DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

EARLY MESOZOIC BASINS WORKSHOP

FIELDTRIP # 1

THURSDAY MAY 14, 1987

Field Guide to the Igneous Rocks of the Southern Culpeper Basin, Virginia

by

Richard P. Tollo
George Washington University

David Gottfried
U.S. Geological Survey

Albert J. Froelich
U.S. Geological Survey

-- U. S. Geological Survey
National Center
Reston, Virginia 22092

U. S. Geological Survey Open-File Report 87-251

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

Early Mesozoic Basins Workshop Fieldtrip #1 -- 1987
Field Guide to the Igneous Rocks of the Southern Culpeper Basin, Virginia

Contents

Introduction

Igneous rocks of the Culpeper basin include 1) two extensive systems of diabase sheets, 2) three systems of chemically distinct diabase dikes, and 3) three series of multiple basalt flows. The diabase intrudes both Upper Triassic and Lower Jurassic strata and the sheets are bordered by extensive contact aureoles. Froelich and Gottfried (in press) have subdivided the sheets on the basis of chill margin geochemistry into high-titanium, quartz normative (HTQ) and low-titanium, quartz normative (LTQ) tholeiite subtypes, correlating these to the bimodal populations of diabase dike compositions originally defined for the eastern North America (ENA) province by Weigand and Ragland (1970). These compositions are chemically similar to those of the York Haven (HTQ) and Rossville (LTQ) diabase sheets of the Gettysburg basin in Pennsylvania (Smith and others, 1975). 40Ar/39Ar age spectra yielding a mean age of 198.4 + 2.1 Ma (Sutter, 1985) supported by paleomagnetic data (Raymond and others, 1982) suggest that the intrusion of HTQ and LTQ diabase was essentially contemporaneous, approximately concurrent with basalt extrusion, and restricted to a relatively short interval within the Early Jurassic. Local field relations, however, indicate that at least some of the LTQ diabase intruded after emplacement of the HTQ sheets (Froelich and Gottfried, in press). The individual HTQ sheets, enclosing extensive orthopyroxene-cumulate zones and (or) evolved granophyre or ferrogabbro sections, appear to have fractionated as systems in which lateral migration and flow differentiation were important. The petrologic systematics of the LTQ sheets show little evidence for differentiation and are generally less well defined. Initial data suggest that these magmas are not part of a direct lineage involving the HTQ diabase.

Dike rocks within the Culpeper basin are divisible into three petrologic subtypes on the basis of geochemistry and orientation. The Seneca dike system trends north-northeast along the eastern margin of the basin but occurs primarily in the Paleozoic metamorphic rocks adjacent to the northeastern edge of the basin (Leavy and others, 1983). These dikes are characterized by HTQ compositions and may form part of a petrologic suite defined by several HTQ diabase sheets and transverse dikes in the east-central portion of the basin (Froelich and Gottfried, in press). The Ashburn-Dickerson dike system, occurring 7-9 mi (11-15 km) west of the Seneca dikes and also striking north-northeast, forms part of the throughgoing Frederick dike system and is characterized by LTQ compositions. These dikes extend through the central portion of the basin (Leavy and others, 1983) and form part of a suite encompassing the LTQ diabase sheets located in that area (Froelich and Gottfried, in press). A series of north- and northwest-trending olivine-bearing dikes comprise a third distinct system and, together with several poorly exposed olivine-bearing plugs, may constitute an olivine normative magmatic suite (Froelich and Gottfried, in press).

A sequence of at least 13 basalt flows is intercalated with Lower Jurassic strata in the west-central portion of the Culpeper basin (Lee, 1979; 1980). These flows comprise three series mapped (from oldest to youngest) as the Mount Zion Church (2 flows), Hickory Grove (2 flows), and Sander (9 flows) Basalts (Lee, 1979; 1980; Lee and Froelich, in press). These basalts include both HTQ and LTQ lavas, although the latter is volumetrically rare and probably restricted to the third flow of the Sander Basalt in the central and northern portions of the basalt outcrop belt (Tollo, in press). The Mount Zion Church and Hickory Grove Basalts and the first flow of the Sander Basalt represent chemically distinct HTQ subtypes that can be correlated throughout the length of the outcrop belt. All overlying flows within the Sander Basalt are locally variable in composition. The stratigraphy of basalt petrochemical types indicates that the composition of succeeding lavas was not controlled simply by tholeiitic fractionation. Correlation of the basalt types along strike suggests that volcanic activity in the basin was initially areally extensive, possibly with significant ponding of lava in the south, but later involved more local and chemically distinct eruptions (Tollo, in press).

This field trip is an introduction to the igneous rocks of the southern Culpeper basin. The first three stops are located within the basalt sequence near Casanova, Virginia, and will provide an opportunity to examine flows assigned to each of the three extrusive series. Stop 1 is located at the base of the volcanic sequence where two flows of the Mount Zion Church Basalt are separated by a thin lens of intercalated strata. Stop 2 provides a cross section through part of the Hickory Grove Basalt at a locality where distinct zones of brittle fracture deformation and subsequent hydrothermal mineral activity are present. Stop 3 is located in Sander quarry where part of a thick ponded sequence comprising the lowermost portion of the Sander Basalt is exposed. Exceptional examples of chemically evolved, coarse-grained differentiates of the basalt will also be examined at this locality. The last three stops are located in the southern part of the Culpeper basin and have been chosen as representative of the lithologic variation characterizing the HTQ diabase sheets in this area. Stops 4a-4c represent a traverse through the eastern flank of the Rapidan sheet and provide a composite cross section of the diabase stratigraphy including the upper and lower chill margins, noritic gabbro cumulates, and leucocratic orthopyroxene diabase. Stop 5 provides a further opportunity to examine the textural characteristics of the orthopyroxene cumulates of this sheet located at the Virginia Granite quarry at nearby Buena. Thin late-stage veins composed of tourmaline + potassic feldspar + chlorite cut the diabase at this locality. Stop 6, located 15 miles (24 km) northeast of Buena at Berry Hill, contiguous to the Rapidan diabase sheet, includes exposures of granophyre and ferrogabbro that may represent the evolved products of typical HTQ differentiation in the Culpeper basin.

Road Log

The field trip begins in the visitors' parking lot at the U.S. Geological Survey in Reston, Virginia. Measured mileage begins at the entrance to this lot at the intersection with South Lakes Drive. Incremental mileage is given in parentheses. The individual stop locations are located on a generalized map of the igneous geology of the Culpeper basin in figure 1.

Cumulative mileage		Description
0.0	(0.0)	Exit lot by turning left onto South Lakes Drive.
0.5	(0.5)	Turn right onto Reston Avenue (Route 602).
3.1	(2.6)	Reston Avenue becomes West Ox Road (Route 608), continue south.
6.4	(3.3)	Intersection of Routes 608 and 50, continue south on Route 608.
7.3	(0.9)	Cross over Interstate 66 (I-66), continue south on

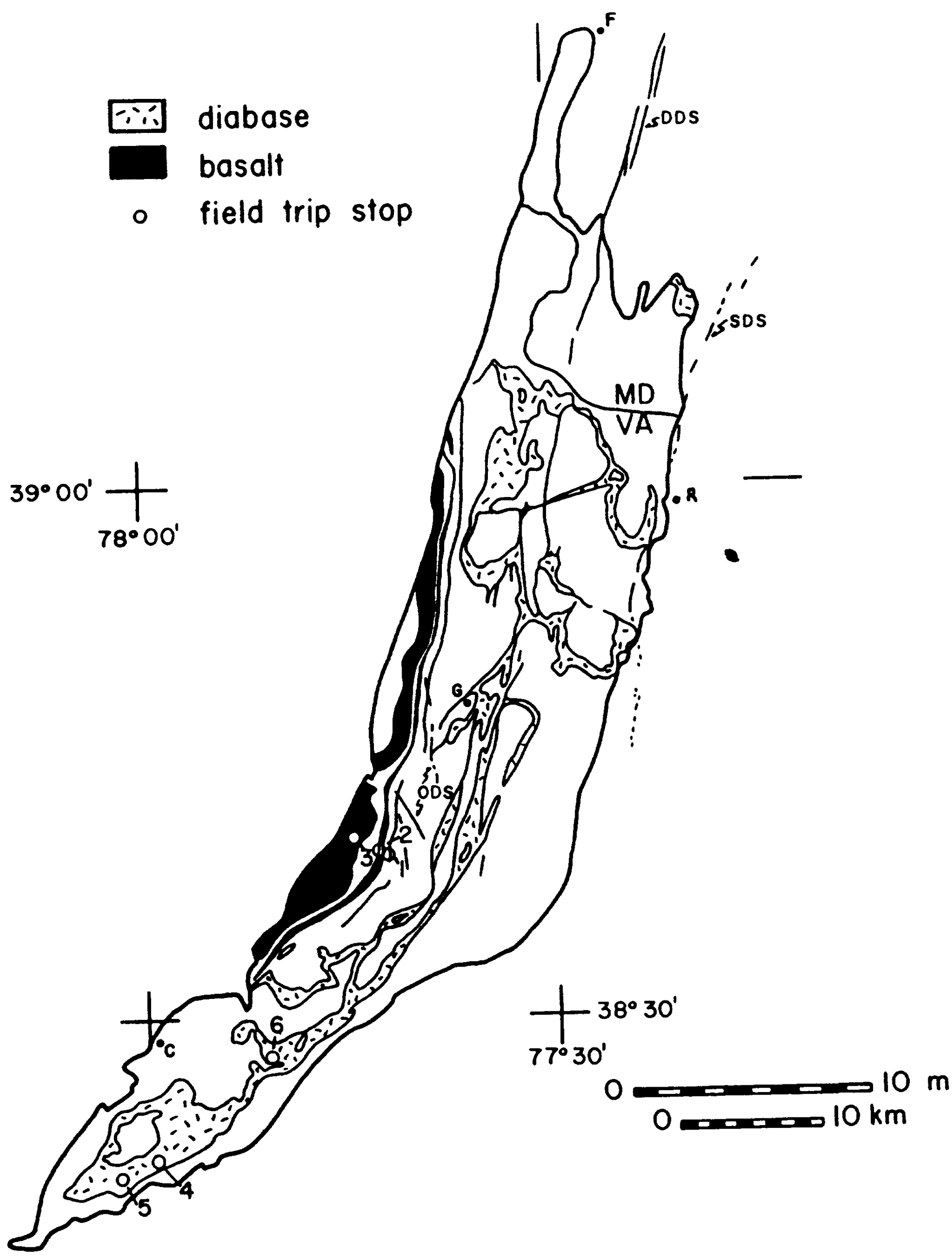

Figure 1: Geologic map showing the distribution of major igneous units within the Culpeper basin. Numbers refer to field trip stops and are keyed to the text. DDS, Dickerson dike system; SDS, Seneca dike system; ODS, olivine-bearing dike system; F, Frederick; G, Gainesville; C, Culpeper; R, Reston.

