# 4. Middle Eocene Igneous Rocks in the Valley and Ridge of Virginia and West Virginia

By Jonathan L. Tso,[1] Ronald R. McDowell,[2] Katharine Lee Avary,[2] David L. Matchen,[2] and Gerald P. Wilkes[3]

## Introduction

The igneous rocks of Highland County, Va., and Pendleton County, W. Va., have fascinated and puzzled geologists since the 19th century. The rocks form a series of bodies, ranging from dikes and sills only a half-meter (m) (1.6 feet (ft)) or so wide (Stop 3), to larger necks and diatremes, such as Trimble Knob (Stop 2), with a diameter of approximately 150 m (500 ft). The bodies are found over a widespread area that tends to concentrate around two centers: Trimble Knob in Highland County and Ugly Mountain in southern Pendleton County (fig. 1).

The igneous rocks contrast sharply with their geological surroundings. Highland and Pendleton Counties lie within the Valley and Ridge physiographic province, a region dominated by folded and faulted Paleozoic clastic and carbonate sedimentary rocks (Butts, 1940; Woodward, 1941, 1943). The igneous rocks of the area intrude and crosscut the sedimentary rocks, which range in age from Ordovician through Devonian, and the Alleghanian-age regional folding (Rader and Wilkes, 2001).

The anomalous nature of these rocks has been recognized for at least a century. N.H. Darton (1894, 1899) described and mapped a number of occurrences of exposed igneous rocks in the area and described their petrology and petrography (Darton and Diller, 1890; Darton and Keith, 1898). Watson and Cline (1913) described the igneous rocks of Augusta County, Va. Over the years, these rocks have been the subject of numerous thesis projects (Dennis, 1934; Garnar, 1951; Kapnicky, 1956; Kettren, 1970; Hall, 1975). In later years, detailed field guides and petrologic descriptions were published in the scientific literature by Garnar (1956) and by Johnson and others (1971).

Prior to 1969, the precise age of the rocks was unknown. It was inferred that they were late Paleozoic or younger, based on crosscutting relations observed in the field (Garnar, 1956). Prior to studies employing radiometric methods, these rocks were thought to be of Mesozoic age (Darton and Diller, 1890; Johnson and Milton, 1955; Zartman and others, 1967), and related to rifting as the Atlantic Ocean basin opened.

However, using K-Ar and Rb-Sr isotopic techniques to date rocks that they thought were temporally related the Devonian Tioga Bentonite, Fullagar and Bottino (1969), came to the surprising conclusion that the rocks were a much younger age of approximately 47 Ma, placing them in the Eocene. This Eocene age is quite significant, making these rocks the youngest known igneous rocks in the Eastern United States.

This discovery sparked more research and speculation about the origin of the rocks. Southworth and others (1993), attempting to synthesize what was known about the rocks, employed isotopic and geochemical methods on both Eocene and Mesozoic igneous rocks over a wide area in Highland, Rockingham, and Pendleton Counties. They came to the following conclusions: (1) the Eocene rocks are bimodal in composition and include mafic (basalt, picrobasalt, and basanite) and felsic (trachyte, trachydacite, and rhyolite) members (fig. 2); (2) radiometric dates combined with paleomagnetic dates are consistently middle Eocene, at around 48 Ma (Trimble Knob in Highland County is the youngest at 35 Ma); (3) the igneous activity was generally short-lived, with the bulk of it occurring within a span of perhaps a few million years; (4) isotopic evidence does not indicate significant crustal assimilation, suggesting that the magmas moved rapidly upward, possibly through deep-seated fractures; and (5) chemical plots of major and minor elements indicate that the mafic and felsic rocks had a common source, possibly in the mantle, and their tectonic environment was consistent with within-plate continental extension. Of note was the discovery that not all the igneous rocks in the region are Eocene. A sample of mica pyroxenite from Pendleton County was dated at 143.8 Ma.

As a result of these studies, several questions, with no scientific consensus, remain. First, the Eocene epoch in eastern North America is not generally known to be a time of great tectonic activity. Poag and Sevon (1989), studying the sediments on the Atlantic Continental Shelf, Slope, and Rise, document relatively low sedimentation rates during the Eocene, with low stream gradients, high sea level, and a trop-

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[1] Department of Geology, Radford University, Radford, VA 24141.

[2] West Virginia Geological and Economic Survey, Morgantown, WV 26507.

[3] Virginia Department of Mines, Minerals and Energy, Division of Mineral Resources, Charlottesville, VA 22903.

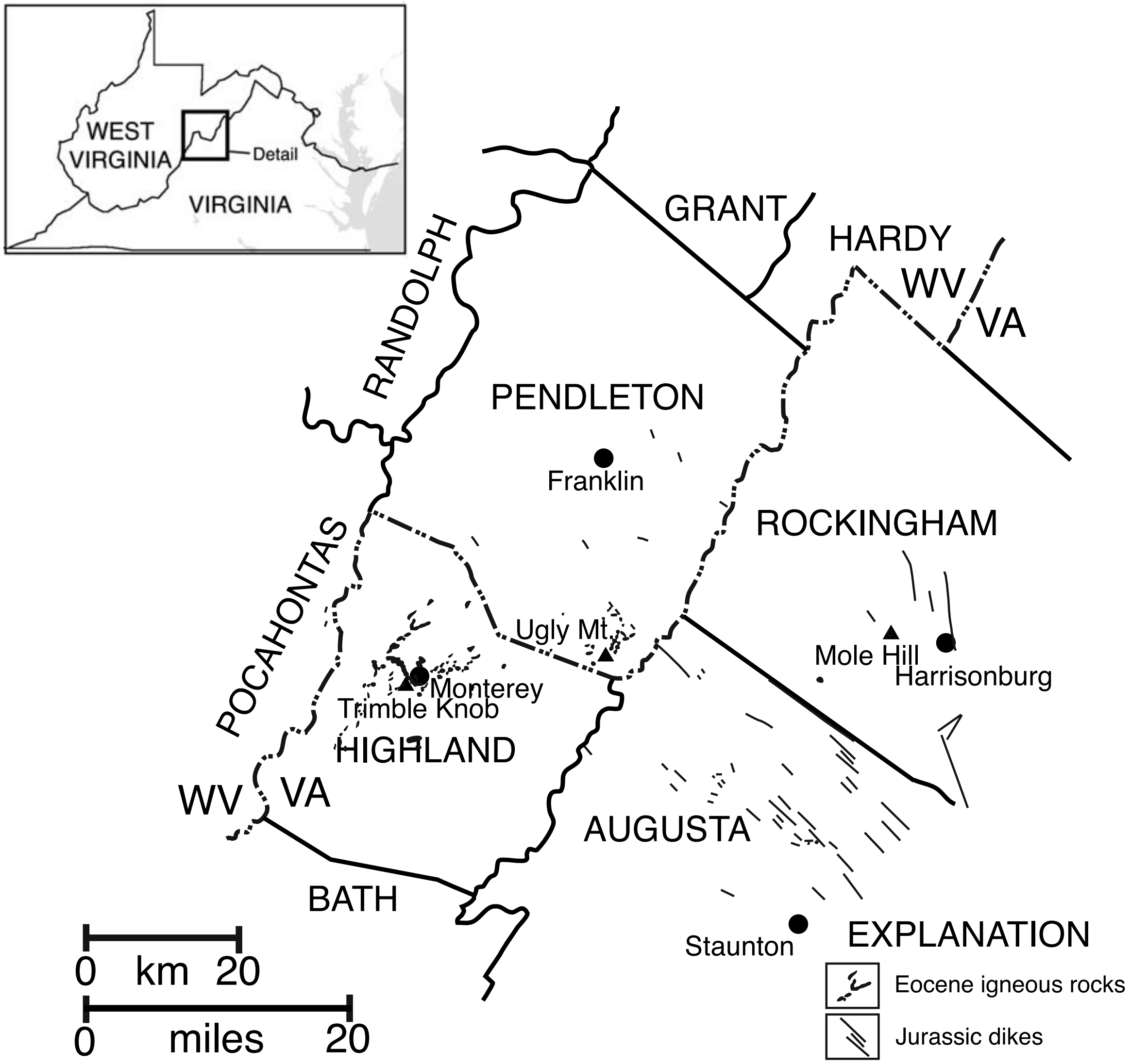

**Figure 1.** Regional map showing the location of the field trip area (in the central box in the upper left inset), the distribution of Jurassic dikes in a part of the Shenandoah Valley, Va., and the middle Eocene igneous rocks in the central Appalachian Valley and Ridge province (modified from Southworth and others, 1993).

ical rainforest environment. In this setting, what caused the igneous activity?

Of the numerous theories that have been proposed, some suggest that (1) a regional basement fracture zone, the 38th Parallel lineament, provided a focus for igneous activity (Fullagar and Bottino, 1969; Dennison and Johnson, 1971); (2) a still-cooling intrusion is responsible for the regional uplift of the “Virginia Highlands” and the nearby hot springs of Bath County (Dennison and Johnson, 1971); (3) a global shift in plate tectonic motion occurred during the Eocene, which resulted in the formation of the Bermuda Rise and was also responsible for igneous activity as far inland as Highland County (Vogt, 1991); (4) the transition between thin Atlantic lithosphere and thick North American lithosphere created a small-scale downwelling convection current, and the Eocene igneous activity was a result of an upwelling return flow (Gittings and Furman, 2001, citing King and Ritsema, 2000); and (5) the North American plate at this time overrode the hinge of the subducting Pacific plate, which reactivated pre-existing structures and produced magmatism (Grand, 1994). Southworth and others (1993) summarized the merits of many of the theories and concluded that a combination of causes (a reactivation of basement fracture zones and a plate-tectonically driven extension of North America, possibly associated with a shift in plate tectonic direction in the Eocene) provided the right conditions to form magma.

A second unresolved question involves how the magma or magmas evolved to form the bimodal compositional range that varies from olivine-bearing basalt to rhyolite. Although the actual relative percentage of mafic rocks versus felsic

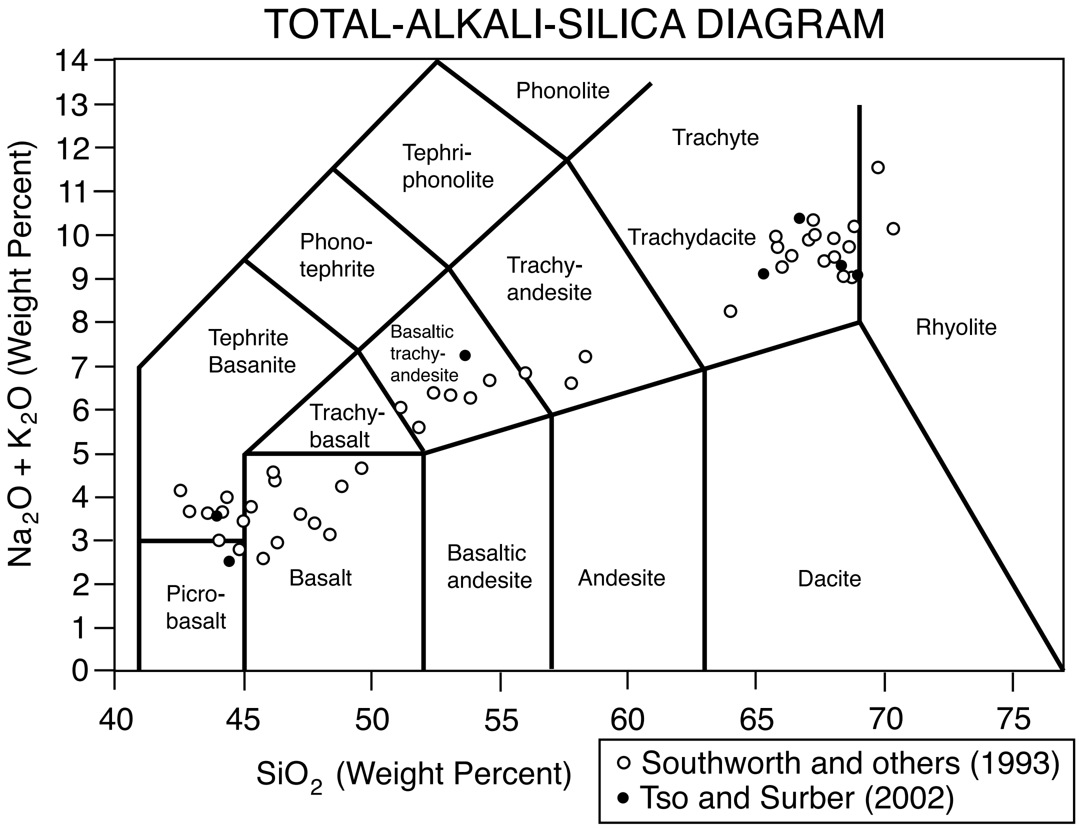

**Figure 2.** Major-element chemical classification based on $Na_2O + K_2O$ against $SiO_2$, based on the method of Le Bas and others (1986). The open circles are analyses from Southworth and others (1993), and the closed circles are from Tso and Surber (2002).

rocks is not known, known exposures (Johnson and others, 1971) suggest that they are present in roughly equal proportions. Southworth and others (1993) concluded that both magma types intruded in approximately the same timeframe. Both magma types can be found in very close proximity, although crosscutting relations are commonly obscured. We will consider this problem further as we visit sites during this field trip. There is much in the way of conflicting data. At the Hightown Quarry in Highland County, a mafic dike cuts across a felsic dike (Rader and others, 1986). Any petrologic model must include a common source for all the Eocene intrusives (Hall, 1975; Southworth and others, 1993) and provide a deep source and minimal assimilation of the continental crust (Southworth and others, 1993).

