposures contain bands of flaser gneiss or mylonite.

The granite consists mostly of blue quartz, perthitic microcline, and antiperthitic plagioclase. Aggregates of biotite, probably after hornblende or pyroxene, form as much as 10 percent of the rock. Minor primary minerals are ilmenite, apatite, and zircon. One specimen from

FIGURE 14.–Texture of Shaeffer Hollow Granite.

FIGURE 15.–Annotated photograph of road cut at Roses Mill (loc. 18) which exposes ferrodioritic charnockite-suite parent rock (f) and gradations to biotitic augen gneiss (a) and mylonitic augen gneiss (m) derived from it.

near Shaeffer Hollow contains 48 percent potassium-feldspar (as large inclusion-filled porphyroblasts), 17 percent plagioclase, 18 percent quartz, 5 percent biotite, 0.7 percent apatite, 0.9 percent sphene (after ilmenite), 0.2 percent zircon, and some secondary minerals.

Equivalents to the Shaeffer Hollow Granite appear to be widespread in this part of Virginia as parts of both the Lovingston and Pedlar massifs. The Lovingston quartz monzonite and pegmatite (Davis, 1974), dated at about 1,080 Ma, the Crozet Granite of Albemarle County (Nelson, 1962), and the Old Rag Granite of Greene and Madison Counties (Allen, 1963) appear to be similar mineralogically and texturally. For example, the Old Rag Granite (Allen, 1963, p. 17) is coarse grained with individual potassium-feldspar crystals up to 4 cm, elongate masses of bluish and smoky quartz up to 2 cm, and small amounts of chloritized biotite. If the units correlate, a relative chronology of rocks across the Rockfish Valley deformation zone is implied.

ROSES MILL PLUTON

CHARACTERIZATION

The term Roses Mill pluton is introduced for ilmenite- and apatite-bearing rocks of a ferrodioritic composition. These rocks are variably altered from a dark charnockite-suite rock to a biotitic augen gneiss as at Roses Mill (loc. 18) where a large road cut (fig. 15) exposes many stages in this gradation. Similar relations are found in numerous landslide scars on the ridge north of Bryant Mountain (for example, at locs. 19, 20).

Rocks of the Roses Mill pluton are found mostly east of the granulites and anorthosite but form a nearly concordant igneous sheet overlying granulite on both flanks of the regional dome (pl. 1).

The Roses Mill pluton has four facies: (1) the massive primary charnockitic ferrodiorite, (2) the secondary biotite augen gneiss, (3) dike rocks in older terranes, and (4) the well-known nelsonites of the district which are closely tied to the other facies by their composition and occurrence.

The chemical compositions of Roses Mill rocks of the first three facies are essentially the same and match those of ferrodiorites reported from other mafic igneous complexes (tables 6, 7), except for higher SiO_2 contents due to xenocrystic blue quartz. Note the extreme Ti, P, Zr, and rare earth values, the very high Fe-Mg ratio, and the low SiO_2 content in relation to the high K_2O content. The mineralogy of fresher rocks is correspondingly distinctive (table 6). Two quartzes (an apparently xenocrystic blue quartz and a colorless clear quartz which is apparently primary), perthitic feldspars, locally rimmed, and uralitic pyroxene are the main minerals. Ilmenite, apatite, and zircon are unusually abundant, with ilmenite free of intergrowths but rimmed by sphene (fig. 16). These fresh rocks are, however, islands in a sea of altered equivalents, the biotite augen gneisses.

TABLE 6.—*Analyses of Roses Mill pluton and related rocks*

[___, Not analyzed or not detected; under *trace elements*, sample nos. 4, 7, 12, and 13 were analyzed only for Zr. P, present. Figures may not add to totals shown due to independent rounding. Analysts and methods are as follows: Sample nos. 1, 2, 3, 5, 6, 11, 14–P. Elmore and colleagues, USGS, Reston, Va. (rapid rock), and W. B. Crandell, USGS, Washington, D.C. (semiquantitative spectrographic); 4, 7, 12, 13–F. Brown and colleagues (rapid rock) and J. Fletcher (spectrographic methods), USGS, Reston, Va.; Sample nos. 8-10–G. J. Davis, University of Georgia (x-ray fluorescence). Sample locations and descriptions are shown on p. 18]

Sample number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Nelsonite	Impure nelsonite	Dike[b]	Dike	Sill[b]	Sill[b]	Massive	Augen gneiss	Turkey Mountain	Massive	Augen gneiss	Augen gneiss	Augen gneiss	Augen gneiss
Major elements, in weight percent														
SiO_2	3.6	27.4	47.8	57.9	46.4	52.9	56.1	56.26	60.85	61.67	49.8	52.0	52.2	60.4
Al_2O_3	3.0	6.1	17.0	14.2	16.4	17.9	16.2	16.79	15.23	14.67	16.3	14.3	14.3	13.4
Fe_2O_3	13.4	6.6	.56	2.3	2.9	.68	3.4	([a])	([a])	([a])	5.2	3.3	4.5	1.6
FeO	22.2	17.8	7.4	6.8	9.0	8.2	6.5	8.74	7.64	8.08	7.6	9.1	8.0	7.6
MgO	2.0	6.8	8.7	2.2	6.5	5.4	1.4	2.04	.91	1.45	1.3	3.3	2.7	2.2
CaO	11.6	10.9	9.1	6.1	11.9	4.4	5.9	4.82	3.35	4.90	5.5	6.7	6.8	5.1
Na_2O	0	.43	1.8	3.0	1.7	4.1	2.9	3.16	2.46	2.62	5.4	3.2	2.2	1.9
K_2O	.68	.38	1.5	2.2	.57	.66	3.2	3.49	4.17	3.30	1.5	1.4	2.6	2.6
H_2O^-	1.9	.19	.08	.15	.37	.14	.25	.94 (H2O− and H2O+)	1.80 (H2O− and H2O+)	0 (H2O− and H2O+)	.10	.26	.20	.04
H_2O^+	1.4	2.4	3.2	1.1	1.0	1.6	.85				1.4	.84	1.5	1.4
TiO_2	30.0	12.8	1.1	2.8	2.0	3.1	1.9	1.57	1.85	1.87	3.0	4.1	3.8	1.6
P_2O_5	9.8	7.8	1.2	1.4	.35	.12	.76	.41	.66	.85	1.8	1.7	1.7	1.1
MnO	.33	.17	.12	.14	.21	.11	.14	.14	.10	.10	.15	.16	.17	.15
CO_2	<.05	<.05	<.05	.01	___	<.05	.01	___	___	___	.05	.07	.01	.10
F	___	___	___	.13	___	___	.09	___	___	___	___	.16	.18	___
Total	99.9	100	99.6	100.4	99.3	99.3	99.6	98.36	99.02	99.51	99.1	100.6	100.9	99.2
Normative minerals, in weight percent														
Q	___	6.94	___	15.8	___	5.05	11.2	8.07	20.74	20.19	5.76	8.34	13.92	23.64
or	1.95	2.25	8.86	12.8	3.37	3.90	18.9	20.62	24.76	19.50	8.90	8.34	15.36	15.36
ab+an	___	6.76	49.10	44.05	48.83	55.71	46.04	47.97	33.12	40.69	61.44	47.54	40.08	34.18
C	___	3.84	___	___	___	2.73	___	.03	2.16	___	___	___	___	.82
di	2.24	___	2.86	8.75	17.78	___	6.10	___	___	.20	8.58	9.83	.95	___
hy	___	27.98	24.54	7.36	17.20	23.02	6.62	14.39	9.22	10.98	3.91	10.58	11.27	15.75
ol	3.50	___	5.24	___	.42	.54	___	___	___	___	___	___	___	___
ap	23.52	18.47	2.84	3.36	.83	.28	1.68	.97	1.56	2.01	4.37	4.37	4.03	2.61
il	47.51	18.97	2.09	5.32	3.80	5.89	3.65	2.98	3.51	3.55	5.78	7.75	7.22	3.04
ru	4.95	___	___	___	___	___	___	___	___	___	___	___	___	___
mt	___	9.57	.81	3.25	4.21	.99	4.87	2.09	2.45	2.61	7.66	4.87	6.52	2.32
lc	1.53	___	___	___	___	___	___	___	___	___	___	___	___	___
Z	___	___	___	___	___	___	.37	___	___	___	.37	___	.18	___
hm	13.44	___	___	___	___	___	___	___	___	___	___	___	___	___
	___	___	___	___	___	___	___	___	___	___	___	___	___	___
Calculated mineral compositions														
fo (percent)	100	___	63.0	___	0.0	100.0	___	___	___	___	___	___	___	___
en (percent)	100–wo	60.5	65.3	46.2	59.1	58.4	36.3	35.3	24.6	32.6	40.2	53.9	57.3	34.8
an (percent)	___	46.2	69.0	42.9	71.1	37.8	46.5	44.3	37.2	45.5	25.8	42.7	53.6	53.0
or:ab:an	100:0:0	25.0:40.4 :34.6	15.3:26.3 :58.5	22.5:44.3 :33.3	6.3:66.6 :27.0	6.5:58.2 :35.3	29.1:37.9 :33.0	30.1:39.0 :31.0	42.7:36.0 :21.3	32.4:30.8 :36.8	12.7:64.8 :22.5	14.9:48.8 :36.3	27.7:33.6 :38.7	31.0:32.4 :36.6

Trace elements, in parts per million

Sample no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Ba	30	200	300	---	100	500	---	1,566	1,731	1,450	300	---	---	2,000
Be	---	---	---	---	---	---	---	---	---	---	3	---	---	<1
Ce	500	300	---	---	---	---	---	---	137	68	700	---	---	200
Co	30	50	20	---	20	30	---	19	15	16	70	---	---	15
Cr	1,000	300	100	---	150	150	---	---	---	---	7	---	---	5
Cu	500	300	15	---	20	30	---	---	---	---	15	---	---	10
Ga	10	10	10	---	10	10	---	---	---	---	15	---	---	15
La	300	200	---	---	---	---	---	19	86	52	300	---	---	150
Li	---	---	---	---	---	---	---	---	---	---	70	---	---	---
Mo	5	5	---	---	3	3	---	.1	.5	.1	7	---	---	3
Nb	7	5	---	---	---	---	---	22	29	34	15	---	---	7
Nd	300	300	---	---	---	---	---	25	127	81	300	---	---	150
Ni	<30	70	50	---	70	---	---	---	---	---	---	---	---	---
Pb	---	---	---	---	---	---	---	30	28	25	7	---	---	15
Rb	---	---	---	---	---	---	---	83	146	78	---	---	---	---
Sc	20	20	10	---	30	10	---	---	---	---	30	---	---	20
Sr	100	200	500	---	200	700	---	344	455	513	500	---	---	500
V	500	300	100	---	150	200	---	130	97	114	50	---	---	70
Y	30	30	5	---	15	5	---	---	---	---	100	---	---	50
Yb	3	3	---	---	1.5	---	---	---	---	---	10	---	---	5
Zr	700	500	20	290	70	---	1,500	292	682	570	1,500	270	810	500

Modal analyses, in volume percent

Sample number	3	6	7A	7B	9	14[l]	15	16	17	18	19	20	21	22	23	24	25
Quartz	P	---	12	9.1	8.9	30.3	---	13.6	19.7	19.2	23.7	7	15.5	9	18	9	P
Plagioclase	50.9	[c]65.1	[c]35	[h]28.7	54.2	24.8	[c]36.6	[c]35.0	29.1	30.3	12.5	[c]23	37.4	46	12	53	44
Potassium-feldspar	---	---	[e]15	[e]29.5	18.7	---	---	[e]27.8	[e]29.1	31.3	[e]31.4	[e]18	---	[e]9	[e]43	1	---
Orthopypoxene	---	2.5	} 9	} 19.4	---	---	30.4	} 16.1	5.8	6.1	---	} 22	---	---	---	---	---
Clinopyroxene	---	4.2			([m])	([m])	4.6		3.3	1.9	---		---	---	---	---	---
Hornblende	[g]30.5	[g]11.5	[g]17	10.0	[g]13.4	---	---	---	[g]6.2	2.9	---	[g]22	---	---	---	---	---
Biotite	P	6.3	---	---	---	23.6	---	---	[f]1.7	2.7	17.4	---	14.0	[k]30	[k]25	[k]24	28.8
Ilmenite	.6	[i]2.9	[i]3.4	2.5	3.1	.2	[d]13.7	[d]4.5	2.2	2.6	2.5	[c]5.4	0.8	2.3	0.8	2.0	[i]1.4
Magnetite	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Apatite	P	.6	2.9	.4	1.1	1.9	11.4	2.7	2.1	1.5	1.8	2.4	2.5	3.6	1.4	2.6	1.8
Hematite	---	---	---	---	---	---	.9	---	---	---	---	---	---	---	---	---	---
Garnet	---	---	5	---	---	---	---	---	---	---	---	---	---	---	---	9	11.2
Epidote group	3.0	6.5	---	---	---	11.1	P	---	.4	1.2	8.7	---	14.6	---	---	---	.9
Chlorite	8.6	---	---	---	---	.5	---	---	.3	---	---	---	1.9	---	---	---	8.7
Muscovite	6.2	---	---	---	---	3.6	.5	---	---	---	1.4	---	10.9	---	---	---	2.4
Sphene	([l])	---	---	---	---	4.0	---	---	---	---	---	---	2.4	---	---	---	---
Rutile	([l])	([l])	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Zircon	---	.2	.6	---	.3	P	---	.3	.1	.2	P	.2	---	.2	.1	.1	.5
Allanite	---	---	---	---	---	---	1.0	---	---	---	---	---	---	---	---	---	---

[a] All Fe reported as FeO.
[b] Included with Roses Mill in spite of compositional differences because these rocks are believed by Herz to be an early stage in the evolution of the Roses Mill magma type.
[c] Antiperthitic.
[d] Ilmenite is not reaction rimmed.
[e] Perthitic.
[f] Reaction rims between magilm and pyroxene.
[g] Largely uralitic.
[h] Antiperthitic with 4.6 percent small twinned plagioclase.
[i] Includes secondary sphene.
[j] Included with ilmenite.
[k] Includes amphibole.
[l] Contains calcite.
[m] Uralitized.

(Table continues on page 18.)

TABLE 6.—Continued

SAMPLE DESCRIPTIONS AND LOCATIONS (CHEMICALLY ANALYZED SAMPLES SHOWN ON PL. 1)

SAMPLE NO. 1. Nelsonite, ilmenite, 68 percent; fluorapatite, 32 percent. Hill North of Tye River, Route 151, Horseshoe Mountain quadrangle.

2. Ilmenite-rich, layered schistose mafic rock (Turkey Mountain?) associated with nelsonite, 20 percent opaque ilmenite-hematite, 15 percent rounded apatite, 50 percent chlorite and amphibole in mats pseudomorph pyroxene, 8 percent brown biotite full of opaque plates, 5 percent quartz in chlorite-amphibole mats. American Cyanamid Company quarry, Piney River, locality 24.
3. Mafic dike 30 ft wide in anorthosite, uralitized, layered felsic and mafic 0.5–2 cm. Dominion Minerals quarry, Piney River quadrangle.
4. Dike in anorthosite. IMC quarry, locality 17.
5. Turkey Mountain ferrodiorite sill, unfoliated, associated rocks layered, near anorthosite contact, kink-banded orthopyroxene (to 10 mm), plagioclase, ilmenite, magnetite, uralitic hornblende, brown hornblende, chlorite. Sp gr=2.989. Locality near sample no. 2 of table 3.
6. Turkey Mountain ferrodiorite sill poorly layered, intrudes at anorthosite contact, mafic rock in ±50-cm interlayers in anorthosite rutile ore zone, coarse grained. Roseland Rutile quarry, locality 15.
7. Roses Mill ferrodiorite (2 specimens) at Roses Mill type locality, locality 18.
8. Roses Mill ferrodiorite, Bryant Mountain, rockslide west side, Arrington quadrangle.
9. Turkey Mountain metacharnockite, coarse feldspars in clots to 1 cm, uralitized pyroxenes to 0.5 cm. Route 655, Arrington quadrangle.
10. Roses Mill or Turkey Mountain charnockite. Route 672, Horseshoe Mountain quadrangle.
11. Roses Mill biotite augen gneiss, West of Colleen. Arrington quadrangle.
12. Roses Mill augen gneiss, Maple Run, South of Piney River quarry. Piney River quadrangle.
13. Roses Mill biotite augen gneiss. Piney River bluffs, upstream of Roses Mill, Piney River quadrangle.
14. Well-foliated biotite augen gneiss. North of Roses Mill, Arrington quadrangle.
15. Layered (possibly cumulate) mafic, ilmenite-apatite rich matrix, felsics in elliptical domains, gabbronorite. Locality 22.
16. Coarse-grained charnockite; pyroxene 1–3 mm, pink-green pleochroic; lamellar crystals; plagioclase embayed with fractures filled by quartz, 0.7 km north of quadrangle boundary on Route 672, Horseshoe Mountain quadrangle.
17. Massive coarse-grained charnockite; orthopyroxene $en_{46.3}wo_{1.7}fs_{48.3}$; clinopyroxene $en_{28.6}wo_{44.0}fs_{20.9}$; antiperthitic plagioclase $an_{43}ab_{55}or_{2}$ in host, $or_{99}an$, in lamellae; Sp gr=2.761. On Route 672, 1.2 km north of quadrangle boundary, Horseshoe Mountain quadrangle.
18. Small charnockitic body 1 km in diameter in Roses Mill biotitic augen gneiss. Medium-grained, unfoliated, largest feldspar to 10 mm, average 3–5 mm. Plagioclase kink-banded, an_{31}; potassium feldspar perthitic; biotite and amphibole as reaction rims and alterations of opaques and pyroxene. 2 km north of Clifford, Piney River quadrangle.
19. Massive, altered charnockite, cut by thin epidote veinlets 2 mm wide; some quartz is rutilated, plagioclase an_{35}, green and brown biotite replaced pyroxene. Arrington quadrangle.
20. Charnockite by granulite contact. Highway 151 at Maple Run, Piney River quadrangle.
21. Coarse augen gneiss, augen 1–2 cm, plagioclase filled with inclusions, epidote veinlet 1 mm wide, north side Willow Run, 60 m west of Route 151, Piney River quadrangle.
22. Roses Mill ferrodiorite with retrograde biotite. Road cut at Route 672 near East Branch Hat Creek, Horseshoe Mountain quadrangle.
23. Roses Mill ferrodiorite with retrograde biotite. Roses Mill on ridge north of Bryant Mountain. Locality 19.
24. Roses Mill ferrodiorite with retrograde biotite. Locality 8.
25. Melano-cataclasite, protomylonite. Possible protolith is Roses Mill. Locality 39.

FIELD RELATIONS

The pluton is clearly igneous and younger than the anorthosite-granulite terrane, although the contact is generally tectonized. Roses Mill rocks contain abundant xenoliths of all the older rocks of that terrane (fig. 17). These xenoliths can be recognized even in the augen gneiss facies (figs. 18, 19). Numerous dikes in anorthosite-granulite terrane (fig. 20) can be recognized as Roses Mill by their distinctive mineralogy (fig. 21) or chemistry (table 6); these dikes typically cut a foliation in their country rocks as do contacts of larger Roses Mill bodies. Unsheared Roses Mill rocks have good igneous textures (fig. 22) and, locally, igneous layering parallel to the base of the pluton. The ferrodioritic chemical composition of the Roses Mill (table 6) has no known equivalent outside the igneous realm.

Primary compositional layering in the Roses Mill is subparallel to contacts with underlying granulite or anorthosite. The gross structure of the pluton appears to be sill-like and concordant to older country rock.

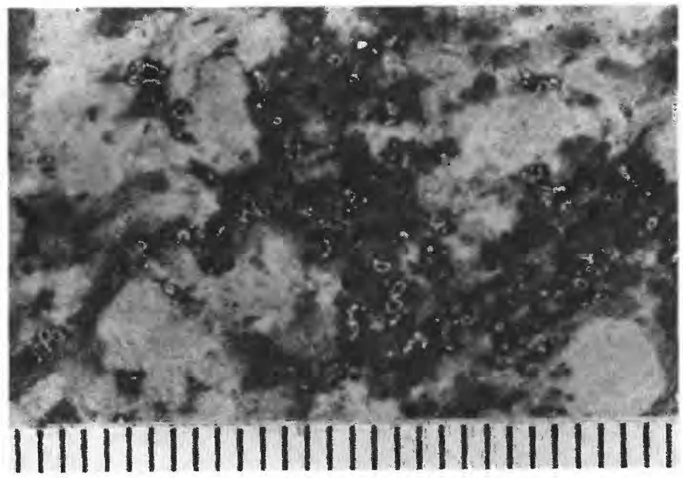


FIGURE 16.—Hand specimen of slightly altered Roses Mill specimen, showing ilmenite (black) rimmed by sphene (white). Other dark constituents are uralitized pyroxene and minor quartz; light constituents are perthitic and antiperthitic feldspars. Millimeter scale.

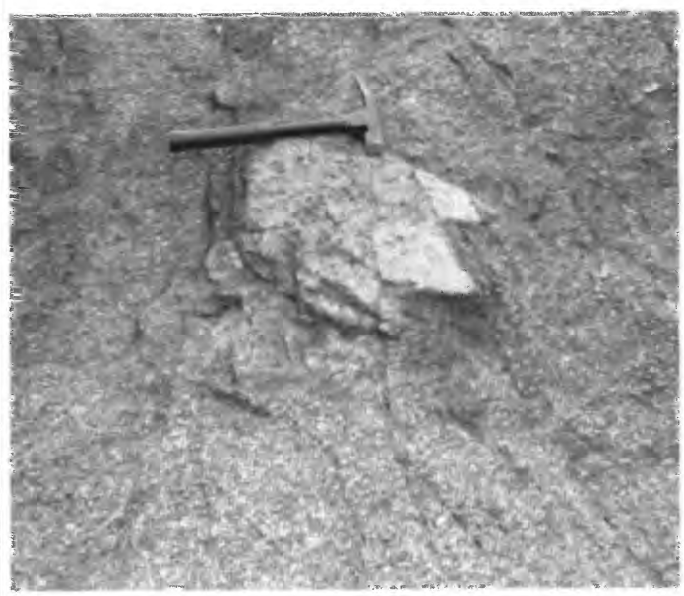


FIGURE 17.—Xenolith of anorthosite in little-altered Roses Mill on Mars Knob (loc. 34).

