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Petrology of a Large Granophyre-Rich Mesozoic Diabase Dike Near Farmville, Virginia

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PETROLOGY OF A LARGE, GRANOPHYRE-RICH MESOZOIC DIABASE DIKE NEAR FARMVILLE, VIRGINIA

by

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B.S. May 1984, Old Dominion University

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ABSTRACT

PETROLOGY OF A LARGE, GRANOPHYRE-RICH MESOZOIC DIABASE DIKE NEAR FARMVILLE, VIRGINIA

Philip Thomas Rogan
Old Dominion University, 1993
Advisor: Dr. Francis Ö. Dudás

Up to 37% granophyre occurs in the center of a 150m-wide Mesozoic diabase dike near Farmville, Virginia. The exceptional abundance of granophyre compared with other Mesozoic diabase dikes suggests unusual petrogenetic processes are involved in formation of the dike. Petrographic analyses show that granophyre increases from 5-10% near the flanks of the dike to a maximum of 37% in the core of the dike, and that granophyre distribution is approximately symmetrical about the center of the dike. Major and trace element concentrations parallel variations in the modal abundance of granophyre, with SiO_2, Na_2O and K_2O increasing in the granophyre-rich portion of the dike, and MgO and CaO decreasing. Fe_2O_3* and Al_2O_3 remain fairly constant. There is a sharp break, not a gradation, between the granophyre-rich and granophyre-poor compositions.

The dike is a high-TiO_2 high-iron quartz-normative tholeiite (average SiO_2 = 53 wt.%), while the granophyric core is much more evolved (max. SiO_2 = 58.4 wt.%). *In situ* differentiation is inconsistent with the sharp compositional

break between components of the dike. Multiple injection of melts generated by differentiation of a parental high-TiO_2 high-iron quartz-normative tholeiite magma is possible, but cannot easily account for the constant Fe_2O_3* and increasing TiO_2 in the granophyre. Magma mixing of basaltic and felsic melts or contamination by crustal melts is also inconsistent with TiO_2 and Fe_2O_3* patterns, and cannot explain the compositional gap. Fractional crystallization and multiple injection of melts related to different parental magmas (TiO_2 = 1.2% and TiO_2 = 1.7%) is the most probable explanation for mineralogical and chemical variation in the Farmville dike.

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INTRODUCTION

The Farmville dike is a large (150m-wide), compositionally zoned, north-trending diabase dike which crosscuts Paleozoic metamorphic country rocks and Triassic sedimentary rocks of the Farmville basin. The dike has margins of quartz-normative tholeiite composition and a granophyre-rich core. This dike has been chosen for study because it contains a large amount of granophyre and appears to be significantly different from most other dikes of Virginia and North Carolina described in previous studies. The study area is located within the Farmville quadrangle, in the southcentral Piedmont of Virginia (Figure 1).

Petrographic studies (Hermes, 1964; Chalcraft, 1972) and chemical studies (Ragland et al., 1968; Weigand, 1970; Steele, 1971; Smith, 1973; Steele and Ragland, 1976; Cummins, 1987; and Whittington, 1988) show that the Mesozoic diabase dikes of eastern North America are a variety of olivine-normative and quartz-normative tholeiitic compositions, and that granophyre is a fairly common accessory component in most of the quartz-normative diabase dikes. In the context of these studies, granophyre can be defined as a fine intergrowth of quartz and alkali feldspar

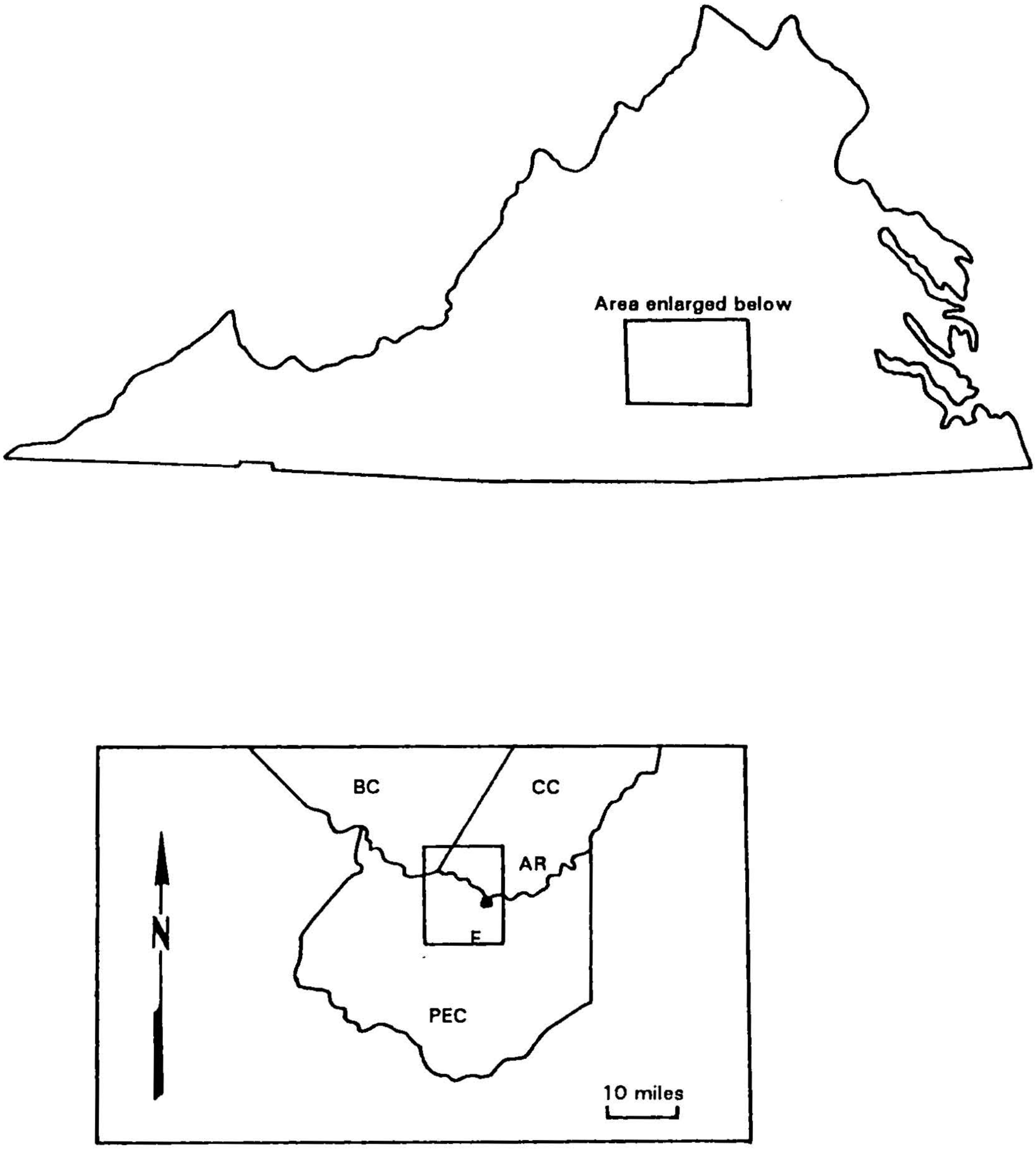


Figure 1. Diagram showing the location of the study area. The study area is located within the Farmville quadrangle, which contains sections of Buckingham County, Cumberland County, and Prince Edward County. The Farmville quadrangle is outlined by the small rectangle in the enlarged area above. AR, Appomattox River; BC, Buckingham County; CC,

(Barker, 1970), and is synonymous with micropegmatite of earlier authors (e.g. Hermes, 1964). Granophyre is common as an interstitial phase in quartz-normative diabases, and in some diabase sheets it forms distinct, granophyre-rich bodies ranging to granitic in composition.

Previous studies of dikes from Maryland to North Carolina have shown that granophyre rarely exceeds a few volume percent and is usually present at less than 1 percent (Hermes, 1964; Ragland et al., 1968; Steele, 1971; Chalcraft, 1972; and Steele and Ragland, 1976), although Hermes (1964) identified one sample in North Carolina which contained 27 percent granophyre.

Although most of these studies documented the variation of compositions between a number of dikes in particular geographical areas, there have been few studies which examined the compositional variation within single dikes or discussed processes to explain this variation. Exceptions include Ragland et al. (1968; the JY dike), Steele (1971; the Pageland dike), and Sol (1987).

Gabbro- or diabase-granophyre associations are common throughout the world (e.g., Karoo dolerites, Walker and Poldervaart, 1949; Northern Wisconsin gabbro-granophyre complex, Leighton, 1954; Stillwater, Hess, 1960; Tasmanian Red Hill dolerite-granophyre, McDougall, 1962; Skaergaard, Wager and Brown, 1968). Granophyre also forms pods or zones of essentially granitic composition in many of the large, quartz-normative diabase sheets of eastern North America (e.g., Walker, 1940; Hotz, 1953; Froelich and Gottfreid, 1985). The key feature is the association of granophyric bodies of granitic composition with mafic rocks of gabbroic composition. The chemical composition of many Mesozoic diabase sheets from northern Virginia northward is strongly differentiated and enriched in SiO_2 and alkalies, commonly resulting in the formation of granophyric bodies (Froelich and Gottfreid, 1985).

A variety of processes has been used to explain chemical variation within diabase sheets and dikes. These processes may ultimately lead to the formation of evolved, granitic compositions. The processes can be grouped into chemical processes and physical processes. Chemical processes include 1) fractional crystallization, 2) crustal contamination of magma by partial melting of wall rock, and 3) liquid immiscibility.

In fractional crystallization, a range of transitional or intermediate compositions is generated, leading, in extreme cases, to the formation of residual granitic melt. In well-exposed fractionated diabase sheets, cumulate layers of olivine or orthopyroxene and clinopyroxene are generally found and represent settling and accumulation of early crystallizing phases. In older literature, fractional crystallization, with or without the action of other processes, was thought to be responsible for the chemical variation of many of the large, Mesozoic diabase sheets in eastern North America (Walker, 1940; Hotz, 1953; Froelich and Gottfreid, 1985). More recent studies (Husch, 1988; Grossenbacher and Marsh, 1992) question the role of fractionation in some of these intrusions. Ernst et al. (1987) attribute chemical variation across and along strike of the Great Abitibi Dike of the southeastern Superior Province in Canada to fractional crystallization and density stratification. One difficulty of fractional crystallization is that 90 % or greater fractionation is required to produce a melt of granitic composition from a basalt, and there is no evidence in the Farmville dike to suggest that this amount of fractionation has occurred.

Partial melting of crustal rocks produces liquids of granitic composition which may mix with or modify basaltic magmas. In this case also, expected end-member compositions would be basaltic and granitic. Partial melting of crustal rocks to produce granophyre in larger layered diabase sheets has been described by Leighton (1954) and Pankhurst et al. (1978), and explains gabbro-granophyre relations in the upper part of the Skaergaard intrusion (Stewart and DePaolo, 1990). However, it is unlikely that the Farmville dike could produce large volumes of granitic partial melt from the local crustal rocks. It may have been possible for the dike to produce small volumes of partial melt along the dike margins, but then concentrations of granophyre would be expected along the dike margins, which is not observed, and does not account for the concentration of granophyre in the core.

Liquid immiscibility has been observed on the microscopic scale in unusually iron-rich basaltic compositions, but not on the macroscopic scale. However, some processes may produce different compositions that effectively behave as immiscible liquids which solidify before they can mix. For example, Grossenbacher and Marsh (1992) suggest that granophyre in the Zora Ring of the Gettysburg diabase sheet may have formed from discrete granitic blobs rising through the diabase sheet. The separation of the two compositions would be accomplished by flow differentiation in the feeder dike. The two magmas would remain distinct because of density and viscosity differences. As with the other two processes, this process would be characterized by basaltic and granitic end-members.

Because of the difficulty of, or lack of evidence for, the action of these chemical processes within the Farmville dike and the difference between the compositions found in the Farmville dike and compositions expected or observed from these processes, there does not appear to be a readily applicable chemical explanation for the presence of granophyre in the Farmville dike.

Physical processes include processes such as multiple intrusion or magma mixing, and act on co-existing mafic and felsic magmas. Physical processes require that sources for the end-member compositions be found.

Multiple intrusion occurs when two or more distinct pulses of magma intrude the same body or structure at different times. Gibson et al. (1987) suggested that the chemical variation in the compositionally zoned Mackenzie dikes is the result of the intrusion of basaltic magma which was later followed by intrusion along the same pathways by a more evolved magma. Intrusion of two pulses of magma has been used to explain chemical variations in diabase dikes in North Carolina by Steele (1971) and Sol (1987). Both studies indicate that multiple pulses of tholeiitic magma were responsible for chemical variation. However, Stoddard et al. (1986) report the occurrence of a group of mainly rhyolitic Mesozoic dikes in the northeasternmost Piedmont of North Carolina. This suggests that more felsic magmas may have been available to modify tholeiitic compositions by multiple intrusion or magma mixing.

In magma mixing, the components represent two co-existing magmas derived from separate sources, or possibly derived from the same source at different times. The abundance and composition of granophyre in the rock could reflect mixing of the two components during magma flow in the dike; viscosity and buoyancy contrasts between mafic and felsic melts may effectively keep them separate.

The poor exposure of the Farmville dike and the fact that the dike was sampled in one location only are limiting factors in this study. These limitations imply that hypotheses involving physical or dynamic factors such as multiple intrusion, magma movement or change of features along strike or with depth cannot be directly addressed. However, the chemical relationships between the granophyre-rich and granophyre-poor portions of the dike can be studied. Therefore, the goal of this study is to put chemical limits on possible processes of granophyre generation, using the Farmville dike as an example. The reasons that the Farmville dike was chosen are:

1. The Farmville dike is one of an extensive swarm of diabase dikes, not all of which show enrichment of granophyre or development of a granophyric core. A study of the Farmville dike may give more insight into granophyre-forming processes.
2. There is an extensive literature on the dikes of eastern North America, and therefore ample material to which the Farmville dike results can be compared.
3. Granophyre-forming mechanisms have been studied in related sills such as the Palisades and

Gettysburg sills. It may be possible to compare and contrast sill and dike environments.

4. The results of this study will add to the essential data base for the Mesozoic diabase dikes.

BACKGROUND

Regional Geologic Setting

The separation of North America and Africa in the early Mesozoic led to the formation of a series of fault-bounded rift basins along the eastern North American continental margin. These basins occur along the eastern North American margin and together form the Newark rift system (Figure 2). The basins contain Late Triassic to Early Jurassic continental clastic sedimentary rocks assigned to the Newark Supergroup (Olsen, 1978: Froelich and Olsen, 1985), and are commonly referred to as Triassic basins. Basaltic magma associated with rifting intruded the basins as diabase dikes and sills, and also formed extrusive basalt flows. Diabase dikes also intruded Paleozoic igneous and metamorphic rocks that surround the basins.

The Newark rift system basins and associated basaltic rocks occur predominantly in the Piedmont province of eastern North America. The Piedmont province is composed of Paleozoic metamorphic rocks and late Paleozoic igneous intrusive rocks. These rocks have a strong regional structural grain that roughly parallels the Appalachian

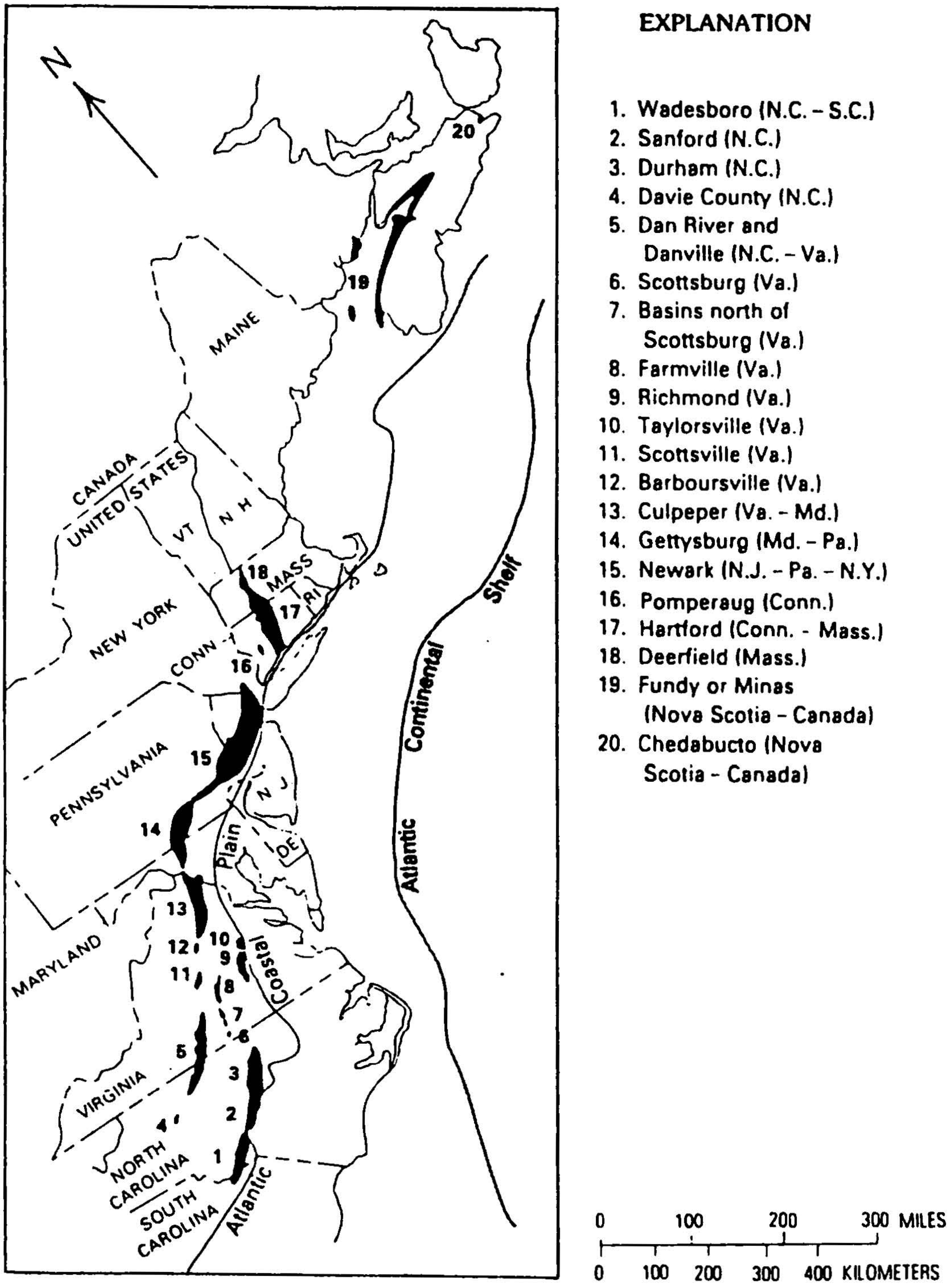


Figure 2. Exposed basins of the Newark Supergroup in eastern North America (from Froelich and Olsen, 1984).

orogen. The Newark basins are faulted half-grabens with margins that generally parallel this regional structural grain.