# Petrology

## Mafic Rocks

The mafic rocks are dark gray to black in color. They range from aphanitic to porphyritic with phenocrysts that include plagioclase, clinopyroxene, and occasionally olivine and biotite (fig. 3). Matrix minerals include abundant thin laths of plagioclase, opaque (magnetite) and clinopyroxene. Some rocks show a parallel alignment of matrix plagioclase, indicating a flow texture. Amygdules may also be present, with zeolite, calcite, and quartz the principal minerals filling the cavities. Xenoliths of country rock are common, and will be observed at Stop 7.

## Felsic Rocks

Compared to mafic rocks, the felsic rocks are more mineralogically variable and texturally complex, and provide more details of their eruptive history. They contrast in the field from the mafic rocks by their light- to medium-gray color when fresh, which weathers to buff to pink. The most abundant mineral in all felsic rocks is plagioclase, which composes 80 to 95 percent of the rock. Matrix textures commonly show parallel alignments of feldspar laths. Most felsic rocks are porphyritic with phenocrysts that include plagioclase (most common), biotite, hornblende, orthopyroxene (rare), and orthoclase (rare) (fig. 4). Amygdules are observed in felsic rocks as well, but less commonly than in mafic rocks.

Felsic rocks can show textural complexity. Felsic rocks observed near Stop 3 contain inclusions of older felsic rock, seen as parallel lenses on the centimeter scale (fig. 5). In thin section, these inclusions are observed as elliptical areas showing internal flow banding in orientations slightly different

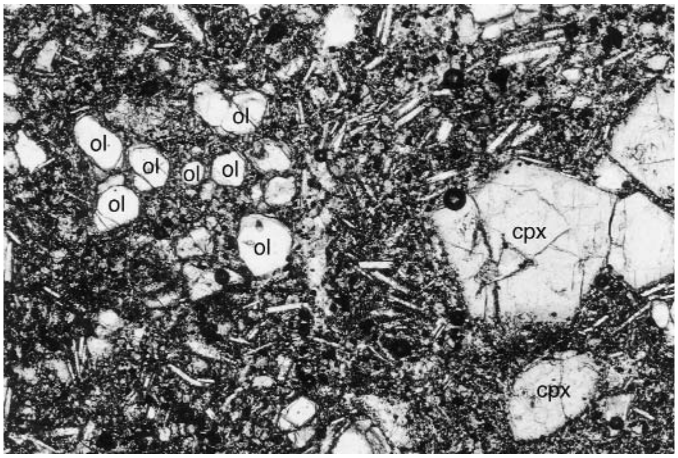

**Figure 3.** Photomicrograph of a porphyritic-aphanitic basalt. Clinopyroxene (cpx) and altered olivine (ol) phenocrysts are set in a fine matrix that contains thin laths of plagioclase. Plain polarized light; length of photo is 2.6 mm.

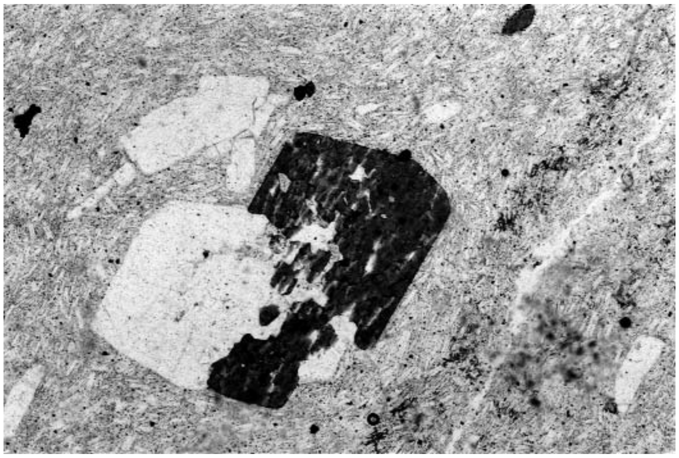

**Figure 4.** Photomicrograph of a porphyritic-aphanitic felsic rock. Plagioclase phenocrysts (white) and hornblende phenocryst (dark; intergrown with plagioclase) are set in a fine matrix of plagioclase laths that show flow structure. Plain polarized light; length of photo is 2.6 mm.

**Figure 5.** Photograph of a felsic rock composed of lens-shaped inclusions of older felsic rock. The inclusions are parallel, imparting a strong flow structure to the rock. Within the lenses, on the microscopic scale, plagioclase laths also show a strong flow structure parallel to the lengths of the lenses.

**Figure 6.** Photograph of volcaniclastic unit at Stop 4 described previously as a diatreme (Kettren, 1970) or volcanic breccia. The elongate clast in the center of the photograph is porphyritic basalt similar to dikes seen elsewhere on the Hull property. See figures 20 and 21 for closer views. Rock hammers for scale.

from the flow banding of the matrix. Felsic rocks may contain xenoliths of sedimentary country rocks. Rocks containing these xenoliths have a finer grained matrix than other felsic rocks, indicating that they cooled more quickly and probably formed near the margin of the body next to the country rock.

## Breccias

A third type of igneous rock is breccia, or diatreme. Unlike mafic and felsic rocks that formed in dikes or sills, the breccias are commonly found in circular bodies that we interpret to represent cross-sectional views of diatreme pipes. The sizes of these bodies range from a few meters in diameter to approximately 150 m (500 ft) (Rader and others, 1986) at Trimble Knob.

In general, breccias contain abundant xenoliths of older igneous rocks, sedimentary country rocks, and individual crystals of various minerals such as plagioclase, olivine, clinopyroxene, hornblende, and biotite, embedded in a fine, highly altered, vesicular matrix. The xenoliths range in size from a few millimeters to approximately 1.25 m (4 ft) in diameter at the Hull Farm (Stop 4; fig. 6) and are typically subrounded in shape. In general, the xenoliths appear unlayered and unsorted. However, in a few places, a crudely developed size sorting is observed as a weak layering of the coarse xenoliths (fig. 7). At Stop 3, the layering is on a scale of 4 to 10 centimeters (cm) (1.6–3.9 inches (in)), and its N. 45° W.

**Figure 7.** Photograph of "Breccia no. 1" at Stop 3. Note the weakly developed beds of coarser clasts that occur below and above the quarter at the left-center of the picture and parallel to the long dimension of the picture.

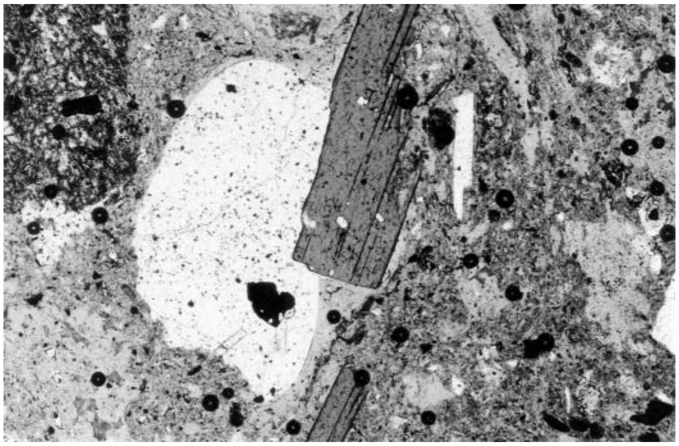

**Figure 8.** Photomicrograph from "Breccia no. 2" (near Stop 3) showing a rounded abraded plagioclase xenocryst with attached biotite. The morphological similarity between single crystals in breccias and those as phenocrysts within xenoliths suggests that many xenocrysts are derived from xenoliths. Other thin sections show various stages of phenocrysts separating out of xenoliths. A mafic xenolith is in the upper left corner. Plain polarized light; length of photo is 2.6 mm.

strike with steep southwest dip runs counter to the predominantly northeast strike of the bedding of the surrounding rocks. Typically, matrices are fine grained, highly altered, vuggy, and generally indecipherable in thin section.

As a general rule, the sedimentary xenoliths are a reflection of the identity of the immediate wall rock. Thus, at Stop 4, clasts of Helderberg Group and Oriskany Sandstone are indicative of the local bedrock, and similarly, at Stop 3, limestone and calcareous shale xenoliths are similar to the Wills Creek and Tonoloway Formations that dominate the area.

Diatremes are typically found in direct association with nearby mafic or felsic dikes or sills, with the overall composition of the diatreme and its igneous xenoliths reflecting the composition of these dikes and sills. We will see two mafic diatremes at Stops 3 and 4. Basalt xenoliths and xenocrysts of clinopyroxene and olivine embedded in a dark, nearly black matrix are common within these diatremes.

On the other hand, diatreme compositions can be complex, with contributions from multiple compositions of igneous rock. Although we will not visit this locality, a dominantly felsic diatreme ("Breccia no. 2") occurs near Stop 3. There, the overall color of the matrix is medium gray, with abundant felsic xenoliths and xenocrysts of plagioclase, biotite, and hornblende reflecting the felsic dikes nearby. However, this diatreme is unusual in that it also contains basalt xenoliths and clinopyroxene and olivine xenocrysts despite the fact that mafic rocks are uncommon in the immediate surrounding area. An implication is that here, the felsic magma that powered the diatreme postdated the mafic intrusion that formed the xenoliths.

Individual crystals are a ubiquitous feature of all diatremes. Many grains are broken fragments of once larger crystals. However, many crystals preserve euhedral shapes. Two sources for these individual crystals are (1) as phenocrysts from the magmas that powered the formation of the breccia pipes and (2) as xenocrysts derived from xenoliths (Mitchell, 1986). In the former situation, these crystals provide an important clue as to the identity of the magma that was active during the emplacement of the diatreme. In the latter case, the xenocrysts are derived from older igneous rock that had become fragmented and disaggregated during the eruption of the diatreme. One sample from a diatreme near Stop 3 shows evidence for this mechanism (fig. 8). There, a biotite-plagioclase xenocryst shows the biotite nearly separated from the plagioclase. The common similarity between xenocrysts in diatremes and phenocrysts in xenoliths suggests that many of these crystals are ones disaggregated from xenoliths, and several thin sections show phenocrysts that were in the process of separating from xenoliths

## Geochemistry

In general, trace element geochemical analyses of the middle Eocene igneous rocks of the area indicate enrichment of lighter elements and depletion of heavier elements compared to the midocean ridge basalt (MORB) standard of Taylor and McLennan (1985; see also fig. 9). Compared to Taylor and McLennan's (1985) chondrite standard, mafic rocks of the area are enriched in all trace elements except scandium (fig. 10). Trace element analyses of the felsic and volcaniclastic (diatreme) rocks of the area show the same trend (figs. 11 and 12) when compared to the chondrite standard.