TABLE 7 – *Compositional comparison of Roses Mill ferrodiorites with some other rocks*

[Figures are in weight percent. Col. no. 1 – Harp Lake Complex (average of 17 analyses); 2 – Michikamau (average of 2); 3 – Morin Complex (average of 6); 4 – Skaergaard (average of 2)]

	Average Roses Mill ferrodiorites (table 6, sample nos. 4, 7, 8, 10–14)	Other ferrodiorites (averages from Emslie, 1978)				Other igneous rocks (averages from Nockolds, 1954)	
		1	2	3	4	Tonalite	Diorite
SiO_2	55.8	49.2	51.5	48.7	47.2	66.2	51.9
Al_2O_3	15.0	13.7	11.0	16.2	14.2	15.6	16.4
Fe_2O_3	3.4	2.8	5.2	6.0	3.7	1.4	2.7
FeO	7.6	13.0	16.4	8.0	16.1	3.4	7.0
MgO	2.1	3.4	.7	2.6	3.2	1.9	6.1
CaO	5.7	7.9	6.2	8.8	9.5	4.6	8.4
Na_2O	3.0	3.2	3.6	3.2	3.1	3.9	3.4
K_2O	2.5	1.2	1.6	1.3	.5	1.4	1.3
TiO_2	2.6	3.0	2.8	3.3	2.4	.6	1.5
P_2O_5	1.2	.7	.8	1.2	.9	.2	.4

FIGURE 18. – Xenolith of anorthosite in augen gneiss facies of Roses Mill unit near Lovingston, Va.

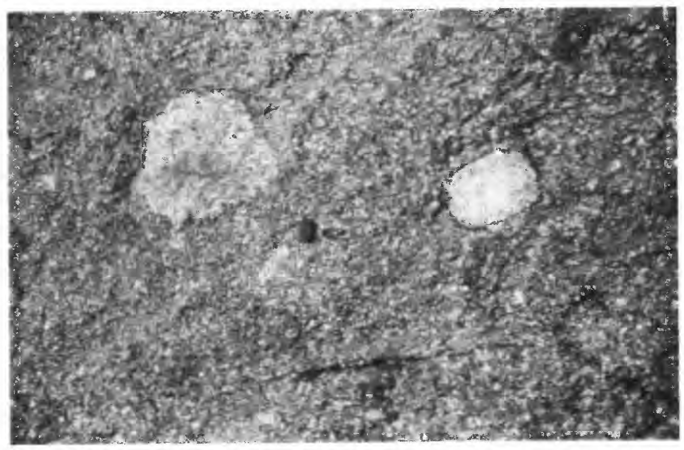


FIGURE 19. – Xenoliths of leucocharnockite in augen gneiss facies of Roses Mill unit near Lovingston, Va.

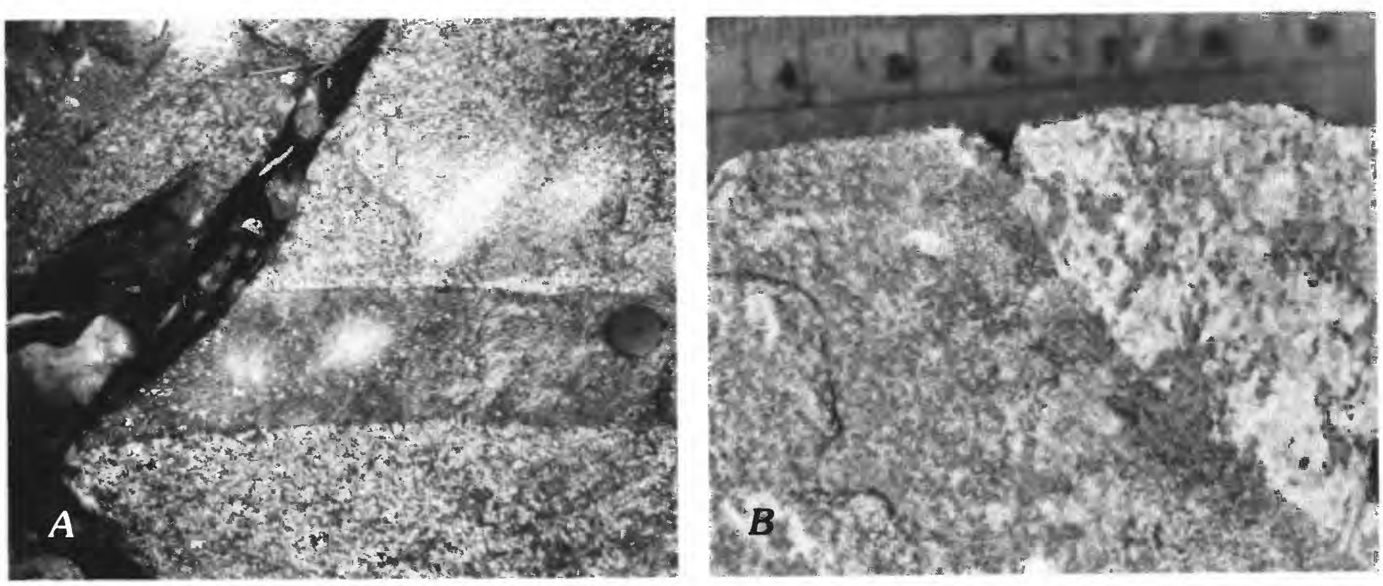


FIGURE 20. – Dike of Roses Mill in foliated quartz mangerite, locality 3. *A*, Outcrop view. Roses Mill dike under lens cap. *B*, Close-up view. Roses Mill dike to left cuts foliation of quartz mangerite to right. Centimeter scale.

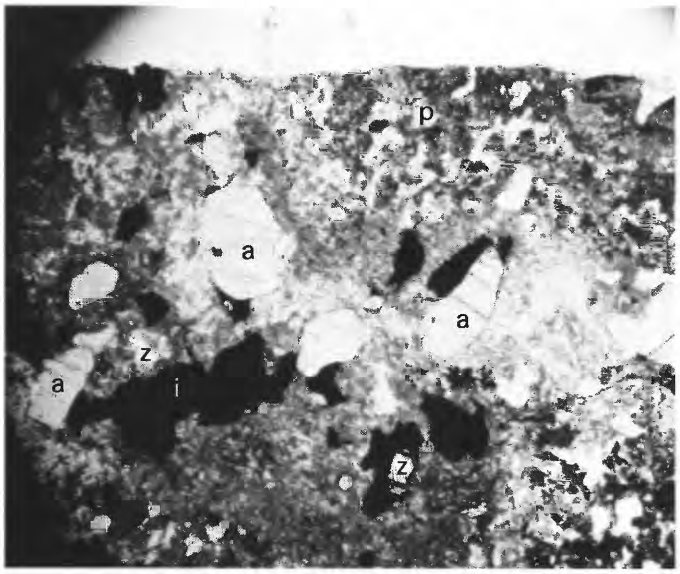


FIGURE 21.—Photomicrograph of Roses Mill dike in anorthosite, locality 17. Note abundant ilmenite (i), apatite (a), and zircon (z) and the alteration products of antiperthitic feldspar (p). Field of view is 1.5 mm, plane light.

STRATIGRAPHIC EQUIVALENCE

The Roses Mill pluton includes several units of previous workers (tables 1, 2). The greatest overlap is with the Lovingston Formation, described as a coarse-augen gneiss and related granite by Bloomer and Werner (1955). The gneiss is largely equivalent to the augen gneiss facies of the Roses Mill. The granite *as mapped* by Bloomer and Werner may be more or less equivalent to our Shaeffer Hollow Granite, an older unit found as extensive xenoliths and roof pendants in the Roses Mill. Bloomer and Werner's description of units is too cryptic to serve as a guide to the basement geology. We have not used the term Lovingston Formation because it includes only one facies of the closely related clan of Roses Mill rocks and also includes parts of older terranes. The Roses Mill, however, is part of the Lovingston massif, a complex of Proterozoic formations east of the ductile deformation zone of Bartholomew and others (1981).

Other areas of our Roses Mill unit are shown as Marshall Formation by Bloomer and Werner (1955). The Marshall Formation was defined as lacking the prominent augen of the Lovingston and had prominent quartzo-feldspathic bands separated by folia of chloritized biotite. We interpret the Marshall Formation of Bloomer and Werner in this district to represent the granulites, the cataclastic rocks, and part of the Roses Mill pluton. Banding described in the Marshall can be attributed both to compositional layering in the case of the granulites and to the development of mylonitic gneisses and schists in granulitic, charnockitic, and gneissic rocks.

Whereas most previous workers associate the nelsonite unit of the Roses Mill with the anorthosite, we find the unit to be a facies of the Roses Mill and Turkey Mountain plutons. As discussed below, nelsonites are found as probable cumulates within the Roses Mill as well as "dikes" in structurally lower units. In those lower units they share the distinctive mineralogy as well as the deformation and metamorphic history of the Roses Mill and show all gradations with Roses Mill dikes.

FACIES

The principal facies of the Roses Mill unit that we distinguished in the field are (1) massive charnockitic ferrodiorite, (2) biotite augen gneiss derived by deformation from ferrodiorite, (3) dike rocks, and (4) nelsonites.

CHARNOCKITIC FERRODIORITE

The Roses Mill facies that can be considered the "parent" of the more widespread biotite augen gneiss facies is the relatively unaltered charnockitic ferrodiorite. It forms Mars Knob, the ridge north of Bryant Mountain, and several other areas to the south such as at Roses Mill (sample nos. 7, 8, table 6). The rock is charnockitic in that it is a granite-suite rock containing pyroxene, though complete to partial uralitization or replacement by biotite of this pyroxene is characteristic of much of the unit. The rock is ferrodiorite in that its mineralogy and geochemistry is distinctive and closely matches ferrodiorites of other anorthosite massifs and of layered igneous complexes (table 7). Ferrodiorite composition shows strong enrichment in iron and titanium (table 7) and is quite unlike that of calc-alkalic rocks; the ratio of iron to magnesium oxides is large (in this case 5), SiO_2/K_2O is low (in this case about 22), and the rock contains high amounts of TiO_2 (2.6 percent), P_2O_5 (1.2 percent), Zr (690 ppm), and rare-earth elements. High SiO_2 of Roses Mill ferrodiorites compared to others is partly a result of contamination by blue quartz xenocrysts.

This facies, where freshest, has good igneous texture (fig. 22*A*) with feldspars about 3 to 5 mm and up to 10 to 20 mm. The rock typically has no primary foliation. It shows a crude mafic-felsic layering along the base, where layers of impure (pyroxene-bearing) nelsonite occur, and elsewhere by trains of xenoliths. Massive contamination by xenoliths and xenocrysts is apparent in some outcrops (locs. 19, 20).

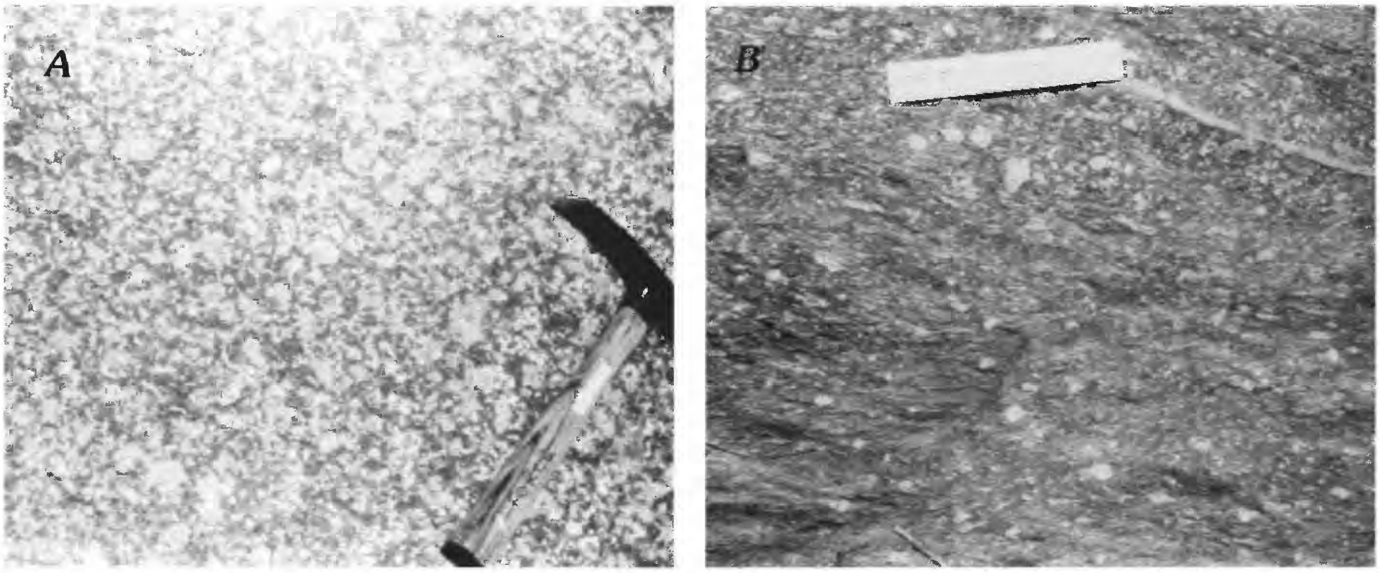


FIGURE 22.—End members in the textural facies of Roses Mill unit. *A*, Massive character and igneous texture of charnockitic ferrodiorite. *B*, Augen gneiss facies derived by retrogression and slight shearing. (Scale is 170 mm.)

The major primary minerals of the freshest rocks are some blue but largely clear quartz, perthitic and antiperthitic feldspar, and pyroxene. The pyroxene is deuterically uralitized, but orthopyroxene commonly can be identified. Two quartzes are present in part because blue quartz xenocrysts are present; blue quartz in xenoliths and large xenocrysts as well as small grains can be found in most outcrops. The more colorless quartz is probably magmatic; it is not obviously rutilated. Perthitic feldspar forms large grains, many of which are also probably xenocrysts as they are characteristic of the most abundant xenolith type and contain equant blue quartz inclusions. Antiperthitic plagioclase, commonly with myrmekite, is generally the most abundant phase (table 6).

The relative abundance of quartz and the two feldspars would classify the rock as a quartz monzonite or a quartz monzodiorite in the Streickeisen (1976) scheme, with total femic constituents averaging 32 percent (sample nos. 5–10, table 6). If massive contamination by blue quartz and perthite xenocrysts as well as digestion of other leucocratic xenoliths occurred as suggested, then the composition of the original igneous parent must have been more mafic. Comparison of chemical compositions with other rock suites (table 7) shows that ferrodiorite is the most appropriate rock name.

Characteristic minor primary minerals of the ferrodiorite are ilmenite, apatite, and zircon (fig. 21). Ilmenite averages 3.0 percent (by volume) and is nearly homogenous in polished section (in contrast to the magnetite intergrowths in ilmenite of the Turkey Mountain pluton). It is rimmed by porcellaneous sphene-anatase intergrowths in even the freshest rocks, though these rims are clearly a secondary feature (fig. 16). Apatite averages 1.6 percent and is high in rare earth elements (table 8). Zircon contents are also extraordinary, up to 0.6 percent by volume, and Zr averages about 700 ppm. Zircon is present as slightly rounded prisms up to 0.5 mm long, and it gave an isotopic U-Pb age of about 970 Ma (discussed in a separate section).

Widespread deuteric alteration by hydrous and secondary minerals has occurred in the Roses Mill unit. In the freshest rocks this alteration consists of sphene-anatase rims on ilmenite, uralite after pyroxene, albite-sericite-clinozoisite replacing andesine, and garnet-chlorite-amphibole intergrowths forming screens between felsic and mafic domains. Further development of secondary metamorphic minerals is discussed in the next section. This growth of secondary minerals correlates with the "unlocking" of the interlocking texture.

AUGEN GNEISS

Biotite augen gneiss is by far the most common rock type of the Roses Mill pluton (table 6, sample nos. 11–14). It is relatively resistant and forms many high hills both east and northwest of the anorthosite. It is dark gray with coarse-grained lighter colored feldspar augen separated by darker folia made up of finer grained quartz, feldspars, and biotite (fig. 22*B*); ilmenite, apatite, and zircon are most abundant in the

TABLE 8.—*Composition of apatite separates from Roses Mill pluton and Pedlar charnockite*

[Figures are in weight percent. Elemental contents in parts per million. Analysis: Instrumental neutron activation by P. Baedecker, USGS, Reston, Va.]

Sample no.	1	2
Fe	2,500	3,400
Co	<2	<2
Cr	<50	<60
Cs	<3	<3
Hf	39.0	8.3
Rb	<200	<200
Sb	<2.0	1.7
Th	34.4	270.0
U	<40.0	185.0
Sc	1.35	.57
La	1,350	3,320
Ce	3,920	8,370
Nd	2,790	3,970
Sm	700	760
Eu	55.2	51.3
Gd	565.0	632.0
Tb	71.0	79.5
Ho	68.0	98.7
Tm	18.0	28.1
Yb	101.0	172.0
Lu	12.3	22.7

SAMPLE DESCRIPTIONS AND LOCATIONS

SAMPLE No. 1. Apatite from Roses Mill ferrodiorite, from Roses Mill, locality 18.
2. Apatite from Pedlar charnockite; locality 27.

biotite-rich folia. Many rocks lack the coarse augen and have the aspect of a medium-grained granitic gneiss but with a composition identical to the augen gneiss. In these, biotite appears either in folia or in patches in a medium-grained felsic matrix. Augen vary in length from about 10 to 80 mm and consist of aggregates of feldspar and quartz or individual large perthitic grains. The feldspars are plagioclase (an_{0-15}) that is filled with inclusions of clinozoisite and sericite and with perthite that is generally clear of alteration but that has abundant inclusions of both blue quartz and biotite. Occasional large angular grains of antiperthitic plagioclase or blue quartz are reminiscent of similar grains in older units and probably represent xenocrysts. Myrmekitic intergrowths of feldspar and quartz are common. The pasty matrix includes finer grained felsic minerals and biotite as well as the important accessory minerals ilmenite (rimmed by sphene), apatite, zircon, epidote, muscovite, and chlorite. Modal analyses show quartz contents averaging 16 percent; plagioclase, in twinned grains that are broken or kink-banded in places, averaging 43 percent; perthitic potassium-feldspar up to 43 percent; biotite, as coarse brownish-red flakes parallel to the principal foliation plane and as ragged greenish flakes with or without any obvious foliation, 14 to 24 percent; muscovite both as coarse flakes parallel to the principal foliation plane and as an alteration product of feldspar; and epidote and clinozoisite, which are fine grained in augen replacing plagioclase and coarser grained in the matrix where they occur as an apparent replacement of mafic minerals. Green amphibole is commonly present also as pseudomorphs of pyroxene or part of a dark pasty matrix. Ilmenite (mostly 3–5 percent), generally about 0.5 mm in diameter, forms the nuclei for grains about 1 to 2 mm which in the rim are fine-grained sphene and anatase; apatite is common (mostly 2–3 percent), and zircon is present in all slides from trace amounts to 0.3 percent. Chlorite is seen as an alteration product, most abundant near zones of cataclasis.

In the section at Roses Mill (fig. 15; loc. 18) a gradation (continuous only on the southeast side) is exposed from ferrodiorite passing on both sides into biotitic augen gneiss with some of the augen gneiss mylonitic. Mineral reactions which form augen gneiss from ferrodiorite can be traced in thin section suites. They are, in general (ignoring silica and volatile transfers):

perthite + antiperthite ———> albite + K + Ca
by formation of albite rims
ilmenite + Ca ———> sphene + Fe
by formation of sphene rims
pyroxene + K ———> biotite + garnet
to form biotitic pasty matrix
antiperthite + Fe —> patchy actinolitic amphibole

This alteration may proceed further at lower metamorphic grades to form much epidote, muscovite, and chlorite.

DIKES

Roses Mill dikes and sills in older rocks are common (figs. 4, 13, 20, 23; locs. 1, 3, 9, 11, 17, 21). They are readily recognized in thin section (fig. 21) or by chemical analysis (table 6, sample no. 4, is typical) but in some cases can be recognized in the field by the mineral assemblage ilmenite-apatite-colorless quartz-green amphibole and by the abundance of feldspar xenocrysts. In only one locality (21) was a Roses Mill dike traced to its parent body.

The dikes range in thickness from tiny apophyses to tens of meters, as in Jenny Creek. Contacts are sharp but unchilled and are planar or irregular. Typically they have a weak metamorphic foliation defined by biotite and amphibole. A dike from the IMC quarry (loc. 17) contains 21 percent of quartz plus feldspar, 38 percent biotite, 24 percent amphibole, 7 percent ilmenite with sphene rims, 3 percent apatite, and 0.3 percent zircon, with minor white mica and epidote.