In contrast to the control of regional Appalachian structure on basin formation, diabase dikes cut across both regional structures and basin margins. King (1961) noted that the dikes form a systematic pattern along the Appalachian region, and that this pattern is generally not controlled by pre-existing structures. King described a systematic variation in dike trend; the dikes trend consistently northwestward from Alabama to North Carolina. The trend rotates to north-northwest in southern Virginia and to the north in northern Virginia. The trend continues to rotate to the northeast across Maryland and Pennsylvania, and this northeast trend continues into New England and Canada. The regional pattern was interpreted to indicate dike emplacement controlled by regional crustal stresses associated with crustal extension and continental rifting prevalent at that time (King, 1971).

Ragland et al. (1983) reported that the North Carolina dikes displayed a more complex distribution pattern than that reported by King (1961), and that the dikes could be assigned to four domains based on dike trends. Domain I consists primarily of northwest-trending dikes. Domains III and IV consist of dikes of a wide variety of orientations, and Domain II consists primarily of north-south trending dikes. The radial pattern of King (1961) is now thought to be the result of three distinct dike swarms; a northwest-trending dike swarm, a north-south-trending dike swarm, and a northeast-trending dike swarm (Ragland, 1991; Milla and Ragland, 1992).

The north-south swarm appears to converge under the South Carolina Coastal Plain to an area near Charleston, South Carolina, and to diverge across North Carolina and into Virginia (Ragland et al., 1983; Ragland, 1991). Trends of individual dikes vary from N15°W to N15°E (Ragland, 1991). These dikes overall are longer, wider, farther apart, and more variable in strike than dikes of the northeast swarm, and they tend to be more evolved than dikes of the other swarms (Ragland et al., 1983; Ragland, 1991). The size, orientation and composition of the Farmville dike indicate that the dike belongs to the north-south swarm.

Dike Chemistry

Petrographic studies (Hermes, 1964; Justus, 1966; Chalcraft, 1972) and chemical studies (Ragland et al., 1968; Weigand, 1970) indicate that there is a large variation in composition of the dikes in eastern North America. The diabase can be grouped into olivine-normative tholeiites and quartz-normative tholeiites, and the two groups can be further divided into subtypes based on SiO_2, TiO_2, and Fe (e.g., Weigand and Ragland, 1970; Smith et al., 1975; Cummins, 1987; Whittington, 1988). Classification of and terminology for the various diabase types have become very complicated since Weigand and Ragland (1970) proposed the first classification scheme. Ragland et al. (1992) and Ragland (1991) attempt to summarize and clarify the terminology, and detailed discussions of the various classifications can be found in Ragland et al. (1992), Ragland (1991), and Cummins et al. (1992).

Weigand and Ragland (1970) noted that dike chemistry shows a strong general regional variation. From New England to Maryland or northern Virginia the dikes are predominantly quartz-normative. The dikes are predominantly olivine-normative in North and South Carolina, while in southern Virginia, Georgia and Alabama both types are present.

Ragland et al. (1983) later identified more complex variations between the dikes from North Carolina. They described four geographic domains in North Carolina based on dike trends, with the two dominant dike trends being northwest and north-south. Olivine-normative dikes dominate the dikes of all domains except the north-south domain, which is dominated by quartz-normative diabase (Ragland et al., 1983; Ragland, 1991). This type of more complex and local chemical variation has not been described for Virginia.

Age

Full reviews of the age of the eastern North American diabase are given in Cummins (1987), Whittington (1988) and Ragland (1991), and only a brief review will be given here. Because the diabase dikes and sills are intimately associated with the Triassic basins (sills intrude basin sediments and dikes cut across basins and sills) the diabase was originally assigned a Triassic age. A variety of studies using paleomagnetic or isotopic dating techniques were conducted to define the timing of emplacement of the diabase (e.g. de Boer, 1967; Armstrong and Besancon, 1970; Dallmeyer, 1975; Smith and Noltimier, 1979; Sutter and Smith, 1979). Overall, the different studies gave somewhat inconsistent results.

Paleomagnetic dates were obtained by de Boer (1967) and Smith and Noltimier (1979). De Boer (1967) assigns the diabase to a single period of igneous activity during the Jurassic. Paleomagnetic dates of Smith and Noltimier (1979) indicated two periods of igneous activity at 190 my and 175 my.

Dikes in the Haile-Brewer, South Carolina display normal magnetic polarity (Bell et al., 1980; Ragland, 1991) while some northwest-trending dikes and Clubhouse Crossroads basalts show reversed magnetic polarity (Philips, 1983). Ragland (1991) suggests that the presence of magnetic reversals indicates igneous activity over a period of at least a few million years.

Armstrong and Besancon (1970) determined K/Ar ages on diabase sills and flows from the Upper Triassic Newark group and from diabase dikes from Connecticut, Pennsylvania, Virginia and North Carolina. Their results indicated that the Newark Supergroup diabase ages clustered around 200 m.y., while the diabase dike ages ranged from 220 m.y. to 240 m.y. with a concentration between 225 m.y. and 230 m.y.

Other authors used $^{40}Ar/^{39}Ar$ incremental release techniques to date the diabase. Sutter and Smith (1979) defined two periods of magmatic activity, the first at 191 ± 4.2 my, and the second at 175.0 ± 3.2 my. Dallmeyer (1975), using chilled diabase samples from the upper and lower margins of the Palisades sill, determined ages of 186 m.y. and 196 m.y. From this he assigned an age of approximately 190 m.y. to the Palisades sill. Sutter et al. (1983) obtained an age of 197 ± 4 m.y. for the Culpeper sill in Virginia.

A recent study by Dunning and Hodych (1990) used U/Pb techniques on zircons from the Palisades and Gettysburg sills and baddeleyite from the Palisades sill. Their results indicated an age of 201 ± 1 m.y. for these two sills.

The inconsistency in dates has been explained by the effects of various processes acting on the diabase. The

K/Ar method assumes a closed system with respect to potassium and argon. The amount of alteration present in many of the diabases, the mobility of potassium, and the potential gain or loss of argon suggest that it may not be a closed system, and the ages determined by this method may not be very reliable. The $^{40}Ar/^{39}Ar$ method is only concerned with the ratio of $^{40}Ar/^{39}Ar$ and may provide more reliable age dates. In diabases where minerals such as baddeleyite occur, U/Pb methods may give the most reliable dates due to the stability of this system. Paleomagnetic dating techniques may be affected because of later tilting or rotation (Whittington, 1988; Ragland, 1991).

Ragland (1991) points out that overall the range of dates has been getting narrower, from approximately 160-230 m.y. in the 1970s to 195-205 m.y. or better today. This improvement is probably due to improvements in dating techniques.

Ragland (1991) reported that diabase dikes from both the northwest and north-south sets in North Carolina have been dated at around 200 m.y. Furthermore, Sutter (1985) indicated that no radiometric age distinctions could be made throughout the eastern North American diabase. Although the Farmville dike has not been dated, these observations suggest that a good estimate for the age of the Farmville dike is 200 ± 10 m.y.

LOCATION AND GEOLOGICAL SETTING

The Farmville dike is located in the south-central Piedmont of Virginia, approximately two miles west of Farmville. The dike has a north-south trend and is interpreted in this study to belong to the group of north-south trending dikes described by Ragland et al. (1983). The dike intrudes both Piedmont metamorphic rocks and the clastic sedimentary rocks of the Farmville Basin. The general geology of the Farmville area is shown in Figure 3.

The Farmville basin is one of a series of Triassic- to Jurassic-age basins that occur in subparallel belts from South Carolina to Nova Scotia. These rocks have been assigned to the Triassic-Jurassic Newark Supergroup (Olsen, 1978; Froelich and Olsen, 1985). Rocks of the Farmville basin include sedimentary breccia, conglomerate, sandstone, siltstone, shale, mudstone, and thin coal beds (Wilkes, 1986).

According to Marr (1981), the Piedmont rocks in the region belong mainly to the Chopawamsic Formation. Maar (1981) describes the Chopawamsic Formation as a lower unit of interlayered chlorite schists, biotite metagraywackes and metabasalts, and small layers of mica phyllites and

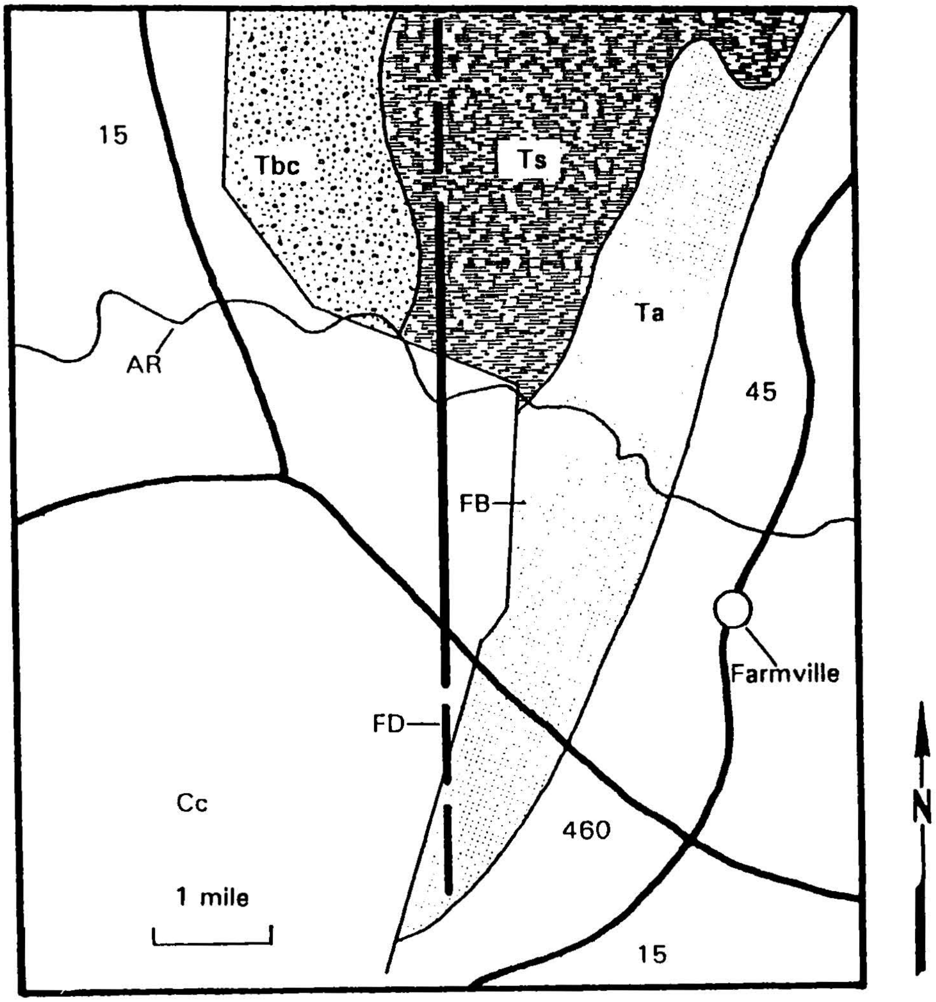


Figure 3. Generalized geology of the Farmville basin area. AR, Appomattox River; FV, Farmville basin; FD, Farmville dike; Tbc, Triassic breccia conglomerate; Ts, Triassic siltstone/shale; Ta, arkosic sandstone; Cc, Cambrian Chopawamsic formation (Modified from Wilkes, 1986).

quartzites, and an upper unit of biotite gneiss, amphibole gneiss, felsic volcanic rocks, talc-tremolite schists and ferruginous quartzites.

Piedmont rocks in the study area which are intruded by the Farmville dike are deeply weathered and poorly exposed. Small exposures near the dike are comprised of weathered schists with interlayered quartzites. These rocks are tentatively assigned to the upper unit of the Chopawamsic Formation.

Diabase dike maps of portions of the Virginia Piedmont have been compiled on a small scale by Cummins (1987) and on a larger scale by Gottfried et al. (1991). Dikes in the Farmville area range from less than 0.25 km to greater than 10 km (the Farmville dike), but the variation in dike widths cannot be determined. Both compilations show 7 to 8 dikes in the Farmville quadrangle and indicate that dike density in and around the Farmville quadrangle to the west, south, and east is relatively low. However, there is a dramatic increase in dike density in the Willis Mountain area to the north and the Andersonville area to the east. This difference is probably due to more detailed mapping in the latter two areas.

Although many of the dikes in the Piedmont have been mapped by outcrop, a large number have been inferred from aeromagnetic data. The following is a brief summary of the geophysics of the Farmville area.

Geophysics

Exposure of Piedmont rocks in Virginia and North Carolina is generally very poor due to deep weathering and vegetation cover. This is especially true for the diabase dikes, where even the larger dikes are found in relatively small or localized occurrences. However, many of these dikes have geophysical expressions, and dike maps include many dikes which are mapped by aeromagnetics (e.g. Burt et al., 1978; Cummins, 1987). The following sections discuss regional and local gravity and aeromagnetic surveys which include the Farmville basin and vicinity.

Gravity

A regional gravity map of the Farmville basin and vicinity was produced by Johnson et al. (1985). Although many dikes have been mapped in this area of the Piedmont (Maar 1981; Ramsey, 1986; Cummins, 1987), none of the dikes, including the large Farmville dike, produces a recognizable gravity anomaly on this map. The portion of the gravity map of the area of the Farmville dike is shown in Figure 4.

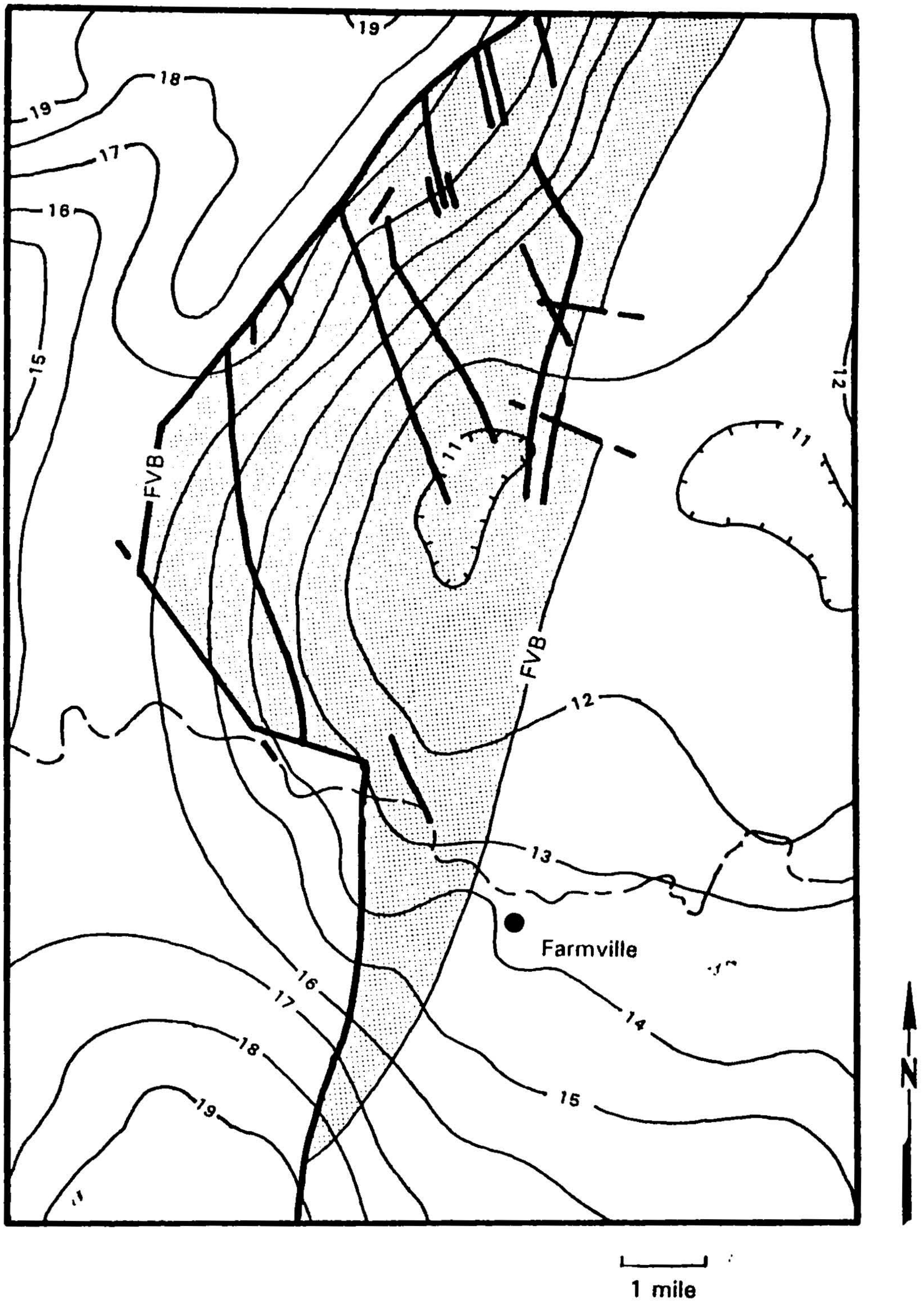


Figure 4. Gravity map of the Farmville basin area. Contours in milligals (modified from Johnson et al., 1985).

James (1991) conducted a detailed gravity survey of the Farmville basin. The Farmville dike produces a slight but recognizable anomaly on his gravity map, and it can be easily distinguished on his second vertical derivative map. With the possible exception of one other dike identified by James near the eastern margin of the basin, no other dikes can be distinguished by simple inspection of the gravity map. Gravity modelling by James along gravity cross-sections shows anomalies that he interprets to represent two other fairly large diabase dikes. According to his model, these two dikes are 100 m to 200 m wide. The actual presence of these dikes has not been verified in the field.