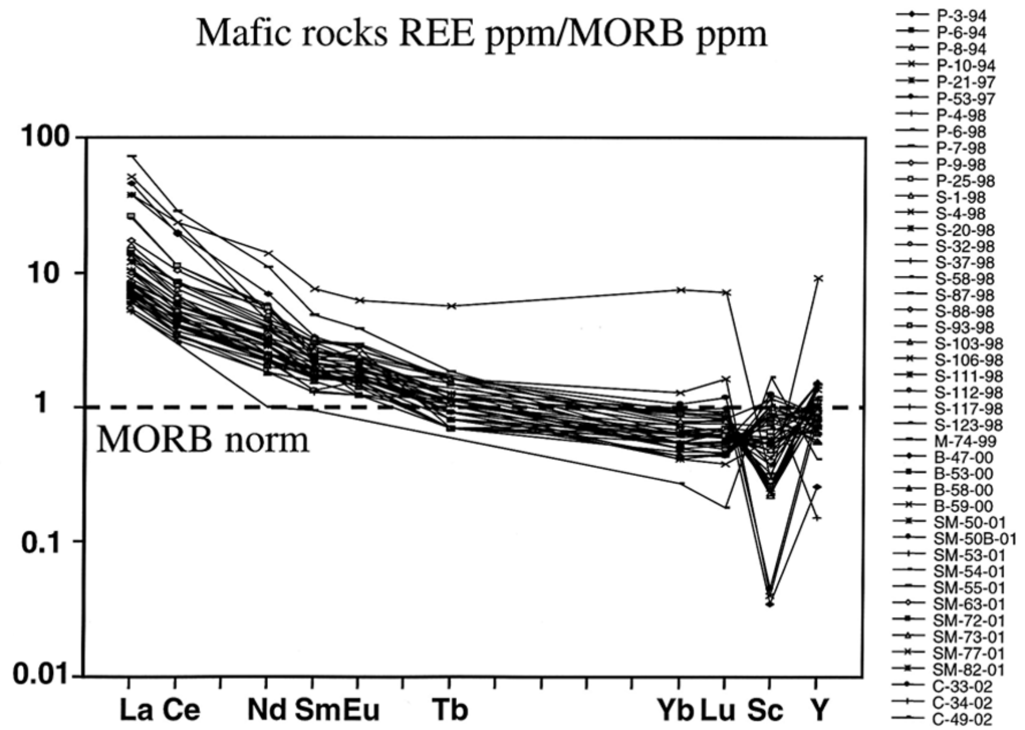

**Figure 9.** Normative plot showing normalized rare-earth-element (REE) concentrations from 44 mafic rock samples plotted against midocean ridge basalt (MORB) standard of Taylor and McLennan (1985). Lighter trace elements are enriched; heavier trace elements are depleted relative to the standard. Refer to McDowell (2001) for sample locations and analytical results.

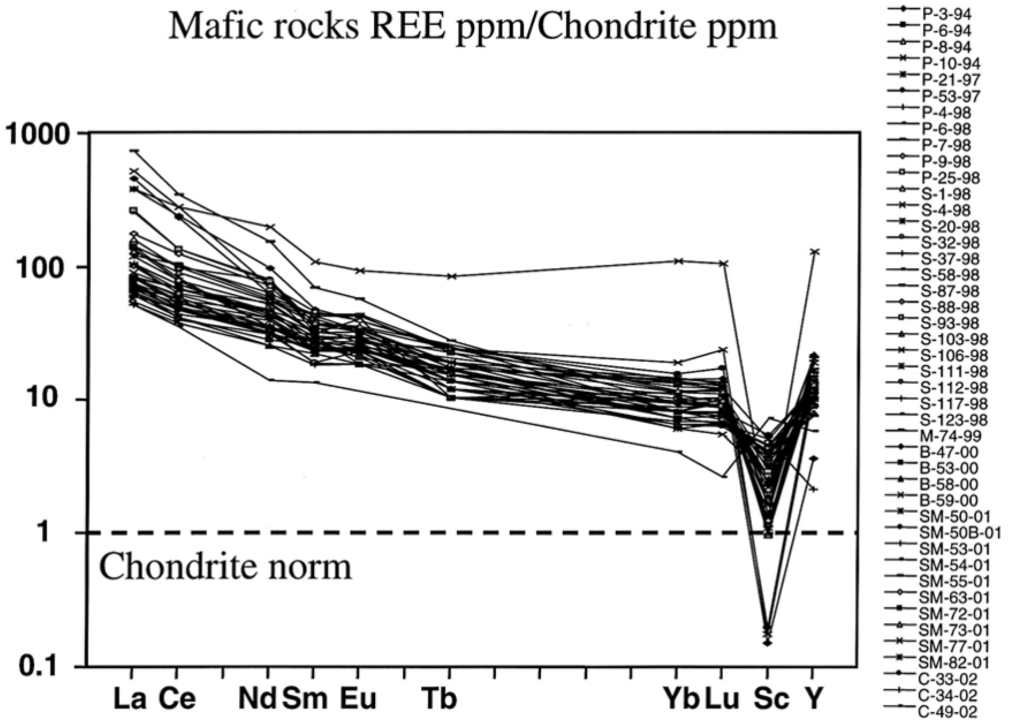

**Figure 10.** Normative plot showing normalized REE concentrations from 44 mafic rock samples plotted against chondrite standard of Taylor and McLennan (1985). Lighter trace elements are enriched; heavier trace elements are depleted relative to the standard. Refer to McDowell (2001) for sample locations and analytical results.

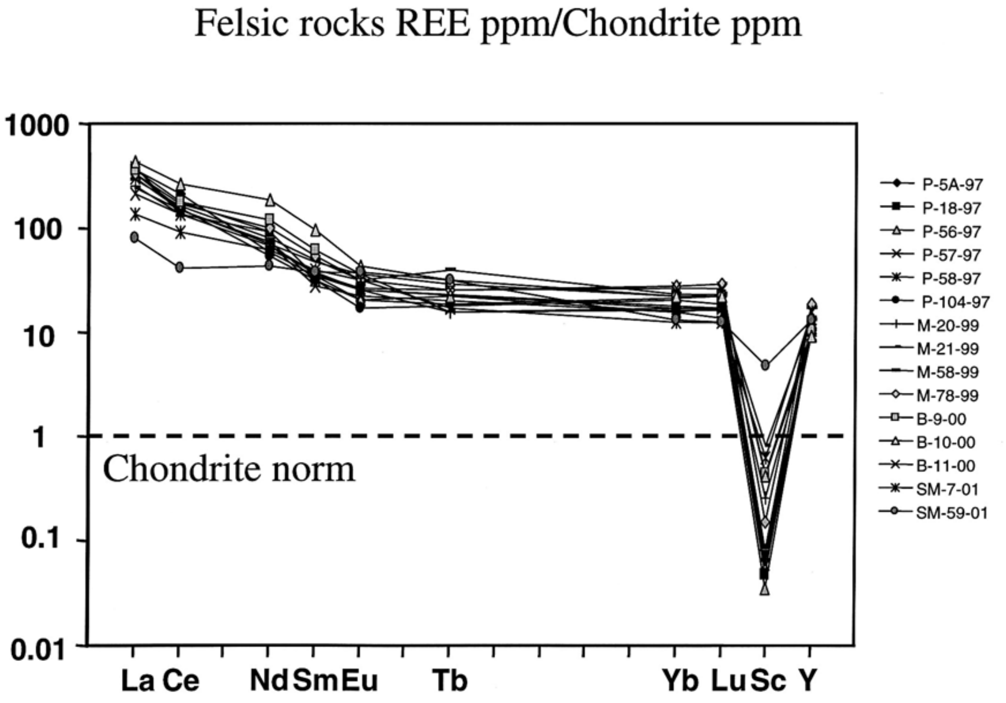

**Figure 11.** Normative plot showing normalized REE concentrations from 15 felsic rock samples plotted against chondrite standard of Taylor and McLennan (1985). All elements except scandium are enriched compared to the standard. Refer to McDowell (2001) for sample locations and analytical results.

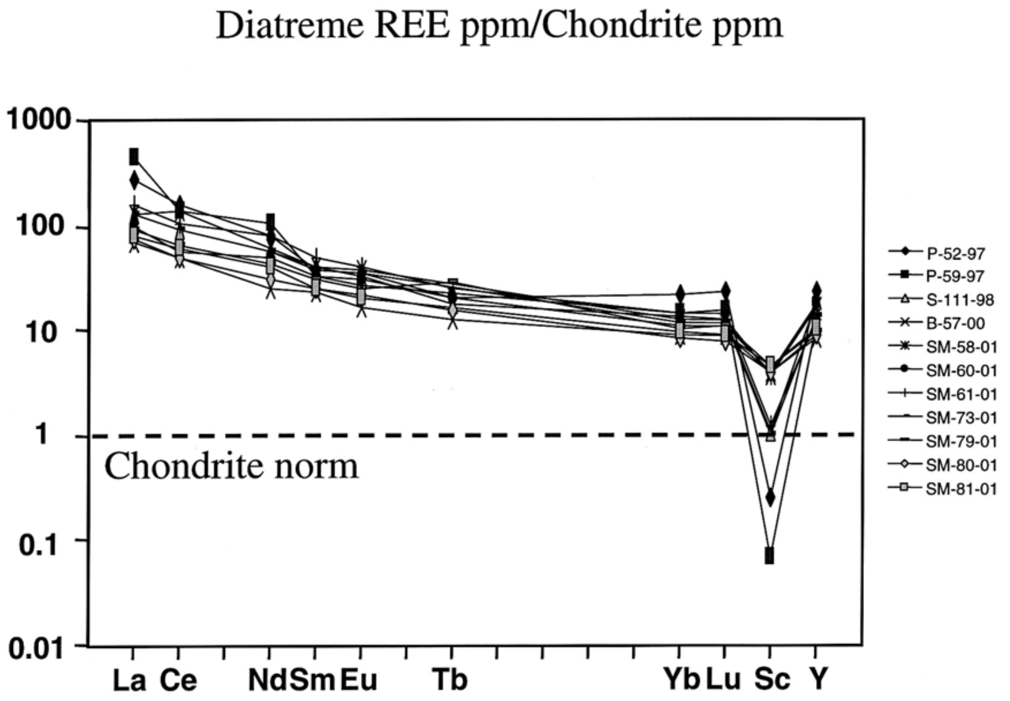

**Figure 12.** Normative plot showing normalized REE concentrations from 11 diatreme samples plotted against chondrite standard of Taylor and McLennan (1985). In general, all elements except scandium are enriched compared to the standard. Refer to McDowell (2001) for sample locations and analytical results.