NELSONITE

Conventional nelsonite of the district is an equigranular rock consisting of about two-thirds ilmenite and one-third apatite in crystals of roughly 1 to 2 mm

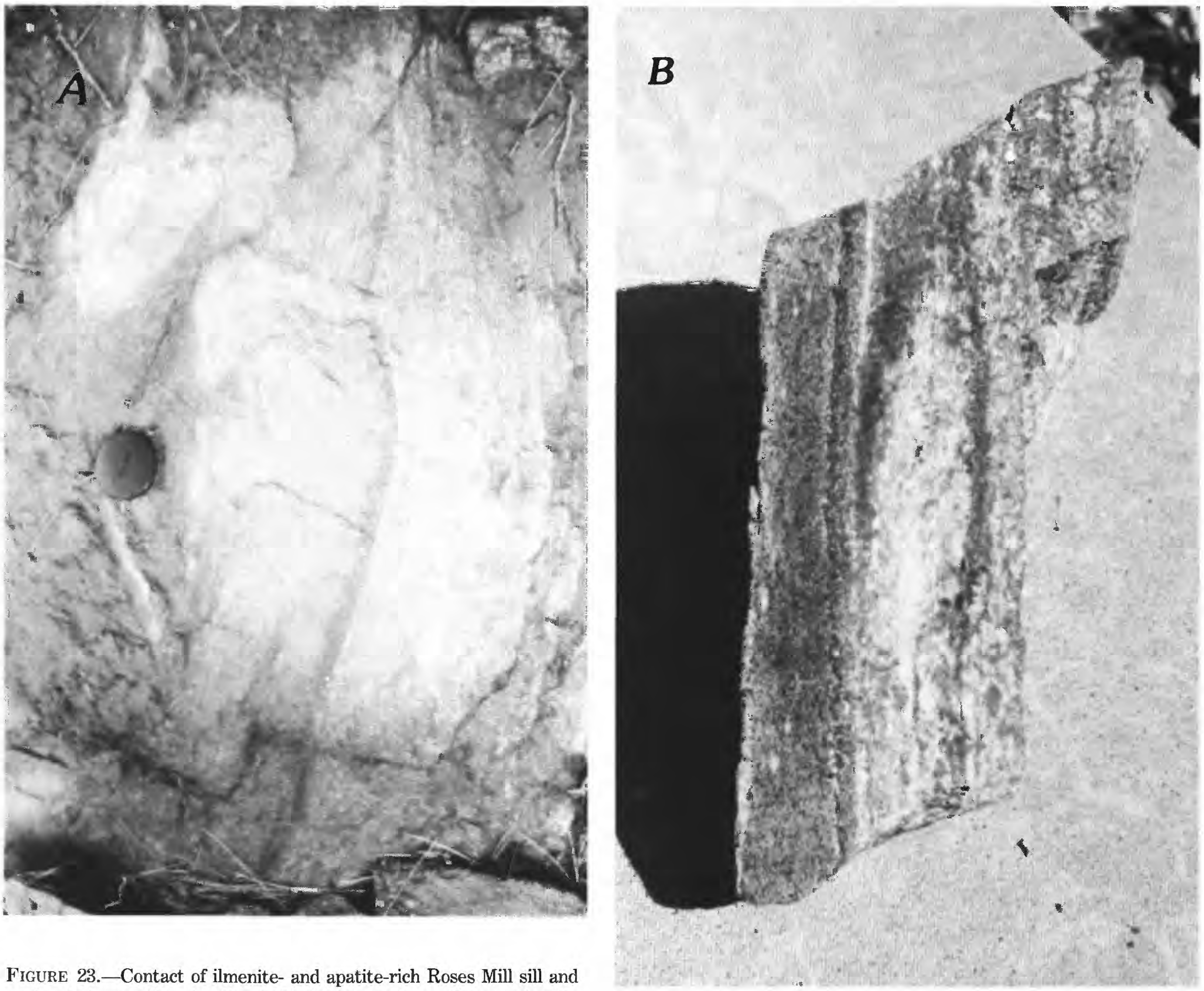


FIGURE 23.—Contact of ilmenite- and apatite-rich Roses Mill sill and banded granulite, locality 1. Dark selvage is on the structurally lower side of the sill and is caused partly by ilmenite which is probably cumulate in origin. *A*, Outcrop view, sill above. *B*, Hand specimen view. Field of view is 22×14 cm. Structural top is to left in both views.

(table 6, sample no. 1). Watson and Taber (1913) and Ross (1941) documented these nelsonites and some variations which occur by the presence of impurities. The bodies are described as dikes of up to 20 m in width.

We find that there are two main types of nelsonite. One type, that described originally, consists of ilmenite and apatite in equigranular textures and occurs as irregular anastomosing veinlets in granulite and anorthosite. The veinlets occur just under the Roses Mill intrusive sheet and are impersistent at depth (judging from drilling results of Fish, 1962, and our mapping near loc. 1). The other type occurs as impure layered nelsonites containing pyroxene and elliptical quartz-feldspar domains (fig. 24) along the base of the Roses Mill sheet (as at locs. 22 and 23). Here ilmenite and apatite form net veins around pyroxene grains, together forming mafic domains enclosing the elliptical felsic domains. These layered bodies are concordant (though discontinuous) with the base of the Roses Mill, and the elliptical domains are elongated parallel to the contact.

The formation of an immiscible liquid, rich in titanium and phosphorus, proposed by Philpotts (1967) as the origin of nelsonite, makes sense in view of the field and petrographic evidence at Roseland (Force and Herz, 1982; Kolker, 1982; Herz, 1984). Some petrologic aspects are discussed in a later section. Here, however, we will relate the different types of nelsonite to their occurrence in relation to this hypothesis.

We visualize the impure layered nelsonite with elliptical domains as an intermediate step in the formation of

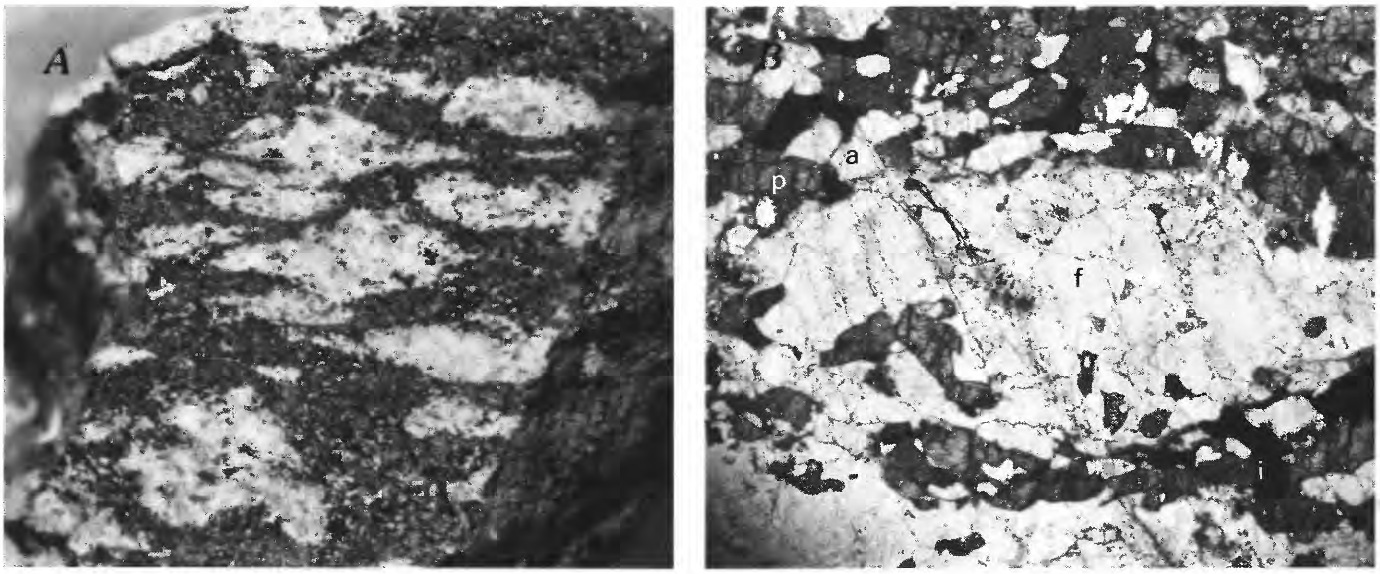
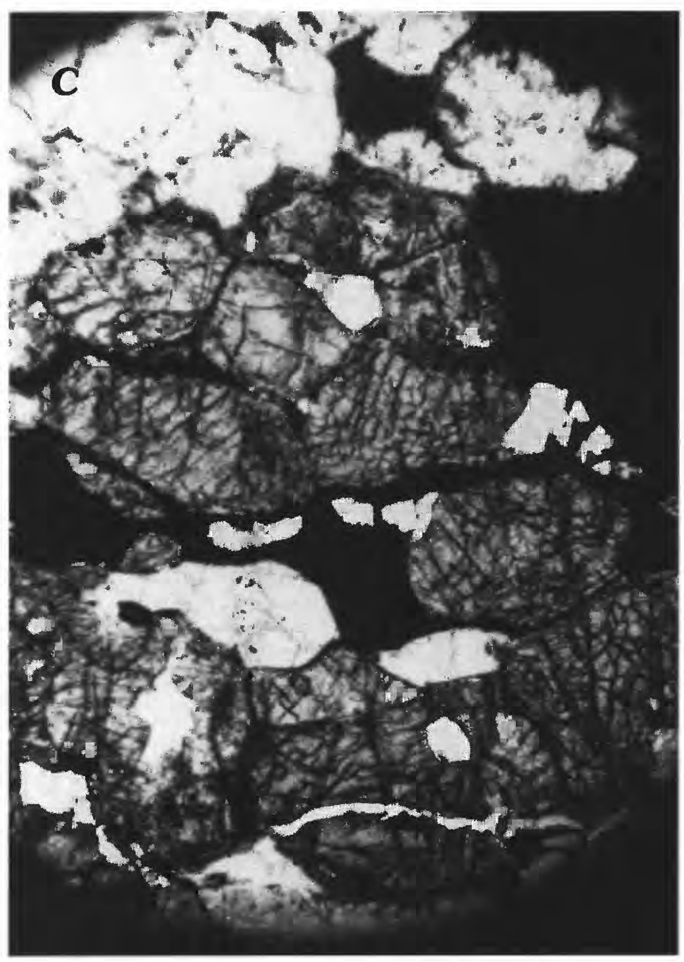


FIGURE 24.–Two pyroxene-plagioclase-ilmenite-apatite rock at the base of the Roses Mill unit at locality 22. We believe the texture is the result of a combination of immiscibility and cumulate processes. *A*, Hand specimen view. Light-colored elliptical domains are plagioclase-rich polymineralic aggregates. Field of view is 50 mm. *B*, Photomicrograph at low magnification showing unstrained texture of plagioclase (f) in elliptical domain, ilmenite (i), pyroxene (p), and apatite (a). Field of view is 12 mm. *C*, Photomicrograph at higher magnification showing net-vein texture of ilmenite and apatite around pyroxene. Field of view is 5 mm.



conventional nelsonite. Layered nelsonite is apparently a cumulate formed along the base of the Roses Mill magma chamber by settling of pyroxene grains and a titanium- and phosphorus-rich liquid immiscible in the main magma, the grains and liquid together forming the net-textured mafic domain. The elliptical felsic domains represent a trapped granitic fraction of much higher viscosity.

Conventional nelsonite could result where the low-viscosity immiscible liquid locally was able to coalesce, penetrate fractures in the base of the Roses Mill magma chamber, and form veins. Pyroxene crystals and felsic domains were mostly left behind.

We conclude that the nelsonites are facies of the Roses Mill pluton (and segregations in the Turkey Mountain plutons, described later), on the basis of the following reasoning:

(1) The nelsonite mineralogy ilmenite-apatite ± zircon is ubiquitous in and characteristic of the Roses Mill.

(2) The layered concordant impure nelsonites appear to be cumulate rocks formed along the base of the Roses Mill intrusive sheet.

(3) Impure nelsonite dikes in older terranes (as at loc. 24; fig. 25) show considerable mineralogic gradation to Roses Mill dikes (as at loc. 17; fig. 21). One Roses Mill sill has a nelsonitic layer along its base (loc. 1; fig. 23).

(4) The occurrence of irregular nelsonite "dikes" in older terranes just under a structurally overlying sheet of Roses Mill suggests derivation from the Roses Mill.

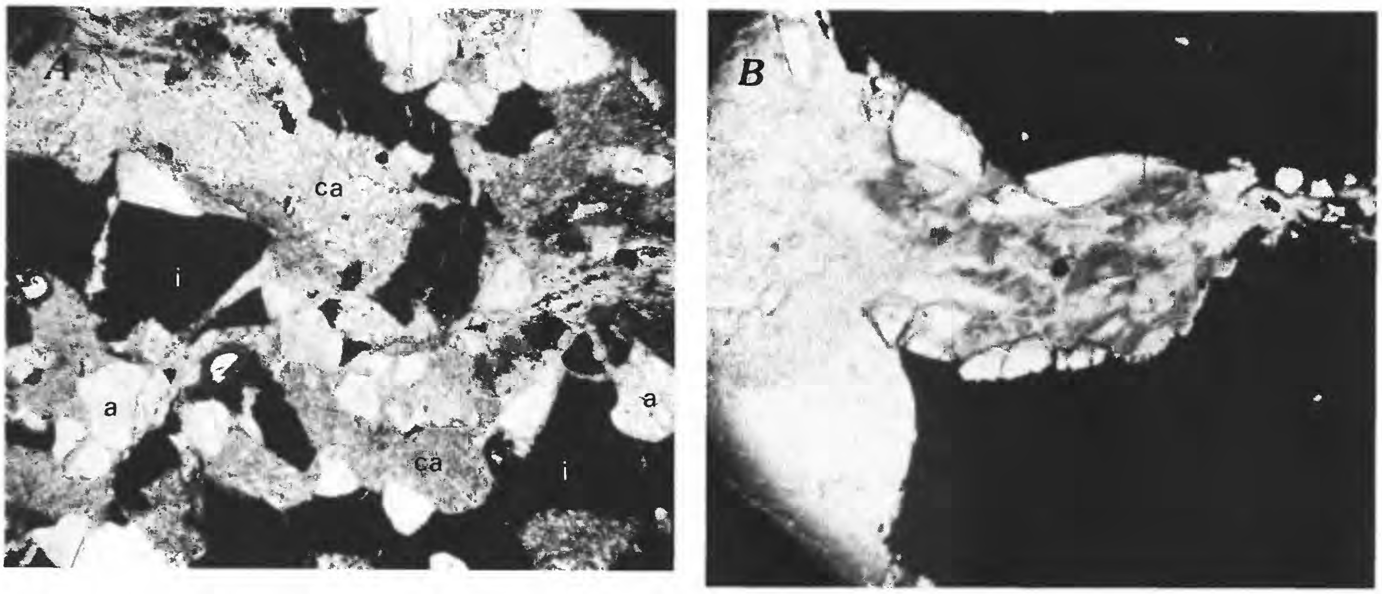


FIGURE 25.—Photomicrographs of impure nelsonite formerly mined for ilmenite at Piney River, locality 24, plane light. *A*, Low-magnification view; field of view is 8 mm. Ilmenite (i) and apatite (a) are the major phases, but chlorite-amphibole (ca) alterations of mafic minerals are common. *B*, High-magnification view of zircon grains. Field of view is 1 mm.

(5) Impure nelsonite dikes contain the same fabric and the same pale amphibole as the Roses Mill, suggesting that the dikes and the Roses Mill have the same history of deformation and metamorphism.

TURKEY MOUNTAIN PLUTONS

CHARACTERIZATION

The term Turkey Mountain is applied to massive to layered charnockite suite rocks and their reworked derivatives as exposed in the area of Turkey Mountain in Piney River quadrangle and elsewhere in the district (table 6, sample no. 9). Turkey Mountain plutons are found to the south and southwest of the anorthosite dome. Regional aeromagnetic maps suggest that the plutons continue to the southwest and can be traced by their strong positive anomalies into the Tobacco Row Mountain quadrangle.

These rocks are not as deuterically altered as rocks of the Roses Mill pluton and thus are more obviously charnockitic; show a wider range of composition which includes charnockite, ferrodiorite, and leucodiorite; contain minor magnetite intergrown in ilmenite; and are locally finely layered. The Turkey Mountain plutons have three facies which correspond to those of the Roses Mill: fresh charnockitic rock, derived biotitic augen gneiss, and nelsonite, which in this unit seems to be concordant only.

STRATIGRAPHIC EQUIVALENCE

All charnockites had been referred to the Pedlar charnockites by previous workers. Bartholomew (1977) first recognized charnockites to the north of this area that were not related to the Pedlar. Our mapping has also shown charnockites and layered mafic rocks, which we assign to the Turkey Mountain and Roses Mill units.

One of these charnockites occurs as a small (intrusive?) body, associated with augen gneisses of the Roses Mill unit. It is coarse grained, dark gray, and massive and has abundant coarse white perthitic feldspar grains unlike the greenish feldspar of the Pedlar.

A larger Turkey Mountain body to the southwest contains islands of fresh charnockitic ferrodiorite in biotite augen gneiss which apparently is derived from the same rock.

FACIES

MASSIVE CHARNOCKITIC ROCKS

Massive charnockites are generally unaltered, especially nearer the core of the bodies; toward the periphery, they are more foliated or show a cataclastic layering with extensive replacement of pyroxenes and plagioclase. The freshest rocks commonly weather spheroidally. Texture of the massive rocks appears to be igneous, hypidiomorphic granular, and the mineralogy is also igneous. Grain size is coarse with the characteristic greasy feldspars commonly 3 to 5 mm and up to 10 to 20 mm; pyroxenes are about 1 to 3 mm in diameter with orthopyroxene 2 to 5 times as abundant as clinopyroxene; feldspars are perthitic microcline, generally inclusion filled, or antiperthitic andesine, an_{31-35}. The largest plagioclase grains are broken or show kinked bands; clear plagioclase or microcline forms smaller grains, and myrmekite is present in many slides. Closely associated with the pyroxenes are the principal accessory minerals: ilmenite-magnetite intergrowths, apatite, and zircon. Biotite has formed as a reaction product around the oxide minerals and the pyroxenes with feldspars, with uralitic amphiboles and sphene formed as an inner reaction product. Modal analyses (table 6) of unaltered rocks show compositional ranges including charnockite, leucodiorite, ferrodiorite, and more mafic rock types. Ilmenite-magnetite intergrowths average 2.5 to 5 percent, apatite 1.5 to 2.7 percent, and zircon 0.1 to 0.3 percent. Amphiboles, epidote, and biotite vary from traces to abundant minerals by replacement of the feldspars and pyroxenes. In some samples that are deformed and replaced by epidote in veinlets, quartz and potassium feldspar have the original abundance. Plagioclase, however, may be under 10 percent and biotite as much as 20 percent, muscovite 2.5 percent, and epidote about 9 percent; pyroxenes and amphiboles are missing.

Layered and apparent cumulate features in Turkey Mountain leucodiorite and ferrodiorite were observed in two places (best at loc. 25); bands rich in pyroxene and ilmenite (with intergrown magnetite) alternate with plagioclase or quartzofeldspathic bands, all in ophitic-textured rock. In some leucodiorites, a vertical segregation is apparent, with mafic minerals concentrated toward the bottoms of layers and plagioclase toward the tops (fig. 26). Some sorting appears to have taken place on the basis of settling velocities, controlled by differences in mineral and liquid densities, or by magmatic currents. Across several layers at locality 25, there is a transition from magnesium-rich pyroxenes interlayered with hypersolvus feldspars at the base toward iron-rich pyroxenes and subsolvus feldspars at the top (Herz, 1984).

BIOTITIC AUGEN GNEISS

Augen gneisses derived from Turkey Mountain precursors are virtually impossible to distinguish from those derived from Roses Mill. The Turkey Mountain, however, is more strongly magnetic on aeromagnetic maps.

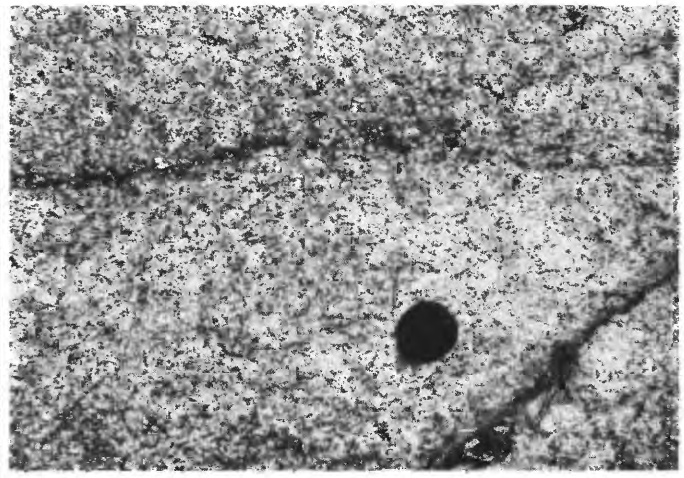


FIGURE 26.–Graded band in ophitic leucodiorite in Turkey Mountain unit at locality 25.

NELSONITE

Nelsonite is present within the Turkey Mountain unit at two localities. At locality 25 it is only float but is immediately adjacent to cumulate leucodiorite. At locality 26, nelsonite is surrounded by normal charnockite and consists of apatite-rich globs 5 cm in diameter and separated by areas which are mostly ilmenite. The rock also contains 5 percent zircon crystals, which are up to 15 mm long, and lumps of quartz. The texture of this nelsonite rock suggests some origin involving both cumulate processes and immiscibility.

ROCKS OF THE PEDLAR MASSIF

The Pedlar massif (of Bartholomew and others, 1981) underlies the northwestern part of the area. Its southern boundary is just within the mylonitic zone, close to the boundary of the George Washington National Forest. The Pedlar massif in this area consists largely of igneous-appearing massive or faintly foliated dark-green charnockitic ferrodiorites, which grade into granitic rocks and minor well-layered mafic and granulitic rocks that may have either a sedimentary or igneous origin. All these rocks were assigned to the Pedlar Formation by Bloomer and Werner (1955). On the 1963 Geological Map of Virginia, the Pedlar Formation extends as far north as Culpeper County giving it a length of about 160 km in a northeast-southwest direction. It is described on the legend of that map as granite, granodiorite, hypersthene grandiorite, syenite, quartz diorite, anorthosite, and unakite, following the usage of Bloomer and Werner (1955).

The field relations of the Pedlar rocks to other units of the map area are not clear because the Pedlar is separated from them by a wide zone of deformation. Our radiometric zircon age of 1,040 Ma and the whole-rock Rb-Sr date of 1,042±35 Ma by Herz and others (1981) suggest that Pedlar ferrodiorite slightly preceded otherwise similar Roses Mill and Turkey Mountain rocks of the units described above. (Compare tables 6 and 9.)

Most of the Pedlar ferrodiorites appear to be relatively massive and bluish gray to dark green in color. Many samples are equigranular, having a hypidiomorphic granular texture, and grain size is from about 0.4 to 1 cm; feldspars tend to be coarser grained than the mafic minerals. The most common rock types appear to be ferrodiorites which contain perthitic microcline and plagioclase, both more or less equant, and finer grained myrmekite; irregularly shaped and strained blue quartz and later colorless quartz; orthopyroxene and clinopyroxenes in varying states of uralitization; brown oxyhornblende; deep-reddish-brown biotite with rutile needles, abundant where pyroxenes are extensively uralitized; and zircon, apatite, ilmenite, magnetite, white micas, and sulfides which are common accessories. Adjacent to zones of deformation, especially inside the cataclastic zone, protomylonite and mylonitic gneiss is developed along with extensive retrograde metamorphism to minerals of the lower greenschist facies.