Because of the generally wide spacing of the Virginia gravity base net, diabase dikes are not readily distinguished on regional gravity maps. Even more detailed local studies may only succeed in identifying the larger dikes. In general, gravity surveys do not appear to be very useful for identifying diabase dikes.

Aeromagnetics

Several large, linear magnetic anomalies can be seen on the Aeromagnetic Map of Virginia (Zeitz et al., 1977). Reconnaissance mapping conducted during this study has shown that anomalies are associated with large dikes near Briery

Creek, Danville, and Drake's Branch, Virginia, and it is interpreted that the other large anomalies also represent large, north-south-trending diabase dikes. The Farmville dike shows up as a relatively smaller anomaly that appears to branch off from a larger, northwest-trending anomaly located to the south of Farmville, near the Briery Creek basin. The Farmville anomaly indicates that the dike continues to the north and cuts across the western section of the Farmville basin, then continues northward through Piedmont rocks north of the basin. Other linear anomalies on the Aeromagnetic Map of Virginia may also be indicative of other large dikes in the area, but they have different trends and none cross the basin.

Figure 5 shows that the Farmville dike produces a strong, easily recognizable, north-south-trending linear magnetic anomaly on the aeromagnetic contour map of the Farmville 15-minute quadrangle (VDMR 1970a). There are also one or two smaller, northwest-trending anomalies that may be associated with dikes, but these have not been field checked. There are also northeast-trending anomalies, but these probably represent the pre-existing structural grain. This could mask the presence of any northeast-trending dikes.

The aeromagnetic anomaly indicates a large difference in magnetic susceptibility between the dike and the surrounding country rock. This difference is most likely

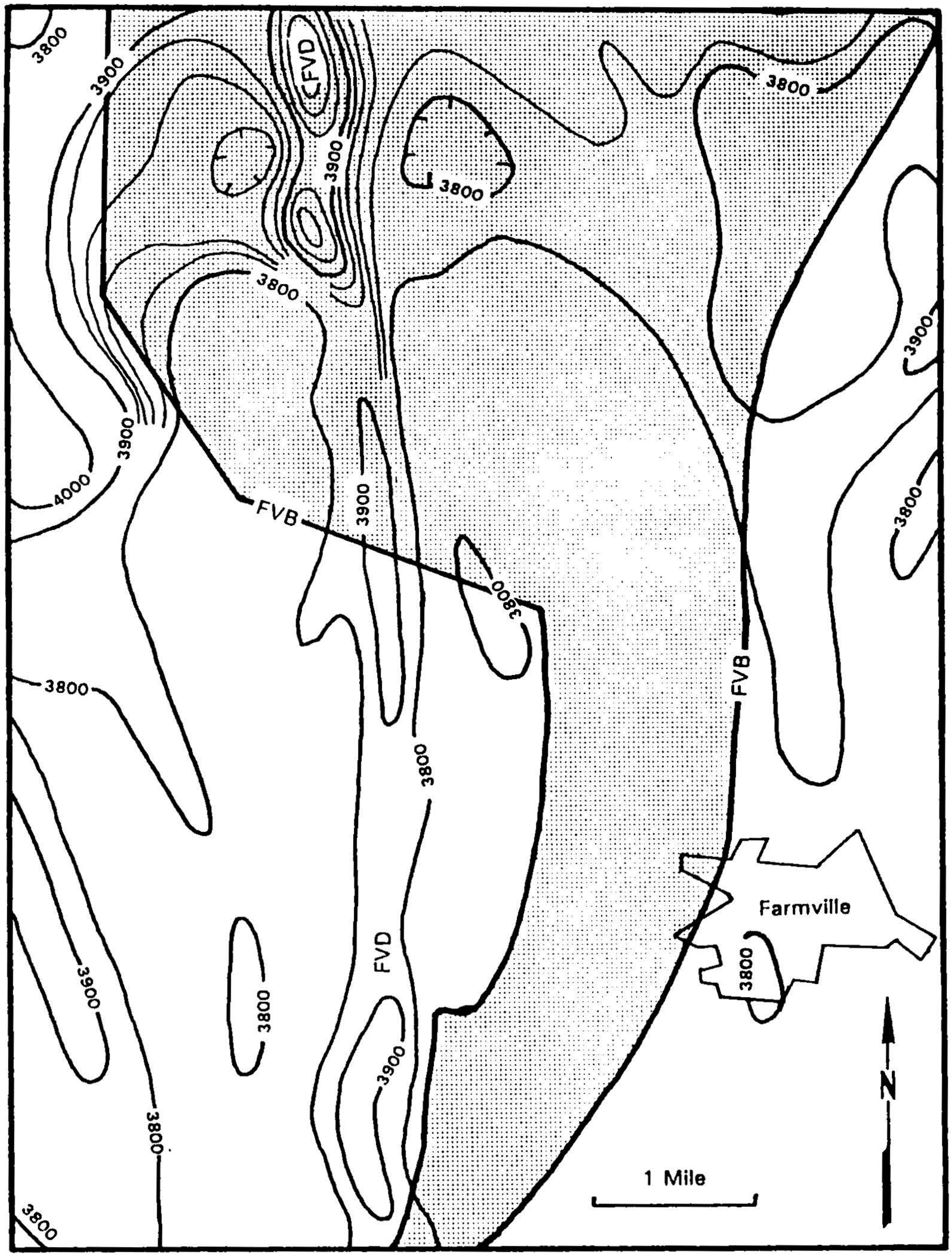


Figure 5. Aeromagnetic anomaly map of part of the Farmville 15-minute quadrangle. 100 gamma contours, 20 gamma intermediate contours. FVD = Farmville dike; FVB = Farmville basin. The dike is indicated by the north-south-trending linear anomaly.

caused by the magnetite in the dike. Magnetite has a high magnetic susceptibility compared to minerals in the country rock.

Sampling

The Farmville dike is exposed in a roadcut along the Route 460 bypass, approximately 2 miles west of Farmville, Va. The exposure is poor due to weathering and overgrowth and the margins of the dike could not be accurately located. Route 460 crosses the dike at a steep angle giving an estimated apparent thickness of approximately 450 m. The calculated thickness of the dike is approximately 150 m.

Where outcrop was available, samples were collected approximately every 3 m. However, most of the dike was covered by vegetation. For this reason, many of the samples collected were float. Because of the possibility of the float samples being transported, the samples were collected only if they were higher up on the roadcut slope, in which case they were assumed to be representative of the dike at the horizontal location of the sample.

A total of forty-five samples were collected across the dike. Of these, a total of thirty-six samples were analyzed, thirty-two petrographically and twenty chemically. Both petrographic and chemical analysis was performed on sixteen of the samples, petrographic analysis only was performed on sixteen samples, and chemical analysis only was performed on on four samples.

The distribution of available outcrop or float resulted in the majority of the samples being collected from the western flank of the dike to the central granophyric core and substantially fewer samples being collected from the eastern flank. Although potential problems with the sampling scheme are readily apparent, the overall coverage is sufficient to define the gross variation across the dike, even though it may not be able to define any finer-scale or more subtle variations within the dike.

PETROGRAPHY

Petrographic Methods

Thirty-two thin sections were prepared from samples of the Farmville dike. The modal analysis of each thin section was completed by point counting, using a grid spacing of approximately 1.5 mm. Between 300 and 400 points were counted on each section. The identity change number was sufficiently high so that one thin section from each sample was sufficient for the variation to be $\leq$ 2% (Chayes, 1956). The point-counting classifications included plagioclase, pyroxene, granophyre and opaques. In the more granophyre-rich samples where the pyroxenes were heavily altered, chloritic patches and green amphiboles were considered to be alteration products of pyroxene and were therefore counted as pyroxene.

General Description

In general, the modal mineralogy of the dike is simple and is similar to the mineralogy found in other diabase dikes and sills in eastern North America. The primary minerals within the dike are plagioclase, clinopyroxene, pigeonite, granophyre and opaques. Accessory minerals include baddeleyite, zircon and apatite. Alteration minerals include chlorite, amphibole, a clay (?) mineral and calcite.

The Farmville Dike displays an intergranular texture. No phenocrysts or autocrysts were identified. The only textural change noted is a coarsening in grain size from the margins to the central, granophyric core.

Alteration of the diabase increases significantly from the flanks of the dike to the granophyric core. Plagioclase near the margins shows only patchy development of sericite while plagioclase towards the center of the dike shows extensive development of sericite. Pyroxene alters to chlorite, amphibole, and opaque minerals. The alteration increases from the margin towards the center, where some pyroxenes are completely altered and almost unrecognizable. The extent of alteration towards the center of the dike makes optical determinations on plagioclase and pyroxene difficult.

The increase of alteration in the dike parallels the enrichment in granophyre and suggests the development of a late-stage aqueous solution which was responsible for alteration.

The results of the modal analysis are given in Table 1. Figure 6 is a plot of cumulative modal percentage vs. distance across the dike. The increase of granophyre in the core of the dike is well defined in this figure. The percentage of plagioclase and augite oscillates across the dike, but both tend to decrease near the center as granophyre increases. Opaques tend to increase towards the center of the dike. The strongest trend is in the enrichment of granophyre from the margins to the center of the dike; the granophyre ranges from 6% near the western margin to 37% near the center.

The Farmville dike can be divided into two zones based on granophyre content; a main diabase body and a granophyric core. This division is made, somewhat arbitrarily, at granophyre greater than twenty percent. This division is made because, except for FV-39, all samples contain either less than 20 % granophyre or greater than 30 % granophyre. This division places FV-39, with 25.4 % granophyre, in the granophyric core group, although it may actually represent a sample transitional between the main dike body and the granophyric core. The change in granophyre in the core

Table 1. Modal analyses of samples from the Farmville dike.

Sample	Pyroxene%	Plagioclase% (An%)	Granophyre%	Opaques%
FV22-7	42.5	49.9 (68)	6.1	1.2
FV22-8	29.4	46.2 (58)	19.6	4.8
FV22-10	35.7	47.7 (75)	13.6	3.0
FV22-11	39.4	48.0 (75)	10.1	2.5
FV22-12	37.3	47.2 (67)	14.3	1.2
FV22-15	37.0	47.9 (69)	12.3	2.8
FV22-16	33.2	58.0 (67)	7.5	1.2
FV22-17	38.0	45.3 (65)	14.7	2.0
FV22-19	41.1	47.7 (66)	9.1	2.1
FV22-20	38.4	46.3 (67)	12.7	2.5
FV22-21	38.7	44.1 (65)	5.0	2.1
FV22-22	39.3	38.5 (65)	16.3	6.0
FV22-23	39.0	39.6 (70)	16.8	4.3
FV22-24	42.0	41.1 (75)	13.6	3.3
FV22-25	37.8	39.5 (69)	18.3	4.3
FV22-28	24.6	41.0 *	31.2	4.6
FV22-29	29.6	27.2 *	37.3	4.4
FV22-30	23.6	39.4 *	36.4	2.7
FV32-33	29.3	32.0 *	32.3	6.4
FV32-35	25.7	33.3 *	37.1	3.8
FV32-36	22.7	37.1 *	33.5	6.1
FV32-37	24.6	36.4 *	37	2
FV32-38	28.5	31.8 *	34.5	5.1
FV32-39	30.8	39.6 *	25.4	4.2
FV32-40	24.5	47.3 (61)	15.5	3.0
FV32-41	35.5	41.8 (64)	18.0	4.6
FV32-43	38.5/35.1••	40.2/42.2 (66)	17.4/17.7	3.8/5
FV32-44	41.5	40.3 (66)	14.5	3.7
FV32-45	41.6	43.9 (70)	11.6	2.9
FV32-46	46.6	38.9 (72)	10.5	3.4
FV32-48	42	43.8 (64)	11.5	2.7
FV32-49	38.6	45.6 (64)	11.6	4.2

* An content could not be determined due to extensive alteration of plagioclase.

•• Sample point-counted twice.

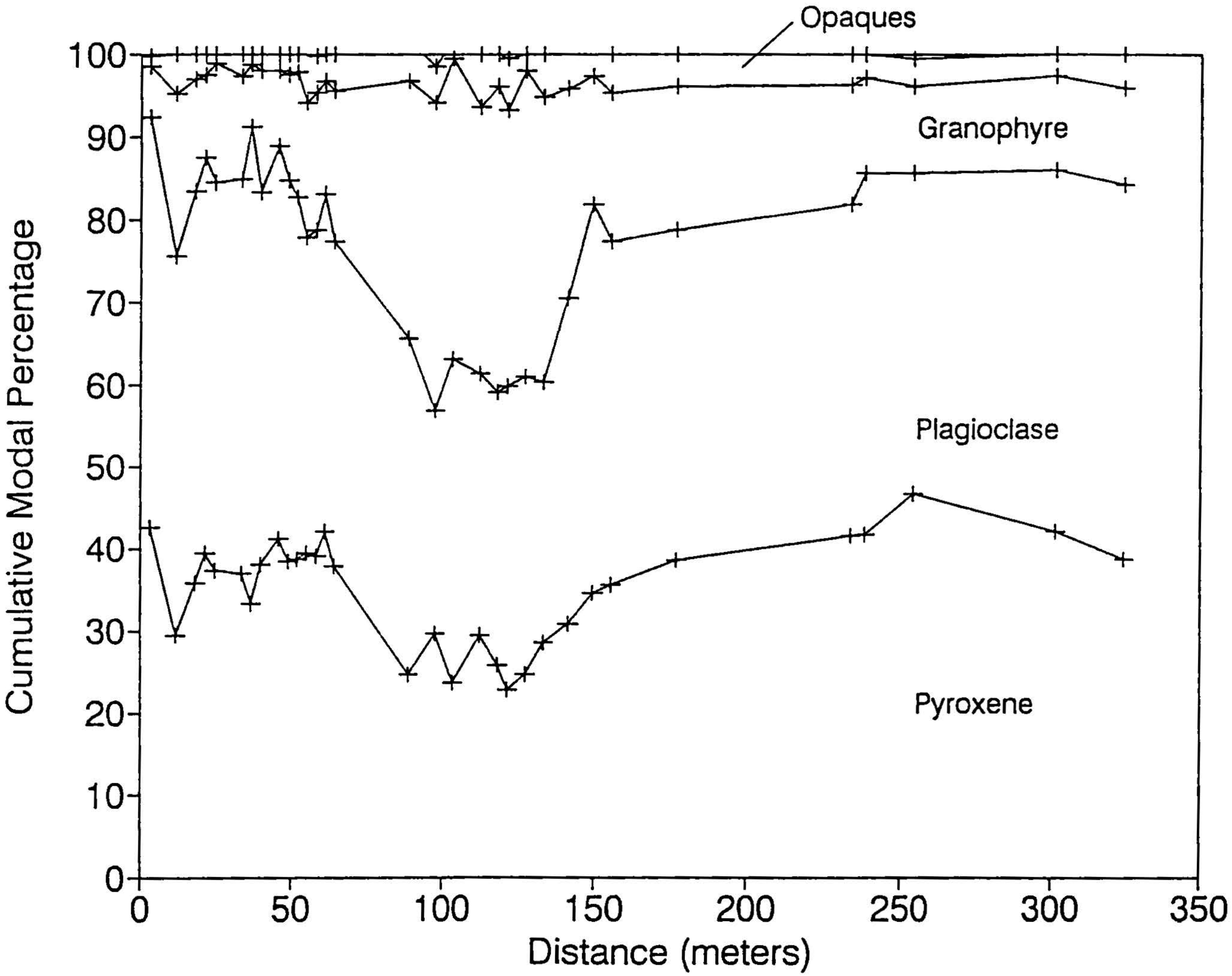


Figure 6. Diagram showing cumulative modal percent of minerals in the Farmville dike.

appears to be a fairly sharp break rather than a smooth or gradual increase.

Plagioclase

The percentage of plagioclase in the samples varies between 27 and 58%. Plagioclase occurs mostly as euhedral to subhedral elongate laths of varying size, but, in general, grain size increases from the margins toward the center. Albite twinning is the most abundant, and Carlsbad twinning is common. Some grains show a more stubby or almost square outline and little or no twinning. Extinction in the elongate laths is undulatory; many of the stubby or square grains show weak zonation.

The anorthite content of the plagioclase was determined by the Michel-Levy method using a flat stage and a 5-axis universal stage. At least 12 grains per slide were used except were the amount of alteration obscured most of the plagioclase. The U-stage was used to rotate (010) cleavages and albite twins so that they were vertical before making measurements. When both Albite and Carlsbad twins were present in a single grain and the grains were in a suitable orientation, the albite-carlsbad method for determining anorthite content was used. Anorthite content varied between 58 and 75 %, and seemed to be fairly constant throughout the dike; there was no large variation or trend noticed across the dike. Variation in An content within zoned grains was not determined because the variation in extinction angle was small (approximately 3 degrees), and indicated that An variation within a particular grain was small.

Pyroxene

The main pyroxene present is augite which comprises 23 to 47% of the rock. It is identified by its moderate relief, pale greenish-gray color, lack of pleochroism, and fair cleavage. The pyroxene is generally anhedral and appears interstitial. In some slides, small augite (?) grains are enclosed in larger, euhedral plagioclase laths.

The pyroxene alters to chlorite, amphibole, and opaque minerals. The alteration increases from the margin towards the center, where some pyroxenes are completely altered and almost unrecognizable.

Small grains of pigeonite were identified in some of the slides. They were identified mainly by their low 2V (close to 0^0). Because of its small grain size and overall optical similarity to the augite, pigeonite percentage could not be determined. No orthopyroxene has been identified in any of the samples.

Granophyre

Granophyre comprises from 6 to 37% of the dike and shows a modal increase from the margins toward the center of the dike. The alkali feldspar is generally altered and has a reddish hue towards the center of the dike. The intergrown quartz has low relief and shows no alteration. Near the center, some of the granophyric patches become relatively coarse, and in some areas quartz forms individual grains. Small apatite needles are fairly abundant in the granophyric patches.

Opaques

Opaque minerals comprise 1 to 6% of the dike. In general, the opaque minerals increase towards the center of the dike. Polished sections were not used to determine the composition of the opaque minerals, but they are probably composed of magnetite and/or ilmenite.