		Route 608.
8.2	(0.9)	Turn right onto Route 29, Lee Highway, proceed west.
11.5	(3.3)	Turn left onto Route 28, proceed south.
19.5	(8.0)	Fork in road, bear left to continue on Nokesville Road.
26.2	(6.7)	Intersection of Routes 28 and 652, continue south on Route 28.
31.0	(4.8)	Entering Catlett.
33.5	(2.5)	Turn right onto Route 616, proceed northwest.
35.4	(1.9)	STOP 1: Turn left off of highway, park on unpaved road. Exposures are located along the railway across Route 616 and to the left.

STOP 1: Mount Zion Church Basalt (Catlett Quadrangle)

The exposures at this stop provide a partial cross section through two flows forming the base of the volcanic sequence in the Culpeper basin (figure 2). The first rocks exposed proceeding northwest along the railway are thin-bedded to finely laminated red sandstones and interbedded siltstones of the Catharpin Creek Formation (Lee and Froelich, in press). Palynological evidence indicates that these strata are Early Jurassic in age with the Triassic-Jurassic boundary located approximately 200 feet (60 m) southeast along Route 616 (Cornet, 1977). The lowermost flow of the Mount Zion Church Basalt is approximately 23 feet (7 m) thick and is composed of dark-gray, fine-grained, sparsely porphyritic basalt. The lower contact with the underlying sedimentary rocks can be located within several feet and it is important to note the lack of obvious contact metamorphism. This is characteristic of the basalt flows in the basin and helps to distinguish the volcanics from fine-grained intrusive counterparts. The two flows exposed at this locality are separated by a thin lens of thin-bedded red sandstone with local silty interbeds. Such intercalated strata are not continuous along strike within the formation. The upper flow at this locality is approximately 75 feet (23 m) thick and is composed of pale-green, generally fine-grained, sparsely porphyritic basalt that is considerably more altered than the lower flow. The upper contact of this flow with the overlying strata of the Midland Formation (Lee and Froelich, in press) is not exposed here, but is interpreted to be located approximately 200 feet (61 m) southeast of the railroad bridge on the tracks between stops 1 and 2 (Lee, 1980).

The basalt comprising both flows at this locality is characterized in thin section by a distinctly glomeroporphyritic texture defined by clusters of subhedral to euhedral augite phenocrysts locally intergrown with relatively rare, generally finer grained, subhedral plagioclase. The groundmass consists primarily of abundant, finely granular augite and microlitic plagioclase locally intergrown with brown serpentine that is probably pseudomorphic after original olivine. Brown intersertal glass (mostly devitrified) is present throughout the groundmass and typically contains abundant skeletal magnetite. Secondary alteration of all phases is considerably more widespread in the upper flow.

The chemical compositions (table 1) of samples from each of the flows exposed at this locality are typical of the range characterizing the Mount Zion Church Basalt and reflect the relative degree of alteration observed in thin section. Values for 10 selected elements from the lower flow sample (MZ-13-86) correspond closely to the average concentrations in two relatively unaltered samples from the geochemical type locality (figure 3). This close

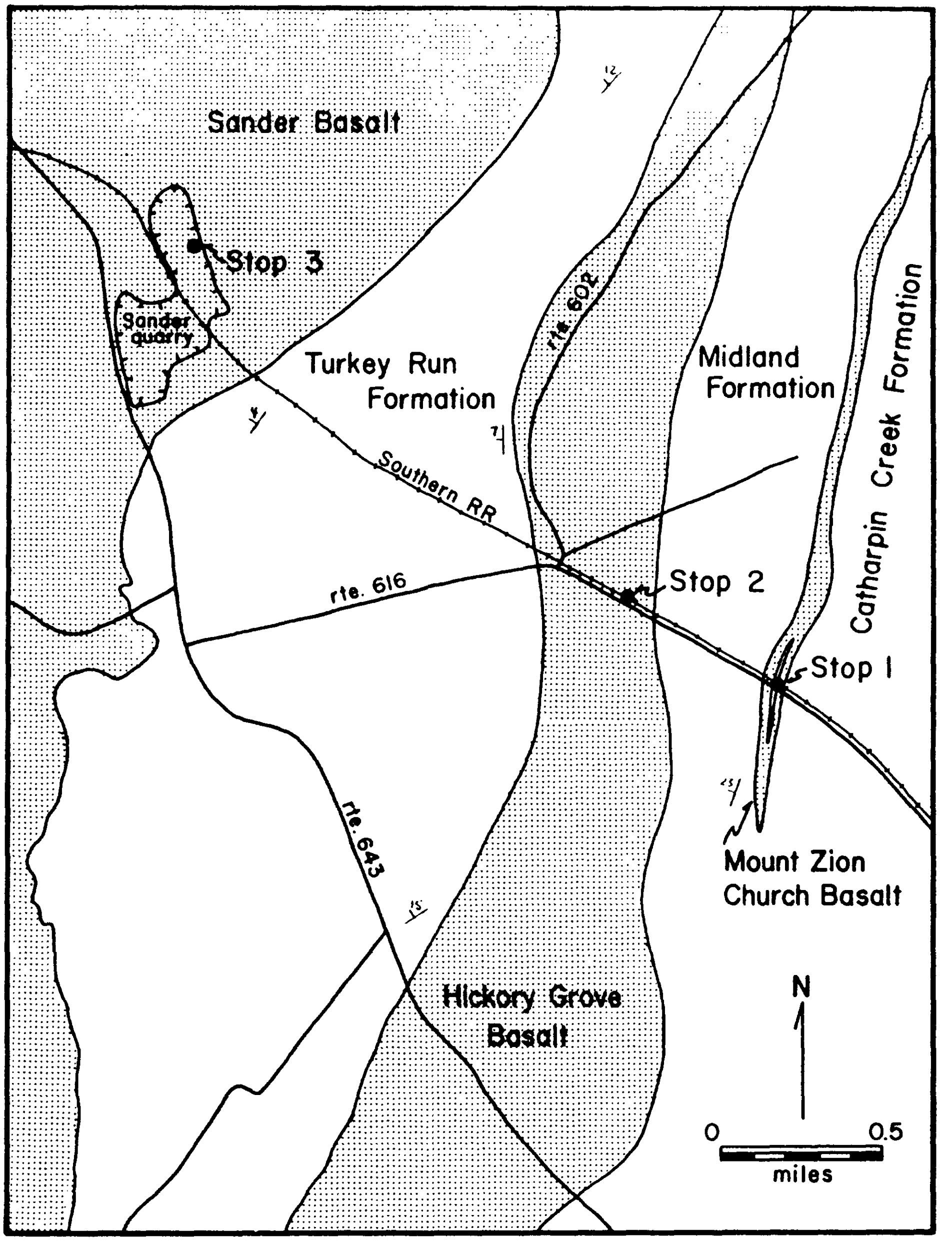

Figure 2: Geologic map of part of the Catlett Quadrangle in the area of Casanova, Virginia, showing the location of field trip stops 1-3. Map modified after Lee, 1980.

Table 1: Major- and trace-element compositions of samples from field trip stops 1 and 2. [Major element analyses are normalized to 100 weight percent (anhydrous); trace-element concentrations are expressed in parts per million (ppm); analytical methods for all geochemical data are described in Appendix A; n, number of analyses]

	Stop 1: Mount Zion Church Basalt		Stop 2: Hickory Grove Basalt
	lower flow	upper flow	
Sample	MZ-13-86	MZ-12-86	HG-16-86
SiO_2	51.89	52.29	53.26
TiO_2	1.15	1.15	1.09
Al_2O_3	14.30	14.52	14.09
Fe_2O_3*	11.14	11.24	13.43
FeO			
MnO	0.18	0.20	0.22
MgO	7.65	7.72	5.15
CaO	11.41	7.77	9.22
Na_2O	2.00	4.91	2.62
K_2O	0.15	0.07	0.74
P_2O_5	0.13	0.13	0.18
Total	100	100	100
n	2	2	2
Nb	7.2	6.9	4.3
Zr	101	101	96
Sr	233	838	260
Zn	84	84	95
Ni	96	87	17
Cr	295	264	14
V	241	240	268
Ce	14		
Ba	182		