Another common facies is distinctly porphyritic, either with pyroxenes poikilitically enclosing feldspar and quartz (as at loc. 27) or the reverse. Phenocrysts of perthitic microcline or broken plagioclase commonly 10 to 20 mm but up to 10 cm in diameter, occur in felsic aggregates about 30 to 50 mm. The plagioclase varies an_{25-36}. Minor blue quartz is in elongate aggregates that are irregular to droplike in appearance, and some grains have rutile needles. Granular, rounded aggregates of orthopyroxene and clinopyroxene, commonly 3 to 5 mm in diameter, occur in mafic clots with apatite, zircon, oxyhornblende, and magnetite. In some samples having both fine- and coarse-grained pyroxene, larger grains appear to be more uralitized. Uralite and saussurite are present to some degree in almost every slide.

Highly leucocratic rocks with feldspars and blue quartz commonly comprising over 90 percent are also common. These rocks appear similar to our Shaeffer Hollow Granite as well as to the Crozet and Old Rag Granites to the north (Nelson, 1962; Allen, 1963); their correlation must await more detailed work in the area. They are typically very coarse grained, with plagioclase somewhat saussuritized and filled with inclusions of opaque minerals, zircon, and apatite; microcline perthite is generally more abundant than plagioclase; quartz comprises 25 percent or less; oxyhornblende and biotite with or without clinopyroxene may also be present. With advanced alteration, clinozoisite and white micas replace the feldspar, and chlorite and amphiboles replace the pyroxenes.

Layered charnockitic rocks are occasionally found within the massive varieties, either with primary or mylonitic layering. The layering varies from a fine scale of only a few millimeters to several centimeters. Primary layered rocks appear to be concordant with the massive rocks, and indeed both have identical mineralogies. Microcline perthite forms crystals up to 6 mm with quartz inclusions. Plagioclase is about calcic-oligoclase to sodic andesine in composition, up to 1 to 2 mm in diameter, and shows kinked deformation bands. Pyroxenes, hornblende, and reddish-brown biotite are abundant in mafic layers, with biotite increasing as uralitization of pyroxene also increases. Apatite, zircon, and ilmenite or magnetite are common as accessory minerals.

Mylonitic layering in some feldspar-rich rocks is shown by elongate, irregular quartz lenses or by mylonitic bands which include the comminuted mafic minerals and quartz. Mylonitic rocks have been retrograded to greenschist facies metamorphic assemblages and are most common nearest the Rockfish Valley Fault where they grade into protomylonites. These are described in a later section.

In addition to the widespread development of retrograde metamorphic assemblages in cataclastic zones, unakite has also commonly formed away from any obvious zone of deformation. Unakite is a product of retrograde metamorphism in which original rock textures are preserved. Mineral assemblages include a dark-green epidote, in amounts up to 50 percent, which replaces both plagioclase and the primary mafic minerals; pink microcline, about 30 percent, and either white or smoky blue quartz, about 20 percent.

POST-GRENVILLE ROCKS

MOBLEY MOUNTAIN GRANITE

The Mobley Mountain Granite underlies and takes its name from Mobley Mountain (1,328 ft, or 409 m) in the southwestern corner of the Piney River quadrangle. The granite is about 7 km long in a northeast-southwest direction and 2 km wide. Abundant irregular and smaller bodies, as well as crosscutting veins, pegmatites, and injection migmatites (figs. 27, 28; locs. 13, 28) are found throughout an area that extends as a halo for 2 km away from the mountain (pl. 1). A model based on gravity data (Eppihimer, 1978) showed a plug-shaped body that reaches a maximum depth of 7.2 km (fig. 29).

TABLE 9.—*Analyses of Pedlar ferrodiorites and charnockites, Massies Mill quadrangle*

[---, not analyzed or not detected; P, present. Figures may not add to totals shown due to independent rounding. Analysts and methods are as follows: Sample nos. 1–3, G. J. Davis, University of Georgia (x-ray fluorescence); 4–F. Brown and colleagues, USGS, Reston, Va. (rapid rock)]

Sample number	1	2	3	4
Major elements, in weight percent				
SiO_2	63.72	63.11	56.12	59.9
Al_2O_3	14.57	14.53	14.98	12.1
Fe_2O_3	([a])	([a])	([a])	2.4
FeO	7.51	7.35	10.57	6.7
MgO	1.16	1.03	2.14	1.4
CaO	4.11	3.80	5.41	5.4
Na_2O	2.76	2.58	2.70	2.4
K_2O	3.16	3.69	2.84	3.6
H_2O^+	.35	.98	.70	.82
H_2O^-				.11
TiO_2	1.53	1.59	2.57	2.3
P_2O_5	.66	.60	1.01	1.3
MnO	.12	.10	.14	.19
CO_2	---	---	---	.02
F	---	---	---	.24
Total	99.03	99.33	99.17	98.9
Normative minerals, in weight percent				
Q	22.95	22.80	13.2	20.48
or	18.67	21.81	16.78	22.57
ab+an	39.43	36.76	43.09	35.19
C	.72	.82	.05	---
di	---	---	---	4.28
hy	10.24	9.58	15.02	8.12
ap	1.56	1.42	2.39	2.88
ilm	2.91	3.02	4.88	3.40
mt	2.42	2.36	3.26	2.66
fr	---	---	---	.28
cc	---	---	---	.13
Calculated mineral compositions				
en (percent)	28.2	26.8	35.5	33.7
an (percent)	40.8	40.6	47.0	36.4
or:ab:an	32.1:40.2:27.7	37.2:37.3:25.5	28.0:38.3:33.8	40.0:38.2:21.8

Sample number	1	2	3
Trace elements, in parts per million			
Zr	637	694	590
Rb	189	144	45
Sr	338	392	444
Nb	41	45	---
Mo	---	.8	---
Co	16	15	22
Ba	1,076	1,132	1,481
La	92	58	52
Pb	61	39	16
Ce	166	112	60
Nd	115	86	90
V	70	79	171
Modal analyses, in volume percent			
Quartz	18.5	21.7	13.2
Plagioclase	[b] 12.6	[b] 24.4	[b] 37.7
Potassium-feldspar	[c] 47.2	[c] 34.8	[c] 24.2
Orthopyroxene	[d] ---	8.2	[e] 17.4
Clinopyroxene	[d] ---	.8	[e] 2.2
Hornblende	15.4	[f] 6.0	---
Biotite	1.3	---	---
Ilmenite	2.6	2.4	3.8
Magnetite	---		
Apatite	1.9	1.4	1.5
Sphene	.5	---	---
Zircon	---	.1	P

[a]All Fe reported as FeO.
[b]Antiperthitic.
[c]Perthitic: 2–5 mm.
[d]Uralite.
[e]Somewhat uralitized.
[f]Oxyhornblende.

SAMPLE NO. 1. Biotite "charnockite," massive, coarse grained, feldspar to 8 mm, mafic 3–5 mm. Piney River, northwest of Jacks Hill.
2. Hornblende charnockite, coarse grained, massive. Rocky Run.
3. Slightly uralitized charnockite, equigranular, medium grained, massive. Just north of Friar Mountain peak.
4. Massive ferrodioritic charnockite with orthopyroxene poikilitically enclosing other phases clinopyroxene, plagioclase, and quartz. Near Jacks Hill on Piney River (loc. 27).

The rock is typically fine to medium grained (finer near contacts), well jointed, massive or weakly foliated, and somewhat more resistant to weathering than its country rocks. The foliation and biotite-rich layers are more abundant toward the contact with surrounding rocks. Mobley Mountain dikes, however, typically show weak foliation even where country rock is strongly foliated (loc. 28).

Typically, Mobley Mountain Granite is yellowish gray and has a characteristic pepper-and-salt appearance from biotite patches about 1 mm in diameter disseminated through granular quartz and feldspar. Chemical analyses show the Mobley Mountain to be an alkaline granite (table 10).

The Mobley Mountain Granite has an intrusive relationship to the Turkey Mountain rocks that nearly surround it. Granite at the contact with the Turkey Mountain is weakly foliated parallel to metamorphic foliation in the Turkey Mountain. Elongate biotite-rich clusters in both rocks appear to be similar in mineralogy and chemical composition, having reddish-brown pleochroism in both the biotites. Away from the contact, no xenoliths are seen in the granite, although abundant Mobley Mountain dikes and sills occur in the Turkey Mountain (fig. 27). Characteristics such as the lack of xenoliths, the lack of chilled contacts and contact aureole, and a roughly synchronous lower amphibolite grade of metamorphism in the country rock imply a relatively deep mesozonal pluton (Buddington, 1959). Data discussed below suggest an emplacement of the granite at a depth of about 18 km.

Aplitic veins and coarse muscovite-quartz-feldspar pegmatites are found in the body and in its country rocks (fig. 27; locs. 13, 28). Veins contaminated with

FIGURE 27.–Dikes of Mobley Mountain Granite. *A*, Stockwork of aplitic Mobley Mountain Granite dikes in foliated and altered Turkey Mountain charnockite on Buffalo River section through Mobley Mountain (loc. 28). Aplite bands are up to 0.3 m thick. *B*, Fine-grained salt-and-pepper-textured dike of Mobley Mountain Granite near locality 18. The dike truncates at least some of the foliation in augen gneiss facies of Roses Mill pluton country rocks.

FIGURE 28.–Migmatite of Mobley Mountain Granite facies, Buffalo River at the mouth of Long Branch. Layering (upper left to lower right) is between darker salt-and-pepper-textured granite and lighter facies including aplite. Exposure is about 5 m high.

mafic material are also found in country rocks (loc. 17, table 10). In the contact zone between charnockitic or granulitic country rock with granite or its veins, mafic minerals in country rock have everywhere been hydrated. Thus intrusion of the granite must have introduced large amounts of water to a previously dry system. The intrusion may correlate with the formation of biotite in the augen gneiss facies of the Roses Mill and Turkey Mountain plutons.

Mobley Mountain granite veins in anorthosite contain dark alkali feldspar (loc. 17). Aplitic Mobley Mountain locally cuts altered black Catoctin(?) dikes (loc. 29).

On the average, the rock contains about 30 percent microcline perthite, 26 percent quartz, 24 percent plagioclase, a sodic oligoclase, 11 percent biotite, 6 percent clinozoisite-epidote, 1 percent muscovite, 1 percent allanite, 0.3 percent each of zircon and sphene, and traces of apatite and fluorite. A pleochroic green amphibole is occasionally seen as inclusions in plagioclase, and rutile needles are seen in biotite.

The microcline perthite varies in grain size from 2 to 3 mm at the center of the body to 0.5 to 1 mm at the borders and in veins in country rock; plagioclase, a sodic oligoclase, forms twinned, broken, and kink-banded grains filled with inclusions of clinozoisite and white micas, and it is generally finer grained than the microcline within the body but coarser, up to 6 mm, in

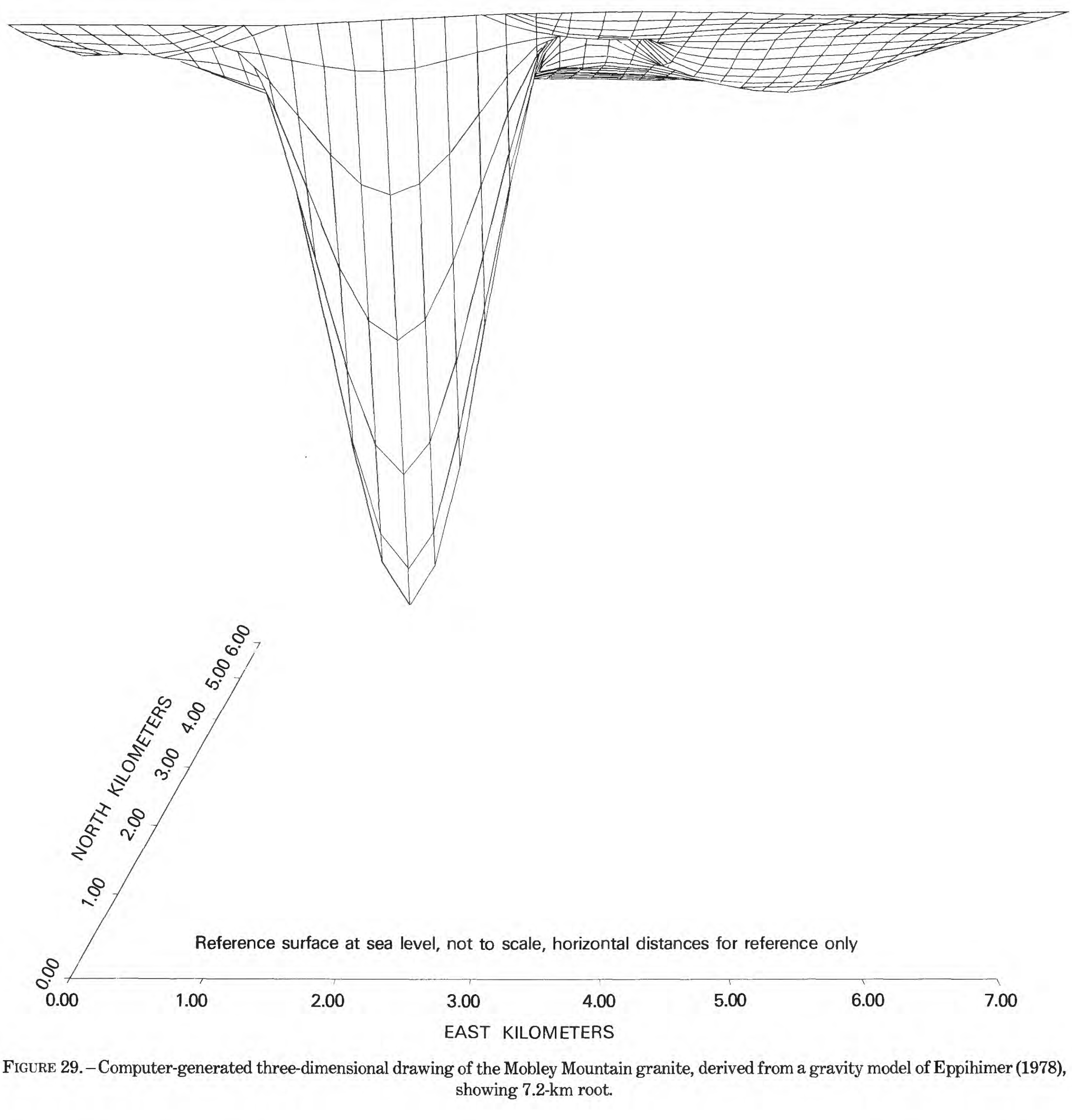


FIGURE 29.—Computer-generated three-dimensional drawing of the Mobley Mountain granite, derived from a gravity model of Eppihimer (1978), showing 7.2-km root.

border areas; quartz is irregular with undulatory extinction in larger grains; biotite shows an olive- or yellowish-brown to yellowish-green or reddish-brown pleochroism and is rutilated in places; muscovite and fine-grained white mica varies greatly in abundance, from about 0.5 percent at the center of the body to 2.0 percent at the border, and appears both as a fine-grained alteration product and as coarse primary-appearing flakes; clinozoisite, epidote, and allanite or florencite (Brock, 1981) are abundant in all specimens from a high at the core of 9.0 percent epidote-clinozoisite with 1.3 percent allanite or florencite to 1.8 percent and 0.8 percent,

TABLE 10.—*Analyses of Mobley Mountain Granite, Piney River quadrangle*

[___, not analyzed or not detected; P, present. Figures may not add to totals shown due to independent rounding. Analysts and methods are as follows: Sample no. 1–P. Elmore and colleagues, USGS, Reston, Va. (rapid rock) and W. B. Crandell, USGS, Washington, D.C. (semiquantitative spectrographic); 2–G. J. Davis, University of Georgia (x-ray fluorescence)]

Sample number	1	2	3
Major elements, in weight percent			
SiO_2	57.2	71.79	66.63
Al_2O_3	18.6	13.87	15.39
Fe_2O_3	1.0	(a)	(a)
FeO	7.7	3.86	6.00
MgO	.77	.18	.34
CaO	2.7	.83	1.68
Na_2O	5.4	2.94	3.06
K_2O	2.9	5.35	5.40
H_2O^-	.09	.36	.22
H_2O^+	1.3		
TiO_2	.73	.30	.44
P_2O_5	.44	.07	.15
MnO	.17	.07	.09
CO_2	.26	___	___
Total	99.3	99.62	99.40
Normative minerals, in weight percent			
Q	4.08	30.03	20.85
or	17.13	31.61	31.91
ab+an	45.70	28.54	33.25
C	8.87	1.90	1.82
di	6.66	___	___
hy	11.01	5.58	8.83
ap	1.04	.17	.36
il	1.39	.57	.84
mt	1.45	.93	1.45
cc	.59	___	___
Calculated mineral compositions			
en (percent)	13.4	8.04	9.59
an (percent)	0	12.18	22.12
or:ab:an	27.3:72.7:0	52.6:41.4:6.1	49.0:39.7:11.3

a All Fe reported as FeO.

Sample number	1	2	3
Trace elements, in parts per million			
Zr	500	254	465
Rb	___	108	95
Sr	500	103	156
Nb	70	___	___
Mo	5	___	___
Ba	700	667	1,650
Be	3	___	___
Ce	200	225	126
Co	7	7	11
Cu	15	___	___
Ga	20	___	___
La	150	106	80
Sc	5	___	___
Y	50	___	___
Yb	5	___	___
Pb	___	16	26
Nd	___	106	96
V	___	9	14

Sample number	2	3	4
Modal analyses, in volume percent			
Quartz	29.3	23.6	25.0
Plagioclase	26.0	18.9	26.4
Potassium-feldspar	29.7	33.3	26.6
Biotite	10.0	11.9	12.0
Muscovite	2.0	.5	.9
Epidote	1.8	9.0	7.4
Allanite/florencite	.8	1.3	.45
Zircon	.3	.4	.22
Apatite	P	___	.56
Ilmenite	___	___	___
Chlorite	___	___	___
Sphene(?)	___	.2	.56
Amphibole	___	.9	___

SAMPLE DESCRIPTIONS AND LOCATIONS (CHEMICALLY ANALYZED SAMPLES SHOWN ON PL. 1, ALL IN PINEY RIVER QUADRANGLE)

SAMPLE NO 1. Contaminated Mobley Mountain Granite dike in anorthosite, 15–50 cm wide, bleached zone against anorthosite; massive, fine-grained, dark gray, 0.1–0.5mm, potassium feldspar, plagioclase zoned An_{32}; biotite in clusters with chlorite, ilmenite with sphene rims. Sp gr=2.72. IMC quarry (loc. 17).

2. Mobley Mountain Granite dike, weak foliation shown by biotite clusters, felsic minerals in 2- to 4-mm aggregates, plagioclase coarse grained with inclusions of biotite, clinozoisite, quartz, muscovite; perthitic potassium feldspar replaces plagioclase. Northwest of Route 619.

SAMPLE DESCRIPTIONS AND LOCATIONS–Continued

3. Mobley Mountain Granite, very weakly foliated, fine-grained, plagioclase to 1 mm with clinozoisite inclusions. Sp gr=2.693. On Mobley Mountain.

4. Mobley Mountain Granite, weak foliation shown by biotite clusters, fine grained, plagioclase 0.7–1.5 mm, clinozoisite inclusions; potassium feldspar appears late. Sp gr=2.69. Northeast of Mobley Mountain, near locality 28.

respectively, at the borders. Zircon is present in all rocks examined microscopically, averaging about 0.3 percent; apatite varies from trace amounts to a maximum of 0.6 percent in veins in country rock, and sphene varies from 0.2 percent to 0.6 percent maximum in veins. Chevkinite and perrierite (including a perrierite-bearing pegmatite just west of St. Marks Church in the Piney River quadrangle) have been reported in the area (Mitchell, 1966), but both minerals are metamict and have similar optical characteristics to allanite; if they are present in these rocks, they have been included with allanite.

The Mobley Mountain Granite has been dated by Rb-Sr at 652±22 Ma (Herz and others, 1981). It appears to be part of a belt of mesozonal granites and related rocks that have also been dated at about 650 Ma and that include Rockfish granodiorite of Davis (1974), granite of the Robertson River Formation of Allen (1963), possibly the Crossnore Complex pluton, and volcanics of the Mount Rogers Formation. To the north, around Lovingston (Davis, 1974), the Rockfish granodiorite, a nonfoliated, medium- to coarse-grained rock covering 5 to 7 km^2, intrudes the "Lovingston" augen gneiss and quartz monzonite. The Lovingston here is similar petrographically to our Roses Mill unit. The Rockfish granodiorite is dated at 572±50 Ma by Rb-Sr (Smith and others, 1981) and at about 730 Ma by U-Pb (Sinha and Bartholomew, 1984). The Robertson River Formation (Allen, 1963; Espenshade and Clarke, 1976), a hornblende granite and syenite in Madison and Green Counties, Va., also appears to be similar to the Rockfish granodiorite and the Mobley Mountain Granite in mineralogy and in contact relationships with the Lovingston gneiss. Its age has been determined by zircon U-Pb at 700 Ma (Lukert and Clarke, 1981). The tin greisen at Irish Creek just west of the map area is related to granites there that appear similar to the Mobley Mountain. The greisen has been dated by $^{40}Ar/^{39}Ar$ at 635±11 Ma (Hudson and Dallmeyer, 1981).

MAFIC DIKES

A variety of mafic and ultramafic dikes are found in the district. They range from metamorphosed to pristine, and compositions range from diabasic through pyroxenitic. Crosscutting between the dikes is locally observed (loc. 21), but relative ages can generally be established only between country rock and individual dikes. Some dikes are metamorphosed and have tectonic fabrics, and these are placed in the regional stratigraphy on the basis of these features. Unmetamorphosed dikes are presumed to be Mesozoic in age.

Roses Mill and nelsonitic dikes have already been described. In addition, the following mafic dike units have been recognized: (1) rare pyroxenites, locally serpentinized; (2) fine-grained altered mafic dikes–Late Proterozoic to early Paleozoic, including probable Catoctin Formation dikes; (3) diabase–(early Mesozoic?); and (4) gabbro–(Mesozoic?).