GEOCHEMISTRY

Sample Preparation and Analytical methods

Only the visibly freshest samples were selected for chemical analysis. For this reason, only fairly large samples were used; smaller samples were generally discarded because enough fresh material could not be obtained. Also, spheroidally weathered samples and samples with thick weathering rinds were generally not used. Exceptions included fairly large spheroidally weathered boulders where fresh material could be obtained from the middle of the sample. Because of this screening, Of the thirty-two samples originally collected for petrographic analysis, only sixteen samples were prepared for chemical analysis. An additional for samples were selected for chemical analysis. The sample preparation method is described in Appendix A.

All samples were analyzed for SiO_2, TiO_2, Al_2O_3, Fe_2O_3* (total iron as Fe_2O_3), MgO, MnO, CaO, Na_2O, K_2O, and the trace elements Zr, Y, Sr, Zn, Cu, Sc, Ni, V, Cr, and Ba. Loss on ignition and P_2O_5 were not determined. The samples were analyzed on the JY 70P Type II inductively coupled plasma atomic emission spectrophotometer (ICP) at the Carnegie Institution of Washington (CIW). Calibration curves were constructed using rock standards BR and AGV-1. These two standards as well as standards DNC-1, NBS-688, BHVO-1, BIR-1, Loihi and W-2 were used as internal standards. Recommended values for all standards except Loihi, which is an in-house standard used at CIW, were taken from the compilation by Govindaraju (1989). Analytical precision for the major and trace elements was determined by replicate analyses of W-2. Precision estimates for the major and trace elements are presented in Table 2.

Ragland and Arthur (1988) indicated that alteration may result in increased variation of a large number of elements, and they recommended that less than 2 percent loss on ignition and unaltered plagioclase be used as screening criteria. Therefore, chemical analyses with oxide totals less than 96 percent when loss on ignition was not determined are considered unacceptable (Cummins et al., 1992; Ragland, 1991; Ragland et al., 1992). The application of this screen to the Farmville data indicates that the analyses of samples FV-24, FV-33, FV-40, FV-41 and FV-45 may be unreliable. In addition, the low SiO_2 content of FV-10 is similar to that of FV-24, FV-33, and FV-45, and suggests that the analysis for FV-10 may be questionable even though the oxide total is greater than 96 percent.

Table 2. Estimate of analytical precision for major and trace elements based on 10 analyses of Standard W-2. Standard deviations for major elements are in percent; standard deviations for trace elements are in parts per million.

	W-2 Expected	W-2 Observed	Standard Deviation	Relative Uncertainty (%)
Oxides				
SiO_2	52.44	51.6	0.71	-1.60 ± 1.35
TiO_2	1.06	1.05	0.02	-0.94 ± 1.89
Al_2O_3	15.35	15.1	0.31	-1.63 ± 2.02
Fe_2O_3*	10.74	10.7	0.24	-0.37 ± 2.23
MnO	0.163	0.17	0.004	4.29 ± 2.45
MgO	6.37	6.42	0.095	0.78 ± 1.49
CaO	10.87	10.9	0.17	0.28 ± 1.56
Na_2O	2.14	2.19	0.14	2.34 ± 6.54
K_2O	0.627	0.62	0.025	-1.12 ± 3.99
Trace elements				
Zr	96	94	9.9	-2.08 ± 10.3
Sr	193	194	4.7	0.52 ± 2.44
Y	19	24	2.5	26.3 ± 13.2
Zn	89	77	20.0	-13.5 ± 22.5
Cu	109	103	7.5	-5.50 ± 6.88
Sc	36	35	1.8	-2.78 ± 5.00
Ni	73	70	7.4	-4.11 ± 10.1
Cr	91	93	4.0	2.20 ± 4.40
V	261	262	8.6	0.38 ± 3.30
Ba	167	182	5.2	8.98 ± 3.11

Results

The results of the major element analyses and CIPW norms are given in Appendix B. The results of trace element analyses are given in Appendix C. The variation of selected oxides and trace elements across the dike is shown in Figure 7. Chemical variation across the dike is symmetrical about the granophyric core. However, the diagrams may not appear symmetrical because the distance on these diagrams is calculated from the location of the first analyzed sample, not from the dike margin. Also, the difference in the number of samples on either side of the core was controlled by sampling limitations in the field. Overall, the diagrams show a systematic variation across the dike.

Figure 8 shows the variation of selected oxides and trace elements versus magnesium number (Mg#). The Mg# is a fractionation index indicating differentiation of a basaltic liquid; the Mg# decreases with increasing fractionation. In order to calculate the Mg#, ferrous iron must be measured or calculated. Total iron was analyzed as Fe_2O_3 (total iron as ferric iron is indicated as Fe_2O_3*); an Fe_2O_3/Fe_2O_3* molar ratio of 0.15 was used to calculate FeO. The Mg# was then calculated using the following equation (Ragland, 1989):

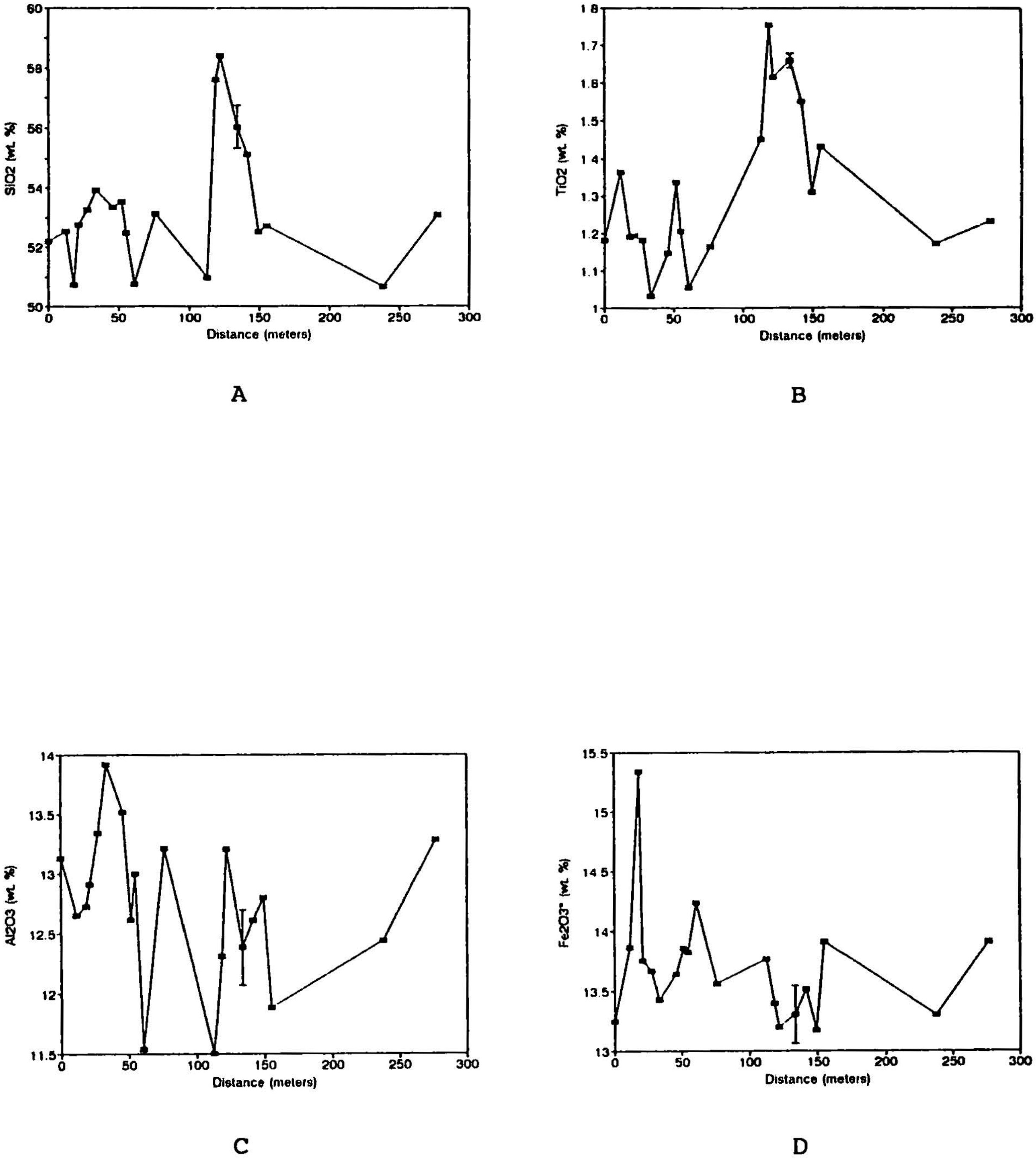


Figure 7. Major oxide and trace element variation versus distance across dike. The error bar indicates ± one standard deviation. A = SiO_2 versus distance. B = TiO_2 versus distance. C = Al_2O_3 versus distance. D = Fe_2O_3* versus distance.

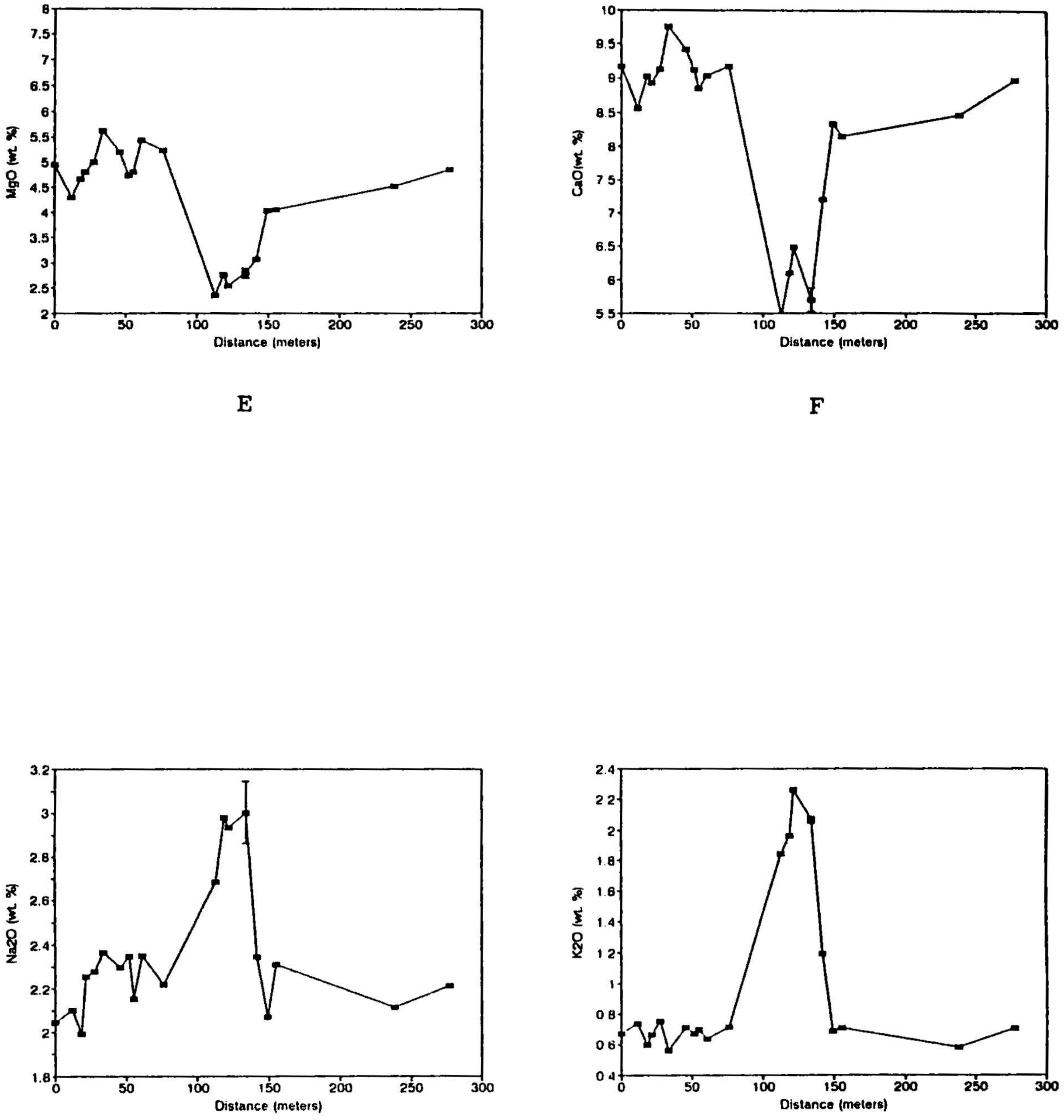


Figure 7. Continued. E = MgO versus distance. F = CaO vesus distance. G = Na_2O versus distance. G = K_2O versus distance.

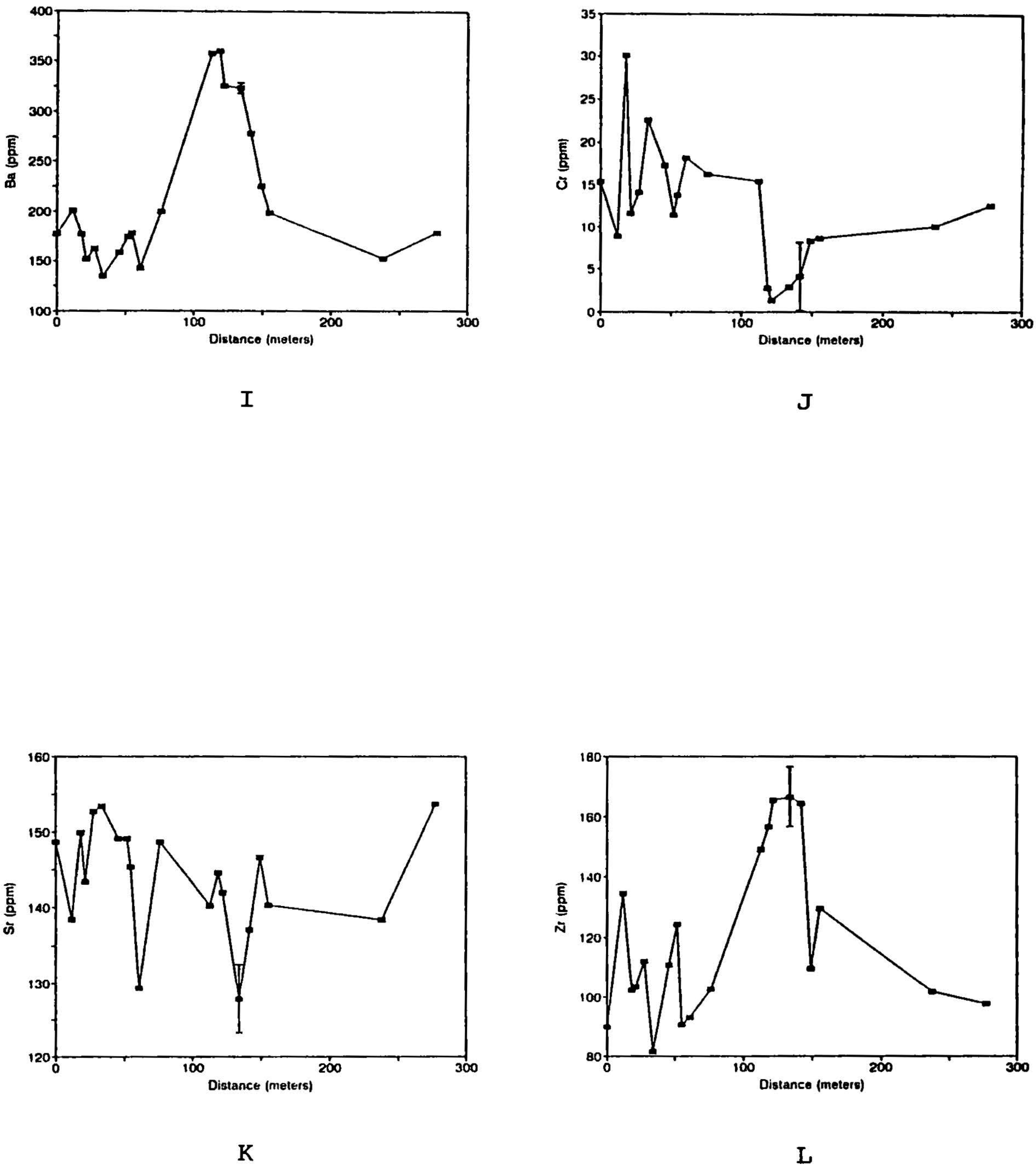


Figure 7. Continued. I = Ba versus distance. J = Cr vesus distance. K = Sr versus distance. L = Zr versus distance.