* total iron expressed as Fe_2O_3

n: number of analyses

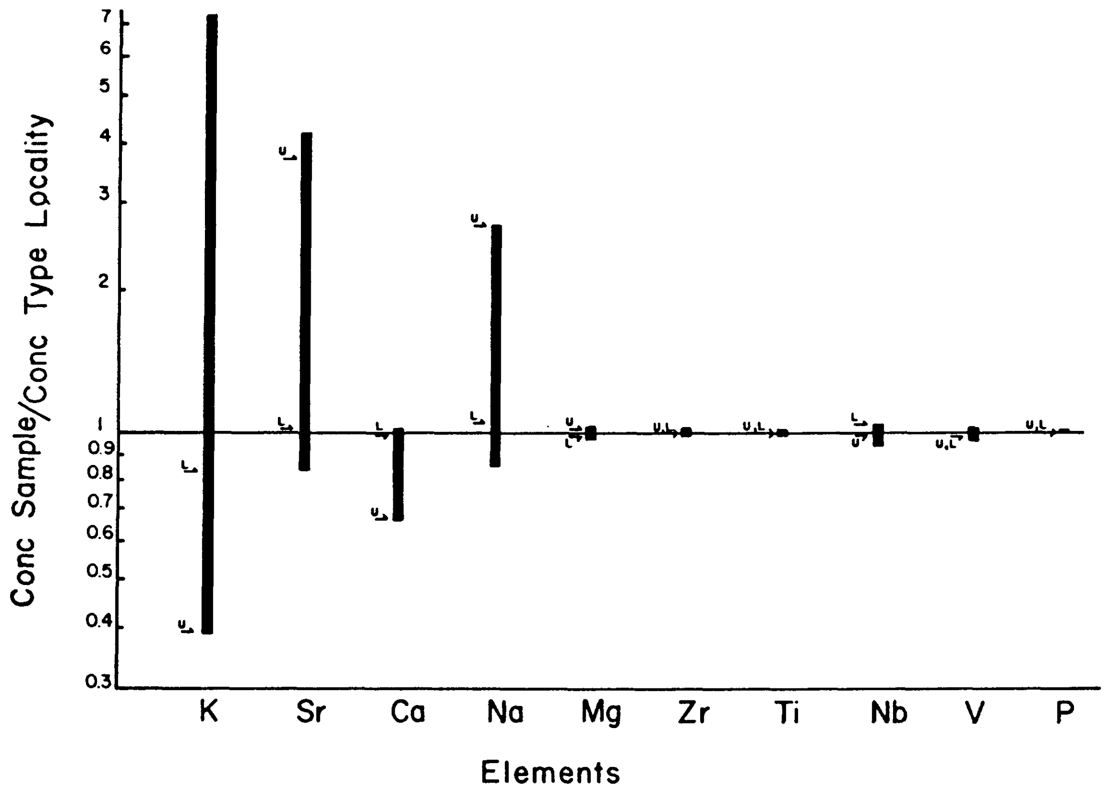

Figure 3: Plot showing the range of values for selected elements from samples of the Mount Zion Church Basalt expressed as a ratio relative to the average concentration of each element in samples from the geochemical type locality (see Tollo, in press, for location). Values for samples from the upper (U) and lower (L) flows at stop 1 are indicated by arrows.

correspondence indicates that these compositions approximate that of the original lava. Values for the highly altered upper flow sample diverge widely from those of the type locality for K, Sr, Ca, and Na, indicating that these elements are mobile during alteration. These data are generally consistent with the observations of Gottfried and others (1978), except for the radical decoupling of Ca and Sr which show pronounced depletion and enrichment, respectively. Values for elements of smaller ionic radii, including Mg, Zr, Ti, Nb, V, and P, exhibit very limited ranges throughout the Mount Zion Church flow series, indicating that alteration has little effect on the concentrations. This characteristic immobility indicates that the concentrations of these elements may be used as indicators of magmatic evolution. It is instructive to note that the enrichment of Na due to alteration is sufficient to yield a spurious olivine normative composition for the altered sample (table 2).

The Mount Zion Church Basalt, like the initial flow series in both the Newark and Hartford basins (Orange Mountain and Talcott Basalts, respectively), is the least chemically evolved of the tholeiitic volcanic sequence, as demonstrated by high values of MgO, Cr, and Ni (Puffer and others, 1981; Philpotts and Martello, 1986; Tollo, in press). Abundances of the trace elements Y and V are consistent with this trend, but values for Ba and Zr are anomalously high in these initial flows, exceeding the levels characterizing the overlying extrusives in each basin. The composition of the Mount Zion Church Basalt closely resembles the median composition of York Haven diabase chilled margins reported by Smith and others (1975). Within the Culpeper basin, the closest analog to the composition of the Mount Zion Church Basalt is represented by the chilled margin of the HTQ Boyds sheet (Froelich and Gottfried, in press), although the major-element compositions of the chilled margins from nearly all of the HTQ sheets are similar.

Return to the vehicles. Turn around on the unpaved road and carefully turn left onto Route 616. Proceed northwest.

36.3 (0.9) STOP 2: Turn right onto Route 747 and immediately park on the left across from the abandoned store. The exposures are located along the railway approximately 1200 feet (360 m) to the southeast.

STOP 2: Hickory Grove Basalt (Catlett Quadrangle)

The exposures at this stop are located within the central portion of the Hickory Grove Basalt (figure 2). The contact between this flow and the overlying strata of the Turkey Run Formation (Lee and Froelich, in press) is located approximately 300 feet (91 m) west of the intersection of Routes 616 and 747 (Lee, 1980). The exposures at this locality are composed of fine-grained, locally porphyritic basalt characterized by pale reddish-gray weathered surfaces typical of the Hickory Grove throughout the basin. Several zones of brittle fractures, which probably represent nearly vertical, minor faults, occur at the eastern end of the roadcut. The largest of these is approximately 6 feet (2 m) wide and strikes N.14°W., parallel to two larger faults mapped in the quadrangle by Lee (1980). The angular basalt fragments contained within these zones are cemented primarily by calcite and quartz. Numerous cavities are present and are partially or wholly filled either with these minerals or with banded gray agate. Slickensided surfaces are abundant throughout the exposure.

Table 2: Normative compositions of samples from field trip stops 1 and 2.

Sample:	MZ-13-86	MZ-12-86	HG-16-86
quartz	3.36	-	4.62
orthoclase	1.11	0.56	4.45
albite	16.77	41.40	22.01
anorthite	29.47	17.24	24.46
diopside	21.61	16.81	17.20
hypersthene	22.64	1.79	21.74
olivine	-	16.90	-
magnetite	1.62	1.62	1.86
ilmenite	2.13	2.13	2.13
apatite	0.34	0.34	0.34

A sample collected from the central portion of this exposure is characterized in thin section by an overall fine-grained, intergranular texture comprised of randomly oriented, subhedral plagioclase laths and granular augite intergrown with relatively sparse, generally altered pigeonite. Relatively rare plagioclase crystals exceeding 1 mm in length may represent phenocrysts. This lack of clear definition between phenocrysts and groundmass is a characteristic distinction between the basalt of this flow series and the first flow of the overlying Sander Basalt, in which both plagioclase and augite form distinct phenocrysts, together comprising as much as 14 modal percent of the rock in this part of the basin. The oxide minerals in this basalt are typically blocky in form and locally approach 0.5 mm in diameter, contrasting sharply with the exclusively very fine-grained, skeletal types that characterize the underlying Mount Zion Church Basalt. Turbid, light-colored mesostasis is present in small amounts in the interstices between grains but is typically too altered to analyze adequately.

The chemical composition of the sample collected from this roadcut (table 1) is typical of the Hickory Grove Basalt and corresponds to the high-iron, quartz normative (HFQ) subdivision of the HTQ magma type, as originally proposed by Weigand and Ragland (1970). Like the second flow series in both the Hartford and Newark basins, the Hickory Grove Basalt is characterized by a composition that is lower in MgO and higher in iron, at nearly constant TiO_2 content, than the underlying volcanic unit. Relative to the Preakness and Holyoke Basalts (Newark and Hartford basins, respectively), the Hickory Grove is the most chemically evolved of the "middle" series, as indicated by the characteristically high values of 72-73 for mafic index (Tollo, in press). Trace-element evidence bearing on the possible derivation of Hickory Grove type basalt from Mount Zion Church type magma is contradictory. Some elements show predicted enrichment (V) or depletion (Ni, Cr), but others remain essentially constant (Zr) (Puffer and others, 1981; Philpotts and Martello, 1986; Tollo, in press).

Gottfried and others (1978) have demonstrated that the concentrations of rare-earth elements (REE) in ENA lavas remain essentially unchanged by the effects of alteration and low-grade metamorphism. Normalized REE patterns of selected samples from the Mount Zion Church and Hickory Grove Basalts (figure 4) support this observation and show the light-REE enrichment and slight negative Eu anomaly typical of HTQ magma types in the ENA province (Ragland and others, 1971). The curves for these basalts show considerable overlap for the light-REE, but diverge for the heavy elements with the Mount Zion Church values (La/Yb = 3.2) somewhat lower relative to the Hickory Grove (La/Yb = 2.6). These data suggest that these basalts were either derived from the same or similar undepleted source materials and have experienced different degrees of heavy-REE (clinopyroxene) fractionation or are derivatives of somewhat different sources.

Return to the vehicles. Turn right onto Route 616 and proceed west.

37.5	(1.2)	Turn right onto Route 643. Proceed north.
38.7	(1.2)	STOP 3: Turn right into entrance to Sander quarry. Proceed cautiously and beware of heavy truck traffic. The exposures to be examined are located along the eastern wall of the northern pit.