PYROXENITE

Pyroxenites have been found at seven places (table 11). Exposure is not good enough at any of them to determine their field relations or form; all but one (no. 6) are in or adjacent to anorthosite, and one of these is also adjacent to nelsonite (no. 1). Pyroxene is orthorhombic at the occurrences (nos. 1, 2, 3, 7) where this could be determined. Occurrence no. 1 consists of more than 90 percent hypersthene in 1- to 2-mm grains rimmed by fibrous amphibole with minor amounts of andesine, green amphibole, magnetite, and sulfides. Occurrence no. 7 consists of similar orthopyroxene grains that show kink banding and exsolution lamellae, but the rock is extensively altered to a mixture of talc-serpentine with amphiboles, epidote, ilmenite with sphene rims, and magnetite with a skeletal structure. The texture is vaguely nodular at nos. 5 and 6 (table 11). Blue quartz, which is common only in pre-Roses Mill rocks, occurs in veins at nos. 3 and 5 (table 11), which suggests that some of these bodies are pre-Roses Mill.

FINE-GRAINED MAFIC FOLIATED DIKES

Dark-gray-green, fine- to medium-grained, foliated retrograded mafic dikes are widespread throughout the area and may represent several periods of emplacement. They intrude virtually all the other rocks, including mylonitic leucocharnockite (loc. 37), but locally they are cut by Mobley Mountain Granite (loc. 29).

These dikes typically are intruded into deformation zones (locs. 30, 37). Chilled margins are locally preserved. The dikes vary in widths from a few centimeters to 10 m. The dikes at locality 30 extend east-west about a kilometer. Metamorphic minerals are albite, biotite, muscovite, quartz, clinozoisite, chlorite, carbonate, and green amphibole. The dikes cut Grenville-age rocks and are altered to greenschist-facies assemblages of Paleozoic age, so they may range from late Grenville to Paleozoic in age.

The exact ages and origin of these dikes are unknown. Possible associations are with (1) Late Proterozoic metabasalts of the Catoctin Formation which are altered to roughly the same degree and form extensive flows both east and west of the Roseland area; (2) gabbro intrusions with associated dikes to the east and north (Bloomer and Werner, 1955, pl. 1), presumably also of Late Proterozoic age; (3) Paleozoic dikes which in South Carolina (Overstreet and Bell, 1965) are related to amphibolites and acid igneous rocks.

DIABASIC DIKES

Mafic dikes, fine and medium grained with well-developed ophitic textures, are found in the area. These dikes range from about 0.3 to 10 m thick and trend within 15° east or west of north and dip steeply. They form a north-south swarm along Jennys Creek for over a kilometer (loc. 31). They have been mapped largely on the basis of float, but where seen in place always show a fine-grained margin grading into a medium-grained core. Smaller dikes are aphanitic and highly altered, largely by weathering processes. Mineral assemblages include plagioclase, in laths and in the groundmass (an_{40}), fine-grained hornblende and chlorite mats that replaced pyroxene, and minor relict pyroxene, ilmenite (commonly skeletal), and sphene.

GABBRO

A postmetamorphic gabbroic rock was found in Crawford Creek, at the south end of the Piney River

TABLE 11.—*Locations of pyroxenite bodies*
[Locations of samples are shown on pl. 1]

Sample no.	Quadrangle	Nearby features	Mineralogy
1	Horseshoe Mountain	Highway 151 and 781 (Bryant)	Orthopyroxene-garnet-plagioclase-magnetite.
2	do.	Highway 151 and 655 (Lanes Ford)	Orthopyroxene.
3	Piney River	Maple Run 1 km west of Highway 151	Orthopyroxene-apatite-blue quartz.
4	do.	Maple Run 1.5 km west of Highway 151	Pyroxene.
5	do.	Maple Run 2 km west of Highway 151	Pyroxene-garnet-blue quartz.
6	do.	North tributary of Mill Creek 1.5 km south of Highway 655.	Pyroxene-garnet.
7	Arrington-Horseshoe Mountain.	At intersection of Highway 724 with quadrangle boundary.	Orthopyroxene-ilmenite-magnetite.

quadrangle and trending north-south (loc. 32). Continuing on the same trend, just north of Route 161, we found a series of thin, vertically dipping, finer grained mafic dikelets. This same north-south trend, near the boundary of the Piney River and Arrington quadrangles, can be easily followed as a distinctive high on both the aeromagnetic map of the area as well as the gravity map. The rock of Crawford Creek is medium grained (2 to 3 mm), ophitic-textured, gabbroic rock with plagioclase, both stubby and lath-like crystals of an_{65} composition, ortho- and clinopyroxene, relict olivine grains and, as scattered flakes, a fine-grained deep-reddish-brown biotite. North of the Crawford Creek area, the rock does not outcrop, but gravity modeling of the dike (Eppihimer, 1978, p. 78) suggests that it is up to 500 m wide and extends to a depth of at least 4.5 km. Its geophysical signature terminates in the Pedlar Formation, just south of the crest of the Blue Ridge and the Catoctin metabasalt. Because of the trend of the dike and its primary igneous mineralogy and undeformed state, we associate it with the period of late (?) Mesozoic mafic dike emplacement.

SURFICIAL DEPOSITS

Mappable surficial deposits are of limited extent in the map area and have not been divided. They occur, however, as three main types:

DEPOSITS OF PRESENT VALLEY SYSTEMS

These are mostly sandy deposits, many of them on active flood plains. Minard and others (1976) found them to be mostly less than 4 m thick, consistent with the occurrence of bedrock outcrops in the adjacent streambeds.

INACTIVE BOULDER FANS

Along the northwest side of the map area three boulder fans derived from charnockites of the Pedlar massif were mapped. The body adjacent to Indian Creek appears to be over 60 m thick.

Many fans along the east side of East Branch Hat Creek resulted from Hurricane Camille in 1969 (Williams and Guy, 1973). These were generally unmappable. In general they are built on pediments of the granulite unit but in a few places are built on older boulder fans, one of which is mapped.

RIDGETOP GRAVEL DEPOSITS

Several ridges in the map area are capped by gravels; only a few gravels are mappable. Their distribution suggests that they originated as deposits of an ancestral Tye River.

RADIOMETRIC AGE DETERMINATIONS

PREVIOUS DETERMINATIONS IN THE REGION

The oldest dates thus far obtained in the southern Appalachians fall in the range 1,600 to 1,800 Ma. U-Pb on detrital zircon from Maryland gave a minimum age of 1,200 Ma and a probable primary age of 1,600 to 1,700 Ma (Grauert, 1972, p. 305). In the area of this study Davis (1974) obtained 1,422 to 1,870 Ma by U-Pb in zircon separated from a coarse fraction (>150 microns) of the "Lovingston augen gneiss." From the fine fraction (<75 microns) of the same rock, 913 Ma was obtained. The later date is concordant while the earlier is highly discordant. The augen gneiss contains porphyroblasts of potassium-feldspar and, less commonly, of blue quartz, up to 5 cm in diameter, surrounded by biotite-rich folia.

Davis obtained U-Pb zircon dates of 1,080 Ma from the "Lovingston quartz monzonite" as well as from the "Lovingston pegmatite." Both dates are considered minimum ages. The quartz monzonite has a mineralogy similar to the augen gneiss but lacks the metamorphic fabric. The pegmatite is a coarse-grained rock, with andesine antiperthite, an_{35}, perthite, and blue quartz, and could be correlative with our Shaeffer Hollow Granite.

Rocks of the Pedlar massif have yielded U-Pb zircon ages of 1,070 to 1,150 Ma (Tilton and others, 1960). At least some of these dates were apparently obtained from granitoid rocks which are related to the Old Rag Granite, dated by zircon U-Pb at 1,140 Ma (Lukert, 1977) and the Crozet Granite, both to the north of this district, and probably older than ferrodioritic Pedlar rocks, which have been dated by whole-rock Rb-Sr at 1,042±59 Ma (Herz and others, 1981).

Age determinations in and near the study area recently published by Pettingill and Sinha (1984) are Roseland Anorthosite, 1,045±44 Ma (Sm-Nd); ferrodioritic plutons of the Lovingston massif, 1,009±26 Ma (Rb-Sr) and 1,027±101 Ma (Sm-Nd); and Pedlar charnockites, 1,075 Ma (U-Pb on zircon).

The youngest dates obtained in the district are on the Mobley Mountain Granite – 652±22 Ma by Rb-Sr whole rock (Herz and others, 1981). The Irish Creek tin greisen, in nearby Rockbridge County, has yielded 634–637±11 Ma by concordant $^{40}Ar/^{39}Ar$ spectra (Hudson and Dallmeyer, 1981) and is probably part of the same igneous event.

The widespread Paleozoic regional metamorphism has not been dated in this area, but elsewhere dates of about 430 Ma (Early Silurian) to about 270 Ma (Early Permian) have been obtained (Bryant and Reed, 1970). Although staurolite has been reported elsewhere in the Lovingston Formation (Bloomer and Werner, 1955), Paleozoic metamorphism only produced low-grade assemblages of the greenschist facies in this area. The regional metamorphism was apparently developed before the final thrusting of the Blue Ridge took place, in the latest Paleozoic (Griffin, 1971).

NEW AGE DATA

U-Pb zircon ages have thus far been determined on five samples from the Roseland District (table 12) by T.W. Stern, U.S. Geological Survey.

Sample 133C gave a slightly discordant age of 980 Ma by $^{207}Pb/^{206}Pb$ (table 12). It is from a layered granulite outcrop in the Tye River above Lanes Ford (loc. 1) and is a banded rock made up of apparently anatectic leucocratic segregations in the granulite. The more mafic (paleosome) part of the granulite has a composition of garnet-graphite-pyrrhotite-ilmenite-blue quartz-perthitic feldspars-pyroxene. The leucocratic (neosome) part consists of platy blue quartz and mesoperthite and contains all the zircons observed in the rock (fig. 5). The specimen was collected about 600 m from the anorthosite contact. The zircons are small and equant and appear to represent a single population.

Sample 86A1, which gave a concordant age of 970 Ma by $^{207}Pb/^{206}Pb$ (table 12), is a ferrodiorite from the Roses Mill type locality (loc. 18) in the Arrington quadrangle. (See tables 6 and 8 for chemical and modal analyses.) It is a massive, medium- to coarse-grained rock consisting of quartz, perthitic potassium feldspar, antiperthitic andesine, orthopyroxene and clinopyroxene, uralitic hornblende, garnet, ilmenite with sphene rims, apatite, and zircon. This rock grades into biotitic augen gneiss. The zircons are a coarse euhedral unzoned single population; no xenoliths were seen near the collected specimen.

Sample 460A gave a slightly discordant age of 1,040 Ma by $^{207}Pb/^{206}Pb$ (table 12). It is a massive Pedlar charnockite-ferrodiorite from near Jacks Hill, Massies Mill quadrangle (loc. 27; table 9), and is coarse grained with orthopyroxene poikilitically enclosing other phases which include blue quartz, clinopyroxene, perthitic

TABLE 12.–*Zircon analytical data and ages for various rock types in the study area*

[Analyst: T. W. Stern, U.S. Geological Survey, Reston, Va. Decay constants and isotopic abundances from Steiger and Jaeger (1978). ppm=parts per million]

Composition and age	Sample number and rock unit				
	133C	86A1	460A	83A	157A
	Granulite neosome	Roses Mill	Pedlar	Shaeffer Hollow Granite	
Pb, ppm	68.3	16.2	42.6	92.5	108.9
U, ppm	437.9	93.3	252.5	268.0	623.1
Th, ppm	174.0	38.1	120.0	74.0	343.1
$^{208}Pb/^{206}Pb$	.14211	.14192	.10385	.57623	.19459
$^{207}Pb/^{206}Pb$	.07481	.07801	.07538	.27120	.08668
$^{204}Pb/^{206}Pb$	.00021	.00046	.00010	.01192	.00101
$^{206}Pb/^{238}U$	.1487	.16366	.16617	.16767	.15553
Age, m.y.	892	977	991	999	932
$^{207}Pb/^{235}U$	1.469967	1.611882	1.694359	2.525860	1.54945
Age, m.y.	918	975	1,006	1,279	950
$^{208}Pb/^{232}Th$	.048633	.048589	.033883	.087479	.04332
Age, m.y.	960	959	675	1,695	857
$^{207}Pb/^{206}Pb$	.071810	.07135	.073955	.109268	.07226
Age, m.y.	980	970	1,040	1,787	993

potassium feldspar, and antiperthitic sodic andesine; accessories include ilmenite, apatite, and zircon. The zircons are a coarse euhedral unzoned single population.

Sample 83A gives discordant ages but is 1,787 Ma by $^{207}Pb/^{206}Pb$ (table 12) on Shaeffer Hollow Granite from a rock slide on the west slope of Bryant Mountain in the Horseshoe Mountain quadrangle (loc. 9). The specimen is medium to coarse grained, with elongated and aligned feldspar phenocrysts, and consists of blue quartz, perthitic feldspar, uralitized mafic minerals, ilmenite with sphene rims, and apatite. One zoned zircon was seen in thin section. Further work designed to unravel the relative ages of several lithologies present in the Shaeffer Hollow Granite at this outcrop is being conducted by T. W. Stern and will be reported separately.

Sample 157A, also of Shaeffer Hollow Granite, gives a slightly discordant age of 993 Ma by $^{207}Pb/^{206}Pb$ (table 12). The specimen was collected on a south-facing bluff of the Buffalo River just west of the bridge at Henleys Store in Piney River quadrangle. It contains blue quartz, granulated large perthitic feldspar, clots of biotite and uralite, and ilmenite with sphene rims.

Table 2 incorporates these new age data with published data in a proposed sequence of events in the Roseland district. The age of the metasediments in the banded granulite unit is pre-1,050 Ma but otherwise unknown. Ages of 1,050 to 970 Ma show that the most areally extensive igneous units are Grenville in age. Ages within this short time interval are consistent with relative ages from crosscutting relations and even suggest that conditions suitable for the formation of blue quartz ended between 980 Ma (Shaeffer Hollow Granite and granulite leucosome) and 970 Ma (Roses Mill). Intrusion of the Mobley Mountain Granite at 635 to 650 Ma was distinctly later than that of the Grenville rocks.

PETROGENESIS OF THE IGNEOUS ROCKS

Herz (1984) presents detailed information on most aspects of igneous petrogenesis for the district. Summaries are presented here, with references to some graphs and tables in that publication. Many of the raw data appear in tables 3–12 of this paper.

ORIGIN OF ANORTHOSITE AND FERRODIORITES

The anorthosite probably formed from a melt in the lowermost crust or upper mantle judging from its low $^{87}Sr/^{86}Sr$ ratios (0.7047–0.7056) and high K/Rb ratio (2,400). Its low Rb/Sr ratio (0.008) suggests that anorthosite is not a partial melt of granulite (Herz, 1984; table 13). Gravity data of Eppihimer (1978) show no positive anomaly associated with the anorthosite, indicating that no large mafic mass is present under it. The anorthosite has become detached from any parental mafic magma source or refractory mafic residuum. It was largely solid at emplacement, judging from extensive autoclasis and a lack of xenoliths. However, abundant anorthosite dikes and coarse-grained rutile-bearing quartz mangerites along its walls indicate some residual liquid and considerable heat (750 °C from rutile-plagioclase pair by oxygen isotopes; 870 °C by Wood-Banno two-pyroxene method; Herz, 1984). These relations allow diapiric movement and emplacement of the anorthosite. Field relations suggest that anorthosite rose into a terrane undergoing metamorphism of the granulite facies and into which granite and ferrodiorites would later be introduced.

The association in space of anorthosite and ferrodiorite both at Roseland and in other Grenville terranes, and their slight separation in time (about 60 m.y.) suggests some cogenetic relation. Yet ferrodiorites consistently crosscut deformed anorthosite in the field at Roseland, and some geochemical arguments suggest that they are not comagmatic. Figure 30 shows that the fields occupied by Roseland Anorthosite and by Roses Mill and Pedlar ferrodiorities are distinct on an AFM diagram. The ferrodiorites are strongly iron-enriched, with no significant trend toward anorthosite. Herz (1984) believes that Rb/Sr (0.14) and K/Rb (441) ratios of Roses Mill ferrodiorites preclude derivation from anorthosite in the lower crust (table 13). Relations among the Roses Mill, Turkey Mountain, and Pedlar ferrodioritic charnockites are also unclear; the Pedlar is separated from the others by a deformation zone. The chemical compositions of the units are similar both for major and minor elements (table 13). Higher Rb-Sr ratios and higher lanthanum in the Pedlar suggest that if any difference exists, the Pedlar is more evolved. This suggestion is consistent with the compositions of coexisting ortho- and clinopyroxenes (fig. 31); a comparison between Pedlar and Roses Mill-Turkey Mountain pyroxenes shows parallel tie lines but a tendency for the Pedlar pyroxenes to be higher in iron. In rock series evolved from the same magma stem, iron enrichment in pyroxenes generally indicates minerals that formed later or at lower temperatures. (However, our zircon ages for the units conflict with this suggestion.) Paleotemperatures listed by Herz (1984, table 7) for the Wood-Banno method are Roses Mill (four specimens), 815–870 °C; Turkey Mountain (one specimen), 870 °C; and Pedlar (one specimen), 755 °C.

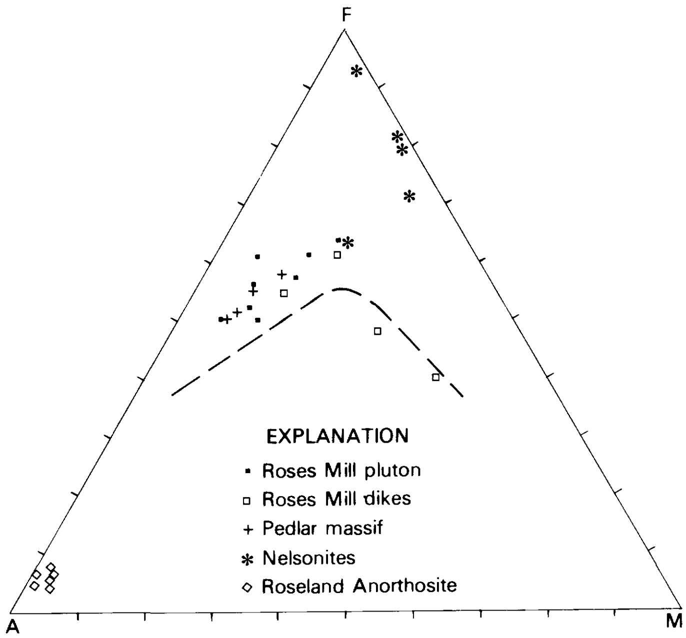


FIGURE 30.—AFM [(Na+K), (Fe+Mn), Mg] diagram showing the relation of Grenvillian igneous rocks of the Roseland district (from Herz, 1984). Dashed line represents boundary between tholeiitic field above and calc-alkaline field below.

TABLE 13.—*Average compositions of Roseland Anorthosite, Roses Mill pluton, Pedlar charnokitic and ferrodioritic rocks, and Mobley Mountain Granite*

[___, not determined]

	Anorthosite (average of four specimens)	Roses Mill (average of eight specimens)	Pedlar (average of four specimens)	Mobley Mountain Granite (average of two specimens)
Major elements, in weight percent				
SiO_2	60.4	55.8	60.7	69.2
TiO_2	.15	2.6	2.0	.37
Al_2O_3	23.6	15.0	14.1	14.7
Fe oxides	.5	11.0	8.7	4.9
MgO	.13	2.1	1.4	.26
CaO	5.0	5.7	4.7	1.3
Na_2O	5.6	3.0	2.6	3.0
K_2O	2.8	2.5	3.3	5.4
MnO	.02	.14	.14	.08
P_2O_5	.08	1.2	.89	.11
Trace elements, in parts per million				
Sr	1,140	535	364	360
Rb	15.5	73	186	102
Zr	___	617	599	___
La	___	88	568	93
Calculated mineral compositions				
K/Rb	2,400	441	234	437
Rb/Sr	.008	.14	.59	.28
$+\delta\,^{18}O$	7.7	7.6	9.3	___
$^{87}Sr/^{86}Sr$	[1].7052	___	[1].7061	.7045

[1] Heath and Fairbairn, 1969.

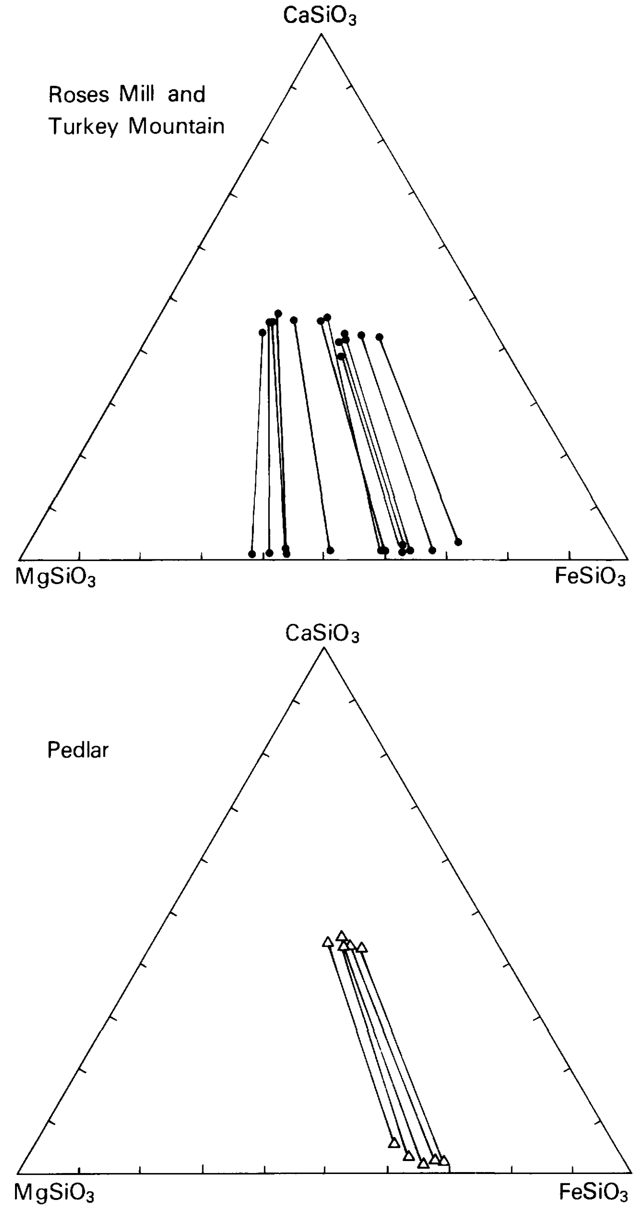


FIGURE 31.—$CaSiO_3$-$MgSiO_3$-$FeSiO_3$ diagrams showing compositions of coexisting orthopyroxenes and clinopyroxenes from Roses Mill, Turkey Mountain, and Pedlar ferrodioritic rocks (from Ames, 1981).