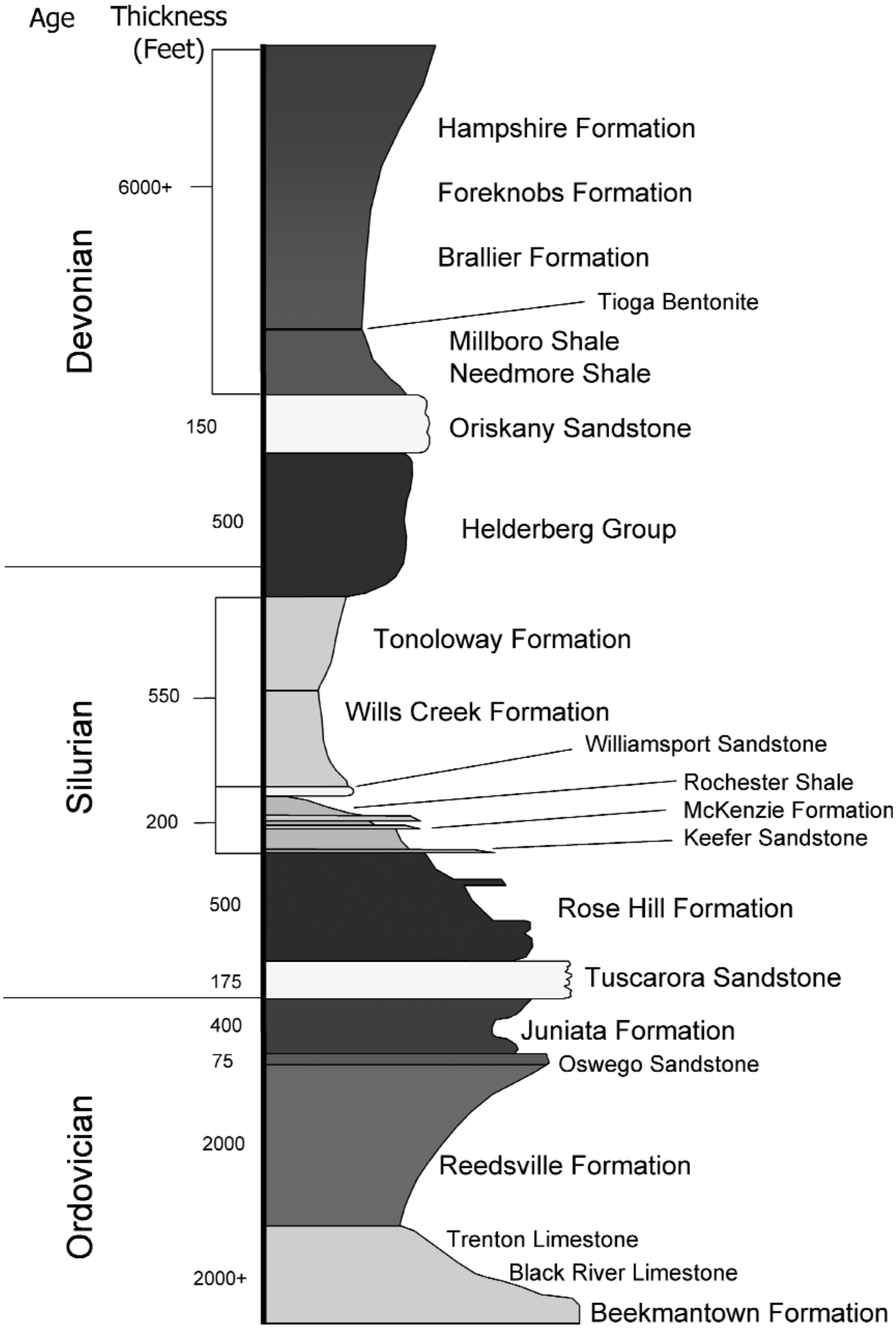

**Figure 13.** Generalized stratigraphic column of the Highland County–Pendleton County area. Stratigraphic thicknesses are in feet and are approximate; column is not drawn to scale.

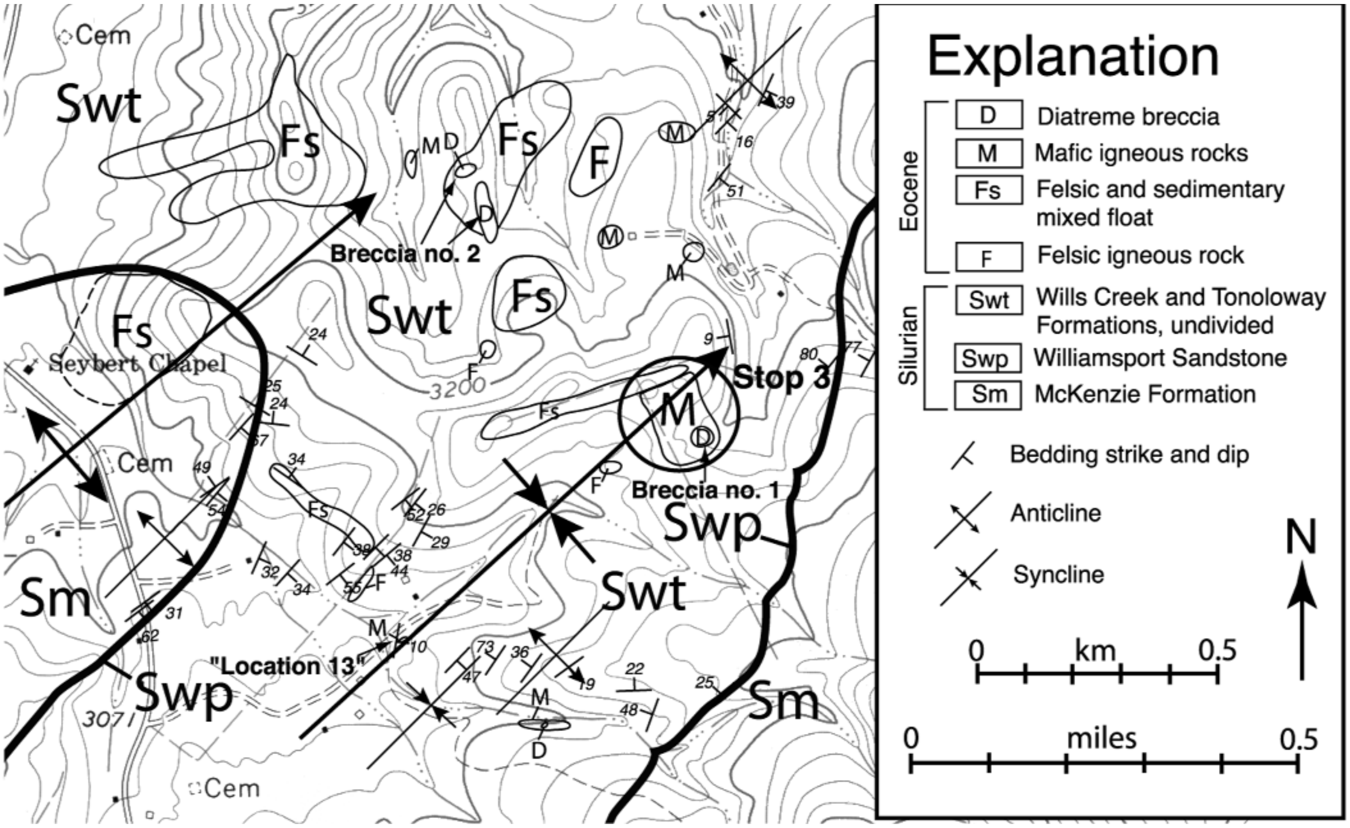

**Figure 14.** Bedrock geology of the area surrounding Stop 3 (the Beverage Farm), modified from Tso and Surber (2002). The circled area is the location of Stop 3. Note the location of two prominent diatremes, "Breccia no. 1" and "Breccia no. 2." Area is located in the Monterey, Va., 7.5-minute quadrangle, approximately 5.6 km (3.5 mi) east of Monterey.

Major elements barium, chromium, sodium, zinc, manganese, strontium, calcium, aluminum, and potassium are enriched (4 to 55 X) in the area's igneous rocks compared to background values (McDowell, 2001) for sedimentary country rocks in the area. The major element thorium is depleted (0.5 X) in the igneous rocks. In general, there appears to have been little transfer of metals from the igneous intrusives into the sedimentary country rocks. This suggests a *dry* emplacement of many of the intrusives, with the fluid phase in the magma being gases rather than liquids like water.

## Interactions with Surrounding Bedrock Geology

The igneous bodies are observed to intrude rocks of the Ordovician Beekmantown Formation through the Devonian Foreknobs Formation (fig. 13). Broad anticlines and synclines dominate the regional structure, with Ordovician rocks found in the cores of the anticlines and Devonian rocks found in the cores of synclines. The regional strike is northeast-southwest, giving the region a strong structural and topographic grain in those directions.

Tso and Surber (2002, 2003) undertook a detailed field study of a small (1 mi$^2$; (2.6 km$^2$) area of intrusions east of Monterey, Va., in the vicinity of Stop 3 (fig. 14). As is typical of this region, bedrock exposure consists of isolated outcrops, and it is rare to find well-exposed contacts between igneous rocks and the surrounding bedrock. Commonly, igneous bodies consist of a patchy distribution of small outcrops exposed in fields, or areas of igneous float, often mixed with sedimentary float. The general outlines of the igneous bodies are commonly surmised by groupings of float patches, or in the case of dikes, linear float trends of similar rock combined with topographic hints such as low ridges and knolls.

Joint data were collected on the outcrops in the area near Stop 3 and along the main roads nearby (fig. 15). Joint strikes have two very strong orientations: in the cross-strike direction of N. 40°–60° W., and in the direction of N. 60°–80° E. Note that this latter joint orientation is not parallel to the overall strike of the bedding (which is approximately N. 45° E.). At "Location 13" (fig. 14), a mafic dike has intruded into the Tonoloway Formation along a joint set which trends N. 78° E. Elsewhere, the trends of the dikes are inferred from the geologic map. Inspection of figure 14 reveals that all the prominent linear igneous bodies in the study area follow the dominant joint sets. Several felsic bodies have linear trends that parallel the northeast joint direction, and there is one prominent felsic dike that parallels the northwest joint direction.

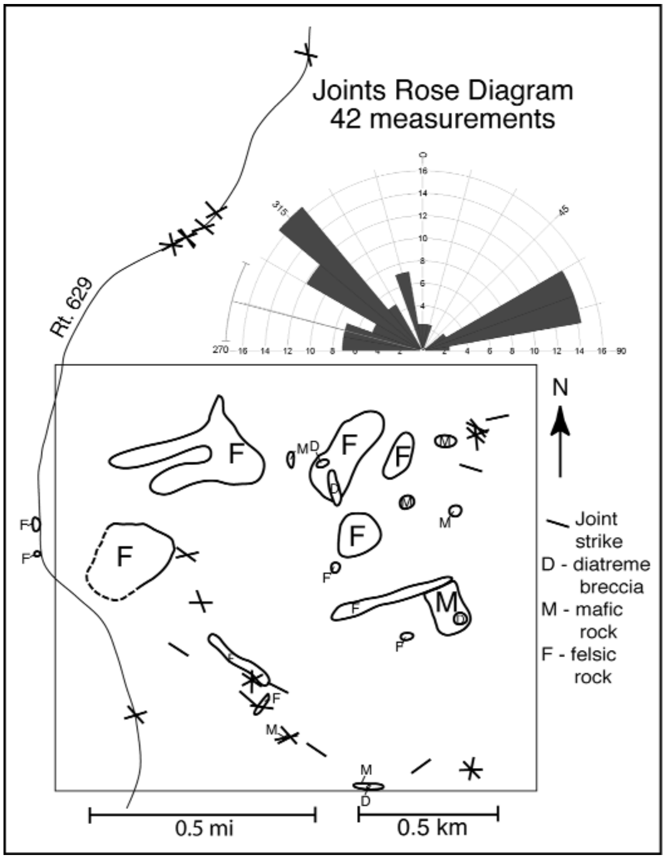

**Figure 15.** Rose diagram of joints and map of joint measurements of the Stop 3 area and along nearby major road (modified from Tso and Surber, 2002).

Where contacts between the dikes and sills and the country rock are exposed, xenoliths are common, but obvious chemical alteration of either intrusion or wall rock is not widespread except for a minor zone of contact metamorphism. Evidence for contact metamorphism will be observed at Stop 7, where a mafic sill/dike has intruded the Millboro Shale, leaving a harder phyllitic zone right at the contact. Another notable locality is at the previously mentioned Hightown Quarry, where the contact was first described by Giannini and others (1987), and in great detail by Good (1992). There, the igneous rocks intrude the Beekmantown Formation, causing a contact zone containing brucite marble.

Exposed contacts between diatremes and country rocks are exceedingly rare. However, at Stop 4 (the Hull Farm), we will have the chance to observe such a locality. In the contact zone, hot fluids have leached carbonate from the country rock, leaving behind only a siliceous “skeleton.”

## Discussion

Although the causes of the magmatism and the geochemical evolution of the magma or magmas remain as debated issues, certain inferences can be made about the eruption history on the basis of fieldwork, geochemical data, and petrographic study.

From joint data, field observation, and mapping, it appears that the dominant joint sets and bedding planes in the region provided the primary pathways for the ascent of both mafic and felsic magmas. The lack of extensive alteration of the wall rocks along dikes and sills where the common aphanitic rocks are in contact with the surrounding sedimentary rocks does not provide evidence of extensive hydrothermal interactions. Geochemical trace element analysis indicates that the emplacement of these rocks was relatively dry.