STOP 3: Sander Basalt (Catlett Quadrangle)

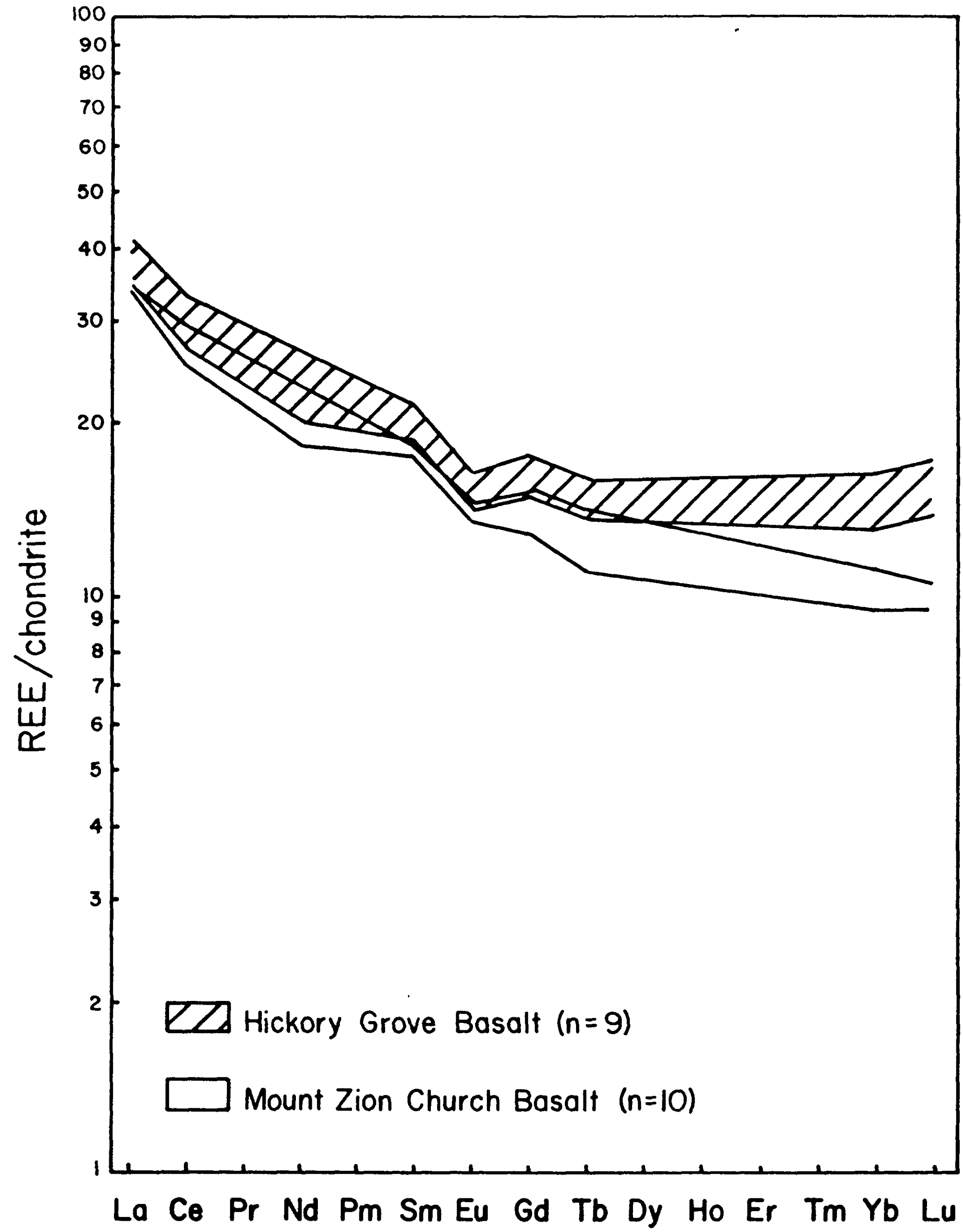

Figure 4: Plot of abundances of rare-earth elements (REE) in selected samples of the Mount Zion Church and Hickory Grove Basalts (n = number of samples analyzed). Data are normalized to average REE abundances in chondrites (Anders and Ebihara, 1982).

Sander quarry provides an important cross section through the lower portion of the Sander Basalt in the southern Culpeper basin. Assuming an orientation conformable with the underlying Turkey Run Formation which is exposed 300 feet (91 m) southeast of the southernmost quarry wall, a minimum stratigraphic thickness of approximately 181 feet (55 m) of basalt is present in nearly continuous exposure. The rocks to be examined at this stop extend from approximately the midpoint of the eastern wall northward to the northwest corner of the quarry and comprise the upper half of the exposed sequence. The basalt at this location is generally greenish- to reddish-gray, fine- to medium-grained, and characteristically porphyritic. The rocks show a moderately developed colonnade-style columnar jointing oriented approximately perpendicular to the regional dip throughout most of the section, except near the northwest corner of the quarry where curvicolumnar entablature is developed. The transition between the two types of columnar jointing is relatively abrupt, occurring over an interval of less than 10 feet (3 m). Medium- to coarse-grained gabbroid veins crosscut the basalt at three locations along the eastern quarry wall (McFall, 1985). These gabbroids form an irregular network of meter-scale veins, are characterized by both sharp and gradational contacts with the surrounding basalt, and, in at least one case, extend across the full width of the quarry floor. The veins are locally associated with abundant sulfides occurring as joint coatings.

The basalt in this portion of the quarry is characterized in thin section by an overall fine-grained inequigranular to sparsely porphyritic texture comprised of randomly oriented grains of plagioclase + augite + pigeonite + oxide with local areas of highly altered mesostasis. Plagioclase is generally coarser grained than the predominantly granular pyroxene and, where locally exceeding 1 mm in length, may represent phenocrysts. Augite and pigeonite are present in subequal amounts and may be distinguished by the typically more altered nature and characteristic herringbone twinning of the former. The mesostasis is typically highly altered, although local patches of identifiable granophyre are present. The oxide phase is dominantly magnetite and ranges from blocky to irregular in habit and from very fine-grained to approximately 0.5 mm in diameter. The medium- to coarse-grained gabbroic veins contain the same plagioclase + augite + pigeonite + oxide assemblage as the enclosing basalt. Elongate augite prisms are typically prominent and locally sufficiently coarse-grained to show herringbone twinning in hand specimen. Oxide minerals occur as both coarse, blocky grains and as very fine-grained overgrowths nucleated on subhedral silicates. Although the overall texture of the rock is medium- to coarse-grained, a considerable amount of very fine-grained mesostasis occurs in the interstices. Typically highly altered and replaced, this mesostasis locally contains abundant apatite(?) needles. Plagioclase and pyroxene crystals extend into such areas with euhedral outlines.

Analyses of samples from near both the top and the base of the exposed sequence (table 3, analyses a and b, respectively) indicate that the basalt in this quarry is dominantly of the type A variety typical of the lowermost Sander flow throughout the Culpeper basin (McFall, 1985; Tollo, in press). This basalt corresponds to the HFQ magma type of Weigand and Ragland (1970). The composition is considerably lower in TiO_2 than those of the uppermost flow units in the Newark (Hook Mountain Basalt) and Hartford (Hampden Basalt) basins, but is quite similar to the average compositions of the "middle" flow units (Puffer and others, 1981; Philpotts and Martello, 1986). This

Table 3: Major- and trace-element compositions of selected samples from Sander quarry [a, average of ten samples (analyzed in duplicate) from a 74-foot (22.5 m) vertical traverse near the base of the basalt in the southern pit; b, sample collected from entablature unit near top of exposed sequence approximately 120 feet (36 m) southeast of the northern corner of the northern pit; c, sample collected from colonnade unit approximately midway along the eastern wall of the northern pit; d, average of two samples collected from gabbroid veins in central portion of northern pit. All data are from McFall (1985). Major-element analyses are normalized to 100 weight percent (anhydrous); trace-element analyses are expressed in parts per million (ppm); n, number of analyses]

	a	b	c	d
Sample	VT	2-4A-84	2-7A-84	2-9/14A-84
SiO2	52.58	51.34	53.30	54.06
TiO2	1.09	1.10	1.31	1.82
Al2O3	13.84	13.82	13.60	11.95
Fe2O3*	13.73	13.86	13.98	16.36
FeO	-	-	-	-
MnO	0.21	0.22	0.21	0.25
MgO	5.56	5.74	4.82	3.42
CaO	9.71	8.70	8.97	8.12
Na2O	2.54	4.76	2.96	2.77
K2O	0.59	0.29	0.67	1.03
P2O5	0.15	0.17	0.18	0.22
Total	100	100	100	100
mafic index	71	71	74	83
n	20	2	2	4
Y	28	28	30	39
Sr	143	190	229	179
Rb	18	9	23	32
Pb	6	5	7	10
Ga	19	18	20	21
Nb	5.2	4.6	5.5	7.9
Zr	91	88	107	140
Zn	109	110	121	116
Ni	30	34	16	11
Cr	20	19	17	n.d.
V	343	330	394	416
Ce	21	20	22	31
Ba	150	151	158	195

*total iron expressed as Fe2O3

n: number of analyses

compositional trend underscores the uniqueness of the Culpeper volcanic sequence. Analyses a and b in table 3 also offer further evidence for the mobility of Ca, Na, K, Sr, and Rb during alteration and serve to demonstrate the immobility of Ti, Y, Ga, Nb, Zr, and V under the same conditions. The REE pattern for such basalt is also, as stated previously, relatively insensitive to the effects of alteration. Data for 9 samples of type A Sander Basalt (fig. 5) show a subdued (La/Yb = 2.0) light-REE enrichment pattern in which the data overlap those of the Hickory Grove for the heavy-REE, and are generally more depleted in the light-REE than either of the underlying flow series. The data suggest that these basalts may share the same or similar source materials but indicate that they are unlikely to be related by any simple fractionation mechanism.