LIQUID IMMISCIBILITY IN THE ROSES MILL AND TURKEY MOUNTAIN PLUTONS AND THE ORIGIN OF NELSONITE

Following Philpotts' (1967) demonstration that melts of dioritic composition separate readily to form two liquids, one with the composition of nelsonite, Force and

Herz (1982), Kolker (1982), and Herz (1984) have proposed that liquid immiscibility was indeed of importance in the formation of nelsonite from a ferrodioritic Roses Mill-Turkey Mountain parent liquid. A low-viscosity liquid rich in titanium and phosphorus apparently segregated, and droplets sank to the base of the magma sheet, locally to coalesce and be injected into underlying units. Field evidence includes primary elliptical felsic domains in layered impure nelsonite at the bases of ferrodiorite sheets (locs. 22, 23; fig. 24). This texture is thought to be a relict immiscible texture of a granitic liquid and one rich in titanium and phosphorus. Euhedral to subhedral pyroxene is present primarily in mafic domains and is thought to represent truly cumulate crystals around which the nelsonitic liquid formed a net-vein system, as ilmenite selvages separate most pyroxene crystals (fig. 24).[4] Presumably zircon crystals are cumulate in these rocks also (loc. 26; fig. 25).

The AFM diagram (fig. 30) shows that impure nelsonites are closely related to Roses Mill compositions, but that purer nelsonites (near the FM join) are separated from them and are across the compositional field of presumed early Roses Mill dikes from normal Roses Mill compositions. Herz (1984) has presented a Grieg diagram, a K_2O-TiO_2-P_2O_5 plot, and Harker diagrams in support of immiscible liquids relating Roses Mill and nelsonite compositions.

MOBLEY MOUNTAIN GRANITE

Brock and others (in press) and Brock (1981) present some information which constrains the emplacement pressure, temperature, and oxygen fugacity of the Mobley Mountain Granite. The temperature is thought to be 656 °C based on oxygen isotope work on quartz-biotite, and the corresponding pressure on the granite solidus is 6 kbar. Primary epidote and high-iron biotite put oxygen fugacity between those of the Ni-NiO and hematite-magnetite buffers. Partial melting of a lherzolitic source in the upper mantle was found to be the only source which explained the bulk composition of Mobley Mountain Granite (table 10) as well as the trace and isotopic ratios (table 13). This finding is consistent with the depth of emplacement (6 kbar corresponds to about 18 km) added to the present root about 7 km deep detected by gravity measurements (Eppihimer, 1978).

[4] This texture has now been detected in ilmenite-rich rocks of the San Gabriel Mountains, California (Force and Carter, 1986).

METAMORPHISM

Herz (1984) has discussed the petrology of metamorphic assemblages of the Roseland district in some detail. Here the petrology will be summarized and related to field occurrences.

GRENVILLE-AGE METAMORPHISM

Grenville metamorphism here is largely of pyroxene granulite facies and affected the banded granulite and anorthosite map units. Probably, granulite facies conditions prevailed through the intrusion of Shaeffer Hollow Granite and Roses Mill and Turkey Mountain plutons also.

GRANULITE FACIES

The banded granulite gneiss and quartz mangeritic lithologies of the banded granulite map unit show metamorphism of pyroxene granulite facies. The leucocharnockite lithology of that unit is discussed in the following section. The same metamorphic minerals with gradually coarsening grain size, in fabrics which cut their mutual contacts, are present moving from granulite into anorthosite; we therefore believe the anorthosite was emplaced under the same metamorphic conditions.

Figure 32 shows the mineral assemblages present on an ACF diagram. Feldspars include perthite, mesoperthite, and antiperthite; quartz is typically deep blue, little strained, disc-shaped, and contains oriented rutile

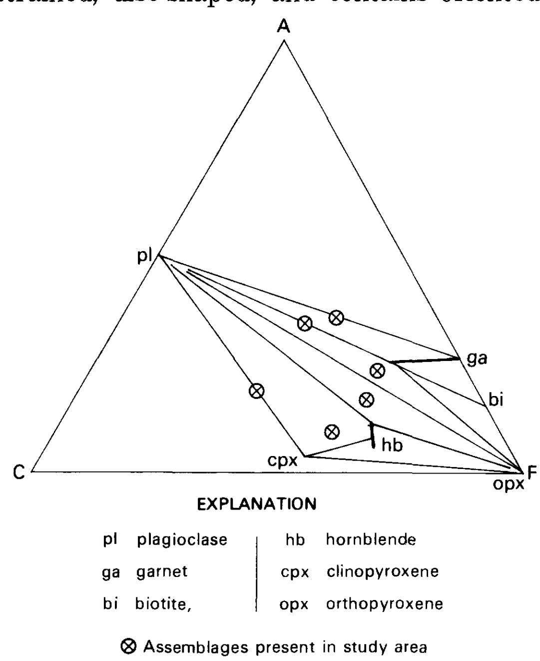


FIGURE 32.—ACF [Al_2O_3, CaO, (Fe, Mg) O] diagram for Grenville-age granulite facies assemblages of the Roseland district (from Herz, 1984). Rocks have excess SiO_2 and K_2O; quartz and potassium-feldspar are additional possible phases.

needles; hornblende and biotite where present are reddish due to high titanium content.

Temperatures indicated by the Wood-Banno method of pyroxene compositions are 930–945 °C; one indicated by the Stormer and Whitney method of feldspar compositions is over 1,000 °C (Herz, 1984; table 7, nos. 105 and 195). However, most orthopyroxene-plagioclase assemblages indicate lower temperatures of metamorphism, probably under 850 °C.

POSSIBLE PARTIAL MELTING

The leucocharnockites of the banded granulite map unit are believed to be a partial melt of the granulite, formed during granulite-facies metamorphism, based on the locally crosscutting nature of these leucocharnockites and their younger age (980 Ma for leucocharnockite vs. >1,050 Ma for granulite). In addition, their platy intergrowths of blue quartz and perthitic feldspar, locally with minor pyroxene and rutile, record the same metamorphic conditions as their host granulites.

Some additional evidence in the texture of the leucocharnockite is useful in deducing the conditions of its formation. The quartz plates, though most commonly parallel to the margins of leucocharnockite bodies, have been observed at a variety of angles to these margins and are locally parallel to the axial planes of folds. The plates in thin section are unstrained, with extinction only slightly undulatory. Many plates are single crystals. Rutile needles in the quartz form an undeformed hexagonal array and locally can be observed crossing polycrystallinity boundaries without deflection or offset. The implied sequence of events is (1) shaping of the quartz by deformation, (2) complete annealing of strain, and (3) exsolution of titania to form rutile needles. As the locally mesoperthitic feldspars imply a temperature of formation of over 600 °C, the precursor titaniferous quartz phase was probably beta quartz.

The blue color of the quartz was investigated for us by Gordon L. Nord with a transmission electron microscope. He found that the color is most likely due not to rutile needles (which are too coarse) but to 0.25-micron (μm) hexagonal plates of an iron-titanium oxide, probably ilmenite, disseminated through the quartz. These particles are of an appropriate size to scatter light and thus cause the blue color; this suggestion is consistent with the fact that the quartz is blue only in reflection but is brown in transmission. The particles are most dense in the most highly colored quartz. Nord also found that the blue quartz contains Dauphine twins, suggesting passage through the alpha-beta transition, implying that original temperatures must have been higher than 573 °C. Formation of both rutile needles and ilmenite plates are probably exsolution phenomena, and we speculate with Nord that this type of blue quartz may be a useful geothermometer.

It thus appears at Roseland that quartz inversion occurred at about 975 Ma, after all granulite-related deformation and anorthosite intrusion but before most ferrodiorite intrusion.

AMPHIBOLITE-FACIES METAMORPHISM

The Roses Mill and Turkey Mountain augen gneisses show especially pervasive amphibolite-facies metamorphism of uncertain age. Large amounts of water were introduced to previously dry rocks during this metamorphism. The characteristic metamorphic minerals are biotite, green amphibole, garnet, and sphene.

Dike sets of the Mobley Mountain Granite cut fabrics formed by the amphibolite-facies minerals of the Roses Mill and Turkey Mountain units (loc. 28; fig. 27), though the dikes themselves seem locally to be somewhat recrystallized and contain a similar mineral assemblage. The Mobley Mountain is everywhere in contact only with the altered, augen gneiss facies. Therefore it seems likely that amphibolite-facies conditions prevailed just before and during intrusion of the Mobley Mountain Granite (650 Ma, at about 6 kbar).

PALEOZOIC GREENSCHIST-FACIES METAMORPHISM

A widespread greenschist-facies deformational-metamorphic event was overprinted on this part of the Appalachians. Throughout the district, cataclasis took place in narrow zones accompanied by greenschist mineralization. The Rockfish Valley deformation zone, which may have formed initially at the end of Grenvillian deformation, was reactivated, as indicated by a universal northeast-trending blastomylonitic fluxion structure formed by orientation of the greenschist-facies minerals chlorite, albite, calcite, and epidote.

The same greenschist assemblage selectively overprinted the older, higher grade assemblages. Retrograde assemblages in the anorthosites, granulites, and charnockitic rocks are present as veins or patches in virtually every outcrop in many zones. Examples are epidote-quartz-sericite veins; patches of uralitization of pyroxene; chloritization of amphiboles, biotite, and pyroxenes; mylonitic septa consisting largely of chlorite, epidote, calcite, and quartz; sphene partially replacing titanium oxides in many rocks; the disappearance of perthitic and antiperthitic feldspars; and the change of oligoclase-andesine to albite + sericite + calcite + clinozoisite. In the Roses Mill augen gneisses and the granitic rocks that already possessed hydrous mineral phases, especially biotite, greenschist metamorphic mineral assemblages are more pervasive. The persistence of higher grade assemblages in all undeformed rocks however, shows that the retrograde mineral reactions did not go to completion in any large area, except within the Rockfish Valley deformation zone. Mineral assemblages suggest that temperatures were 400 °C to 500 °C and that total pressures were 4 to 6 kbar (Turner, 1968, p. 286).

STRUCTURE

The structural evolution can be divided into four periods:

(1) Pre-Grenvillian structures limited to the layered granulite gneisses.

(2) Grenvillian structures that penetrate the granulites and anorthosite and cut their mutual contacts. Correlative mineral assemblages of (1) and (2) are those of the granulite facies.

(3) Post-Grenvillian Proterozoic structures, correlative with lower amphibolite-facies mineral assemblages.

(4) Paleozoic structures, typically local and correlative with greenschist-facies mineral assemblages.

All the pre-Mobley Mountain Granite units contain a foliation dipping steeply southeast which belongs mostly to the third period, with local overprinting during the fourth. The two most important structural features of the area, the dome and mylonitic rocks, probably were also initiated in the third and reactivated in the fourth period.

PRE-GRENVILLIAN AND GRENVILLIAN STRUCTURES

Many banded granulite outcrops show fold sets that are not mappable. These are mostly tight or isoclinal folds of compositional layering with gneissic foliation in the axial plane (figs. 7, 8); as many as three fold sets can be seen in some granulite outcrops (loc. 2). Fabrics are formed by granulite-facies mineral assemblages. Blue quartz veins and platy-textured leucocharnockite segregations are parallel to axial planes and cut compositional layering in older folds (but are also folded themselves in younger ones; examples of both at loc. 6). The foliation marked by platy textures locally cuts granulite-anorthosite contacts (fig. 11) and so must be postanorthosite; it is believed to be of Grenville age. However, this foliation is mostly concordant to the anorthosite and ferrodiorite intrusive sheets and is folded by the later regional dome.

SOUTHEAST-DIPPING FOLIATION

All the older units contain a foliation striking northeast, dipping steeply southeast. Commonly a down-dip lineation formed by crinkled biotite and granulated feldspar is present. The less deformed portions of the anorthosite lack this foliation, as do the massive ferrodioritic facies of the Roses Mill and Turkey Mountain units, but the foliation strongly affects other portions of both units. Indeed the augen gneiss facies of Roses Mill and Turkey Mountain units is defined by the strength of this foliation. As foliation strength increases, original mineralogy and igneous texture of these rocks fade. Xenoliths, however, are still recognizable. At locality 18, the foliation is refracted around a block of unaltered ferrodiorite (fig. 15).

Where the banded granulite unit is in contact with the Roses Mill unit, older Grenville-age foliations in the granulite are cut by the Roses Mill, but the regularly southeast-dipping foliation is shared by both.

The mineral assemblage that is related to this foliation in the Roses Mill unit is biotite-garnet-albite-sphene (lower amphibolite facies), and the foliation is cut by Mobley Mountain Granite; hence, we assign it to the Late Proterozoic. Greenschist-facies assemblages presumably of Paleozoic age are commonly overprinted with the same orientation, forming mylonitic zones. These zones contain chlorite, epidote, and carbonate.

REGIONAL COMPLEX DOME

The structure most apparent from the map pattern of units (pl. 1) is an elongate dome oriented northeast-southwest, measuring at least 22 km by 5 km. At Mars Knob it is a doubly plunging medial syncline. The lowest structural unit of the dome is the anorthosite, which intrudes the structurally intermediate but oldest unit, the layered granulites; both are intruded by rocks of the highest structural unit, consisting of the Shaeffer Hollow Granite and the Roses Mill and Turkey Mountain ferrodiorites. The lower anorthosite-granulite contact is irregular in detail, having abundant anorthosite dikes and sills, but the anorthosite dips away along the flanks of the dome (cross section of pl. 1; TJB and TJF drill holes, app. 1; locs. 15, 36). Compositional layering and foliation in the granulite are also folded into a complex dome so that where the long axis of the dome is in granulite, its position can be mapped (for example, loc. 35).

The structurally highest unit contains the young ferrodiorite plutons. In places, the plutons are in direct contact with the anorthosite or granulite, but in most places, this lower contact is sheared, and mylonites containing chlorite, epidote, and carbonate separate the units (locs. 33, 34; fig. 33). However, the presence of some unsheared contacts (loc. 34), dikes of the Roses Mill pluton in older rocks, and xenoliths of granulite in the Roses Mill all suggest that no regional thrusting took place on this contact. Along the southern flank of Horseshoe Mountain (north of the map area), where augen gneisses of the Roses Mill unit close around the dome, a compositional banding or old foliation wraps around parallel to the form of the fold, whereas a younger shear foliation strikes northeast and dips steeply southeast, that is, approximately parallel to the axial plane of the fold. These rocks are too weathered to indicate the mineral assemblage in the shear foliation with certainty. It seems likely, however, that the pervasive foliation dipping steeply southeast throughout the area (discussed above) is parallel to the axial plane of the long axis of the dome and contemporaneous with doming.

MYLONITIC ROCKS AND RELATED DEFORMATION

A belt of mylonitic rocks, 2 to 4 km in width and part of an extensive zone that can be traced both northeast and southwest of the district, separates charnockitic rocks of the Pedlar massif to the northwest from the anorthosite-granulite-Roses Mill terrane to the southeast. Plate 1 shows the zone as an overprint on presumed protoliths, which are Shaeffer Hollow Granite, leucocharnockite, and quartzo-feldspathic granulite through most of the zone. Along its northwest margin the zone is derived from ferrodioritic rocks of the Pedlar massif. Shear foliation dips steeply southeast throughout. To a large extent, the mylonitic zone was mapped as Marshall Formation by Bloomer and Werner (1955), a correlation which we reject. Bartholomew (1977) mapped an extension of the same zone having a width of about 10 km in the Sherando and Greenfield quadrangles immediately northeast of the study area, and Bartholomew and others (1981) called it the Rockfish Valley deformation zone. In that section of the zone, however, the dip of mylonitic foliation is gentle.

Where the rocks of the zone are derived from coarse felsic rocks as at localities 37 and 38, a well-developed fluxion structure and abundant felsic augen are present (fig. 34). Conjugate shear fabrics are visible (fig. 35), and pseudotachylite is also present at locality 37. Secondary minerals in sheared rocks include biotite, muscovite, chlorite, albite, quartz, epidote, and sphene. Intensity of deformation is highly variable where the zone is in felsic rocks, and much relatively undeformed rock occurs in all sizes from hillsides to hand samples. Some of these are identifiable as leucocharnockites and Shaeffer Hollow Granite.

FIGURE 33. – Dark mylonite (m) separating leucocharnockite (l) under child from Roses Mill unit (r) under vegetation. Mylonite is chlorite-epidote-calcite-bearing and cuts foliation of leucocharnockite. Hat Creek, locality 33.

FIGURE 34.–Cataclastic facies of leucocratic charnockite, probably Shaeffer Hollow Granite, near locality 38. Some domains suggest the texture of the precursor.

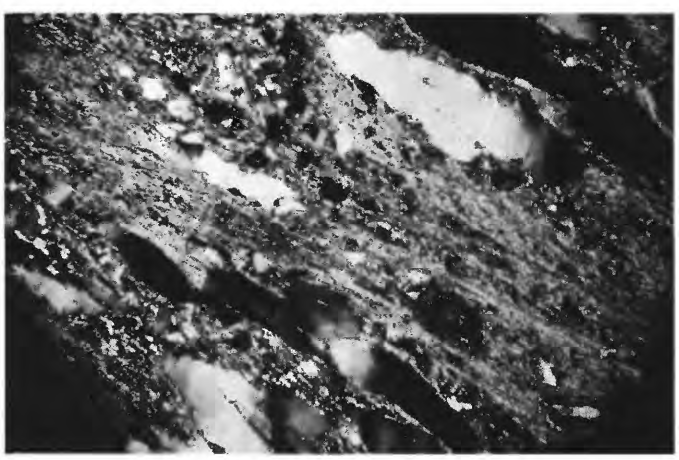


FIGURE 36.–Photomicrograph of protomylonite developed from more mafic but quartz-bearing rock at locality 39. Field of view is 2 mm, crossed polarizers.

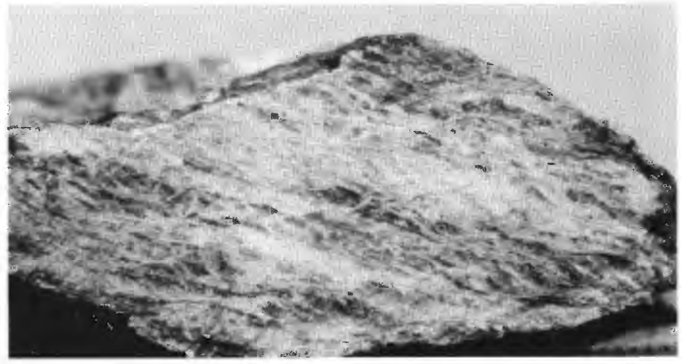


FIGURE 35.–Multiple or conjugate shear fabrics in the cataclastic facies of leucocharnockite from locality 39. Field of view is 7 cm.

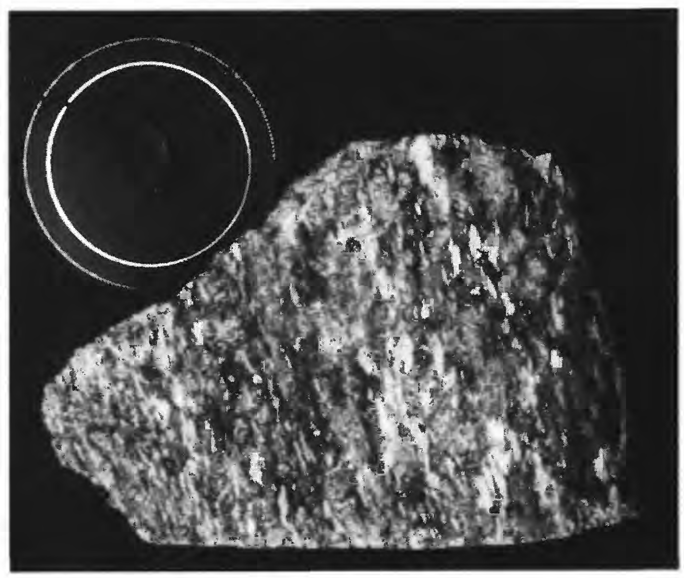


FIGURE 37.–Intermediate stage in the development of protomylonite from massive Pedlar charnockite at locality 40. Note cross-fracturing and resultant realignment of feldspars. Pyroxenes have gone to uralite which forms a lineated paste. Field of view is 70 mm.

Also along the eastern portion of the zone are some areas where the protoliths of sheared rock were mixtures of felsic and mafic rocks (loc. 39). The mafic components apparently include quartz mangerite and Roses Mill ferrodiorites (fig. 36).

Along the western margin of the zone the protolith was clearly ferrodioritic rocks of the Pedlar massif. Intensity of shearing increases smoothly from massive coarse-grained igneous-textured rock containing pyroxene toward the west, through retrograded and lineated rock with realigned and cross-fractured perthitic porphyroclasts (fig. 37) to dark protomylonites (loc. 40) with a matrix of biotite, ilmenite, sphene, chlorite, muscovite, quartz, and epidote.