The diatreme bodies, however, tell a different history. The extensive hydrothermally altered matrix, the dissolved contact in evidence at Stop 4, and the rounded nature of xenoliths indicate either a dynamic, abrasive, water-rich environment for the formation of these bodies or a very reactive vapor phase.

The consensus of how diatremes form has evolved since they were first studied. Early theories called for an “explosive boring” process, in which pulses of magma from the mantle or lower crust rapidly rise through fractures, shattering the country rock until the magma reaches a critical depth where reduced pressures allow dissolved gases ($H_2O$ and $CO_2$) to separate from the magma and violently blow out (Mitchell, 1986). The gas streams upward, mixing with rock in a process called “fluidization,” forming an abrasive stream that “sandblasts” its way upward with enough force that solid particles are held in suspension by the “fluid” stream of gas, enlarging conduits and forming much of the breccia in the pipe.

In the last several decades, the role of “hydrovolcanism” has become increasingly recognized as a key player in diatreme formation (Mitchell, 1986; Lorenz, 1986). In this process, magma moves upward through joints until it reaches a rich source of ground water. At the contact between the hot magma and cooler ground water, the water flashes to steam, shattering the bedrock while incorporating some of the magma. The material is then expelled upward, breaching the ground surface and becoming airborne. The material falls around the vent to form a ring of tuff with a central crater (“maar”). There are two points to emphasize: (1) the eruption lasts as long as there is an adequate supply of ground water and not when magma runs out and (2) the eruption begins at shallow depths (200–300 m; 650–1,000 ft). Shallow depths and low pressure are necessary in order for water vapor explosions to occur (Lorenz, 1986). Once the eruption gets going and as long as the water supply lasts, the crater propagates downward, using up the water and creating an increasingly deeper "cone of depression" in the ground water table, thus allowing the pipe to deepen (fig. 16). As the pipe propagates downward, normal faulting occurs along the sides, thus allowing the pipe to widen while the sides collapse. The eruption style is both pyroclastic in nature and episodic. Thus, not only will ejected material form layers of tuff around the maar, it will also fall back into the crater itself, causing pyroclastic bedding within the pipe. Layered kimberlitic diatremes in western Montana that contain graded beds on scale of 1.2 to 30.5 cm (0.5–12.0 in) have been described by Hearne (1968). As the diatreme propagates downward, older bedrock clasts will increasingly be found in the higher beds of tuff surrounding the maar. During the pauses between eruptions, the tuff forming the walls of the central depression may slide back into the crater in the form of lahars. These deposits may become interlayered with pyroclastic beds within the diatreme. Once the water supply is used up, the hydrovolcanic phase of the eruption ends and later magmas may work their way up the pipe to form dikes that crosscut the previously deposited breccia.

Important to the hydrovolcanic model of diatreme formation is the fact that this is a relatively low-temperature process. Thus, hydrovolcanic diatremes do not show extensive contact metamorphism of the country rock. The formation of the diatreme walls is predominantly one of collapse, not of outward explosion. For this reason, extensive faulting of the bedrock outside of the diatreme is not commonly observed. Within the diatreme, along the walls, concentric normal faults form as the sides collapse down.

The diatremes of Highland and Pendleton Counties have much in common with the hydrovolcanic model. The abundance of xenoliths of country rock, crude layering observed in some localities, lack of contact metamorphism with the country rock, lack of strong deformation of the country rock, and the hydrothermal alteration of the matrix are similar to hydrovolcanism described in other parts of the world (Mitchell, 1986; Lorenz, 1986).

An interesting aspect to this mechanism is the fact that as material collapses into the pipe, rocks from higher in the stratigraphic section may fall into lower levels of the pipe and be preserved. Thus, it is possible to preserve younger rocks, which elsewhere have been eroded away, as xenoliths in diatremes. This situation has been observed at a diatreme near Stop 3 (labeled "Breccia no. 2" in figure 14). The surrounding bedrock is limestone and shaly limestone of the Silurian Wills Creek and Tonoloway Formations. However, in addition to these formations, this diatreme also contains xenoliths of black shale. The shale is found within the breccia both as clasts 2 to 3 cm (0.8–1.2 in) in diameter and as weathered-out chips in the soil overlying the diatreme. The lithology, color, and weathering characteristics of these chips do not resemble what is found in the surrounding Wills Creek and Tonoloway Formations, but are more similar to younger shales within the Devonian rocks such as the Millboro Shale. Kettren (1970), in his study of rocks in Highland County, reported a similar situation. In a breccia body, he found a Lower to Middle Devonian pelecypod from a black shale xenolith that he identified as possibly being from the Marcellus Shale. Kettren (1970) identified the surrounding host bedrock as lowest Devonian Keyser or Coeymans Limestone of the Helderberg Group, suggesting to him there was "at least 500 ft of vertical mixing." Alternatively, younger xenoliths can also originate from units embedded in a thrust sheet deeper in the crust. This would require a major subsurface thrust fault placing older rocks over younger rocks such as the Millboro Shale. However, geologic cross sections constructed through the region (Shumaker, 1985; Kulander and Dean, 1986) show no indication of such a fault under the field area.

In "Breccia no. 2," the minimum distance to the source of these xenoliths can be estimated by calculating the stratigraphic thickness between the bottom of the Millboro Shale and the top of the Tonoloway Formation, assuming no structural complications. Various workers have made differing estimates on the stratigraphic thickness. Figure 13 gives an estimate of at least 650 ft (198 m), although using the data from Butts (1940), the thickness estimate is 1,100 ft (335 m). Mitchell (1986) notes that in diatremes associated with kimberlites, inclusions have been demonstrated to have descended as much as 1,000 m (3,280 ft). This intriguing observation then provides a minimum estimate as to how much overlying rock has been eroded away since the Eocene, providing independent confirmation about the erosion rate of this region of the Appalachians since the Eocene. Using the range of stratigraphic thickness, the estimate of 198 to 335 m (650–1,100 ft) from Highland County diatremes is well within estimates of erosion for other localities in the southern Appalachians. For example, Mathews (1975) estimated 2,000 m (6,600 ft) of erosion since the beginning of the Cenozoic on the basis of sediment volumes in the Atlantic Ocean, and Matmon and others (2003), using $^{10}$Be techniques, estimated an erosion rate of approximately 30 m/m.y. for the Mesozoic and Cenozoic.

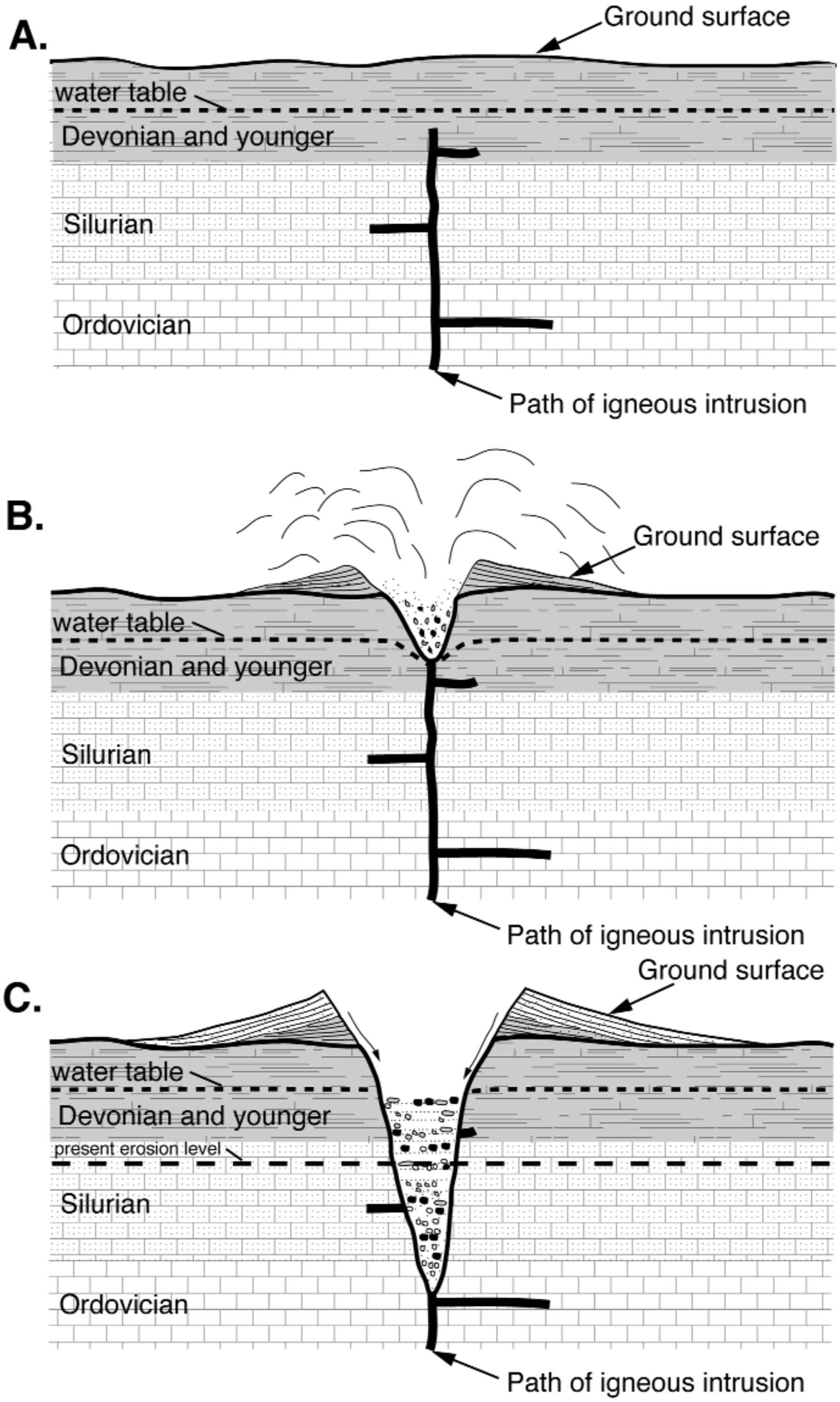

**Figure 16.** Eruption sequence of an Eocene diatreme following the hydrovolcanic model. A, Eruption commences when an intrusion reaches shallow depths and encounters a rich source of ground water; B, the breccia pipe propagates downward, creating a cone of depression of the water table, while a tuff ring forms around the central crater and the walls of the pipe collapse downward; C, material collapses into the pipe, allowing rocks from higher in the stratigraphic sequence to fall to lower levels, while forming some crude layering. Debris flows away from the crater walls to form volcaniclastic layering.

**Figure 17.** Photograph of Trimble Knob, a basaltic volcanic neck or plug, near Monterey, Va. View is to the south.

**Figure 18.** Photograph of the area of Stop 3, looking northwest. The dark patches in the center of the picture are exposures of "Breccia no. 1." Mafic rock dominates the area immediately surrounding the breccia to the line of grassy knolls behind and uphill from the breccia. Running along the crest of the line of knolls is a northeast-trending felsic dike. The large ridge in the background is Monterey Mountain. Grazing cows provide scale.

## Stop Descriptions

### Stop 1. Confederate breastworks on Shenandoah Mountain.

The roadside historical park offers exceptional scenery from the overlook. The high ridge on the straight skyline 11 miles (18 km) to the west is in Highland County; Jack Mountain is formed by tilted strata of the Silurian Tuscarora Sandstone. The slightly higher knob on this skyline ridge is Sounding Knob (elevation 1,308 m; 4,291 ft), an Eocene basalt plug that happens to rise up through the high ridge of Jack Mountain. The low mountain with a building having a prominent light-colored roof is Bullpasture Mountain. The Battle of McDowell on May 8, 1862, was fought mainly on the northwestern side of that mountain, and it resulted in a Confederate victory that prevented Union forces from penetrating eastward toward the Shenandoah Valley.

*Contributed by Dr. John M. Dennison, Professor Emeritus of Geology, University of North Carolina, Chapel Hill, N.C.*

### Stop 2. View of Trimble Knob.

Trimble Knob (fig. 17) has been variously described as a volcanic neck, a plug, and as a diatreme (Rader and others, 1986). Although in shape this feature resembles basaltic cinder cones in the Western United States, no cinders, ash beds, or lava flows are present.