The basalt in the central and southern portions of the northern pit is considerably more chemically evolved than that exposed elsewhere and corresponds to the type E category of Tollo (in press). Sample 2-7A-84 (table 3, analysis c) was collected approximately midway along the eastern wall and is characterized by marked enrichment in Si, Ti, P, Zr, and V, slight enrichment in Fe, Y, and Nb, and depletion in Mg and Cr. All of these elemental trends are consistent with the development of type E basalt by tholeiitic fractionation of type A. The type E basalt is associated with coarse-grained gabbroids that occur as irregular, anastomosing veins and dikelets cutting the basalt. Chemical analyses of two samples from such veins (table 3, analysis d) indicate further enrichment in Si, Ti, Fe, P, Zr, V, Y, and Nb accompanied by depletion in both Mg and Cr relative to the enclosing type E basalt. These data strongly suggest that these are segregation gabbroids formed by tholeiitic fractionation of type E basalt. Such fractionation would be consistent with the parallel REE patterns showing enrichment by the gabbroids in all elements relative to the surrounding type E basalt (figure 6). These veins are somewhat similar in scope to those reported from lava lakes on Kilauea (Wright and Okamura, 1977; Helz, 1980), but in this case do not occur as subhorizontal sheets. As at Kilauea, the mode of origin and mechanism of emplacement of such large volumes remain problematical, although textural evidence indicates that the segregation material was (1) probably relatively rich in volatile content, (2) emplaced into an at least semi-rigid basalt host, and (3) not quenched along the margins. The marked increase in iron with only slight increase in SiO_2 is similar to that observed in basalt-segregation vein pairs by Kuno (1965), who interpreted the trend as indicative of crystallization under conditions of relatively low oxygen fugacity.

Return to the vehicles and carefully drive through the quarry. Beware of heavy truck traffic. Turn right onto Route 643 (eventually becomes Route 672) and proceed north.

42.5	(3.8)	Turn left onto Route 15/17/29. Proceed south.
48.9	(6.4)	Entering Opal.
49.6	(0.7)	This subtle ridge is underlain by the fourth flow of the Sander Basalt. The low-lying roadcut on the left is composed of type B basalt and represents the first occurrence of a petrochemical type other than the type A in the stratigraphy of the Sander Basalt in the southern Culpeper basin.
60.3	(10.7)	Intersection with Route 663 near Brandy Station. Continue west-southwest on Route 15/29.

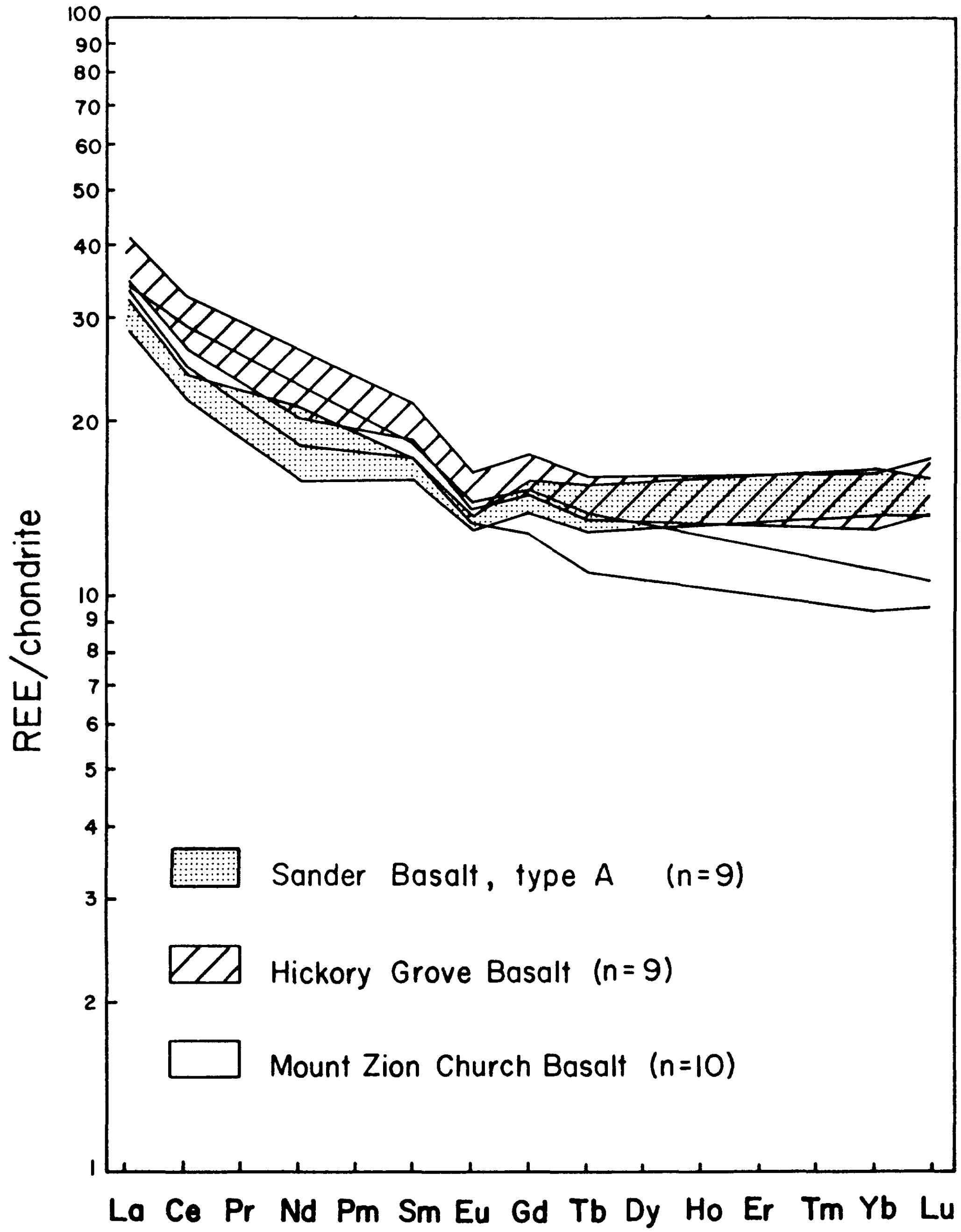

Figure 5: Plot of abundances of rare-earth elements (REE) in 9 samples of type A Sander Basalt from the lowermost Sander flow (n = number of samples analyzed). REE patterns of Mount Zion Church and Hickory Grove Basalts from figure 4 are plotted for comparison. Data are normalized to average REE abundances in chondrites (Anders and Ebihara, 1982).

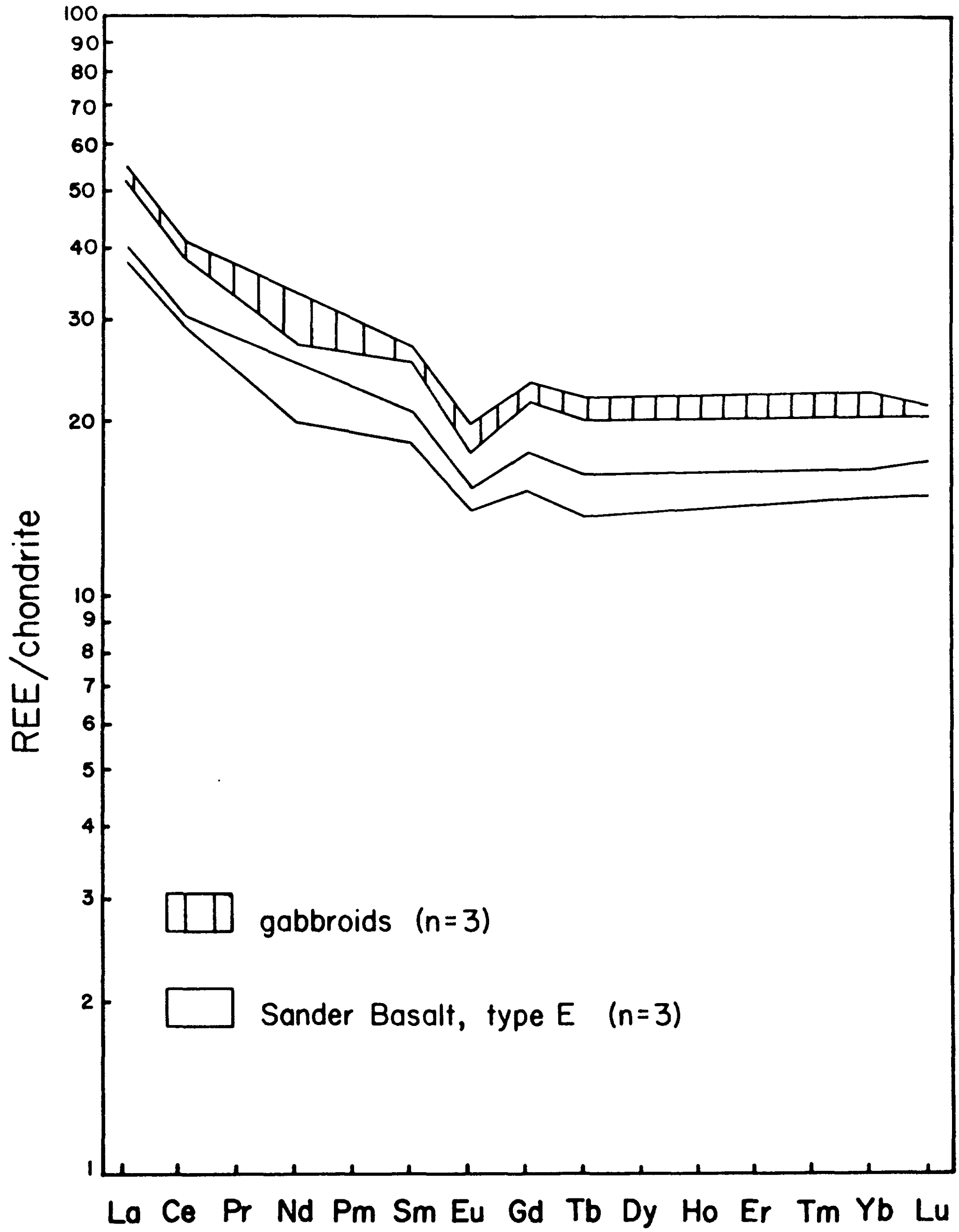

Figure 6: Plot of abundances of rare-earth elements (REE) in type E basalt and associated segregation gabbroids from Sander quarry (n = number of samples analyzed). Data are normalized to average REE abundances in chondrites (Anders and Ebihara, 1982).