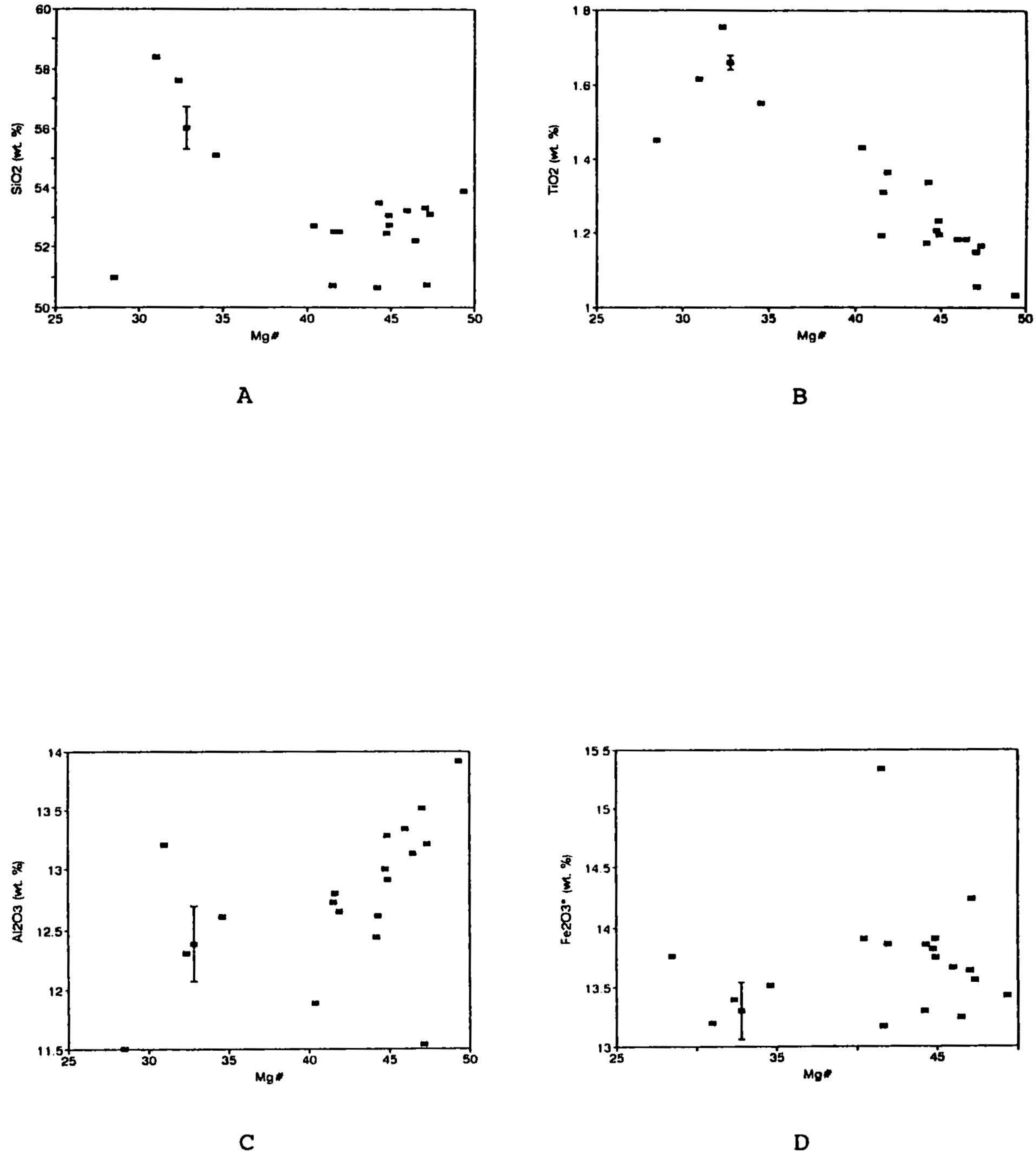
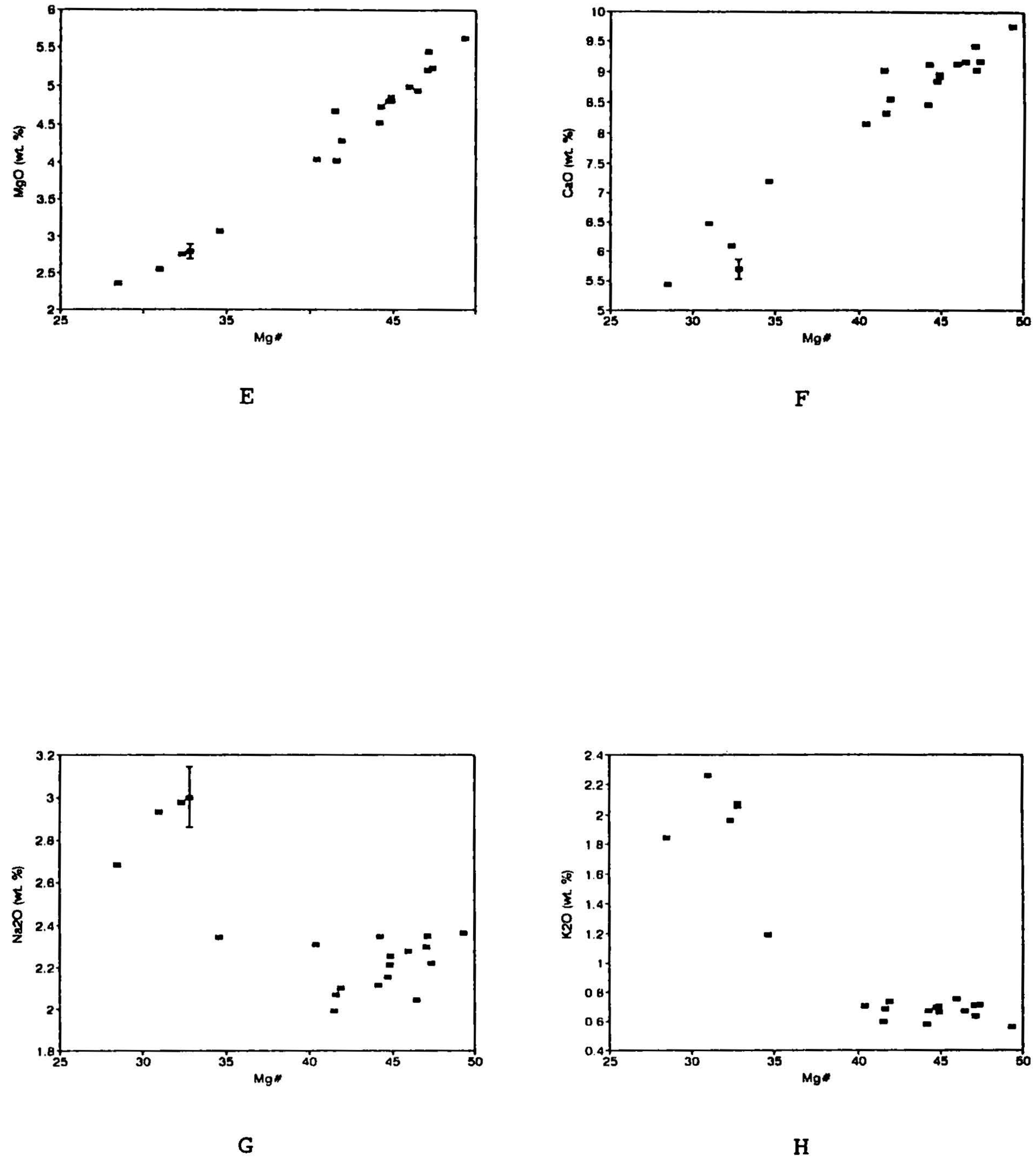


Figure 8. Major oxide and trace element variation diagrams versus Mg#. The error bar indicates ± one standard deviation. A = SiO_2 versus Mg#. B = TiO_2 versus Mg#. C = Al_2O_3 versus Mg#. D = Fe_2O_3* versus Mg#.



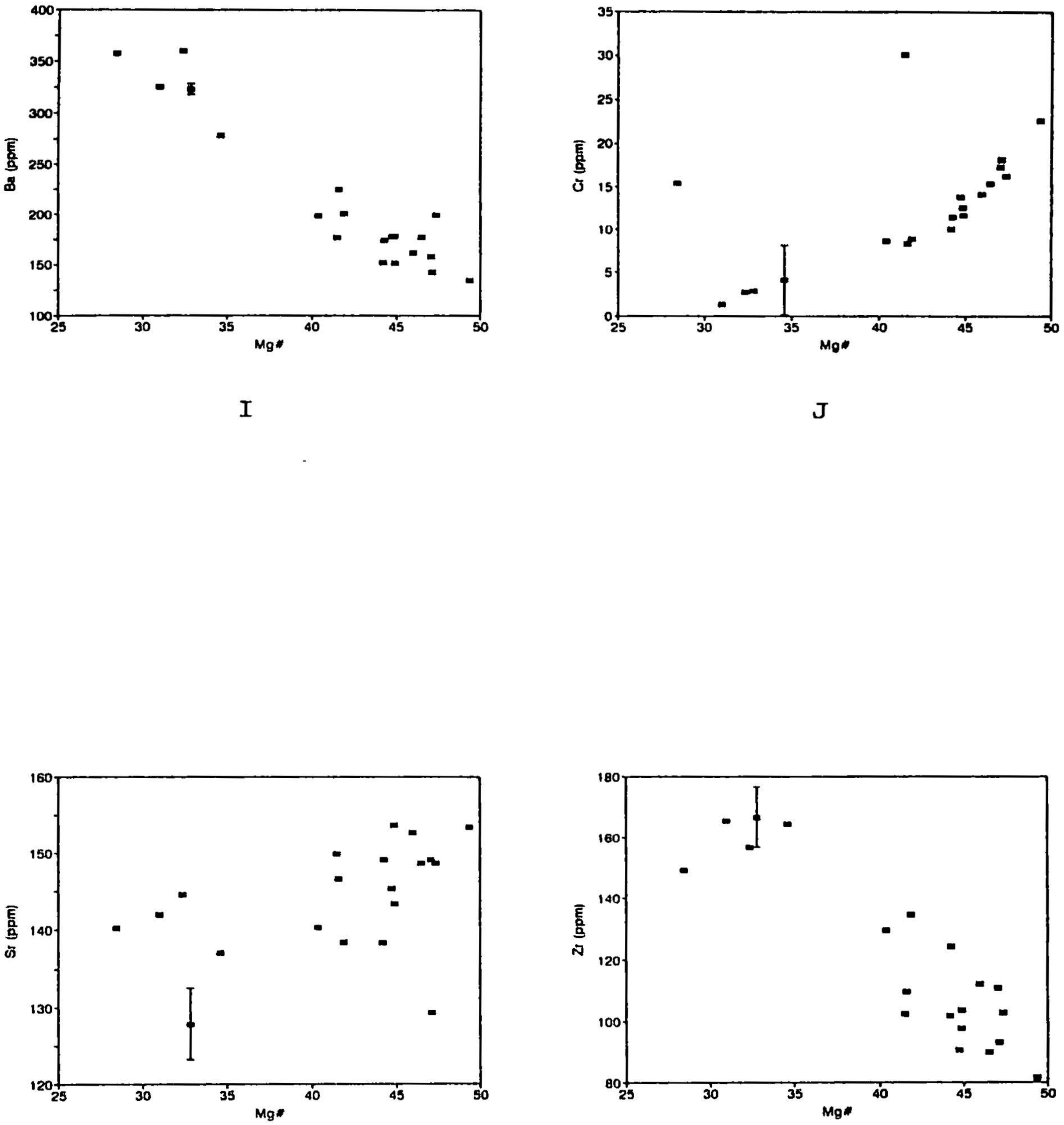
E

F

G

H

Figure 8. Continued. E = MgO versus Mg#. F = CaO versus Mg#. G = Na_2O versus Mg#. H = K_2O versus Mg#.



I

J

K

L

Figure 8. Continued. I = Ba versus Mg#. J = Cr vesus Mg#. K = Sr versus Mg#. L = Zr versus Mg#.

Mg# = 100*{(wt.% MgO/EW(MgO)/[wt.% MgO/(EW(MgO)+wt.% FeO/EW(FeO)]}

where EW is the equivalent weight of the oxide.

Other fractionation indices such as MgO variation and the mafic index (MI) have been commonly used in studies of eastern North American diabase. The MI is defined as Fe_2O_3* X100/(Fe_2O_3* + MgO). Whittington (1988) suggests two advantages of using the Mg# rather than MI. First, the one-to-one molar substitution of Fe^{2+} for Mg^{2+} in certain minerals is distorted in the MI because the MI is based upon weight percent oxides. Second, the Mg# has direct significance for mantle equilibration; for a melt in equilibrium with a mantle peridotite (forsterite content of olivine of 88-92 %), the Mg# is between 68 and 72 (Irvine, 1977). For these reasons, the Mg# is used as the fractionation index in this study.

In general, SiO_2, TiO_2, Na_2O, K_2O, and the incompatible trace elements Zr and Ba increase with decreasing Mg#, and reach a maximum in the granophyric core, while MgO, CaO and Cr decrease to a minimum in the core. Strontium, aluminum and Fe_2O_3* show less well-defined patterns. Aluminum is scattered, but it shows some decrease with Mg# in the main dike body and remains constant or increases very slightly in the core. Iron also is scattered, but it appears to increase slightly in the main dike body and decrease slightly in the granophyric core.

The variation diagrams show two distinct groups which correlate with the main dike body and the granophyric core, indicating that the composition of the dike is bimodal. Average compositions of the samples from the main dike body and from the granophyric core are given in Table 3.

In most of the diagrams, the two fields are separated by gaps in both the Mg# and element concentration, as is seen for example in the SiO_2 and CaO diagrams. The Mg# gap indicates either a sudden increase in iron, a sudden decrease in MgO, or both. The fact that iron appears to decrease slightly in the core suggests that the Mg# gap is controlled by a fairly rapid decrease in MgO. Certain oxides such as TiO_2 and MgO show variation within the main dike body. SiO_2 in particular shows a curious trend. SiO_2 is enriched in the core, yet it appears to decrease slightly with fractionation in the main dike body.

Classification

All samples from the Farmville dike are quartz tholeiitic as indicated by normative quartz and hypersthene. Figure 9 is an MI-TiO_2 plot, which is commonly used to classify eastern North American quartz diabase compositions.

Table 3. Average compositions for the main Farmville dike body samples and the granophyric core samples. The variation is ± one standard deviation.

	Average Diabase (n = 12)	Average Granophyre (n = 3)
SiO_2	53.0 ± 0.50	57.3 ± 1.2
TiO_2	1.23 ± 0.11	1.68 ± 0.07
Al_2O_3	13.0 ± 0.52	12.6 ± 0.50
Fe_2O_3*	13.7 ± 0.25	13.3 ± 0.10
MnO	0.21 ± 0.01	0.18 ± 0
MgO	4.80 ± 0.48	2.69 ± 0.13
CaO	8.96 ± 0.45	6.09 ± 0.39
Na_2O	2.22 ± 0.11	2.97 ± 0.03
K_2O	0.69 ± 0.05	2.10 ± 0.15
Total	97.8	98.9
Norms		
Q	8.4	11.6
or	4.1	12.4
ab	18.8	25.1
an	23.5	14.8
di	17.5	13.0
hy	19.0	14.7
mt	3.0	2.9
il	2.3	3.2
AN%	55.5	37.1

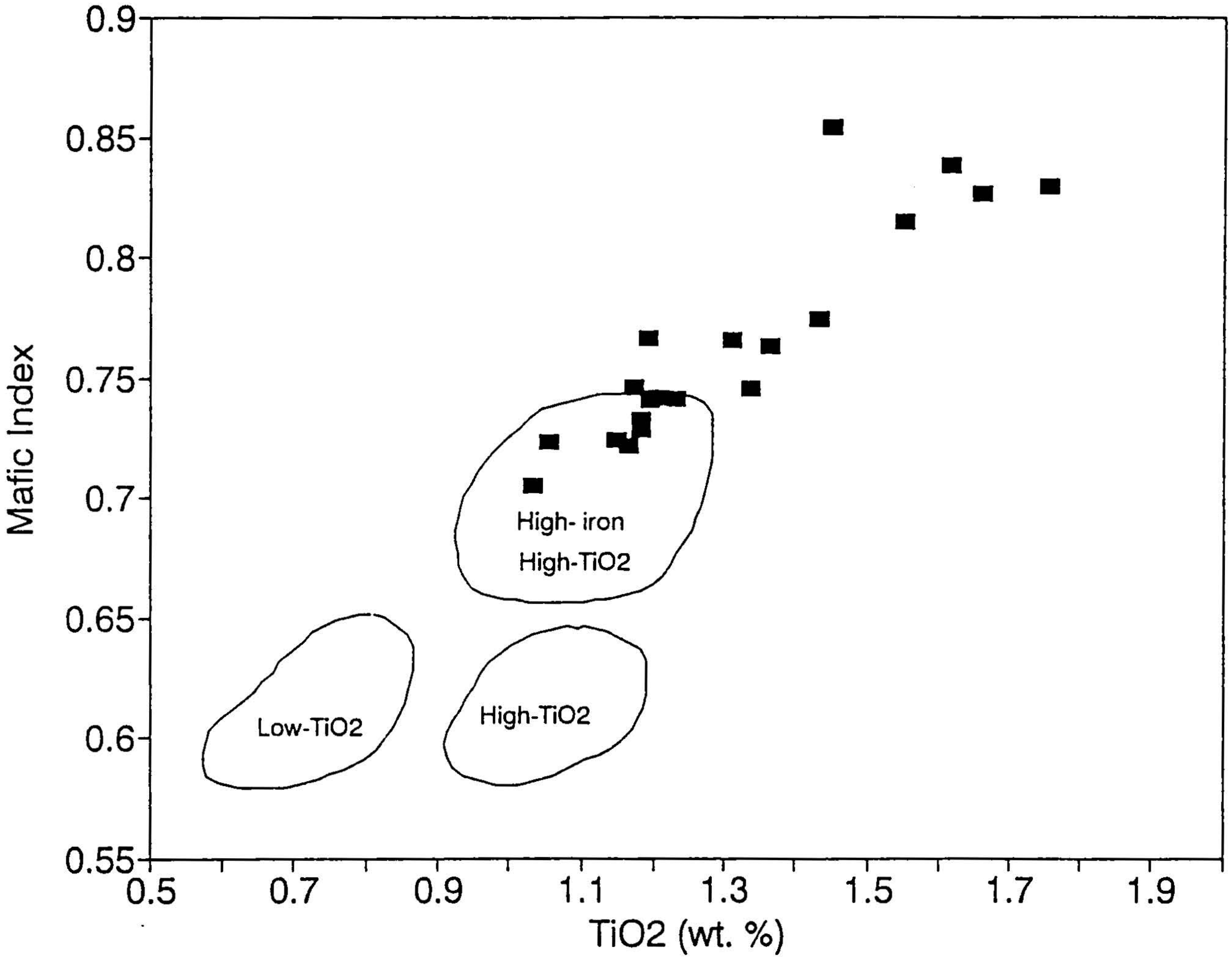


Figure 9. MI versus TiO_2 diagram. Fields are from Weigand and Ragland (1970).

The two compositional groups are easily distinguished in this plot. The data for the main dike plot in the high-TiO_2 high-Fe_2O_3* (HFQ) field of Weigand and Ragland (1970) and extend beyond it. The data for the core of the Farmville dike plot in a distinct group and are higher in MI and TiO_2.

The Farmville data are plotted on a total alklies versus SiO_2 plot in Figure 10. The plot shows a distinct gap in $Na_2O + K_2O$ between the main dike and the core. All samples are subalkaline (Irvine and Baragar, 1971).