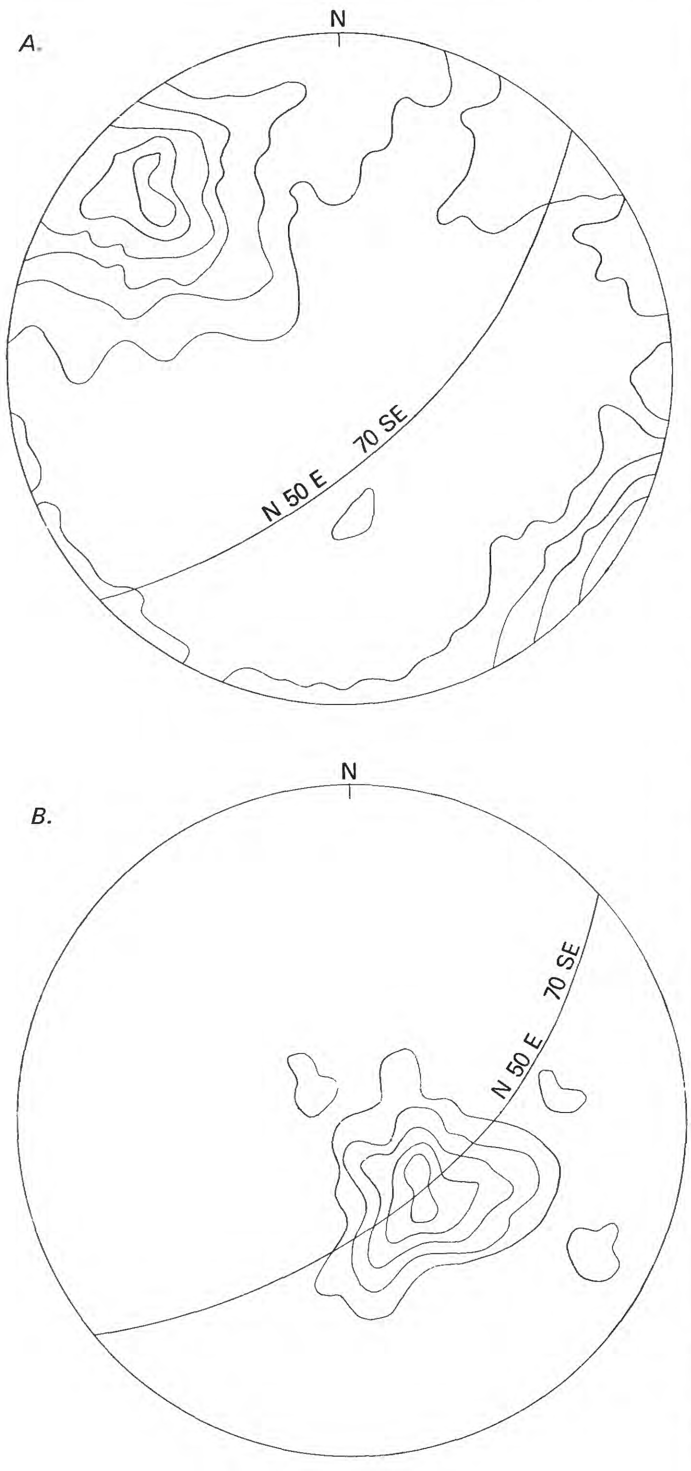


FIGURE 38. – Contoured plot on equal-area lower hemisphere stereonet of: *A*, Poles to mylonitic foliations (202 points). *B*, Mineral lineations (62 points) from mylonitic zones in Horseshoe Mountain quadrangle (after Bailey, 1983).

Bailey (1983) plotted the orientation of mylonitic foliation and lineation (fig. 38) in a small study area which overlaps the northern end of the mylonitic zone of our study area. He concluded that the orientation of foliation clusters around strike N. 50° E., dip 70° SE, and the lineation around trend S. 42° E., plunge 65° SE. The orientation of lineation in mylonitized older leucocratic gneisses may in part be the intersection of shear foliation and the steeply dipping northwest-striking layering present in this area.

The age of formation of the various features of the zone is not clear. A Late Proterozoic deformation probably formed much of the steeply dipping shear foliation, as the metamorphic grade of secondary minerals is locally too high for Paleozoic deformation. A slightly foliated and recrystallized greenstone dike probably of Catoctin age cuts this foliation at a low angle at Lowesville (loc. 37). Within most zones, however, the mineral assemblage is chlorite, albite, white micas, and epidote, suggesting a Paleozoic age. Bartholomew (1977) has evidence of predominantly Paleozoic movement in his section of the zone. Thus, the zone apparently formed in Late Proterozoic time but was reactivated during the Paleozoic.

The previously discussed southeast-dipping foliation common throughout the area may be viewed in the context of the Rockfish Valley deformation zone as a distributed shear foliation related to the Rockfish Valley zone. Limits to the degree of shear strain on this foliation in the Roses Mill rocks are set by xenoliths which are frayed but still recognizable (fig. 39).

POSSIBLE DIAPIRISM

Many features of the structure of the area are consistent with diapiric emplacement of anorthosite into a deep crustal granulite terrane and subsequent diapiric emplacement of anorthosite-granulite terrane into a shallower terrane containing the Roses Mill and Turkey Mountain units. The major dome would be a feature produced by emplacement. The concordance to the dome of older structures in granulite and anorthosite may be a result of emplacement also, as Martignole and Schrijver (1970) have documented nappe-like features at the edge of diapirically emplaced anorthosite elsewhere. The truncation of Roses Mill-Shaeffer Hollow boundaries against older units would represent faulting that occurred during emplacement, but the intimacy of the units as implied by the xenolith and dike relations shows the units were originally adjacent, as would be the case with diapiric emplacement of a competent rock. The older components of shear foliation along both flanks of the dome could be concurrent with emplacement. The lack of this shear foliation in the medial syncline of Mars Knob supports diapiric emplacement, as differential movement would have been minimal there. Emplacement would presumably have been Late Proterozoic, as

FIGURE 39.—Xenolith of leucocharnockite in Roses Mill unit which has been partially granulated and elongated during the formation of biotite augen gneiss. Ruler is 16 cm long.

the formation of shear foliation is the latest event that could accompany emplacement; younger mylonites, such as those at the base of the Roses Mill, could have followed features related to emplacement but must be postemplacement.

MINERAL RESOURCES

ANORTHOSITE-BORDER RUTILE (+ILMENITE) DEPOSITS

Rutile deposits along the margin of the anorthosite body were mined at Roseland from 1900 to 1949 and gave the district a name as a rutile resource. The need to reevaluate this resource, in the face of recurring need for a domestic rutile supply, led to this study. None of the resources are currently economic, however.

DISTRIBUTION AND CHARACTER

The rutile deposits are present along the contacts of Roseland Anorthosite with its country rocks (not along contacts with postanorthosite units), mostly from Piney River to Roseland.

The deposits consist of coarse-grained (mostly >1 mm) rutile disseminated in concentrations of 1 to (rarely) 10 percent through the impure coarse-grained facies of anorthosite, which is present along major contacts and as sills or dikes, and through adjacent rocks of the banded granulite map unit, especially quartz mangerite. Ilmenite is commonly present also, mostly as coarse separate grains. The rutile-bearing zone on the anorthosite margin gives way toward the granulites to rocks containing ilmenite and toward anorthosite to rocks without oxides.

ORIGIN

The distribution and occurrence of rutile suggest that its origin is related to the chemical gradient present along contacts of anorthosite and older rocks. Titanium originally present in other minerals was stable as rutile along this contact, where iron activity was too low to combine all titanium in ilmenite, and metamorphic environment was too high in grade for sphene in rocks of this composition (Ramberg, 1952; Force 1976). Little migration of titanium occurred; rutile abundance is roughly the same as average TiO_2 content of quartz mangerite. In a few places (fold noses?) such as in parts of the Roseland pit (loc. 15; fig. 40), rutile concentrations are significantly higher.

DESCRIPTIONS OF RESOURCE DATA

The resource that we are attempting to quantify is the disseminated rutile along anorthosite contacts as previously described. No resource figures of this sort have been published except in the Hillhouse (1960) dissertation. Fish (1962) stopped short of such a figure, but contributed data which we used. The absence of an authoritative and inclusive rutile resource figure has led to extraordinary confusion and duplication in compilations such as the one by Peterson (1966).

Our data come from good to excellent exposures along four streambed sections (Piney River near loc. 5; Allen Creek near loc. 41; Jenny Creek near loc. 3; Tye River at loc. 14), the Roseland pit and adjacent exposures in the Tye River (loc. 15), 11 drill cores in five clusters (pl. 1; app. 1), and Fish (1962). Rutile abundance was estimated volumetrically from sawed slabs with visual comparison charts and then converted to weight percent. In some locations, composite values from chip samples were obtained, or rutile was physically separated from saprolite matrix and its abundance established by weighing. Thickness values are mostly apparent and therefore maxima, as the true orientations of rutile-bearing intervals could be determined neither in the field nor in drill cores, except in two places. The following descriptions are arranged from south to north.

In the Piney River bed, a long section between locality 5 (pl. 1) and sample no. 2 (table 3) exposes coarse impure anorthosites containing rutile and ilmenite and some granulite screens. Rutile averages about 3 percent (+3 percent ilmenite) in a 21-m interval but 1 to 2 percent

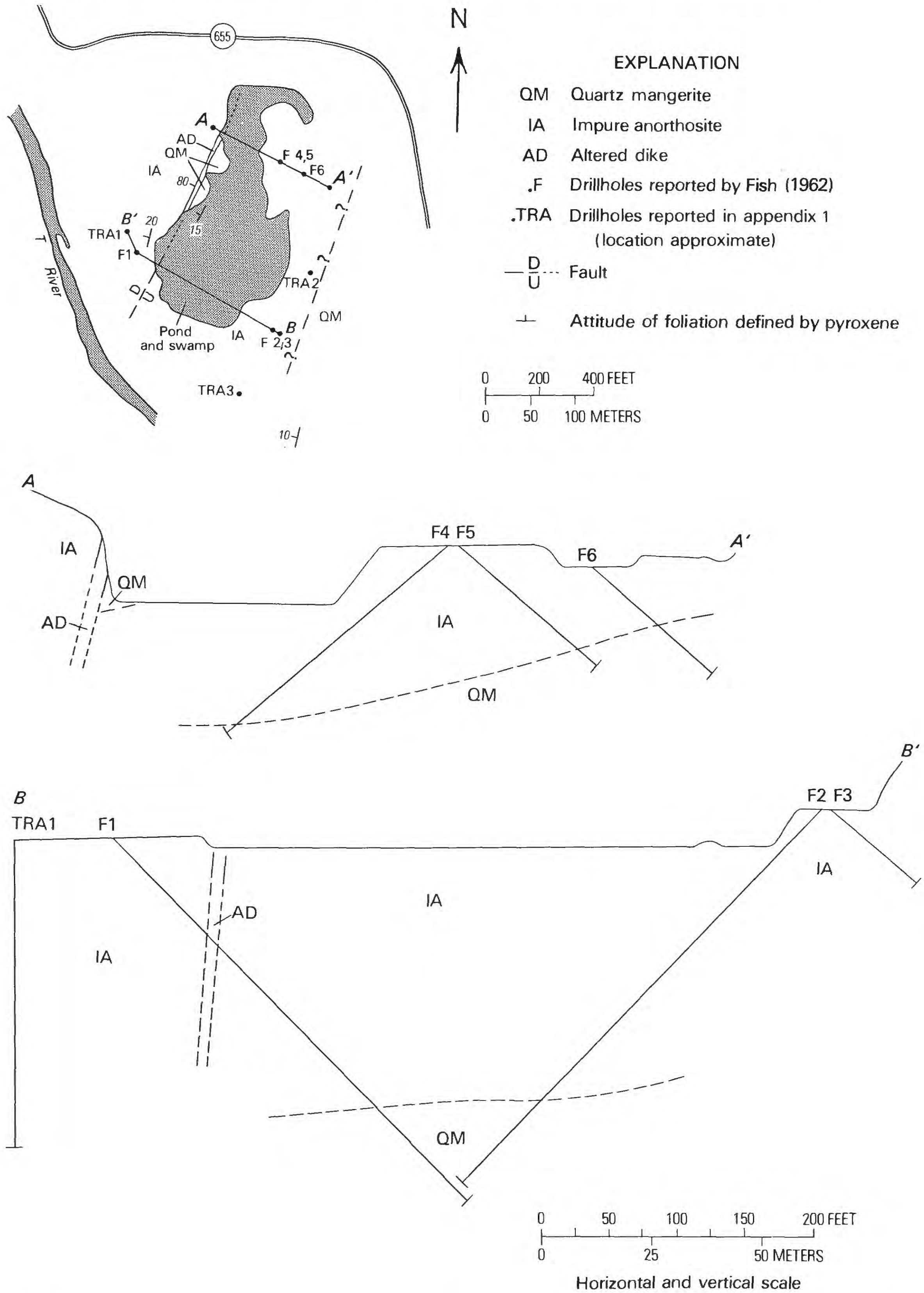


FIGURE 40.—Sketch map and cross sections of the Roseland rutile quarry, locality 15. Drill-hole information is from appendix 1 (this report) and Fish (1962); base is from Fish (1962, figs. 5, 7, 8).

(with 1 percent ilmenite) in additional zones having an aggregate thickness of at least 6 m.

In drill core TPB2 (app. 1) between Piney River and Allen Creek, two intervals contain rutile. The upper interval of 58 m apparent thickness averages about 2.5 percent rutile and 2 percent ilmenite but is repeated by folding. The lower 76-m interval averages 3 percent rutile and 2 percent ilmenite. The rutile is in coarse impure anorthosite, present as sills in garnetiferous quartz mangerite.

In the bed of Allen Creek at locality 41, rutile is present in a large sill of coarse impure anorthosite which is openly folded in such a manner that it is parallel to the streambed for a long distance. Intervals totaling 34 m apparent thickness average 1 percent rutile and 1 percent ilmenite, but a 3-m interval averages about 2 percent rutile and 1 percent ilmenite. Northwest of this unit, one passes into an extensively saprolitized mixture of anorthosite sills and quartz mangerite, locally containing nelsonite bodies. The saprolite contains 0 to 1.5 percent rutile and 1.5 to 7 percent ilmenite. Due to complex cross-folding in the area, the thickness of the unit represented by saprolite may be as little as 50 m.

The drill hole TJB1, between Allen Creek and Jennys Creek, contains a 20-m interval which averages 1.5 percent rutile, with grades locally as high as 5 percent, in anorthosite and coarse impure anorthosite.

In the bed of Jennys Creek near locality 3, an interval of 6 m apparent thickness contains rutile in anorthosite and in oxide-rich lenses with ilmenite in sheared coarse impure anorthosite, both present as dikes in quartz mangerite. Average grades for the interval are 1 percent rutile and 7 percent ilmenite.

In the bed of Tye River at locality 14, a 6-m anorthosite dike in quartz mangerite forms the center of a 12-m interval which averages about 2 percent rutile and 2 percent ilmenite.

Data from Roseland (loc. 15) are from Fish (1962), drill holes TRA1–3, and our examination of streambank and quarry exposures. Figure 40 shows our interpretation of the information. Coarse impure anorthosite is present as a gently dipping sill(?) in quartz mangerite. On the west side of the quarry, a fault which cuts the upper contact is intruded by a sheared diabase dike. The anorthosite sill is about 64 m thick and averages 2.4 percent rutile and 4.9 percent ilmenite (from 29 analyses of this material in Fish, 1962). Rutile continues into both overlying and underlying quartz mangerite for at least 27 additional meters, in concentrations mostly less than 1 percent and averaging about 0.5 percent rutile and 3.6 percent ilmenite. (Average calculated from Fish is consistent with our observations of drill cores TRA1–3 and streambank exposures.)

Other sections to the north and south of those described here contain so little rutile that we believe we can give the length of the rutile-bearing zone as 4 km. If the seven localities described are considered random sections through a rutile-bearing zone, average widths can be calculated, and rutile resources at different rutile grade minima can be specified. In table 14, an average dip of 30° for the rutile-bearing zone was assumed. Calculation of resources to 50 m of depth thus yields a 100-m width down the dip for the zone.

This method is designed not to block out reserves but to arrive at an approximate figure for the rutile resources of the district. The most important source of error would be rutile-bearing zones in our sections that are not exposed. In this sense the values in table 14 are minima.

Rutile resources in the district are only on the order of a million metric tons. Under present conditions, not even the material with over 2 percent rutile could be mined profitably. Extending the lower grade cutoff to 0.5 percent (where rutile would be a byproduct of ilmenite mining) would not increase the rutile resource much. The Roseland rutile pits, already mined out, represent about 10 percent of the rutile resource in the district, at some of the highest grades observed.

ILMENITE DEPOSITS RELATED TO NELSONITE AND FERRODIORITE

Nelsonite (ilmenite-apatite rock) both as a petrologic curiosity and as an ilmenite resource is the subject of an extensive literature. Calculation of comprehensive ilmenite resource figures, however, has been attempted only by Fish and Swanson (1964).

Ilmenite resources of the Roseland district are not currently economic, though ilmenite was mined as recently as 1971. The nelsonites, though high in grade, are mostly too small and discontinuous to be mined profitably by modern methods. Large-volume deposits are present only at much lower grades and are of recent economic interest only as saprolite. The ilmenites of the area are approximately stochiometric and are thus at a

TABLE 14.—*Rutile and ilmenite resources in anorthosite-border deposits*

Rutile grade minimum (percent)	Average grades (percent)		Average thickness in seven sections (m)	Resource in 50-m depth (metric tons mineral concentrate)	
	Rutile	Ilmenite		Rutile	Ilmenite
2	2.5	3.0	33	8.6×10^5	10.3×10^5
1	1.2	1.5	9	1.1×10^5	1.4×10^5
.5	.7	4	15	1.1×10^5	6.2×10^5

distinct disadvantage compared to altered ilmenite with high TiO_2 contents mined elsewhere in placer deposits. Zircon and apatite are also present in ilmenite deposits of the Roseland district.

ORIGIN

All the rocks of the ferrodiorite-nelsonite clan are high in TiO_2, present mostly as ilmenite. The Roses Mill and locally the Turkey Mountain and Pedlar units have high disseminated ilmenite values. Magmatic processes have locally formed ilmenite concentrations (1) possibly by differentiation in parts of the Turkey Mountain, forming disseminated ilmenite deposits, (2) by cumulate-like settling of immiscible titanium-rich liquids, forming impure nelsonite along the bases of ferrodiorite sheets, and (3) by further emplacement of this liquid into underlying units, forming nelsonite "dikes." These processes are discussed in preceding sections, by Force and Herz (1982), and by Herz and Force (1984).

DISSEMINATED ILMENITE

The average ilmenite content of the Roses Mill unit is 2.8 volume percent, and values as high as 8 percent have been observed. Virtually every outcrop of the Roses Mill contains minor segregations of ilmenite with apatite and mafic minerals. In some areas, especially in the augen gneiss facies, the ilmenite is extensively altered to microcrystalline sphene and anatase along rims and fractures (fig. 16). Saprolites over Roses Mill lithologies high in fresh ilmenite may some day be considered resources. Natural washing of such saprolite by Hurricane Camille is responsible for some rich placers noted by Minard and others (1976).

Ferrodioritic rocks of the Pedlar Massif have ilmenite contents like those of the Roses Mill. Alteration to sphene is typically less than in Roses Mill, but upgrading by saprolitization is less also.

The Turkey Mountain pluton is more differentiated than the Roses Mill, and some facies contain high concentrations of ilmenite intergrown with minor amounts of magnetite. There is typically little alteration to sphene except in augen gneiss and in cataclastic facies. Ilmenite-rich facies were observed along Mill Creek upstream of Highway 778 and along Beaver Creek (Minard and others, 1976, fig. 3). The most promising occurrence, however, is that which was mined until 1971 at locality 36. Saprolite developed from an ilmenite-rich Turkey Mountain facies was mined in two pits separated by St. Marys Church. Our sampling indicates that the most recently mined ore contained about 8 percent magnetic ilmenite and 5 percent less-magnetic ilmenite. Both types are pure ilmenite to x-ray diffraction. The more magnetic variety is made so by the presence of about 1 percent magnetite as aligned blebs about 4mm across. The less magnetic ilmenite contains 50.6 percent TiO_2; the more magnetic, 50.4 percent TiO_2; and both contain about 370 ppm vanadium (analyses by rapid rock and emission spectrographic techniques by Floyd Brown, Z. Hamlin, D. W. Golightly, and Janet Fletcher, USGS). Minor zircon and rutile but no apatite were also present in the saprolite ore.

Fish (1962) undertook an evaluation of ilmenite resources in saprolite over an unmined portion of this body of ilmenite-rich Turkey Mountain. The averages of his values for ilmenite contents (calculated from TiO_2 contents and therefore maxima) are 16.7 percent for saprolite and 16.1 percent for fresh "diorite" (Turkey Mountain) beneath it. Saprolite thickness was fairly consistent at 30 m along the crest of the ridge. On the basis of surface exposures and one drill hole (Fish, 1962, p. 25), we estimate that the thickness of fresh Turkey Mountain under saprolite varies from 0 to only about 10 m; this body overlies anorthosite. The bottom of existing open pits must be on or near the anorthosite contact. Fish's maps show that the ore body occupies about 0.63 km^2. The figures imply that the body contains 7.7×10^6 t (metric tons) of ilmenite, of which about 6.3×10^6 t still remain after mining. In view of our more direct figure for ilmenite content, we estimate the remaining ilmenite resources at 5.0×10^6 t.

IMPURE CONCORDANT NELSONITE

Probable cumulate concentrations of ilmenite were observed at the base of the Roses Mill intrusive sheet at two localities (22 and 23) and within the Turkey Mountain at another two (25 and 26). The Roses Mill localities are similar. The concentrations are at least 3 m thick and look like dark augen gneisses in which the augen are aligned parallel to the base of the unit and consist of quartz and feldspar; the matrix consists of two pyroxenes and ilmenite. In a previous section we discuss the role of immiscible liquids in the formation of this rock type. The rock contains 7 to 10 percent ilmenite. At locality 22 this material forms a veneer on a hillside over an area of about 0.1 km^2, and the ilmenite resources are thus about 10^5 t. The resources may be considerably greater if the cumulates have appreciable continuity.

One Turkey Mountain impure nelsonite occurrence (loc. 26) is among charnockite outcrops and consists of apatite clots in a matrix of ilmenite and apatite grains, large (up to 15 mm) zircon crystals, and quartz lumps. The lithology may be as little as a meter thick and is vaguely banded. Resources are unknown and depend largely on the continuity of nelsonite bands.

NELSONITE "DIKES"

By tradition, the ilmenite resources of the Roseland district occur as nelsonite "dikes." We find, as did Fish and Swanson (1964), that these nelsonites are lenticular and discontinuous and that no appreciable ilmenite resources are present in nelsonite (table 15), except in the large body at Piney River (loc. 24) over which weathered ore is already mined out. U.S. Bureau of Mines records (Force and Lynd, 1984) show that about 5×10^6 t of ilmenite remain in this body.