66.6	(6.3)	Exit from Route 15/29. Turn left onto Route 3/522 and proceed southeast over Route 15/29.
67.3	(0.7)	Turn right onto Route 522. Proceed south.
70.7	(3.4)	Intersection with Route 615. Bear left to continue on Route 522.
74.6	(3.9)	Turn right onto Route 647. Proceed southwest.
75.4	(0.8)	STOP 4a: Turn right onto Route 655 and park along the right shoulder. The exposures are located along Route 655 on both sides of the intersection with Route 647.

STOP 4a: Rapidan diabase sheet (Unionville Quadrangle)

Stops 4a-4c represent a cross section through the eastern flank of the Rapidan sheet and provide an opportunity to examine the variety of diabase lithologies which comprise this HTQ layered intrusion. The chemical composition of samples collected along a traverse across the sheet is presented in table 4. At this location, the sheet dips gently toward the northwest and is approximately 1,200 feet (360 m) thick. The basal contact of the diabase in this area strikes approximately northeast and is located adjacent to Route 647 for several miles east and west of this intersection. Fine-grained hornfels at the base of the sheet is present in the field south of the intersection and along the adjacent Route 655. Dark-colored, fine-grained to aphanitic diabase in the ditch along Route 655 on the north side of the intersection represents part of the chilled margin of the sheet. Boulders and outcrops located within approximately 50 feet (15 m) of the intersection northwest along Route 655 are composed of dark-colored, medium-grained, orthopyroxene-bearing diabase (sample K-6, table 4) that contrasts sharply with the fine-grained diabase of the chilled margin. Farther northwest, medium-grained diabase locally contains prominent phenocrysts of golden-colored orthopyroxene and is interpreted to represent the base of a cumulate zone within the intrusion.

A sample (K-7, table 4) collected from the chilled margin zone contains 1.1 weight percent TiO_2 and 8.3 weight percent MgO (figure 7), values similar to those characterizing the chilled margins of other HTQ sheets in the Culpeper basin (Froelich and Gottfried, in press). Contents of the incompatible elements P, Nb, Zr, and Y are correspondingly high, indicating enrichment relative to the main body of the sheet and reflecting the nature of the magma chilled near the contact. It is important to note that all of the other samples collected along this traverse have higher MgO contents than the chilled margin (figure 7), suggesting that all are cumulate in origin. Gottfried and Froelich (1985) have described a similar pattern in the Boyds HTQ diabase sheet. Chondrite-normalized REE patterns of the sample suite representing a traverse through the Rapidan sheet (figure 8) support the cumulate interpretation because the chilled margin samples show maximum values for both light- and heavy-REE.

Return to the vehicles and proceed northwest on Route 655.

75.9	(0.5)	STOP 4b: Park along the right shoulder. The exposures are located along the road and in the woods to the southeast and northwest.

STOP 4b: Rapidan diabase sheet (Unionville Quadrangle)

The rocks at this locality are within the lower part of the sheet and are typical of the noritic gabbro cumulate zone characterizing the intrusion in

Table 4: Major- and trace-element compositions of selected samples from the Rapidan diabase sheet (field trip stops 4 and 5). [Major-element analyses are expressed in weight percent; trace-element analyses are expressed in parts per million (ppm). Sample Ra-A1, analyzed by X-ray fluorescence spectroscopy by B.D. Leavy, New Mexico Institute of Mining and Technology, Socorro; all other samples by ICP, USGS analysts, Reston, Virginia. Sample K-1, hybridized hornfels; all other samples diabase. Major elements analyzed by Hezekiah Smith and Norma Rait, 1986; trace elements analyzed by G.A. Wandless, J.S. Kane, J.D. Fletcher, S.L. Fleming, R.G. Johnson, and M.W. Doughten]

Sample	K-1	K-2	K-3	K-4	K-4A	K-5	K-6	K-7	RA-A1
SiO_2	48.9	52.0	51.9	52.2	50.8	50.9	51.1	52.0	52.05
TiO_2	0.90	0.76	0.41	0.63	0.76	0.83	0.88	1.1	0.48
Al_2O_3	19.5	13.6	15.6	13.1	11.6	13.0	13.0	13.6	12.17
Fe_2O_3	7.3	2.0	1.6	1.9	2	1.9	2.0	2.2	11.89*
FeO	2.2	8.2	6.3	7.2	8	7.9	7.8	8.2	
MnO	0.20	0.19	0.16	0.18	0.18	0.17	0.17	0.18	0.16
MgO	4.7	8.9	9.3	10.4	12.4	10.6	9.9	8.3	13.20
CaO	6.0	11.7	12.7	12.0	10.4	10.9	11.0	10.6	9.31
Na_2O	3.7	1.8	1.7	1.5	1.5	1.7	1.7	1.9	1.56
K_2O	4.3	0.38	0.26	0.29	0.40	0.45	0.56	0.64	0.20
P_2O_5	0.30	0.07	0.04	0.07	0.09	0.10	0.12	0.14	0.04
H_2O+	1.5	0.66	0.46	0.61	0.68	0.49	0.62	0.89	0.30'
H_2O-	0.18	0.15	0.16	0.16	0.23	0.24	0.29	0.31	
CO_2	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.01	
Total	99.69	100.43	100.60	100.25	99.06	99.20	99.16	100.07	101.36
Nb	19	4.5	<2.0	3.8	5.1	5.3	6.5	6.8	-
Rb	248	9	6	8	16	13	21	29	8.1
Sr	811	172	189	149	140	154	159	179	128.8
Zr	141	66	35	55	81	81	86	104	37.6
V	110	200	180	200	190	180	180	190	9.8
Y	38	21	12	17	21	20	19	30	
Ba	627	119	90	112	111	112	126	171	
Cr	110	310	420	450	810	660	620	400	
Cu	4	87	37	58	76	84	92	110	
Ni	45	86	100	110	190	150	130	91	
Zn	166	70	63	68	72	78	70	81	
Co	31	46	45	42	52	45	52	52	

* total iron expressed as Fe_2O_3

' loss on ignition

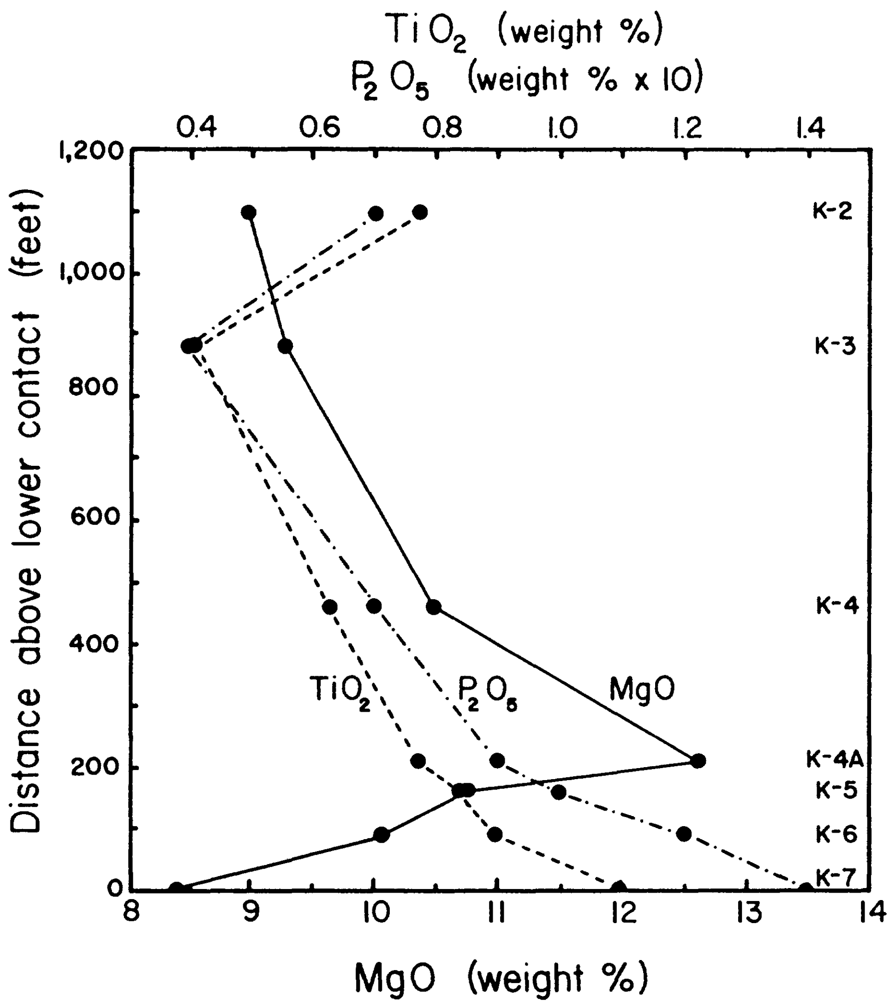

Figure 7: Abundances of selected elements plotted as a function of distance above the lower contact of the Rapidan diabase sheet. Data are from samples collected along the Route 655 traverse (stops 4a-c) described in the text and table 4. All data were normalized to 100 weight percent (anhydrous) before plotting.

this area. Outcrops and boulders located along the road and in the woods toward the southeast are composed of dark-colored, medium- to coarse-grained, orthopyroxene- (opx-) rich diabase represented by samples K-4A and K-5. This diabase differs texturally from that exposed farther southeast primarily in the coarse equigranular texture and abundant opx phenocrysts. The high MgO content (figure 7) of a sample from this cumulate zone reflects the abundance and composition of the constituent opx. Values for TiO_2 and P_2O_5 are predictably lower relative to the chilled margin, consistent with the REE patterns (figure 8). Toward the northwest, the diabase is characterized by an overall medium-grained, granular texture and a marked increase in modal plagioclase. This plagioclase-rich, leucocratic diabase is a locally significant lithology within the upper cumulate zones of this intrusion where it occurs interlayered with darker colored, opx-rich diabase. The meso-scale textural features of such layering are well exposed in the Virginia Granite quarry at stop 5.