Like many of the igneous bodies you will see today, the basalt core of Trimble Knob is surrounded or *mantled* by lithified volcaniclastic material, hence the interpretation of the feature as a diatreme. The suggestion is that rapid and violent emplacement of the basalt to a near-surface position, associated with the rapid release of fluids, shattered the country rock adjacent to the basalt body. This produced a chaotic collection of fragments of country rock, basalt, and a finely comminuted matrix of rock flour, all of which lithified. Southworth and others (1993) give a date of 35.0±0.5 Ma for the basalt of Trimble Knob, making it the youngest of all igneous rock units you will see today.

### Stop 3. Beverage Farm diatreme, basalt, and felsic rock.

All three igneous types (diatreme, mafic, and felsic rocks) are exposed on the rolling hills of the Beverage Farm (see fig. 14). The small knolls and subtle ridgelines are typical of how the igneous bodies influence the topography and crop out, as scattered patches of exposed rock and areas of mixed igneous and sedimentary float (fig. 18). Soil cover and grass make it difficult to precisely determine the boundaries of these bodies, and contact relations with the surrounding rock are only rarely observed. Many isolated smaller bodies are mapped as having a circular or oval shape based on single outcrops and patches of float, but the true shapes of these bodies are unknown. In some cases, dike-like shapes may be inferred from linear trends of outcrop and float of similar rock. Although dikes can be observed in roadcuts or quarry walls, attempts to trace them away from where they are exposed are difficult.

Near the farmhouse, an outcrop of the Wills Creek or Tonoloway Formation contains a typical mafic dike that follows the N. 78° E. trend of the regional joints ("Location 13"

**Figure 19.** Photograph of an older breccia inclusion in "Breccia no. 1" at Stop 3. The dark angular grains are clinopyroxene crystals, and the lighter rounded features are vugs. Quarter for scale.

of figure 14). The highly weathered, narrow dike is not traceable for any significant distance in the field behind the outcrop nor does it provide any topographic expression, thus causing speculation that perhaps the region is crisscrossed by an untold number of bodies that have yet to be found.

*Hike the farm roads to visit a concentrated group of exposures on the small knoll 0.7 km (0.4 mi) to the northeast of the farmhouse.*

"Breccia no. 1" crops out on the side of a small knoll where the pasture grass gives way to a black-brown rocky rubble and soil. This body is characterized by a chaotic assortment of angular to rounded xenoliths of mafic igneous and sedimentary country rock and sizes (up to 15 cm; 5.9 in), with single crystals (xenocrysts) embedded in a fine powdery matrix with up to 70 percent of the rock composed of xenoliths and xenocrysts. Xenoliths identifiable in the field include red iron-stained aphanitic mafic rock, gray limestone, chips of shaly limestone, and earlier-formed breccia.

By means of a hand corer, fresh breccia was recovered for thin sectioning. Thin section analysis reveals that: (1) igneous xenoliths include both finer grained (0.1 mm) vesicular aphanitic plagioclase—clinopyroxene basalt and slightly coarser grained (0.2 mm), non-vesicular aphanitic plagioclase-clinopyroxene basalt; (2) xenocrysts (augite, olivine, and rare hornblende) are commonly 1- to 2-mm size, and bounded by both well-defined crystal faces and broken and fragmented surfaces; (3) the matrix is highly altered, fine grained, and basically indecipherable, although there are areas of sheet silicate that resemble chlorite and fibrous zeolite; (4) samples commonly contain numerous rounded vugs that are filled with carbonate or zeolite; and (5) some of the vugs, judging from their shapes, are replaced xenocrysts and xenoliths.

By brushing the rubble away, relatively fresh breccia can be observed. Although most of the diatreme is highly unsorted, crude layering in the form of beds of coarser xenoliths on the 4- to 10-cm scale (1.6–3.9 in) (see fig. 7) is observed. The strike of the layers (N. 45° W.) cuts sharply against the regional northeast strike of the surrounding beds of sedimentary rock.

A feature of this diatreme is the presence of xenoliths composed of older breccia (fig. 19). A thin section reveals that it differs from the usual breccia in that it contains single crystals of well-terminated 2- to 5-mm clinopyroxene that are much coarser than those from the surrounding mafic rock, and that it lacks xenoliths of any type.

"Breccia no. 1" sits at the edge of a larger area of aphanitic mafic rock. The mafic rock consists of aphanitic, vuggy plagioclase-clinopyroxene basalt and porphyritic basalt with olivine, augite, and plagioclase phenocrysts.

Just north of the diatreme, following the crest of a small ridge that trends approximately N. 72° E. (along one of the dominant joint directions) is a series of small patchy outcrops that expose a felsic dike. The rock is light gray with plagioclase and rare hornblende and biotite phenocrysts in a plagioclase-dominated matrix that commonly has parallel laths.

## Stop 4. Hull Farm basalt and diatreme.

Exposed in the creek bed to the north of the road is an unusual rock unit previously described as a volcanic breccia (Garnar, 1951, 1956) and as a diatreme breccia (Kettren, 1970). A volcanic breccia is a deposit of angular pieces of volcanic and country rock that can form in several ways. The more common of these are described below.

(1) A gas or steam explosion ejects shattered bedrock fragments, volcanic rock, and ash into the air which subsequently fall back into the crater—the material is still hot and is typically welded together because the volcanic rock fragments and ash may be close to melting temperature. This volcanic breccia is called an explosion, fallback, or diatreme breccia, and it is extrusive in nature;

(2) A sudden withdrawal of magma from beneath a volcano can stress the country rock and any volcanic deposits on top of it so that the entire structure collapses into the magma chamber. The jumble of angular debris may be welded together. This is a collapse breccia, and it has no extrusive component to its formation.

The key feature of these types of volcanic deposits is the *angular* pieces of volcanic and country rock (making it a breccia rather than conglomerate), the presence of ash, and the lack of any evidence of flow—either flow layering or flow lineations.

The dark-colored rock unit in the streambed has several features that appear to be at odds with the interpretation of the unit as a diatreme breccia. The rock itself is a boulder mudstone or volcaniclastic conglomerate consisting of a dark matrix of very fine grained material surrounding and support-

**Figure 20.** Closeup photograph of the volcaniclastic unit at Stop 4 exposed in the streambed just south of the Hull residence. Rounded to subrounded clasts of basalt, Oriskany Sandstone, and limestone from the Helderberg Group are identified (arrows). Margin of large basalt clast shown in figure 6 is marked by a dashed line. Rock hammer for scale.

ing a large of number of rock fragments. These rock fragments are polymict and most are rounded. The most obvious fragment is a boulder of porphyritic basalt approximately 1.2 m (4 ft) in length (see fig. 6). Also present are cobbles and pebbles (fig. 20) of the porphyritic basalt, clasts of the fine-grained matrix material, clasts of light-gray limestone (Silurian-Devonian Helderberg Group), and clasts of light-gray quartz sandstone (Devonian Oriskany Sandstone); in general, these are subrounded to rounded. There are weak indications of flow in the unit in the form of surfaces covered with small (less than 1 cm (0.4 in) in diameter) pebbles (fig. 21). These concentrations of pebbles appear on only the east side of the large basalt clast seen in figure 6 and may represent a lag deposit deposited on the leeward or *downstream* side of the basalt clast.

McDowell speculates that this unit might be the lithified remains of a lahar deposit. A *lahar* is a debris or mudflow produced contemporaneously (usually) with extrusive volcanic activity. Volcanic events typically create a strongly localized weather anomaly associated with violent rainfall in the vicinity of the volcano. Heavy rainfall mixes with volcanic ash and any loose volcanic debris and soon produces a gravity flow having the consistency of wet concrete and as much momentum as the gradient of the volcano's slope will allow. Modern lahars incorporate trees, buildings, houses, and pieces of country rock as they move rapidly downhill. Because a lahar can contain a large amount of freshly erupted volcanic material, the temperature of the lahar deposit may be close to the boiling point of water. A solidified lahar should be a collection of fragments of various sizes and shapes (both rounded and angular), including boulders, caught up in a very fine grained matrix, lithified into a material resembling concrete, and perhaps showing some flow structures. That description seems to fit this outcrop.

Extrusive volcanic activity associated with the middle Eocene igneous rocks in this area has not been documented. The presence of a possible lahar deposit suggests otherwise. Drilling or geophysical survey work may be required to determine the exact nature of this material.

In the hillside just to the east of the Hull residence, the contact between volcaniclastic material and country rock (Oriskany Sandstone) is exposed. All calcite cement has been removed from the rock, leaving only the original quartz grains in a clay-rich matrix that crumbles in the hand. This suggests that the interaction between country rock and volcaniclastic material was a reactive one. The volcaniclastic material may have been very hot and contained acidic fluids.

A porphyritic basalt dike is exposed in the small valley to the north of the Hull residence (fig. 22). This igneous body protrudes from the ground to a height of approximately 1.2 m (4 ft) and is roughly 0.6 m (2 ft) wide. Abundant, large pyroxene phenocrysts up to 0.6 cm (0.2 in) in diameter are visible. In thin section, these phenocrysts may be euhedral or corroded.

Typical of most of the igneous bodies in the area, this dike is surrounded by volcaniclastic material. Clasts within this material may be rounded or angular and the matrix mate-

**Figure 21.** Closeup photograph of the volcaniclastic unit at Stop 4 exposed in the streambed just south of the Hull residence. Concentrations of small pebbles are observed only on the east side of the large basalt clast (margin marked by dashed line) shown in figure 6. This suggests that the pebbles represent a lag deposited from horizontal flow on the leeward side of the large clast. Rock hammer for scale.

rial typically weathers to irregular rubble less than 1 cm (0.4 in) in diameter. Is the volcaniclastic material an emplacement breccia as suggested at Trimble Knob, making it essentially contemporaneous with the dike? Did the dike intrude existing volcaniclastic debris? Is the volcaniclastic material part of a lahar deposit that flowed around the dike? What was the surface topography like here in the Eocene? Are these the remnants of an extrusive igneous event?

## Stop 5. Ugly Mountain overview.

Brushy Fork Dam, on the right, was constructed by the U.S. Soil Conservation Service (now the Natural Resources Conservation Service) for local flood control. In 1996, heavy rain in the aftermath of Hurricane Fran caused the dam to be overtopped and the spillway stripped to bare bedrock. Reclamation has since recovered the site. Ugly Mountain, visible to the south of the reservoir, has the highest topographic relief in the immediate area.

## Stop 6. Brushy Fork albitite dike.

*The dike is exposed in the streambed and water may be high so* ***be prepared to get your feet wet.***

Ugly Mountain to the west is a middle Eocene plug or volcanic neck with a diatreme breccia near its top and on its west flank (Garnar, 1951, 1956). The rock that you are standing on is one of several dikes that radiate out in an easterly direction from Ugly Mountain. The dike (fig. 23) here is approximately 9 m (30 ft) wide, trends N. 83° E., and has been dated at 42.8±0.5 Ma (Southworth and others, 1993). The light-orange to pinkish color of the dike is a product of weathering. If you break off a piece of the rock, you will see that it has a thick, brown weathering rind with occasional dark-blue or steel-gray mineralized bands. The latter are probably pyrolusite, a common secondary mineral in this area; it precipitates out of near-surface ground water. Fresh samples of this rock are nearly white or yellowish white. The texture is aphanitic and resembles a very fine grained quartz sandstone. In thin section, this unusual rock consists almost entirely (>95 percent) of a felted mat of equigranular, euhedral crystals of albite (sodium plagioclase), a smattering of small, euhedral biotite? crystals, and rare ilmenite. The absence of quartz, the small number of mafic minerals, and the fine grain size suggest that this rock is properly named a rhyolite or dacite, but because of the unusually high content of sodium plagioclase, the rock was termed an *albitite* by Garnar (1951, 1956).

Another interesting feature of this rock is the presence of parallel foliations resembling sedimentary bedding. In reality, these layers are shrinkage cracks resulting from differential cooling. The country rock here consists of shales and siltstones of the Devonian Brallier Formation. The Brallier, visible approximately 15 m (50 ft) downstream, is dipping steeply toward the southeast at 50°. The albitite dike intruded a fracture and cuts across strike at an angle of 52°.