Our studies of the regional geology cast some new light on the origin of nelsonite "dikes." In a previous section we gave our reasoning for associating nelsonite with the Roses Mill and Turkey Mountain units. One relation needs enlarging here; the "dikes" are found in older rocks near contacts with large Roses Mill intrusive sheets. Reconstruction of these sheets before folding shows that the nelsonites were emplaced just below them. Since the nelsonites appear to be derived from the Roses Mill, they must have been emplaced from above. This sequence is consistent with the occurrence of impure concordant nelsonite at the base of the Roses Mill sheet and with the discontinuity of nelsonite at depth (observed in the area of loc. 1 and by Fish (1962) in his drill holes). Emslie (1978) has documented similar relations between ferrodiorites and nelsonites elsewhere.

The emplacement of nelsonites given the above relations is discussed in a previous section, where it is concluded that a titanium and phosphorus-rich magma immiscible in Roses Mill magma (see Philpotts, 1967, who demonstrated the existence of such immiscible magmas) coalesced on the floor of the sheet and was preferentially injected into the country rock.

TABLE 15.—*Titanium-mineral resources of the Roseland district*

[All figures (approximate) are in million metric tons mineral concentrate]

	Rutile	Ilmenite
Anorthosite-border rutile (+ilmenite) deposits	1	2
Disseminated ilmenite in ferrodioritic differentiates	0	5
Cumulate ilmenite in impure nelsonite	0	.1
Nelsonite "dikes" (from Fish and Swanson, 1964)	<<.1	.1
Piney River nelsonite (Force and Lynd, 1984)	0	5
Placer deposits in the Roseland district (from Minard and others, 1976)	<.1	.2

OTHER TYPES OF TITANIUM-MINERAL DEPOSITS

Minard and others (1976) measured titanium-mineral resources located by Herz and others (1970) in placer deposits of the Roseland district. Resources are small (table 15) because volumes of deposits are small.

A "rutile nelsonite" has been described near the town of Piney River (Watson and Taber, 1913; Fish and Swanson, 1964). We did not study this occurrence and are not able to place it in our chronologies or associations. Its resources are believed to be small.

FELDSPAR RESOURCES

The only presently operating mines in the district are for feldspar aggregate in anorthosite. Until 1980 feldspar (marketed as "aplite") was mined for glass products. The quarries are toward the center of the body where the anorthosite is relatively pure, though Roses Mill dikes (loc. 17), granulite screens, and crenulated ultramylonites are present. The existing quarries are apparently enlargements of natural streambank outcrops where anorthosite was of acceptable quality; large surrounding tracts, however, should consist of similar materials. Drilling at the Dominion Minerals property south of Piney River showed that the anorthosite is at least 90 m thick.

ZIRCON RESOURCES

Zircon is a characteristic phase of all the ferrodioritic rocks of the district and averages 0.2 to 0.4 weight percent. Zircon is also found in related nelsonites of both the cumulate and "dike" type. Where these rocks could be mined for titanium minerals, zircon could be a byproduct. Where these rocks have been mined, tailings presumably contain zircon. Locally, saprolites may constitute zircon resources.

PHOSPHATE AND RARE-EARTH RESOURCES

The ferrodiorite clan of rocks also has characteristically high apatite content that is concentrated with ilmenite in nelsonitic facies. Around the turn of the century there was much study aimed at recovering the phosphate in nelsonites, but no interest is being shown at present. Ilmenite resources in saprolite contain little apatite, so apatite is a minor potential byproduct of mining ilmenite from saprolite.

Apatite from nelsonite and ferrodiorite is also a resource of rare-earth elements (table 8).

GRAPHITE RESOURCES

The banded granulites of the district characteristically contain coarse flake graphite, locally in concentrations of greater than 5 percent. Graphite-bearing zones are tens of meters wide, but continuity of the zones was not established, and no resource estimates were attempted.

KAOLIN RESOURCES

Kaolinite is present in the district mostly as a weathered residue over anorthosite. It was intermittently mined around the turn of the century. Lintner (1942) in an unpubished U.S. Bureau of Mines report, estimated kaolinite resources as about 5 million metric tons at 30 percent Al_2O_3 present as many small deposits averaging 3 to 4 m thick.

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APPENDIXES

1. Log of 11 core holes shown on plate 1.
2. Descriptions of localities shown on plate 1.

APPENDIX I: SIMPLIFIED LOG OF 11 CORE HOLES

Appendix 1 is a simplified log of 11 core holes (locations shown on pl. 1 and (or) fig. 40), logged by the authors from cores lodged with the Virginia Division of Mineral Resources, Charlottesville, and acquired by U.S. Borax Corporation. All dips are approximate.

Hole TPB 1, Piney River quadrangle

Depth(m)	Description
0–70	Coarse impure anorthosite
70–130	Anorthosite

Hole TPB 2, Piney River quadrangle

0–17	Coarse impure anorthosite with ilmenite and rutile.
17–20	Roses Mill body with shallow dip
20–40	Garnet-pyroxene granulite with banding dipping 30°, minor ilmenite and sulfide.
40–57	Coarse impure anorthosite with ilmenite and rutile, in concordant contact with overlying granulite.
57–63	Catoctin Formation (?) dike with steep dip containing xenolith(?) of anorthosite.
63–98	Coarse impure anorthosite with ilmenite and rutile, showing banding which passes through vertical, then dips 30° near base.
98–133	Quartz mangerite with foliation dipping 30° cut by steep contact with anorthosite above; sulfides, magnetite, ilmenite, garnet; anorthosite sills and dikelets; local graphitic layers.
133–209	Coarse impure anorthosite with coarse ilmenite and rutile; steep upper contact.
209–218	Anorthosite

Hole TPB 3, Piney River quadrangle

0–23	Garnetiferous granulite, weathered through most of interval.
23–27	Roses Mill body
27–31	Quartz mangerite
31–68	Coarse impure anorthosite with ilmenite and rutile, containing a 3-m body of Roses Mill and several steeply dipping nelsonites of up to 1 m apparent thickness, commonly with shear-foliated bases.
68–76	Missing

Hole TPB 3—Continued

Depth(m)	Description
76–94	Coarse garnet-graphite granulite with isoclinical folds, locally cut by nelsonites up to 3 m apparent thickness, dipping an average of 45°, commonly outlined by shears.
94–97	Dike(?) of coarse impure anorthosite
97–157	Garnet-graphite granulite interbedded with and grading downward to garnetiferous mangerite, locally also with graphite.

Hole TPQ 1, Piney River quadrangle

0–16	No recovery
16–28	Coarse impure anorthosite with minor ilmenite and rutile; foliation dips 30°.
28–35	Quartz mangerite with foliation and contacts concordant with surrounding anorthosite; high in sulfides; cut by anorthosite dikelets.
35–38	Banded garnetiferous granulite, locally approaching mangerite in composition, cut locally by coarse impure anorthosite.
38–59	Coarse impure anorthosite low in oxides with three thin Roses Mill sills.
59–91	Migmatite of coarse impure anorthosite in granulite.
91–93	Leucocharnockite with rutile, cut by steep fault.
93–374	Mangerite, with a few anorthosite sills at the top.

Hole TJB 1, Arrington quadrangle

0–14	No recovery
14–21	Coarse leucocratic granulite with minor rutile.
21–41	Anorthosite, locally with rutile up to 5 percent.
41–57	Garnetiferous granulite with gently dipping banding
57–77	Anorthosite

Hole TJB 2, Arrington quadrangle

0–14	No recovery
14–44	Granulite with foliation dipping 30°
44–48	Coarse impure anorthosite, with ilmenite and rutile, cut by mafic dike.
48–56	Banded granulite with upper surface in sharp contact with anorthosite; banding dips 30°.

Hole TJB 2—Continued

Depth(m)	Description
56–63	Roses Mill body with upper surface dipping steeply in opposite direction to granulite; lower surface, slightly sheared, is horizontal.
63–68	Mangerite with minor interlayered leucocratic granulite; banding dips 30°.
68–70	Coarse impure anorthosite
70–88	Steep dike of Roses Mill
88–98	Anorthosite
98–109	Roses Mill body with gradational (replacement or assimilation?) contacts with anorthosite on both margins.
109–118	Anorthosite
118–120	Steep Catoctin Formation(?) altered dike with chilled margins.
120–148	Anorthosite

Hole TJF 1, Arrington quadrangle

0–9	No recovery
9–23	Mangerite
23–25	Coarse impure anorthosite
25–57	Anorthosite

Hole TJF 2, Arrington quadrangle

0–15	No recovery
15–64	Mangerite with minor rutile, anorthosite dikelets, and gently dipping foliation toward the top, becoming massive below.
64–70	Coarse impure anorthosite
70–107	Anorthosite
107–112	Coarse impure anorthosite

Hole TRA 1, Arrington quadrangle (shown also on fig. 40)

0–18	Anorthosite with rutile
18–34	Anorthosite
34–50	Anorthosite with ilmenite and rutile

Hole TRA 1—Continued

Depth(m)	Description
50–57	Granulite and quartz mangerite
57–72	Anorthosite
72–80	Quartz mangerite
80–143	Anorthosite, locally with minor rutile
143–158	Coarse impure anorthosite with ilmenite and rutile.
158–197	Quartz mangerite
197–231	Coarse impure anorthosite with interlayered quartz mangerite.

Hole TRA 2, Arrington quadrangle (shown also on fig. 40)

0–10	No recovery
10–16	Coarse impure anorthosite containing ilmenite and rutile.
16–58	Quartz mangerite with gently dipping foliation, many anorthosite dikelets containing rutile; two gently dipping thin Roses Mill bodies near 27 m.
58–62	Coarse impure anorthosite with ilmenite and rutile.
62–78	Anorthosite with rutile bearing lithologies interlayered with barren lithologies.
78–105	Roses Mill, locally with shear foliation dipping 30°.
105–110	Quartz mangerite with foliation dipping 45°.

Hole TRA 3, Arrington quadrangle (shown also on fig. 40)

0–7	No recovery
7–23	Coarse impure anorthosite with ilmenite and rutile.
23–50	Quartz mangerite
50–54	Coarse impure anorthosite
54–58	Quartz mangerite
58–81	Roses Mill body massive in upper part but altered to augen gneiss below.
81–88	Quartz mangerite
88–91	Anorthosite

APPENDIX 2: LOCALITY DESCRIPTIONS FROM PLATE 1

1 ——— Tye River upstream of Lanes Ford, Horseshoe Mountain quadrangle. Reference section for banded granulite gneiss lithology. Garnet-graphite (pyrrhotite) gneisses have platy blue quartz-feldspar bands (fig. 5) as wide as 2 m. The latter contain zircons dated at about 980 Ma. At each end of this straight reach of river are sills of Roses Mill plutons; the sill to the northeast has a cumulate (?) selvage of ilmenite and apatite at the base (fig. 23).

2 ——— Allen Creek in Piney River quadrangle. Garnetiferous granulite with possible bedding outlined by layers rich in garnet (fig. 8) or pyrrhotite. Some outcrops contain multiple sets of folds. Saprolites to the north and south are developed on mesocratic quartz mangerites locally with anorthosite dikes and nelsonite veins; these are resources of ilmenite and (or) rutile. See appendix 1 for logs of nearby drill holes.

3 ________ Jennys Creek in Arrington quadrange (fig. 3). Nearly massive quartz mangerite to the south becomes progressively more foliated, then altered by anorthosite dikes to the north. The most altered quartz mangerite contains rutile. A small Roses Mill dike (fig. 20) is also present.

4 ________ West Branch Hat Creek in Horseshoe Mountain quadrangle. Garnet-bearing mangerite and quartz mangerites are intruded concordantly by leucocharnockites, then offset by steep brittle fractures.

5 ________ Piney River upstream of town of Piney River in Piney River quadrangle. Banding in granulite unit is formed in part by concordant leucocharnockite-quartz mangerite alterations. The leucocharnockite has the typical platy texture (fig. 6). Just upstream are coarse pyroxene- and blue quartz-bearing anorthosites containing rutile (fig. 12).

6 ________ West Branch Hat Creek in Horseshoe Mountain quadrangle. Quartz mangerite and leucocharnockite in concordant layers are folded together with some platy blue quartz wrapped around fold noses but most blue quartz parallel to axial planes.

7 ________ Piney River downstream of town of Piney River in Piney River quadrangle. A quartzose anorthosite dike cuts banding of granulite. A foliation parallel to the dike is marked in part by blue quartz plates which cross compositional layering. Small amounts of rutile are present, mostly in the dike.

8 ________ Landslide scar on west-facing ridge slope at 1,340 ft elevation, Horseshoe Mountain quadrangle. Shaeffer Hollow Granite gneiss forms a large square-cornered xenolith in Roses Mill. Both units contain xenoliths of platy leucocharnockite.

9 ________ Landslide scar on west-facing slope at 1,200 ft, below trail crossing, Horseshoe Mountain quadrangle. Shaeffer Hollow Granite gneiss with tabular feldspar contains tight folds cut by a Roses Mill dike which is itself folded, sheared, and boudinaged (fig. 13).

10 _______ Allen Creek bed just below Route 676 crossing, Piney River quadrangle. Homogeneous anorthosite with minor blue quartz and mylonitic bands. Cleavage surfaces of large relict feldspar crystals are visible. Narrowly defined, these crystals are up to 20 cm long, but counting those which are clearly cut by mylonite or are only slightly bent, they are up to about 3 m long.

11 _______ Tye River bed, Arrington quadrangle. Banded granulite is cut by an anorthosite dike, and both in turn are cut by a xenocryst-laden Roses Mill dike (fig. 4). Strong foliation in anorthosite parallels banding in granulite; Roses Mill is weakly foliated. Accessible only during dry season.

12 _______ Indian Creek bed, Piney River quadrangle. Foliated quartz mangerite is cut by anorthosite dikelets (fig. 10), some of which contain rutile, and structurally overlain by the main anorthosite body, probably with a thrust contact.

13 _______ Bed of Maple Run, Piney River quadrangle. Quartz mangerite is cut both by an anorthosite sill (fig. 11) and by a Mobley Mountain Granite pegmatite with graphic textures and coarse muscovite.

14 _______ Tye River in Arrington quadrangle. A steep 6-m anorthosite dike cuts quartz mangerite with a weak horizontal foliation. Both the dike and adjacent quartz mangerite contain rutile.

15 _______ Roseland rutile pit, near Tye River and Route 655, Arrington quadrangle. Impure marginal facies of anorthosite with megacrysts of antiperthite, pyroxene, blue quartz, and rutile. Quartz mangerite is in contact with anorthosite along a fault intruded by an altered black dike. Rutile was mined here until 1949. See also appendix 1 and figure 40. The adjacent river section just downstream shows gently dipping banded granulites with blue quartz oriented in a second foliation, quartz mangerite, and a Roses Mill sill, locally sheared.

16 _______ Tye River, boundary between Arrington and Horseshoe Mountain quadrangles. A long interval of streambed exposures and a high adjacent road cut consists mostly of whitish muscovite mylonite and schist after anorthosite, separating healthier anorthosite augen.

17 _______ Former IMC feldspar quarry, Piney River quadrangle. The material being quarried is nearly homogeneous anorthosite with little quartz or pyroxene. Granulation of anorthosite is obvious, and much replacement by darker gray clinozoisite has occurred. Thin zones of ultramylonite occur, and at the north end of the quarry is a disrupted Roses Mill dike (chemical analysis, table 6; photomicrograph, fig. 21). The adjacent stream section contains veins of dark orthoclase, a facies of Mobley Mountain Granite, in otherwise homogeneous granulated anorthosite.

18 _______ Roses Mill road cut by Piney River, Arrington quadrangle (fig. 15). Charnockite-suite rocks of ferrodioritic composition with igneous texture, altered only to garnet and uralite, grade by deformation and retrogression into biotitic augen gneiss with mostly secondary minerals. Mylonitic augen gneiss interrupts the progression on the northwest but not the southeast side.

19 _______ Landslide scar on west-facing slope from 900 ft elevation to top of ridge, Horseshoe Mountain quadrangle. Roses Mill unit. Two intervals of biotitic augen gneiss are toward the base of the ridge, and two intervals of massive charnockitic ferrodiorite are toward the top. Both rocks

have recognizable xenoliths of older granulite and charnockite units. An intermediate facies seems massive but without interlocking texture in outcrop and in hand specimen shows foliated biotite. Catoctin Formation(?) dike at about 900 ft.

20 _______ Landslide scar in west-facing slope at 1,100–1,300 ft elevation, Horseshoe Mountain quadrangle. Roses Mill unit. Shear foliation in biotitic augen gneiss cuts an older igneous foliation marked by phenocryst elongation and xenolith trains in charnockitic ferrodiorite.

21 _______ Tributary of Jennys Creek at Highway 56, Arrington quadrangle. A north-south-trending dike of Roses Mill is intruded into anorthosite and leucocharnockite and, locally, is so loaded with xenocrysts and xenoliths derived from these rocks that the dike could be described alternatively as a net vein system. North of the road the dike bends westward and is cut by a younger north-south-trending dike with chilled margins. Southward the Roses Mill dike lithology grades into Roses Mill augen gneiss.

22 _______ Low road cut on Route 655 south of Roseland, Arrington quadrangle. The base of the Roses Mill pluton here is a two pyroxene-plagioclase-ilmenite rock (fig. 24) with flattened elliptical feldspathic domains which may indicate the presence of immiscible liquids along the base of the Roses Mill magma chamber. This rock forms a veneer over the hillside above.

23 _______ South flank of Mars Knob, Horseshoe Mountain quadrangle, in natural outcrops just east of long driveway. Rock as at locality 22 at the contact between the Roses Mill of Mars Knob and the older rocks in the valley.

24 _______ Former Piney River ilmenite pit of American Cyanamid Co., Piney River quadrangle. Some fresh pyritic chloritic nelsonite (fig. 25) is exposed in the floor of the pit with schistosity dipping steeply southeast. The wallrocks now exposed are saprolitic but include anorthosite, quartz mangerite, and their sheared equivalents.

25 _______ Smith farm north of Route 778, Piney River quadrangle. Turkey Mountain unit is here a banded ophitic-textured leucogabbro consisting mostly of two pyroxenes and plagioclase with minor ilmenite-magnetite intergrowths. The bands are of cumulate origin and some are graded, showing stratigraphic top to the southwest (fig. 26). Float of true nelsonite is present a few meters to the northeast.

26 _______ Hillside exposures just east of Route 778, Piney River quadrangle. Impure nelsonite forms a single(?) outcrop among poor exposures of charnockite of the Turkey Mountain unit. Clots of apatite up to about 5 cm in diameter are in a matrix which consists of finer grained ilmenite and apatite and coarse zircon (15 mm) as euhedral crystals.

27 _______ Road cut on Route 827, Massies Mill quadrangle. Ferrodioritic charnockite of the Pedlar massif, with orthopyroxene poikilitically enclosing quartz and feldspar (tables 9, 12).

28 _______ Bed of Buffalo River, Piney River quadrangle. Stockwork of aplitic Mobley Mountain Granite dikes in foliated biotite augen gneiss facies of Turkey Mountain pluton (fig. 27).

29 _______ Bed of Mill Creek upstream of Route 778, Piney River quadrangle. Altered black dikes cut Turkey Mountain charnockites but are cut (in small outcrop on south bank) by aplitic Mobley Mountain Granite dikes.

30 _______ Bed of Piney River under tailings pond, Piney River quadrangle. Altered black dike is intruded into shear zone parallel to river, but the dike margins are themselves sheared. The host rock is dark granulite with banding at a high angle to mylonitic foliation.

31 _______ Bed of Jennys Creek, Arrington quadrangle. Swarm about 3 m wide of altered diabase dikes with chilled contacts against anorthosite.

32 _______ Crawford Creek, Piney River quadrangle. Mafic dikes of gabbroic composition cut augen gneiss facies of Turkey Mountain pluton.

33 _______ West Branch Hat Creek near Route 673, Horseshoe Mountain quadrangle. Green mylonite 3 m thick separates leucocharnockite from Roses Mill unit (fig. 33). Banding in leucocharnockite is cut by mylonite.

34 _______ Landslide scar on northwest flank of Mars Knob at about 1,100 ft elevation, Horseshoe Mountain quadrangle. Contact of massive facies of Roses Mill unit above, intrusive into platy leucocharnockite below. Roses Mill here contains a variety of xenoliths including anorthosite, and near the base is a 3-m-thick chlorite-epidote-carbonate ultramylonite.

35 _______ Hillside outcrops east of East Branch Hat Creek and north of Route 673, Horseshoe Mountain quadrangle. Banded granulites show two old fabrics, locally at nearly right angles, one of compositional layering and a younger foliation of mineral orientation striking northwest.

36 _______ Open pit ilmenite mines near St. Marys Church, adjacent to intersection of Routes 778 and 621, Piney River quadrangle. Ilmenite was mined from saprolite over ilmenite-rich basal portions of a Turkey Mountain ferrodiorite. This saprolite extends down approximately to a gently west-dipping contact with underlying anorthosite. Anorthosite is exposed in streambeds and was encountered at depth in a drill hole through the remaining portion of this resource, which is the hill southeast of the highway intersection. The saprolite contains

weathered dikes of aplitic Mobley Mountain Granite.

37 ------- Bed of Piney River at Lowesville, Piney River quadrangle. Varying degrees of cataclasis, predominantly of leucocharnockite. Local pseudotachylite. A Catoctin Formation (?) metabasalt sill appears to postdate some shearing here.

38 ------- Hillside outcrops near Ivy Hill Church, Indian Creek Valley, Piney River quadrangle. Leucocratic charnockite with minor mafic material is sheared with some new mineral growth and acquisition of a banding parallel to shearing. Some domains retain relicit textures (fig. 34).

39 ------- Piney River near Woodson. Sheared mixture of leucocratic charnockite and Roses Mill (or Pedlar) rocks, both forming larger augen and with textures from augen gneiss to mylonite (figs. 35, 36).

40 ------- Bluff above Indian Creek, Piney River quadrangle. Dark biotite-pyroxene Pedlar charnockite to the west progressively becomes more deformed eastward into protomylonite, by fracturing of feldspar and retrogression and smearing of mafic minerals (fig. 37).

41 ------- Bed of Allen Creek, boundary between Arrington and Piney River quadrangles. Sill of coarse impure anorthosite containing minor rutile. The southern contact is mylonitic.