Return to the vehicles and proceed northwest on Route 655.

76.3	(0.4)	STOP 4c: Park along the right shoulder. The exposures are located along the road and in the woods to the southeast and northwest.

STOP 4c: Rapidan diabase sheet (Unionville Quadrangle)

The rocks in this area are in the upper portion of the sheet. Exposures within and around a small abandoned pit south of the road approximately 0.1 mile (160 m) southeast are principally medium-gray to dark-colored, medium-grained, opx-bearing diabase locally interlayered with a leucocratic, plagioclase-rich variety. The chemical composition of a sample from this leucocratic variety is characterized by lower MgO contents (9.3 weight percent) and increased Al_2O_3 (15.6 weight percent), relative to the opx-cumulate, reflecting the increased modal abundance of plagioclase. The REE pattern for sample K-3 shows the lowest relative abundances and a distinct Eu anomaly indicative of the cumulate plagioclase (figure 8). Lee (1980) has mapped the upper contact of the sheet approximately 0.25 mile (400 m) toward the northwest just east of well-bedded, fine-grained hornfels of the roof rocks. Precise location of the contact is difficult, however, because of the zone of fine-grained, hybrid lithologies resulting from interaction between the diabase and hornfels (sample K-1, table 4). Rocks typical of this hybridized zone are exposed along Route 655 approximately 0.2 mile (320 m) northwest of the pit. The upper chilled contact is exposed, however, in roadcuts along Route 522, west of the intersection with Route 655.

Return to the vehicles and proceed northwest on Route 655.

77.7	(1.4)	Turn left onto Route 652. Proceed southwest.
78.9	(1.2)	Turn left onto Route 615. Proceed south.
81.1	(2.2)	STOP 5: Turn left into entrance to the Virginia Granite Company quarry. Proceed cautiously and beware of heavy truck traffic. The exposures to be examined are located in the pit north of the office.

STOP 5: Rapidan diabase sheet (Rapidan Quadrangle)

The rocks exposed in this quarry provide an indication of the dynamic events that characterized the crystallization history of the Rapidan magma. The quarry is located within the lower portion of the sheet and correlates approximately with the opx-rich zone at stop 4b. The dominant lithology is a

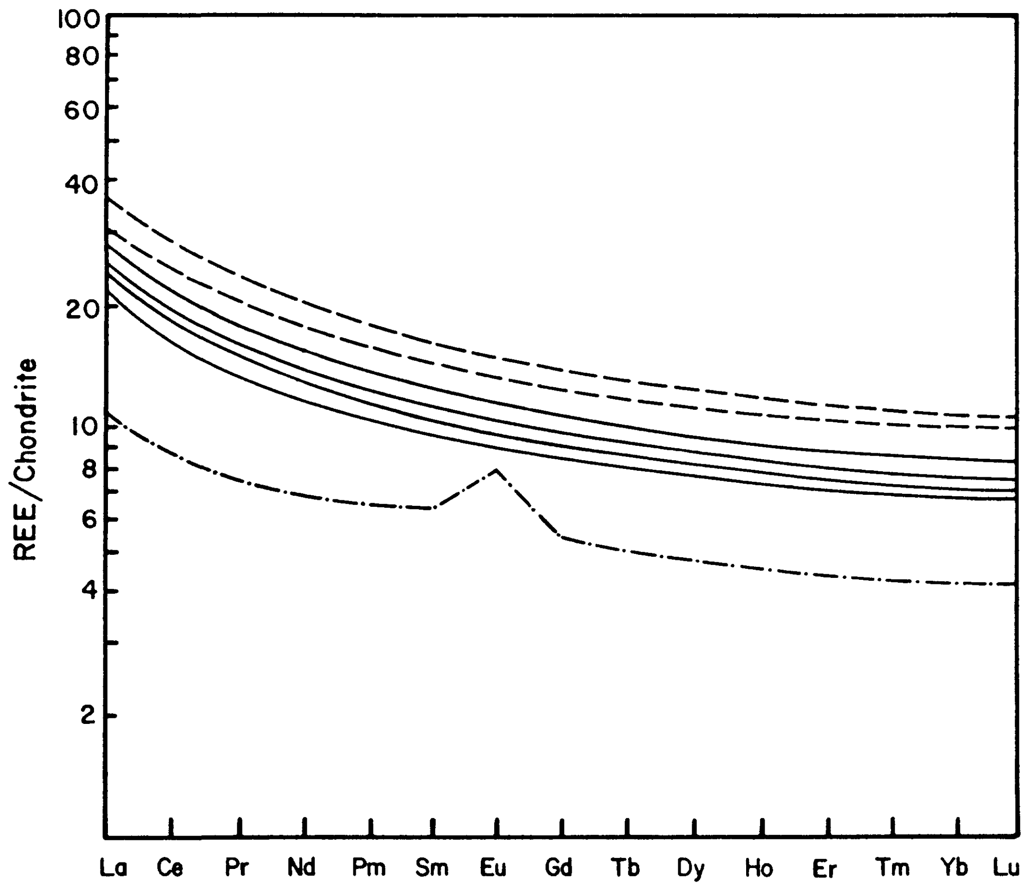

Figure 8: Rare-earth element (REE) patterns of the Rapidan HTQ diabase sheet along the Route 655 traverse. Data are normalized to average REE abundances in chondrites (Anders and Ebihara, 1982). Data include one additional sample of the the chilled margin collected nearby along strike. Petrologic types include (a) fine-grained diabase of chilled margin (dashed), (b) opx-bearing diabase (solid), and (c) plagioclase-rich diabase (alternating dash-dot).

medium-grained, sparsely porphyritic to equigranular, opx-rich diabase that is locally interlayered with a light-colored, plagioclase-rich anorthositic variety. Geochemical data for sample RA-A1, opx-cumulate diabase from this locality, presented in table 4, indicate close similarity in MgO content with opx-rich diabase from stop 4b on the Route 655 traverse. The subparallel layering and local scour and fill features of the diabase in this quarry provide evidence for magma currents during emplacement and crystallization of the diabase. Anastomosing veinlets of leucocratic diabase cutting the darker variety are a further indication of the complex magma mechanics. A conspicuous vein, several inches in width, cuts the diabase in the pit directly north of the office. The vein, part of a local network, is composed of tourmaline + chlorite + potassic feldspar and appears to have recrystallized the diabase within a narrow zone adjacent to the contacts.

Return to the vehicles and carefully drive along the access road from the quarry. Beware of heavy truck traffic. Turn right onto Route 615 and proceed northward.

85.6	(4.5)	Turn left onto Route 522. Proceed north.
89.1	(3.5)	Turn right onto Route 3. Proceed east.
96.5	(7.4)	Turn left onto Route 669. Proceed north.
98.9	(2.4)	STOP 6: Turn right and proceed cautiously up the hill on the private road. The rocks to be examined are exposed in two locations along the road.

STOP 6: Berry Hill, Germanna Bridge diabase sheet (Germanna Bridge Quadrangle)

The rocks at this locality are typical of the highly fractionated lithologies comprising a significant portion of the Germanna Bridge diabase sheet. The main volume of this sheet is composed of very sparse opx-bearing HTQ diabase generally similar in composition to the upper part of the Rapidan sheet. Sparse opx-bearing diabase has been traced from the northeast end of the Rapidan sheet through the diabase offshoot east of "The Ridge" in the Culpeper East Quadrangle and into the Germanna Bridge diabase sheet. The geochemical similarity and general map relations (figure 1) indicate that the Germanna Bridge sheet probably represents a northeast extension of the Rapidan sheet. Medium- to coarse-grained, syenitic granophyre is exposed along the road in front of the barn where it is associated with fine-grained granophyre and diabase. Medium- to coarse-grained, magnetite-bearing ferrogabbro is exposed behind the barn. The chemically evolved nature of these rocks is apparent from the low MgO contents and marked enrichment in TiO_2 and P_2O_5 shown in table 5 and figure 9. This locality represents the closest occurrence of such fractionated lithologies to the opx-bearing diabase examined at stops 4 and 5. Therefore, these rocks may represent part of the geochemical complementary fraction that is apparently missing within the Rapidan sheet. This would suggest considerable migration and fractionation of magma by lateral flow differentiation (Gottfried and others, 1985).

Return to the vehicles and cautiously proceed down the driveway. Turn right onto Route 669 and proceed northwest. Follow Route 669 to Brandy Station. Route 15/29, accessible via Route 663, is located north of Brandy Station and provides access to Reston and other destinations.