**Figure 22.** Dike of porphyritic basalt exposed at Stop 4 just north of the Hull residence. Co-author (Matchen) visible in the photograph is 1.8 m (5.9 ft) tall.

**Figure 23.** Dike of albitite (>95 percent sodium plagioclase) exposed in Brushy Fork Creek at Stop 6 shows cooling fractures that resemble sedimentary bedding. Unit trends N. 83° E. and is approximately 9 m (30 ft) wide.

Also of note here are a number of core holes drilled for paleomagnetic analysis (Ressetar and Martin, 1980), which confirmed the middle Eocene age of this igneous body.

## Optional Stop. Wilfong Church gabbro.

The igneous rock exposed here is coarser grained than at Stop 7 and probably should be classified as a gabbro on the basis of its texture. Garnar (1951, 1956) referred to it as a diabase because of the predominance of calcium plagioclase over pyroxene (fig. 24). Both euhedral and corroded pyroxenes are present in this rock, suggesting two stages of precipitation of these minerals, with the euhedral crystals representing the later stage. This igneous material has not been dated but is assumed to belong to the middle Eocene group.

NOTE: A mica pyroxenite dike dated at 143.8±1.8 Ma (Southworth and others, 1993) is present 1.6 km (1 mi) to the east.

The very poorly exposed country rock here is Devonian Brallier Formation, an interbedded shale, siltstone, and sandstone unit that directly overlies the Devonian Millboro Shale. In fact, the contact between the two units is probably within 15 m (50 ft) of the dike.

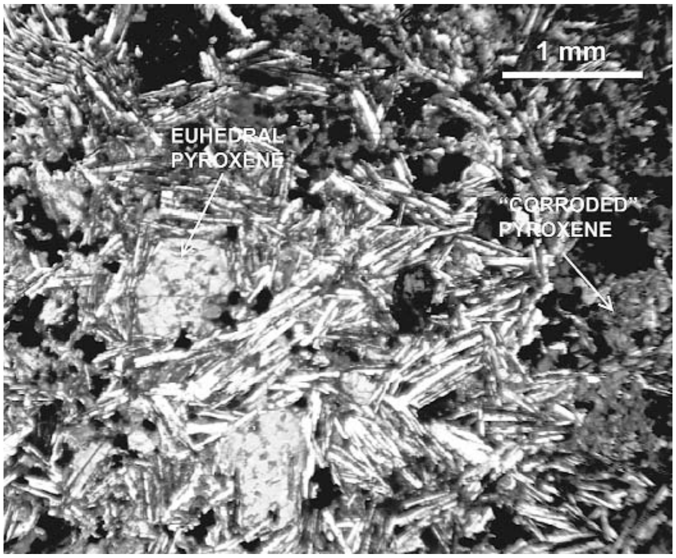

**Figure 24.** Photomicrograph of gabbro from Wilfong Church (Optional Stop). Pyroxenes suggest different times of precipitation. Euhedral crystals are late; corroded crystals are early. Crossed polars.

## Stop 7. Sugar Grove sill-dike.

The hillside in front of you is formed by the silty shales of the Devonian Millboro Shale (section described in Woodward, 1943). Originally flat-lying strata of the Millboro have been folded into the steep east limb of a broad syncline whose axis is centered along the crest of Shenandoah Mountain, visible to the east. Here, the Millboro is dipping approximately 60° to the southeast. The folding of the syncline occurred while the Millboro was buried thousands of meters below the land surface. We believe this to be true because when rocks are subjected to compression, they are more likely to bend if they are confined or surrounded by an equally strong pressure. This confining pressure corresponds to the weight of overlying rocks.

The Millboro also exhibits another kind of deformation. A number of nearly vertical joints cut across the rock and intersect to form two distinct sets at a 30° angle. These brittle fractures form when rocks are subjected to extensional forces that tend to pull them apart *or* to compressional forces with greatly reduced confining pressure. Without confining pres-

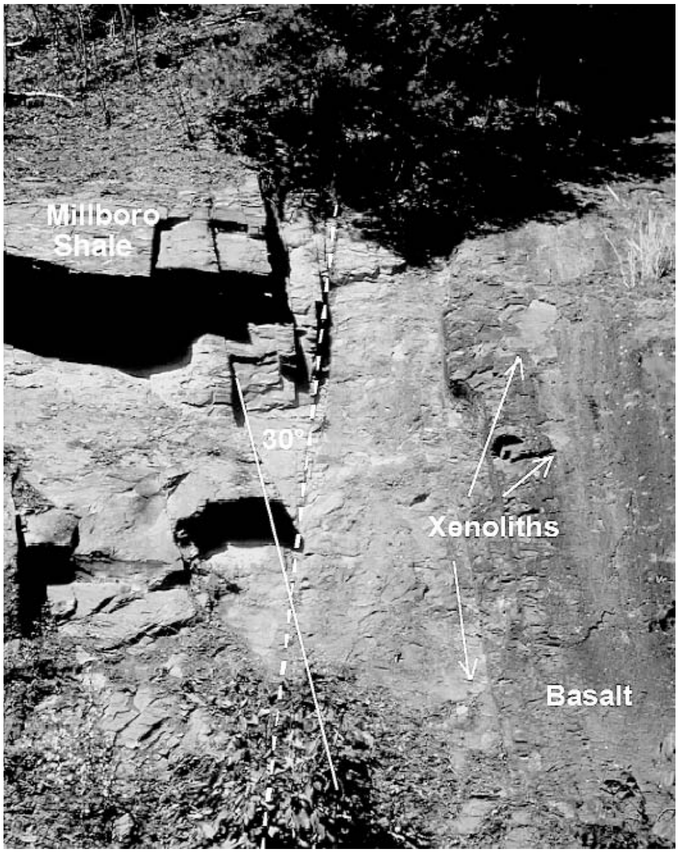

**Figure 25.** Contact between the Millboro Shale and the dike portion of the Sugar Grove basalt sill-dike at Stop 7. Basalt intruded along a joint (dashed line). Notice that a second joint set intersects the first at a 30° angle. Also notice the 0.25- to 0.5-m (0.8–1.6-ft)-diameter xenoliths of Millboro Shale in the basalt and the apparent flow foliation in the basalt.

sure, rocks will break and move relative to each other (faulting); when minimal confining pressure is present, rocks will fracture without movement (jointing). This suggests that the joint sets were formed by the compression of Millboro strata overlain by a greatly reduced thickness of rock—decidedly after folding had occurred.

Today, the Millboro has been exposed by an extensive period of erosion that has removed several thousand meters of Devonian through Mississippian sedimentary rock overburden. The exposed Millboro here is a geological hazard because the steeply dipping and fractured rock spalls off and slides down the dip surface into the roadbed at the foot of the slope. You can see that the highway at this point and at other spots along our travel route has been built up on artificial fill and shows evidence of recent landslides and rock fall.

An additional geologic event has affected the rocks at this outcrop. Long after the Millboro was tilted, jointed, and much of the overlying strata removed, magma with a basaltic composition migrated upward toward the surface and intruded these rocks. The dark-reddish-brown rock unit exposed before you is not part of the Millboro Shale. It is a *sill-dike* of middle Eocene basalt dated at 43.1±2.1 Ma (Southworth and others, 1993).

The shales of the Millboro immediately adjacent to the basalt have a phyllitic sheen due to contact metamorphism. In addition, you will find small- and large-diameter (up to 1 m; 3 ft), irregularly shaped pieces of Millboro Shale within the basalt. These xenoliths clearly postdate the structural deformation of the Millboro.

The body of igneous rock observed here is unusual in that it changes *character* over the width of the outcrop. Igneous material first reached the near surface by moving upward along one of the large joints within the Millboro (fig. 25). At this point, the igneous body is a dike that cuts across the bedding of the Millboro at approximately right angles. As the igneous material got closer to the surface, it intruded between the bedding of the Millboro by simply pushing the strata apart. This portion of the igneous body is a sill because it parallels the bedding of the country rock. During the latter stages of intrusion, broken pieces of Millboro Shale were picked up and included in the molten material as xenoliths. The igneous material cooled and the remainder of overlying sedimentary rock eroded away, leaving the exposed sill-dike we see today.

There is another apparent paradox here. The igneous rock making up the sill-dike is a porphyritic, amygdaloidal basalt. It has the aphanitic groundmass of an extrusive volcanic rock as might be associated with a lava flow, yet we believe that it is intrusive. When igneous intrusions occur within a few meters to a few hundreds of meters of the surface, cooling occurs rapidly at rates similar to those experienced by lava. This is especially true when ground water is present in the near-surface rock. The end result is a very fine grained igneous rock texture such as is seen here.

Basaltic magmas typically melt at 1,000 to 1,300°C (1,800–2,300°F) depending on depth of burial and water and gas content (Hyndman, 1972). The slightly phyllitic nature of the Millboro near the basalt indicates contact metamorphism. It should be noted, however, that metamorphic alteration does not appear extensive here, and it is possible that the temperature of the molten material was significantly cooler than those listed above. The north end of the sill is in direct contact with the underlying Millboro. A zone of alteration 10 cm (0.3 ft) wide is present and is marked by a slight yellow coloration of the rock material. The underlying Millboro shows little alteration other than the phyllitic sheen observed elsewhere in the outcrop. More important, geochemical analyses of samples from the basalt of the sill-dike, the contact zone, and the adjacent Millboro Shale do not indicate any wholesale transfer of trace or other metals from the basalt into the country rock, which would be the case if a large volume of liquid were present in the magma or if a large volume of ground water were present in the country rock. Here, we see the effects of a *dry* emplacement. The resulting contact metamorphic features are related primarily to heating rather than to hydrothermal alteration of the country rock.

There are a number of vesicles and amygdules present in the basalt. Many of the amygdules have been filled with crystals of calcite, quartz, and zeolites (see Kearns, 1993) after the basalt was emplaced and was cooled or cooling. The number and size of vesicles and amygdules appear to increase upward toward the exposed upper surface of the sill. The basalt itself consists of an equigranular, aphanitic groundmass of calcium plagioclase crystals, with phenocrysts of euhedral biotite and euhedral to corroded pyroxenes, probably augite (fig. 26). The phenocrysts indicate that the magma stopped its ascent to the surface long enough for the larger crystals to begin to precipitate. The corrosion of the pyroxene crystals indicates that they were in disequilibrium with the rest of the magma as it rose closer to the Earth's surface; they are partly resorbed. The aphanitic, *felted* groundmass of calcium plagioclase is the result of a final, relatively rapid stage of cooling near the surface.

Last, notice the cylindrical holes drilled into the surface of the sill-dike. Small cores were taken from the basalt (Ressetar and Martin, 1980) using a diamond coring drill. These samples, carefully marked with their compass orientation with respect to the Earth's magnetic north pole, were subjected to paleomagnetic analysis which yielded a middle Eocene date and confirmed the results of radiometric dating.

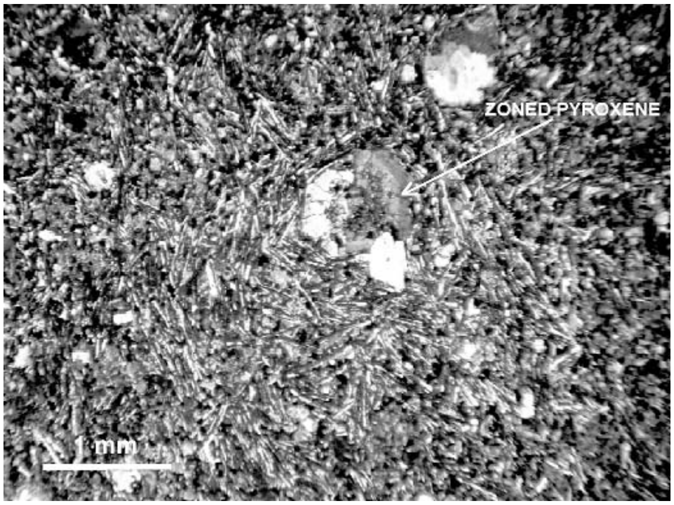

**Figure 26.** Photomicrograph of amygdaloidal basalt from Sugar Grove, Stop 7. Euhedral pyroxene with compositional zonation is visible, as is the groundmass of plagioclase with felted texture. Crossed polars.