Figure 11 is a plot of TiO_2 versus MgO. This plot has been used to classify eastern North American quartz-normative diabases as either relatively incompatible element -enriched or incompatible element-depleted (Puffer and Philpotts, 1988; Cummins et al., 1992; Milla and Ragland, 1992). The Farmville data plot along an extension of the incompatible element-depleted trend and indicate that the Farmville dike belongs to the incompatible element-depleted group. This is consistent with the findings of Cummins et al. (1992) and Milla and Ragland (1992) for quartz-normative diabases in Virginia and the Carolinas. The trend in this plot has been interpreted to be a fractionation trend, and suggests that the magma that the Farmville dike magma fractionated from a low-TiO_2, quartz-normative parental magma.

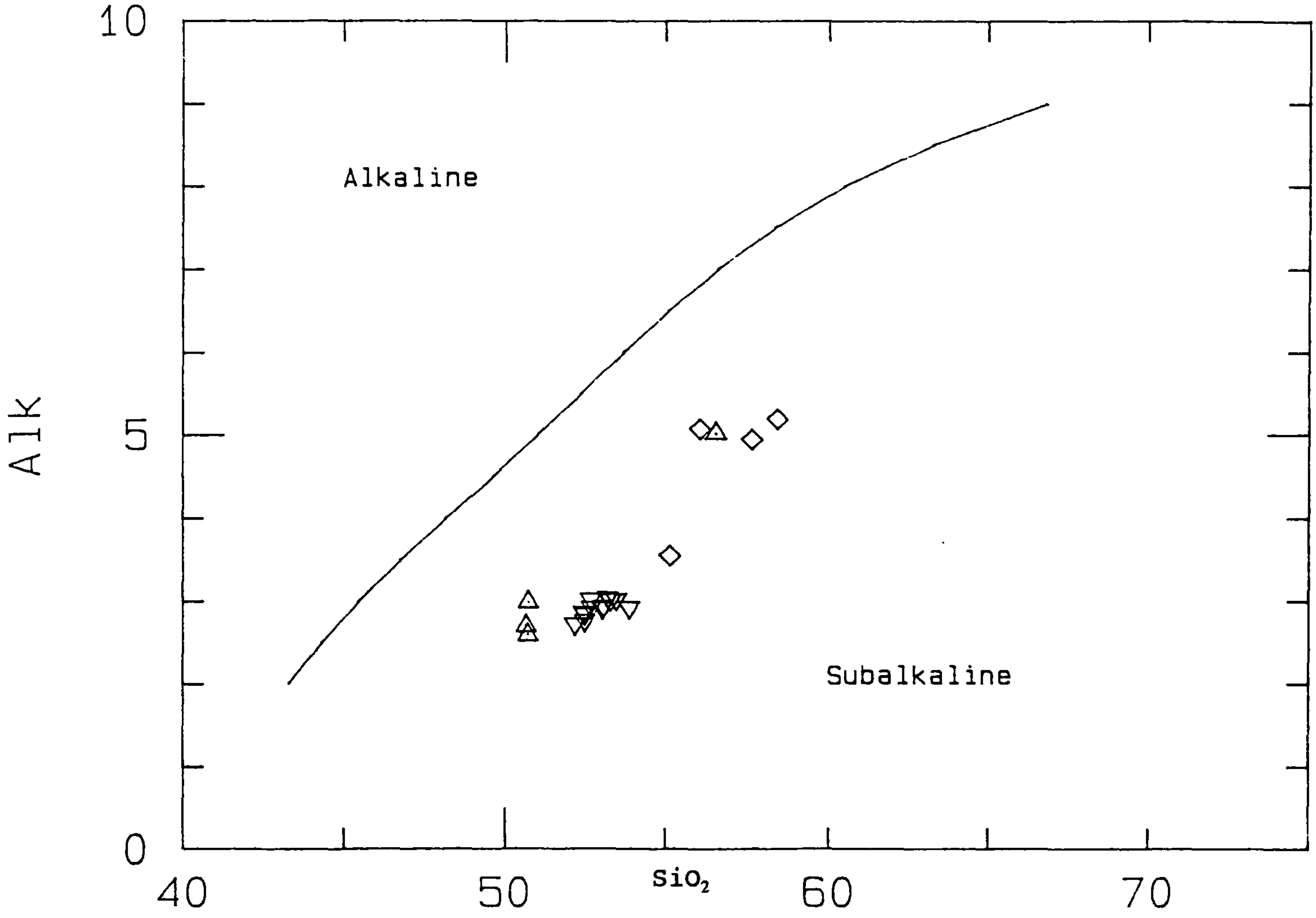


Figure 10. Alkali:SiO_2 diagram with the dividing line of Irvine and Baragar (1971). Inverted triangles = main dike; triangles = questionable samples; diamonds = core.

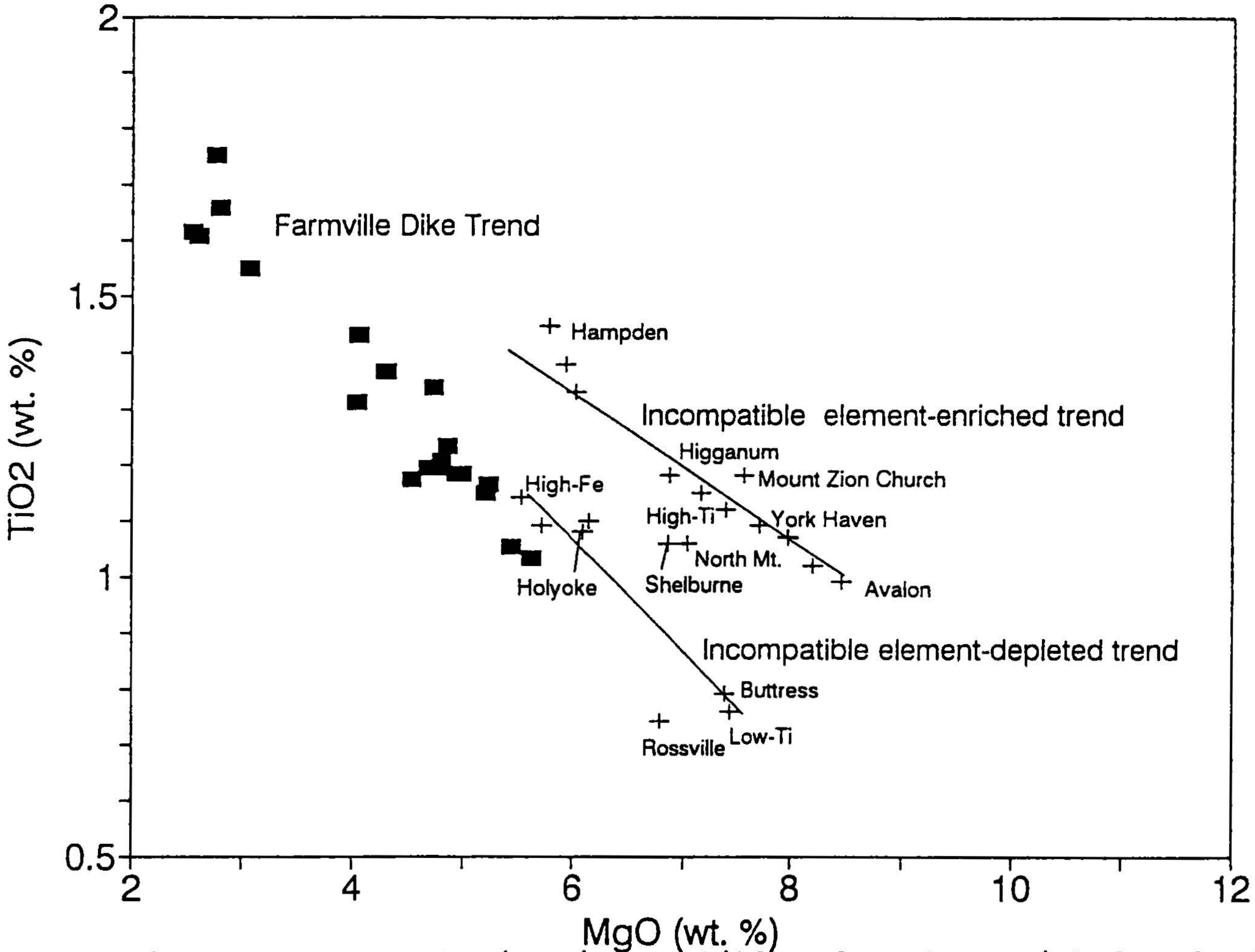


Figure 11. Plot of TiO_2 versus MgO showing incompatible element -enriched and -depleted trends for eastern North American basalts. The Farmville dike plots on an extension of the depleted trend. Crosses = Puffer and Philpotts (1988), Filled squares = Farmville dike samples. (modified from Puffer and Philpotts, 1988.)

The results indicate that the main body of the Farmville dike can be classified as an incompatible element -depleted, high-TiO_2 high-iron quartz-normative tholeiite. The composition of the main dike body is actually a basaltic andesite and appears to be more highly evolved than is commonly recognized in the region from Virginia to the Carolinas, although high-TiO_2, high-iron composition is common in the north-south dike swarm. The core composition is even more highly evolved.

Qualitative Comparison with similar rock types

The chemistry of the Farmville dike and the granophyric core can be compared to similar rock types from other areas. The average composition of the main body of the Farmville dike is compared to other quartz-normative tholeiites in Table 4. The dike is very similar to both Weigand's (1970) eastern North American high-iron quartz-normative average and the average of Ragland's (1991) composition of the north-south dike swarm in North Carolina. The dike has slightly higher TiO_2 and slightly lower Al_2O_3, MgO, CaO, and Na_2O than the two averages. The dike is also similar to compositions found in New England as indicated by Sample 1003E from a New Hampshire dike (Sundeen and Huff, 1992), except that it is much lower in MgO and slightly higher in

Table 4. Comparison of the average composition of the Farmville dike main body with selected quartz tholeiite compositions of other eastern North American diabases and from other provinces.

	a	b	c	d	e	f	g	h
SiO_2	53.0	51.7	53.71	53.3	53.05	52.7	52.39	53.1
TiO_2	1.23	1.18	2.9	1.23	1.06	1.88	1.11	1.13
Al_2O_3	13	14.6	11.79	13.7	14.07	12.8	14.41	14.1
Fe_2O_3	2.05	11.2*	3.26	---	13.66*	13.4*	13.52*	13.7*
FeO	10.4	---	12.42	10.25**	---	---	---	---
MnO	0.21	0.18	0.23	0.19	0.22	0.28	---	---
MgO	4.8	7.6	2.27	7.57	5.33	5.3	5.7	5.44
CaO	8.96	10.56	6.3	10.8	9.87	8.52	9.86	9.27
Na_2O	2.22	1.92	3.05	1.95	2.59	2.53	2.35	2.43
K_2O	0.69	0.6	1.57	0.66	0.61	0.95	0.65	0.76

* Total iron as Fe_2O_3
** Total iron as FeO

a. Average main Farmville dike body.
b. Lower chill margin, Dillsburg sill (Hotz, 1953, Average of samples 21 and 284
c. Average of intermediate granophyre Samples 479 and 645 (Hotz, 1953).
d. Sample 1003E from southern New Hampshire tholeiitic dike (Sundeen and Huff, 1992).
e. Mean of Preakness basalt P-2 (Tollo and Gottfried, 1992).
f. North Mountain basalt mafic pegmatite sample MCK3B (Dostal and Greenough, 1992).
g. Average of 12 High-iron quartz-normative diabases (Ragland, et al., 1992).
h. Average of 48 samples from the north-south dike swarm (Ragland, 1991).

Table 4. Continued.

	i	j	k	l	m	n	o	p
SiO_2	50.11	53.9	54.1	52	52.1	51.66	52.69	51.69
TiO_2	3.43	1.44	0.7	1.2	1.12	0.76	1.14	0.99
Al_2O_3	12.73	14.84	15	14.2	14.22	14.95	14.21	14.58
Fe_2O_3	5.17	2.75	10.2*	1.35	11.65*	11.77*	13.87*	1.56
FeO	9.97	9.7	---	8.9	---	---	---	8.43
MnO	0.32	0.2	0.1	0.15	0.19	0.2	0.22	0.19
MgO	3.73	2.99	6.7	7.6	7.41	7.44	5.53	8.45
CaO	7.3	8.51	10.7	10.3	10.66	10.8	9.86	11.68
Na_2O	2.33	2.27	1.9	2	2.12	2.23	2.51	1.91
K_2O	1.76	1.54	1	0.85	0.66	0.48	0.64	0.4

i. "Intermediate Rock" sample W-687-4 (Leighton, 1954).
j. Red Hill Transitional quartz dolerite sample M222 (McDougall, 1962).
k. Chill Margin, Red Hill Dike (McDougall, 1962, Table 8, Column 1).
l. Chill margin average, Palisades sill (Walker, 1969)
m. High-titanium quartz-normative diabase (Weigand, 1970).
n. Low-titanium quartz-normative diabase (Weigand, 1970).
o. High-iron high-titanium quartz-normative diabase (Weigand, 1970).
p. Average avalon diabase (Papezik and Hodych, 1980, average of 7 analyses).

Na_2O. The dike is more silicic than most of the other compositions and approaches the values for the intermediate granophyre of Hotz (1953), but the dike is much lower in TiO_2 and K_2O and higher in MgO and CaO. The Farmville dike is also similar to compositions from other areas such as the Red Hill transitional quartz dolerite of McDougall (1962).

The average composition of the Farmville dike granophyre is compared to other granophyres in Table 5. The silica content of the various granophyres shows a relatively wide range with the Farmville granophyre at the low end. With the exception of Al_2O_3 and FeO, the core is very similar to the sample from a New England felsitic pluton (Sundeen and Huff, 1992). Analysis C indicates that the core is also similar to evolved compositions of New Jersey (Husch, 1992), with the exception that the dike is much lower in TiO_2 and lower in iron.

The SiO_2 content of the Farmville granophyre is similar to that of the Red Hill fayalite granophyre of McDougall (1962) and is slightly less than that of the Red Hill granophyre sample M206 (McDougall, 1962).

Titanium in the Farmville granophyre is higher than in the other granophyres, although sample 601 (Hotz, 1953), sample W-687-3 (Leighton, 1954) and the two Red Hill granophyre samples (McDougall, 1954) all have TiO_2 concentrations above 1.4 %. The Farmville dike has greater MgO than all of the other granophyres and higher CaO than

Table 5. Comparison of the average composition of the granophyric core samples with rocks of transitional and granophyric compositions from other provinces.

	a	b	c	d	e	f	g	h
SiO_2	57.3	57.7	57.4	58.81	61.69	66.04	63.19	70.2
TiO_2	1.68	1.25	2.58	1.26	1.46	1.03	1.41	0.56
Al_2O_3	12.6	20	11.68	12.02	12.61	12.72	12.22	12.33
Fe_2O_3	2	---	---	5.77	2.98	2.48	3.67	3.12
FeO	10.2	7.03**	14.5**	9.38	8.32	6.55	4.71	2.63
MnO	0.18	0.26	0.19	0.21	0.15	0.11	0.13	0.06
MgO	2.69	2.42	1.74	0.72	0.77	0.54	1.68	0.76
CaO	6.09	4.74	5.49	5.03	4.04	2.65	3.57	0.9
Na_2O	2.97	2.82	3.2	3.91	5.71	4.62	4.3	4.17
K_2O	2.1	2.75	2.1	2.39	0.57	2.26	2.26	3.57

** Total iron as FeO

a. Average Farmville dike granophyric core.
b. Sample 460A from felsitic pluton (Sundeen and Huff, 1992).
c. Baldpate Mountain Sample T1 (Husch, 1992).
d. Hedenbergite granophyre 3047, Skaergaard intrusion (Wager and Deer, 1939).
e. Granophyre sample 601 (Hotz, 1953).
f. Granophyre sample 560 (Hotz, 1953).
g. "Intermediate rock" sample W-687-3 (Leighton, 1954).
h. "Intermediate rock" sample W-687-2 (Leighton, 1954).

Table 5. Continued.

	i	j	k	l	m
SiO_2	57.7	61.39	58.59	68.51	57.9
TiO_2	1.43	1.48	1.56	0.9	1.8
Al_2O_3	15.56	12.26	11.26	12.81	14.7
Fe_2O_3	3.76	5.58	3	1.85	5.1
FeO	7.54	6.36	10.8	3.48	3
MnO	0.2	0.19	0.19	0.11	0.16
MgO	1.2	1.09	1.35	0.85	2.8
CaO	6.56	4.78	3.66	2.45	4.8
Na_2O	2.65	2.56	3.68	3.2	6
K_2O	1.82	2.62	2.52	4.14	3.5

i. Red Hill fayalite granophyre sample M223 (McDougall, 1962).
j. Red Hill granophyre sample M206 (McDougall, 1962).
k. Granophyre, Palisades sill 790-ft height (Walker, 1969).
l. Loch Uisg granophyre (Pankhurst, et al., 1978, average of 8 samples).
m. Granophyre, sample DP-2-222.5 (Ratcliffe and Burton, 1988).

all but the Red Hill fayalite granophyre. Sodium is close to that of the Red Hill granophyres and the Loch Uisg granophyre, while K_2O is close to that of sample 560, sample W-687-3, and the Red Hill fayalite granophyre. The Farmville granophyre closely resembles the Red Hill fayalite granophyre and the Baldpate Mountain (New Jersey) sample, except that the TiO_2 is much higher in the Baldpate Mountain sample.

In summary, the main Farmville dike body closely resembles typical eastern North American high-TiO_2 high-iron quartz-normative tholeiite while the core more closely resembles more evolved, silicic or intermediate compositions.

Discussion of Chemistry

Any petrogenetic model for the Farmville dike must explain the mineralogical and chemical variations within the dike. The main body of the Farmville dike is a fairly typical high-TiO_2, high-Fe_2O_3* quartz-normative tholeiite, containing clinopyroxene, plagioclase, opaques, and granophyre, while the core is much more evolved and contains abundant granophyre.

The dike displays a bimodal composition. The core is distinguished from the main dike by a Mg# gap and distinct gaps in some major and trace element data. The core is enriched in SiO_2, TiO_2, Na_2O, K_2O, and the incompatible trace elements Zr and Ba, and depleted in MgO, CaO and Cr. Nickel is very low in all analyzed samples. Aluminum and Fe_2O_3* show less well-defined patterns. Aluminum shows some decrease in the main dike body and remains relatively constant or increases very slightly in the core. Iron appears to increase slightly in the main dike body and decrease slightly in the granophyric core.