Table 5: Major- and trace-element compositions of selected samples from the Germanna Bridge diabase sheet (field trip stop 6). [Major-element analyses are expressed in weight percent; trace-element analyses are expressed in parts per million (ppm). FG-84-20B, ferrogabbro; FG-84-20A1 and A2, pink granophyre; FG-84-20A3, diabase, medium grained. Major elements analyzed by Hezekiah Smith, J.W. Marinenko, and Norma Rait, USGS, Reston, Virginia, 1986; trace elements analyzed by G.A. Wandless, USGS, Reston, Virginia, 1986]

Sample:	FG-84-20A1	FG-84-20A2	FG-84-20A3	FG-84-20B
SiO_2	57.8	59.0	52.5	52.2
TiO_2	1.8	1.8	1.2	1.7
Al_2O_3	12.5	13.7	15.4	16.0
Fe_2O_3	4.4	5.3	3.0	3.7
FeO	6.8	3.6	7.5	8.5
MnO	0.18	0.14	0.22	0.16
MgO	1.1	0.77	5.5	3.3
CaO	5.7	4.0	9.9	5.9
Na_2O	4.9	5.2	2.6	4.3
K_2O	2.2	2.5	0.83	2.7
P_2O_5	0.76	0.77	0.2	0.24
H_2O^+	0.98	1.8	1.1	2.0
H_2O^-	0.72	0.98	0.34	0.54
CO_2	0.02	0.01	0.01	0.03
Total	99.86	99.57	100.30	101.27
Nb	24	29	8.4	10
Rb	66	75	43	112
Sr	146	120	213	407
Zr	322	386	110	158
Y	131	121	30	42
Ba	390	405	265	373
Ce	163	123	27	56
La	84	82	15	28
Cr	<8	<5	61	<20
Cu	120	33	140	170
Ni	<5	59	59	35
Zn	52	48	82	122
Co	26	13	42	39

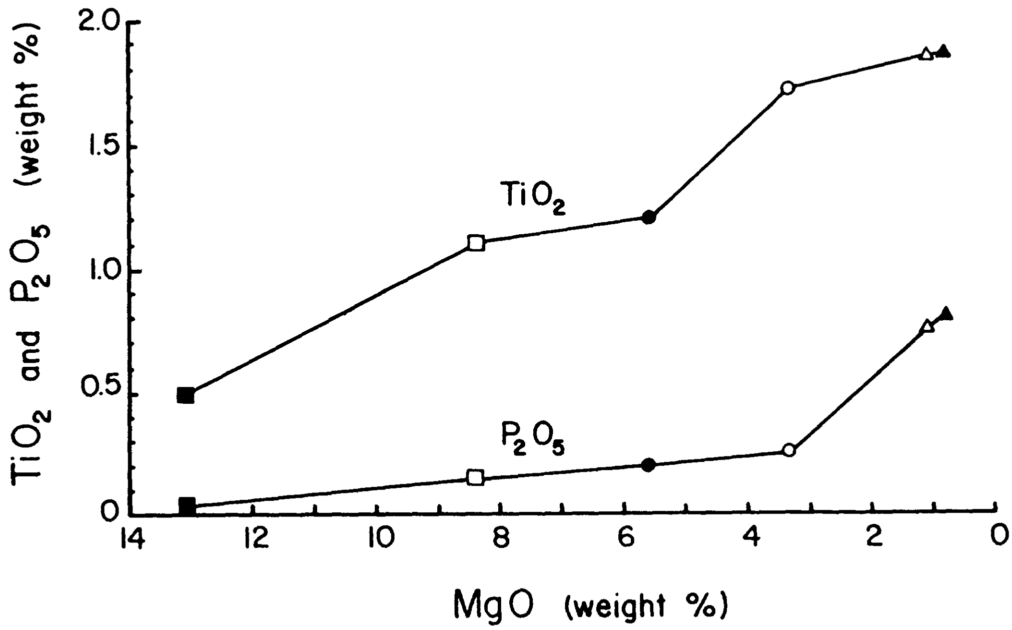

Figure 9: Plot of TiO_2 and P_2O_5 versus MgO for four samples from the area of Berry Hill (stop 6): gray, medium-grained diabase (filled circles), ferrogabbro (open circles), syenite (open triangles), and pink syenite granophyre (filled triangles). Data for the chilled margin (open squares) and opx-cumulate diabase (filled squares) of the Rapidan sheet are plotted for comparison. All data were normalized to 100 weight % (anhydrous) before plotting.

References

Anders, Edward, and Ebihara, Mitsuro, 1982, Solar-system abundances of the elements: Geochimica et Cosmochimica Acta, v. 46, p. 2363-2380.

Cornet, Bruce, 1977, The palynostratigraphy and age of the Newark Supergroup: University Park, Pennsylvannia State University, unpub. Ph.D. thesis, 506 p.

Froelich, A.J., and Gottfried, David, in press, An overview of Early Mesozoic intrusive rocks of the Culpeper basin, Virginia and Maryland, in Proceedings of the Third U.S. Geological Survey Workshop on the Early Mesozoic Basins of the Eastern United States: U.S. Geological Survey Bulletin 1776.

Gottfried, David, Annell, C.S., and Schwarz, 1978, Geochemistry of subsurface basalt from the deep corehole (Clubhouse Crossroads Corehole 1) near Charleston, South Carolina - magma type and tectonic implications: U.S. Geological Survey Professional Paper 1028-G, p. 91-113.

Gottfried, David, and Froelich, A.J., 1985, Geochemical and petrologic features of some Mesozoic diabase sheets in the northern Culpeper basin, in Proceeding of the Second U.S. Geological Survey Workshop on the Early Mesozoic Basins of the Eastern United States: U.S. Geological Survey Circular 946, p. 86-91.

Gottfried, David, Ragland, P.A., and Froelich, A.J., 1985, Styles of differentiation of some Mesozoic diabase sheets in the eastern United States [abs.]: Geological Society of America Abstracts with Programs, v. 17, p. 595.

Helz, R.T., 1980, Crystallization history of Kilauea Iki lava lake as seen in drill core recovered in 1967-1979: Bulletin Volcanologique, v. 43, p. 657-701.

Kuno, Hisashi, 1965, Fractionation trends of basalt magmas in lava flows: Journal of Petrology, v. 6, p. 302-321.

Leavy, B.D., Froelich, A.J., and Abram, E.C., 1983, Bedrock map and geotechnical properties of rocks of the Culpeper basin and vicinity, Virginia and Maryland: U.S. Geological Survey Miscellaneous Investigations Map I-1313-C, scale 1:125,000.

Lee, K.Y., 1979, Triassic-Jurassic geology of the northern part of the Culpeper basin, Virginia and Maryland: U.S. Geological Survey Open-File Report 79-1557, 29 p., 16 pl., scale 1:24,000.

------1980, Triassic-Jurassic geology of the southern portion of the Culpeper basin and the Barboursville basin, Virginia: U.S. Geological Survey Open-File Report 80-468, 19 p., 18 pl., scale 1:24,000.

Lee, K.Y., and Froelich, A.J., in press, Triassic-Jurassic stratigraphy of the Culpeper and Barboursville basins, Virginia and Maryland: U.S. Geological Survey Professional Paper 1472.

Philpotts, A.R., and Martello, Angela, 1986, Diabase feeder dikes for the Mesozoic basalts in southern New England: American Journal of Science, v. 286, p. 105-126.

Puffer, J.H., Hurtubise, D.O., Geiger, F.J., Lechler, Paul, 1981, Chemical composition and stratigraphic correlation of Mesozoic basalt units of the Newark basin, New Jersey, and the Hartford basin, Connecticut: Geological Society of America Bulletin, Part II, v. 92, p. 515-553.

McFall, K.S., 1985, Petrography and geochemistry of the constituent flows of the Sander Basalt, Culpeper basin, Virginia: senior thesis (unpublished), George Washington University, 36 p.

Ragland, P.C., Brunfelt, A.O., and Weigand, P.W., 1971, Rare-earth abundances in Mesozoic dolerite dikes from eastern United States, in Brunfelt, A.O. and Steinnes, Eiliv, eds., Activation analysis in geochemistry and cosmochemistry: Oslo, Universitetsfarlaget, p. 227-235.

Raymond, C.A., Ellwood, B.B., Chaves, Lisa, and Leavy, B.D., 1982, Paleomagnetic analyses of lower Mesozoic diabase ans basalt from the central and southern Appalachians [abs.]: Geological Society of America Abstracts with Programs, v. 14, p. 76.

Smith, R.C. II, Rose, A.W., and Lanning, R.M., 1975, Geology and geochemistry of Triassic diabase in Pennsylvania: Geological Society of America Bulletin, v. 86, p. 943-955.

Sutter, J.F., 1985, Progress on geochronology of Mesozoic diabase and basalts, in Proceedings of the Second U.S. Geological Survey Workshop on the Early Mesozoic Basins of the Eastern United States: U.S. Geological Survey Circular 946, p. 110-114.

Tollo, R.P., in press, Petrographic and major element characteristics of Mesozoic basalts, Culpeper basin, Virginia, in Proceedings of the Third U.S. Geological Survey Workshop on the Early Mesozoic Basins of the Eastern United States: U.S. Geological Survey Bulletin 1776.

Weigand, P.W., and Ragland P.A., 1970, Geochemistry of Mesozoic dolerite dikes from eastern North America: Contributions to Mineralogy and Petrology, v. 29, p. 195-214.

Wright, T.L., and Okamura, R., 1977, Cooling and crystallization of tholeiitic basalt, 1965 Makaopuhi Lava Lake, Hawaii: U.S. Geological Survey Professional Paper 1004, 78 p.

Appendix A

Analytical Methods

Major- and trace-element analyses for the basalts (table 1 and 3) were performed by R.P. Tollo and students using X-ray fluorescence spectrometry at the Analytical Geochemistry Laboratory of the University of Massachusetts in Amherst. Major- and trace-element analyses for the hornfels and most of the diabases (tables 4 and 5) were performed by analysts at the U.S. Geological Survey analytical laboratories in Reston, Virginia, using inductively coupled plasma source spectroscopy (ICP) and atomic absorption spectrophotometry (AA). Rare-earth analyses for all samples were performed at the USGS facility using instrumental neutron activation analysis techniques (INAA).