## Acknowledgments

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## ROAD LOG FOLLOWS

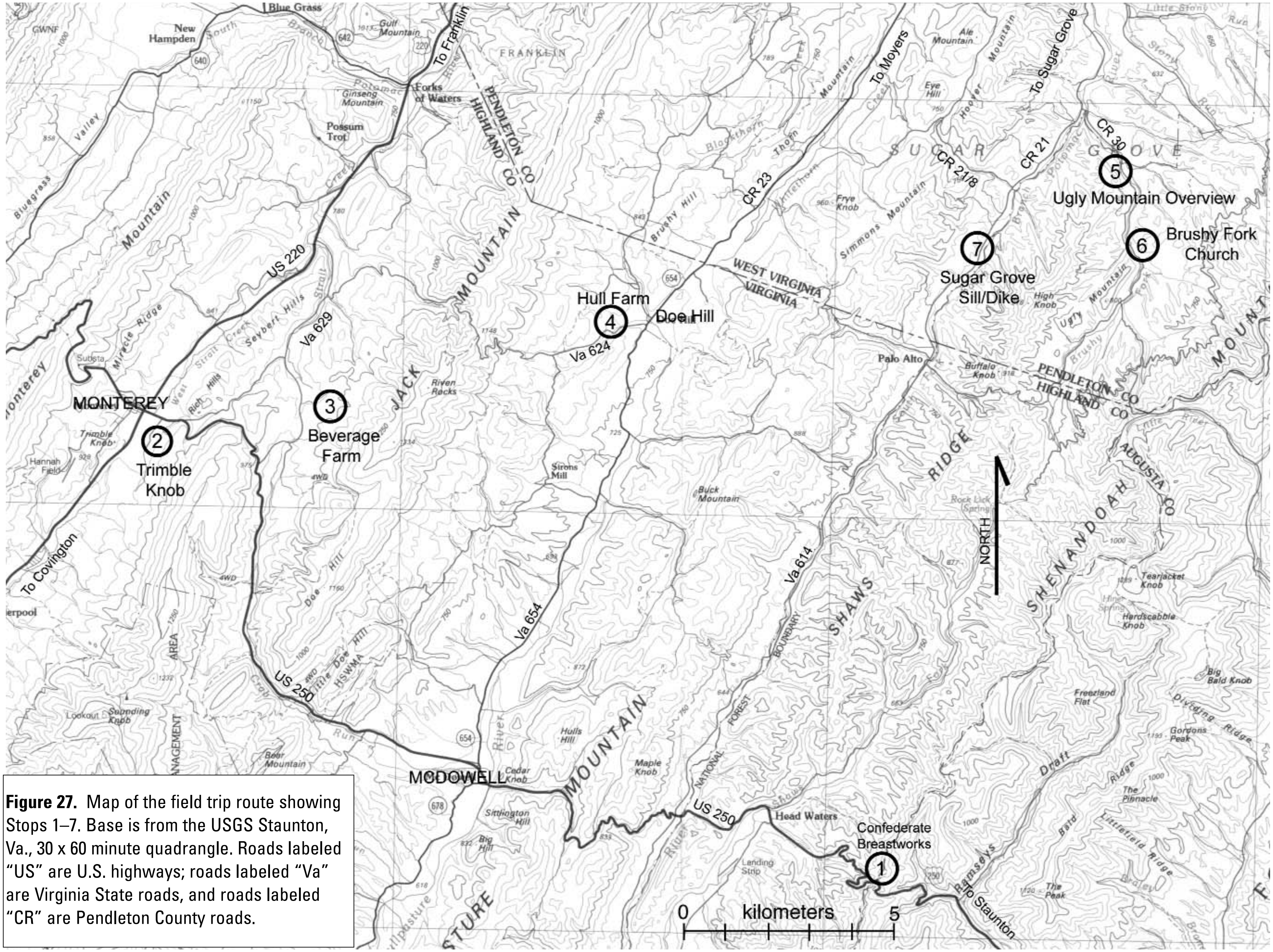

**Figure 27.** Map of the field trip route showing Stops 1–7. Base is from the USGS Staunton, Va., 30 x 60 minute quadrangle. Roads labeled "US" are U.S. highways; roads labeled "Va" are Virginia State roads, and roads labeled "CR" are Pendleton County roads.

# Road Log

See text for description of each stop, and figure 27 for stop locations.

## Day 1

From Washington, D.C., travel west on I-66 to junction with I-81. Turn south on I-81.

### Mileage

| Incremental | Cumulative | |
|---|---|---|
| 0.0 | 0.0 | Junction of I-81 and Va. 275 (Woodrow Wilson Parkway) in Staunton. Turn right (west) onto Va. 275. |
| 1.3 | 1.3 | Cross U.S. 11, continue west on Va. 275. |
| 3.6 | 4.9 | Junction of Va. 275 and U.S. 250. Turn right (west) onto U.S. 250. |
| 4.6 | 9.5 | Craigsville. |
| 9.9 | 19.4 | West Augusta. |
| 6.2 | 25.6 | Shenandoah Mountain. Turn into parking area at Confederate breastworks. |

## Stop 1. Confederate breastworks on Shenandoah Mountain (elevation 893 m; 2,930 ft).

### Mileage

| Incremental | Cumulative | |
|---|---|---|
| | | Turn right (west) from breastworks parking area onto U.S. 250. |
| 2.9 | 28.5 | Village of Head Waters. |
| 0.7 | 29.2 | Crest of Shaws Ridge (elevation 701 m; 2,300 ft). |
| 1.1 | 30.3 | This landslide occurred in 1998 and was seated in one of the ash beds of the Devonian Tioga Bentonite. The subsequent remediation by Virginia Department of Transportation can be seen. |
| 1.3 | 31.6 | Top of Bullpasture Mountain (elevation 835 m; 2,740 ft). |
| 2.7 | 34.3 | Village of McDowell. |
| 7.2 | 41.5 | Top of Jack Mountain (elevation 1,038 m; 3,406 ft). |
| 1.7 | 43.2 | Downtown Monterey. |

## End of Day 1.

## Day 2

### Mileage

| Incremental | Cumulative | |
|---|---|---|
| 0.0 | 0.0 | Junction of U.S. 250 and 220 in Monterey. Travel east on U.S. 250. |
| 0.2 | 0.2 | Junction of Va. 649 and U.S. 250. Turn right (south) onto Va. 649. |
| 0.5 | 0.7 | Travel south on Va. 649, past high school, to “End State Maintenance” sign and stop. |

## Stop 2. View of Trimble Knob.

### Mileage

| Incremental | Cumulative | |
|---|---|---|
| | | Retrace route back to U.S. 250. |
| 0.5 | 1.2 | Junction of Va. 649 and U.S. 250. Turn left (west) onto U.S. 250. |
| 0.2 | 1.4 | Junction of U.S. 250 and U.S. 220. Turn right (north) onto U.S. 220. |
| 3.6 | 5.0 | Junction of U.S. 220 and Va. 629 (Strait Creek Road). Turn right (east) onto Va. 629. |
| 2.7 | 7.7 | Turn left into entrance to Beverage Farm.<br>Park at main house. |

## Stop 3. Beverage Farm diatreme, basalt, and felsic rock.

Observe the rocks near the main house, then hike northeast approximately 0.7 km (0.4 mi) along the farm road to the small knoll that exposes “Breccia no. 1” and surrounding mafic and felsic rocks (fig. 14). *Note: As this location is on private property, **obtain permission from the landowners** before visiting the stop.*

### Mileage

| Incremental | Cumulative | |
|---|---|---|
| | | Board vehicles, return to Va. 629 and turn left (south). |
| 1.1 | 8.8 | Junction of Va. 629 and U.S. 250. Turn left (east) onto U.S. 250. |
| 6.4 | 15.2 | Junction of U.S. 250 and Va. 654 in McDowell. Turn left (north) onto Va. 654. |
| 7.1 | 22.3 | Junction of Va. 654 and Va. 624 in the village of Doe Hill. Turn left (west) onto Va. 624. |
| 1.3 | 23.6 | Turn right into Hull Farm. Pull into driveway and park. |

## Stop 4. Hull Farm basalt and diatreme.

*Note: As this location is on private property, **obtain permission from the landowners** before visiting the stop.*

### Mileage

| Incremental | Cumulative | |
|---|---|---|
| | | Board vehicles, turn left (east) onto Va. 624, and return to Va. 654 in Doe Hill. |
| 1.3 | 24.9 | Junction of Va. 624 and Va. 654 in Doe Hill. Turn left (north) onto Va. 654. |
| 1.2 | 26.1 | State line. Leave Highland County, Va., and enter Pendleton County, W. Va. Va. 654 becomes Doe Hill Road (County Road (CR) 23). |
| 5.5 | 31.6 | Junction of Doe Hill Road and Simmons Mountain Road (CR 23/2). Turn right (east) onto Simmons Mountain Road. |
| 2.9 | 34.5 | Simmons Mountain Road becomes Crummets Run Road (CR 21/8). Continue straight (east) on Crummets Run Road. |
| 1.7 | 36.2 | Junction of Crummets Run Road and Sugar Grove Road (CR 21). Turn left (north) onto Sugar Grove Road. |
| 1.5 | 37.7 | Junction of Sugar Grove Road and Brushy Fork Road (CR 30). Turn right (east) onto Brushy Fork Road. |
| 1.1 | 38.8 | Pull off in parking area to right of road at the junction of Fleisher Run Road (CR 30/2). |

## Stop 5. Ugly Mountain overview.

**Mileage**

| Incremental | Cumulative | |
|---|---|---|
| | | Continue ahead on Brushy Fork Road. |
| 1.6 | 40.4 | Park near, but do not block, church driveway. |

## Stop 6. Brushy Fork albitite dike.

Walk downstream (west) 69 m (75 yards) to streambed outcrop of albitite dike. Use caution in stream as rocks are slippery and the water is cold. Please take samples from rock already broken.

**Mileage**

| Incremental | Cumulative | |
|---|---|---|
| | | Board vehicles and retrace route on Brushy Fork Road back to Sugar Grove Road. |
| 2.6 | 43.0 | Junction of Brushy Fork Road and Sugar Grove Road.<br>Turn left onto Sugar Grove Road. |
| 0.2 | 43.2 | Park on east side of the road and walk across road to outcrop.<br>*Use caution as outcrop is close to road.* |

## Optional Stop. Wilfong Church gabbro.

**Mileage**

| Incremental | Cumulative | |
|---|---|---|
| | | Continue south on CR 21. |
| 2.3 | 45.5 | Park on the west (left) next to the outcrop. *Use caution as outcrop is close to road.* |

## Stop 7. Sugar Grove sill-dike.

**Mileage**

| Incremental | Cumulative | |
|---|---|---|
| | | Turn around and travel north on Sugar Grove Road. |
| 5.2 | 50.7 | Junction of Sugar Grove Road and Moyer Gap Road (CR 25) in the village of Sugar Grove.<br>Continue right on Sugar Grove Road. |
| 10.0 | 60.7 | Junction of Sugar Grove Road and U.S. 33 in Brandywine.<br>Turn right (east) onto U.S. 33. |
| 7.6 | 68.3 | State line and top of Shenandoah Mountain (elevation 1,052 m; 3,452 ft). |
| 10.4 | 78.7 | Rawley Springs. |
| 9.8 | 88.5 | Harrisonburg city limits. |
| 0.6 | 89.1 | Junction of U.S. 33 and High Street.<br>Turn right onto High Street. |
| 0.4 | 89.5 | Junction of High Street and Cantrell Avenue.<br>Turn left onto Cantrell Avenue. |
| 0.3 | 89.8 | Cross U.S. 11. Continue straight on Cantrell Avenue. |
| 1.2 | 91.0 | Junction of Cantrell Avenue and East Market Street.<br>Turn right onto East Market Street. |
| 0.5 | 91.5 | Junction of East Market Street and I-81. |
| | | Turn north onto I-81 and return to Washington, D.C. |

## End of Day 2.