Also, some elements (e.g., TiO_2, CaO, MgO), in addition to being enriched or depleted in the core, show variation within main dike. The variation in Mg# may indicate fractionation of a ferromagnesian mineral such as clinopyroxene. The Mg# gap between the main dike body and the core indicates a fairly abrupt decrease in MgO between the main dike and the core, and this is seen in the data for MgO. One question to be answered is what process may explain the slight but apparent decrease in SiO_2 in the main dike?

INTERPRETATIONS

Major Oxide Fractionation

Two models were used to determine whether crystal fractionation can explain the chemical variation in the Farmville dike. A simple graphical method was used to model oxide fractionation trends controlled by the removal of specific minerals. This method was used to investigate fractionation from the average Farmville dike composition and from the model parental composition calculated by regression (discussed later in Magma Mixing section). The removal of a certain percent of a mineral produces a vector which represents the fractionation trend for that mineral. The amount and composition of a crystallizing assemblage needed to produce a certain compositional change can then be estimated by vector addition of the fractionation trends of other minerals.

Changes in composition of SiO_2, Al_2O_3, and CaO were calculated for 10 % fractionation of plagioclase (An_{60-75}), clinopyroxene, pigeonite, orthopyroxene, and olivine using the average Farmville dike values as the original

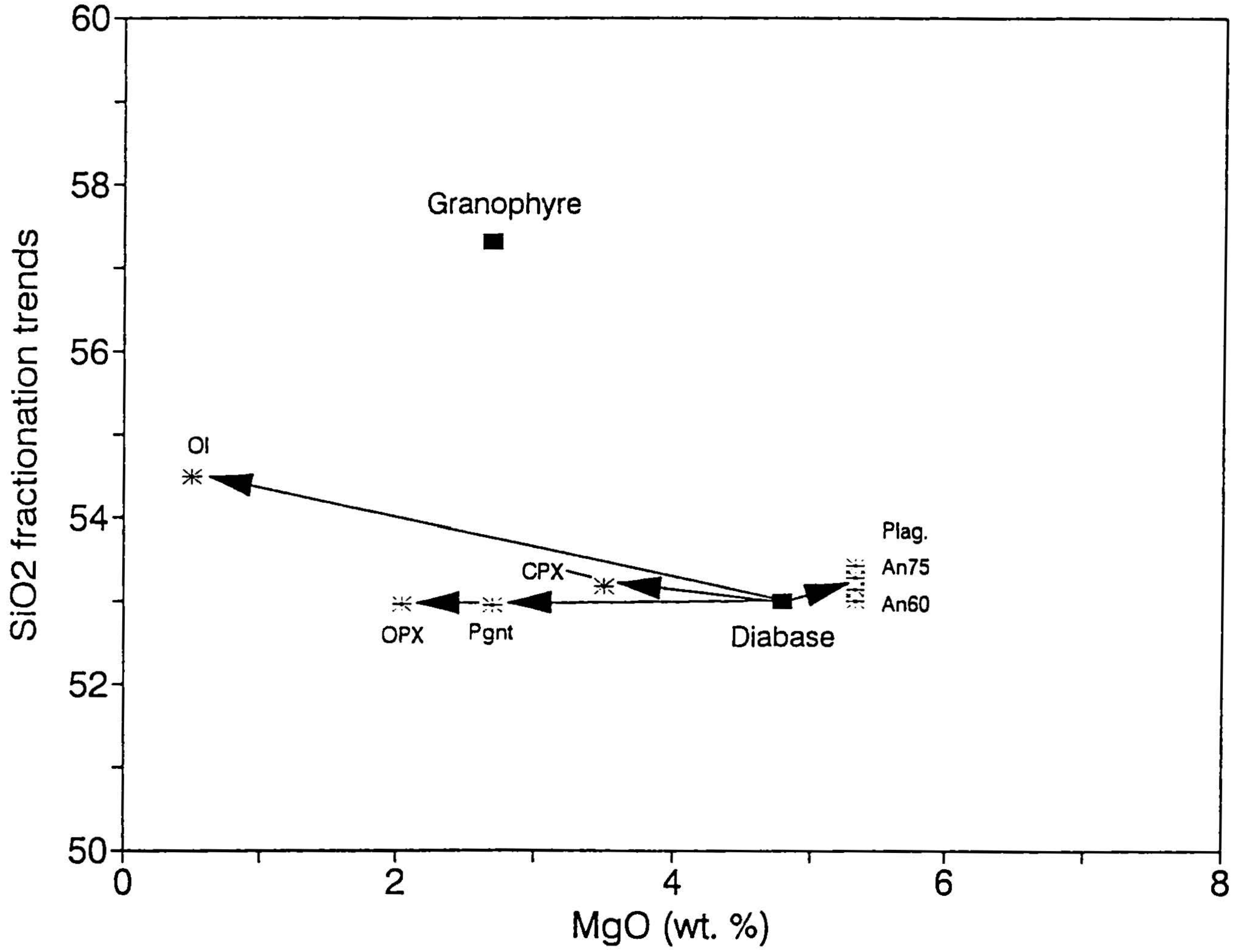


Figure 12. Mineral fractionation trends for SiO_2. Ol = olivine; OPX = orthopyroxene; Pgnt = pigeonite; CPX = clinopyroxene; and Plag = plagioclase (An varied from 60-75).

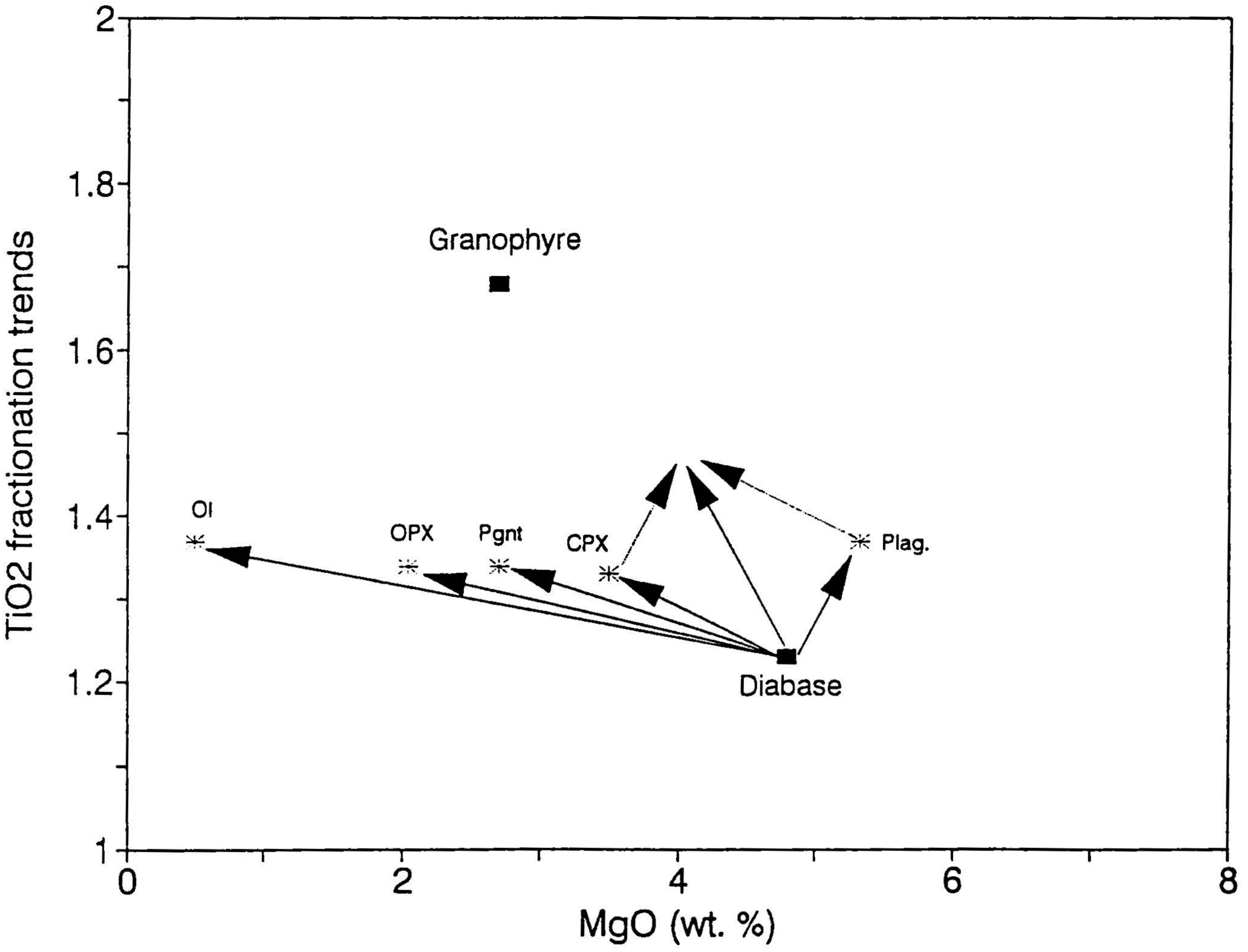


Figure 13. Mineral fractionation trends for TiO_2. Ol = olivine; OPX = orthopyroxene; Pgnt = pigeonite; CPX = clinopyroxene; and Plag = plagioclase (An varied from 60-75).

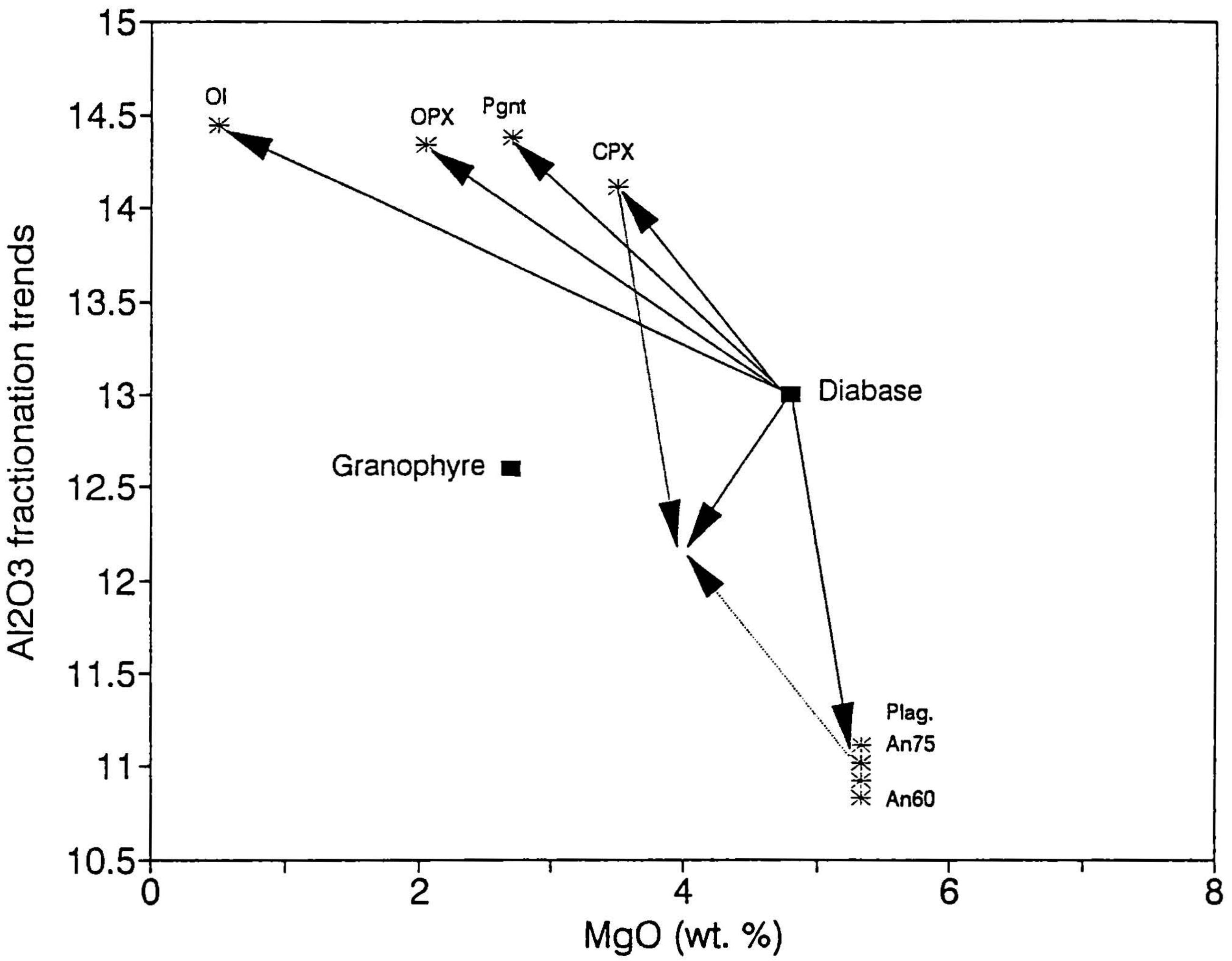


Figure 14. Mineral fractionation trends for Al_2O_3. Ol = olivine; OPX = orthopyroxene; Pgnt = pigeonite; CPX = clinopyroxene; and Plag = plagioclase (An varied from 60-75).

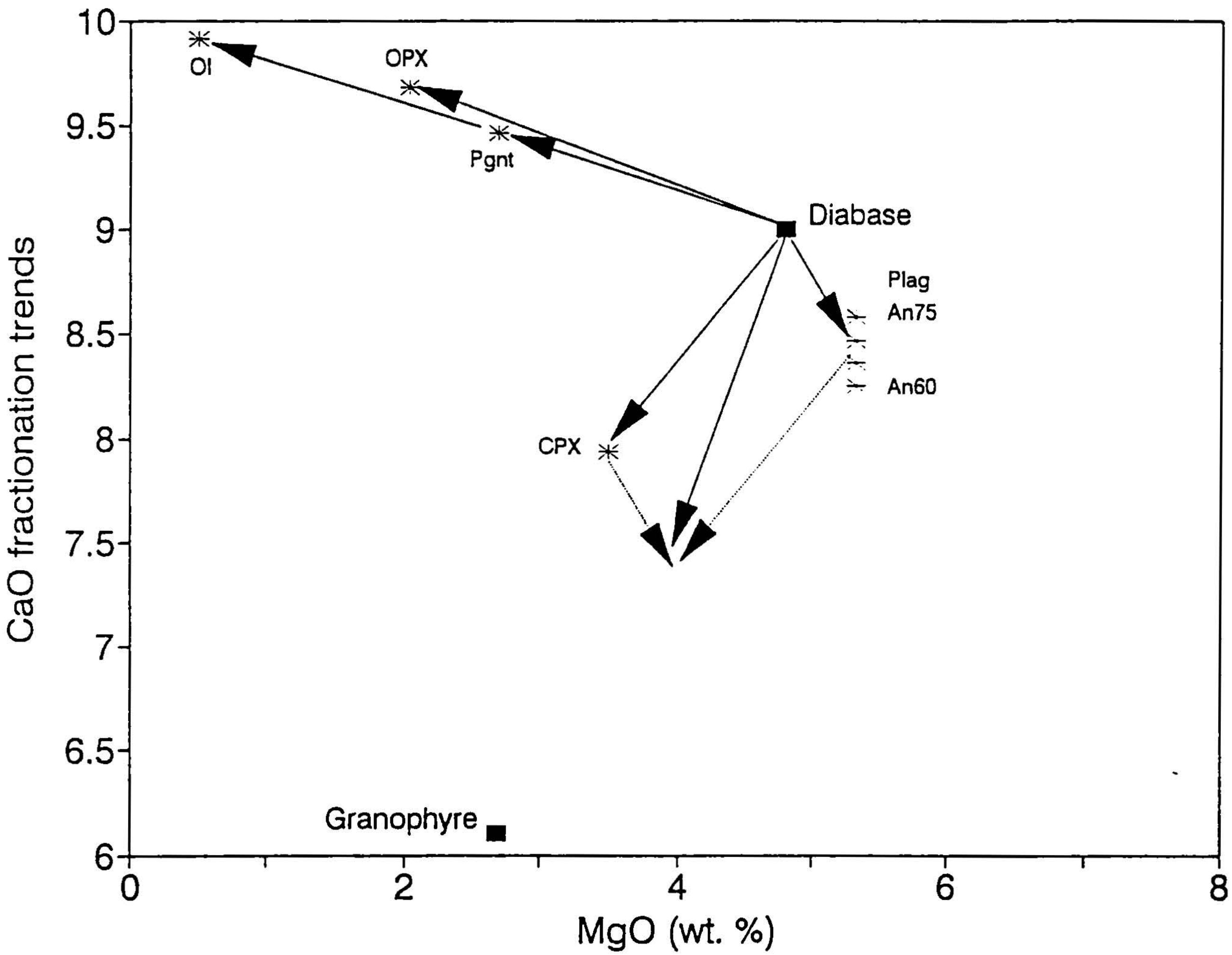


Figure 15. Mineral fractionation trends for CaO. Ol = olivine; OPX = orthopyroxene; Pgnt = pigeonite; CPX = clinopyroxene; and Plag = plagioclase (An varied from 60-75).

Table 6. Summary of mineral control on oxide variation by fractionation.

	Plagioclase An_{60-75}	CPX	Pigeon-ite	OPX	Olivine
SiO_2	Little Change	Small Increase	Small Decrease	Small Decrease	Increase
Al_2O_3	Decrease	Increase	Increase	Increase	Increase
CaO	Decrease	Decrease	Increase	Increase	Increase
MgO	Increase	Decrease	Decrease	Decrease	Large Decrease
TiO_2	Increase	Increase	Increase	Increase	Increase

composition. These particular oxides were selected because all are major constituents of one or more of these minerals. Clinopyroxene, orthopyroxene and olivine compositions used are from Husch (1992), and the pigeonite composition is from Dostal and Greenough (1992).

The fractionation trends for each oxide are plotted against MgO in Figures 12 through 15, and the results for fractionation of a Farmville parent composition are summarized in Table 6. Also shown on each figure is an example of a graphical solution for crystallization of 10 %clinopyroxene + 10 % plagioclase. The resultant vector indicates the amount and direction of the compositional change.

The graphs also suggest a possible mechanism for producing the slight decrease in SiO_2 observed in the main Farmville dike body. Figure 12 shows that crystallization of either orthopyroxene or pigeonite can cause a slight decrease in SiO_2. Petrographic analysis showed that pigeonite is present in the dike. Early crystallization of pigeonite could explain the slight decrease in SiO_2.

Approximately 50 % crystallization is suggested by these models. The models indicate that the residual composition for Al_2O_3, CaO, TiO_2, can be closely approximated by fractionation of 15-20 % CPX + 15-20 % plagioclase, and minor changes to produce a closer fit can be accomplished by fractionation of less than 5-10% olivine or pigeonite. In the case of the Farmville dike where pigeonite has been identified, it seems justified to suggest that crystallization of pigeonite may account for slight variations in the model.

One difficulty in the fractionation model is explaining why TiO_2 continues to increase in the core while iron stays relatively constant or decreases slightly. Although this simple model can account for TiO_2 variation by crystallization of a simple plagioclase + clinopyroxene + pigeonite assemblage, crystallization of a TiO_2-rich magnetite (i.e., with TiO_2 exceeding that of average diabase) should cause a depletion in TiO_2. Continued enrichment could be explained if the crystallizing magnetite was TiO_2-poor. Magnetite increases slightly in the core of the dike. A slight increase in a TiO_2-poor magnetite could cause the iron to begin to drop while the TiO_2 continues to increase. The composition of the opaques in the dike is unknown, therefore, this hypothesis cannot be assessed in this study.

Reasonable solutions can be found for the other oxides, but there is no simple solution for SiO_2. Figure 12 shows that removal of any of the minerals except olivine produces small changes in SiO_2, and to produce the residual composition would require a much larger percentage of crystallization and probably a much different assemblage than described above. If magnetite is added to the crystallizing assemblage, it would force SiO_2 to increase in the remaining melt, contrary to the observed pattern in the main dike.

The results of this graphical analysis suggest fractionation can explain the variation of some of the elements, but that fractionation alone cannot explain the variation of all elements. It is unlikely that more sophisticated models that account for changes in the compositions of the precipitating solids as a function of changing melt composition would be more successful in modelling all of the observed compositional variation.

Trace Element Fractionation

Fractional crystallization in a closed system is commonly modeled by the Rayleigh equation (Hart and Allegre, 1980). Given the original and residual concentrations of a trace element, Rayleigh fractionation models can be used to estimate amounts of fractionation required to produce observed changes in trace elements. These estimates can indicate how much fractionation is needed and whether a fractionation model is realistic. The Rayleigh fractionation equation is

$$C_l = C_o F^{(D-1)}$$

where C_l = element concentration in the residual liquid, C_o = element concentration in the original liquid, F = fraction of liquid remaining, and $\bar{D}_i$ = the bulk partition coefficient. For these calculations, C_o is taken to be the calculated granophyre-free basalt composition for a particular element, and C_l is the concentration in the Farmville granophyre.

Rayleigh fractionation models were used to evaluate fractionation for the incompatible elements TiO_2, K_2O, Ba and Zr, and for Sr which is a compatible element in plagioclase. The purpose of this modeling was to determine if a crystal fractionation model could explain trace element variation in the Farmville dike. If crystal fractionation were the primary process, the amount of crystallization required by the model for each element should be consistent. The model was initially applied to the incompatible elements Ti, K, Zr and Ba with the simplifying assumption that the bulk partition coefficient ($\bar{D}_i$) equals 0. Setting $\bar{D}_i = 0$ calculates the maximum amount of residual liquid (F), or the minimum amount of crystallization, required to produce the observed changes in each element. The results of these calculations are presented in Table 7.

The calculations show a range of values for the amount of residual liquid, which varies from 7 % for K to 45% for Zr and 56 % for Ti. This range of values is consistent with the results from the graphical models and indicate that

Table 7. Results of Rayleigh fractionation calculations for percent residual liquid remaining after fractionation to produce observed trace element changes. F is the amount of residual liquid remaining with $\bar{D}_i = 0$.

	D	F
Ti	0	0.56
K	0	0.07
Ba	0	0.21
Zr	0	0.45

fractionation alone cannot account for the total variability within the dike.

The model was also used to estimate F using Sr. The Sr concentration decreases in the residual liquid. $\bar{D}_{Sr}$ is greater than 1 because Sr is a compatible element in plagioclase. However, Sr is an incompatible element for other phases in the Farmville dike, but it can enter clinopyroxene. For Sr calculations,

$$\bar{D}_i = D_{Sr}^{Plag} * \%Plag. + \bar{D}_{Sr}^{CPX} * \%CPX,$$

and from modal analyses, plagioclase and clinopyroxene fractions were set at 50 %. $\bar{D}_{Sr}^{Plag}$ was set at 2 and $\bar{D}_{Sr}^{CPX}$ was set at 0.1. $\bar{D}_i = 1.05$, and $F = 0.015$, or 1.5 % residual liquid. These results indicate that over 98 percent fractionation must occur to produce the observed changes in Sr, and there is no evidence that this much fractionation has occurred.

The amount of residual liquid is model-dependent, and can vary by adjusting D_{Sr}^{Plag} and $\bar{D}_{Sr}^{CPX}$, or by increasing or decreasing plagioclase or clinopyroxene, but the results still require a fairly large amount of fractionation. For example, for 60% plagioclase and 40% clinopyroxene, $F = 0.4$. The results suggest that relatively small changes in the ratio of the crystallizing phases can produce significant changes in the amount of calculated residual liquid. These results also suggest that a crystallizing assemblage with greater than approximately 50% clinopyroxene is unlikely because the resulting F is greater than 1 -- the amount of residual liquid is greater than the amount of original liquid, which is unrealistic. These results place a limitation on the ratio of potential crystallizing phases.

The results of crystal fractionation modeling indicate that the observed variation cannot be accounted for by simple fractionation within the dike alone. Other processes are required to explain the increase in SiO_2 and the compositional gap. Major element and trace element models are consistent in predicting that 50 % or more fractional crystallization would be required to explain the compositional variation by fractionation alone.

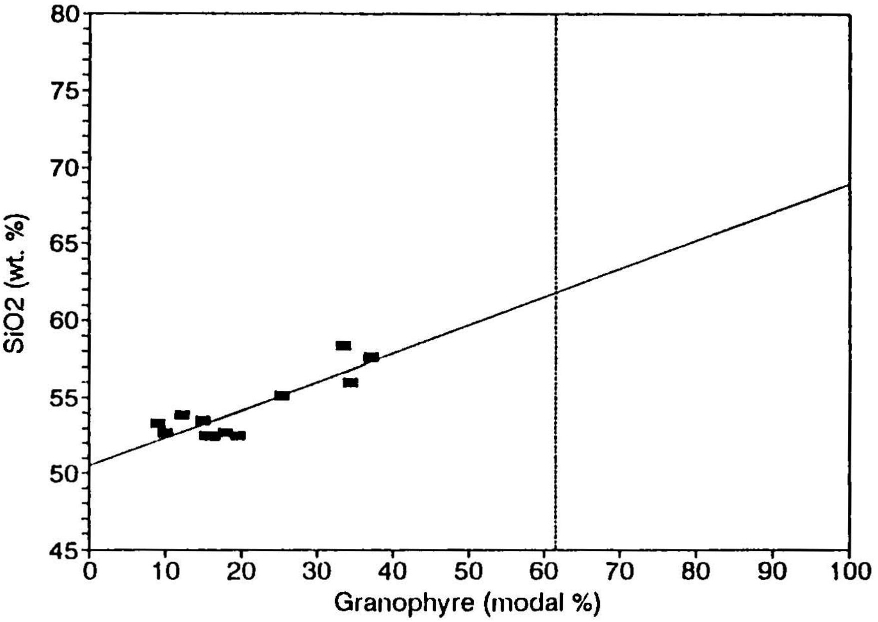
Magma Mixing

A simple magma mixing model was attempted to determine whether the limitations of the fractionation model could be overcome by mixing of two magmas. This model assumes that compositional variation in the Farmville dike is the result of mixing of a more mafic parental magma with a more felsic magma of unknown composition. The compositions of the two end-members were estimated by regression of dike chemistry against volume percent granophyre. This combines the two major types of information available-chemical and petrographic-and uses both to constrain a possible model.

Regression of percent oxides/elements vs granophyre gives, to a first approximation, the required compositions of granophyre-free basaltic magma and basalt-free granophyre end-members for mixing. The calculated concentration at zero percent granophyre is then the granophyre-free basalt composition, and the concentration at 100 percent granophyre is the basalt-free granophyre composition. An example of the regression is given for SiO_2 and MgO in Figure 16. All other elements were calculated in a similar manner. The calculated end-member compositions are presented in Table 8. Also given in the table is the chemistry of a silicic dike sample from Stoddard (1992).

One obvious limitation with this model is that the calculations for a few of the components are negative. The felsic end-member was recalculated by assuming that the composition of the liquid at the percent granophyre where MgO was equal to zero was the maximum possible composition for the liquid. MgO equals zero at 61.3 percent granophyre, therefore, the felsic liquid composition was recalculated at 61.3 percent granophyre. The recalculated composition is given in Table 8.

The results indicate that there are three obvious problems with attempting to explain the variation within the dike by magma mixing. The first problem is the required



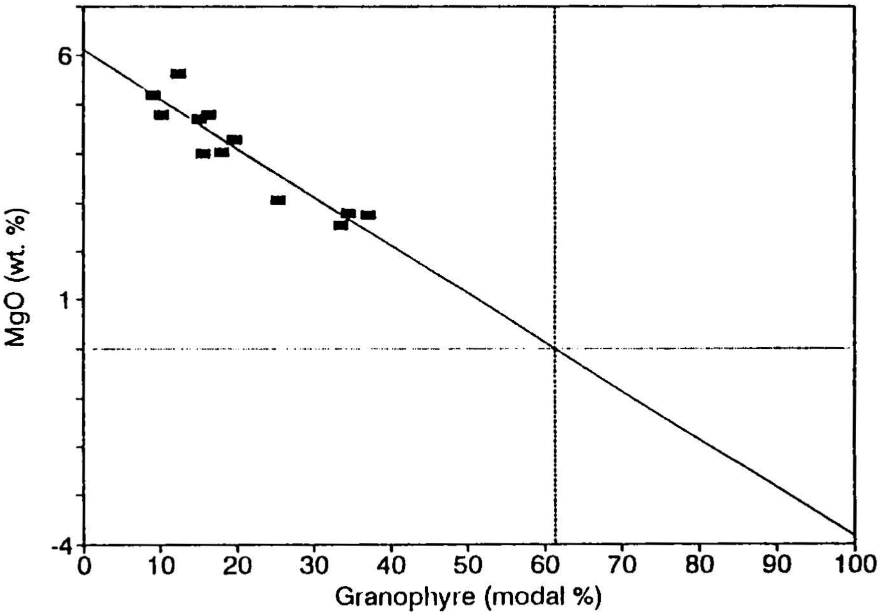


Figure 16. Example of regression for estimating granophyre-free basalt and basalt-free granophyre end-member compositions. Dotted vertical line is percent granophyre (61.3 %) at MgO = 0. An example of the recalculation at 61.3 % granophyre is shown for SiO_2.

Table 8. Calculated compositions of granophyre-free basalt and basalt-free granophyre. Oxides are given in weight percent, trace elements are given in ppm. 1 = granophyre-free basalt; 2 = basalt-free granophyre; 3 = recalculated granophyre (composition calculated at 61.3 volume percent granophyre); 4 = Sample FT10/H1 (Stoddard, 1992); 5 = HR1A/R1 (Stoddard, 1992).

	1	2	3	4	5
SiO_2	50.5	68.8	61.7	66.2	61.5
TiO_2	0.94	3.10	2.26	0.97	0.89
Al_2O_3	13.3	10.9	11.8	12.6	13.5
Fe_2O_3	13.9*	12.4*	13*	3.96	5.37
FeO	--	--	--	4.42	3.03
MgO	6.10	-3.86	0	.39	0.25
CaO	10.8	-2.54	2.62	1.45	2.84
Na_2O	1.82	4.78	3.64	1.9	2.1
K_2O	-0.18	5.94	3.57	4.72	4.61
Zr	74	337	236	963	920
Cr	21	-34	-13	---	---
Ba	69	831	536	---	---
Sr	158	107	127	155	132

* Total iron as Fe_2O_3.

composition of the felsic end-member. The second problem is the amount of mixing required by the model, and the third problem is that simple mixing of a basaltic end-member and an felsic end-member cannot explain the decrease in SiO_2 seen in the main dike body.

The major element chemistry of the granophyre-free basalt is similar to typical low TiO_2 quartz normative tholeiites except TiO_2 is a little higher than average. With the exception of MgO and CaO, the calculated composition of the basalt-free granophyre is comparable to typical granitic compositions except for very high TiO_2. The recalculated felsic composition is still TiO_2-enriched and is an intermediate, rather than granitic, composition. Intermediate to felsic dikes in northern North Carolina have been reported by Stoddard (1986, 1992). The occurrence of these dikes suggest that felsic magmas could have been available in the area to mix with or influence the more prevalent tholeiitic magma. However, a qualitative comparison of Stoddard's (1992) felsic composition with the calculated granophyre compositions shows that the felsic composition is much lower in TiO_2 and lower in iron, and higher in calcium, and much higher Zr.

The amount of mixing required can be estimated by applying the lever rule to the diagrams. The modal percent granophyre for the average main dike body is approximately 15 percent, while the modal percent granophyre for the average granophyric core is approximately 35 percent. These values indicate that the amount of mixing required to produce the average main dike composition and the average granophyric core composition is 20-25 percent and 55-60 percent, respectively.

A felsic magma with the required TiO_2 enrichment and overall composition is unlikely. Also, the model requires high and variable degrees of mixing. Therefore, the results indicate that magma mixing alone is unlikley to explain the variation within the Farmville dike.

Although this section discussed magma mixing, the same rationale can be applied to contamination by a crustal partial melt. Initial or minimum partial crustal melts are granitic in composition, and it is unlikely that a crustal melt with the required composition could be produced. It is also unlikely that wholesale assimilation of solid crustal material of the required composition could have occurred. Selective contamination could possibly account for enrichment in certain elements such as potassium (Watson, 1982), but cannot explain enrichment in other incompatible elements or SiO_2.

Multiple Intrusion

The results of the above models indicate that the chemical and mineralogical variations within the Farmville dike are complex and cannot be readily explained by a single simple petrogenetic model. Fractional crystallization can account for much of the variation in some of the elements, but cannot account for the compositional gap, the total variation in incompatible elements, or the amount of increase in SiO_2. A magma mixing model could account for the increases in SiO_2 and alkalies, but would require that the felsic magma be enriched in TiO_2, which seems unlikely, and cannot explain the compositional gap. Also, there is a problem with the potential source for the felsic magma. Comparison of the model composition with local felsic dikes described by Stoddard (1992) indicates that it is unlikely that magma mixing with the felsic dike magmas could have produced the variation in the Farmville dike.

The previous models have looked at chemical variation patterns with respect to some sort of differentiation index (either MgO or volume percent granophyre). However, the pattern of variation across the dike may also give insight into possible processes. The compositional gap indicates an abrupt change in dike chemistry. A possible process which may explain this change would be a second pulse of a felsic or more evolved magma. However, some of the difficulties with felsic magmas discussed above and the question of potential sources of the magma still remains.

Discussion of Models

The poor exposure of the Farmville dike and the fact that the dike was sampled in one location only are limiting factors in this study. These limitations imply that hypotheses involving physical or dynamic factors such as multiple intrusion, magma movement or change of features along strike or with depth cannot be directly addressed. However, the chemical relationships between the granophyre-rich and granophyre-poor portions of the dike could be studied. Because of the limitations, the goal of this study was to put chemical limits on possible processes of granophyre generation within the Farmville dike. No detailed attempt was made to address Farmville dike parental magmas, except as modeled for magma mixing, or address magma sources for the Farmville dike or other possible melts. However, some speculation on a possible second magma pulse can be made.

Small amounts of granophyre are very common in quartz-normative diabases and represent late- stage, SiO_2- and alkali-enriched residual fluids. These fluids become trapped in interstitial voids during the latest stages of the solidification of a magma and form interstitial granophyre. Potential problems are encountered when trying to explain formation and concentration of granophyre to form granophyre-rich bodies such as in the core of the Farmville dike. There does not appear to be a simple way of producing the granophyre by fractional crystallization in place, and simple end-member magma mixing is unlikely because of the required composition of the felsic end-member.

Most of the characteristics of the Farmville dike could be explained by some fractionation within the dike followed by intrusion of a second pulse of more evolved, somewhat TiO_2-enriched magma derived from a basaltic magma at depth. This magma or a similar magma type may also have been parental to the Farmville dike magma.

Many studies suggest that granophyric bodies are either formed or enlarged migration of a granophyric liquid through a coexisting basaltic melt. Granophyre segregation is possible, for example, by gravitative separation due to density differences between the granophyre and the basalt or diabase, and by it's subsequent concentration at another, usually higher, location (McDougall, 1962; Froelich and Gottfried, 1985; Shirley, 1988; Tollo et al., 1988).

The increase in TiO_2 in the Farmville dike is difficult to explain by magma mixing of basaltic and granitic magmas because of the amount of TiO_2 enrichment required for the granitic melt. The explanation that the dike represents intrusion by a second pulse of more evolved, TiO_2-enriched magma derived from some fractionation process of a basalt at depth also presents problems, but this process is more palatable because the second magma would not be required to be so TiO_2-enriched. In fact, the TiO_2 concentration of the granophyric core is well within the TiO_2 range recognized in eastern North American diabases. Even if a second pulse of evolved magma mixed with some of the residual liquid in the dike, the required TiO_2 concentration would not be as great as in the magma mixing model because TiO_2 in the dike is much higher than in the model parent magma.

SUMMARY

In this study, petrographic, modal analyses of thirty-four samples and chemical analyses of major and trace elements in 20 samples provided data to constrain petrogenetic models for generation of granophyre-rich zones within the Farmville dike. Overall, the Farmville dike is compositionally similar to the high-Fe, high-TiO_2, quartz-normative group of Mesozoic eastern North American diabase. The composition, size, and trend of the dike indicate that the dike belongs to the north-south dike swarm of Ragland (1991). These are generally longer, wider, commonly quartz-normative and more evolved than other dikes in North Carolina and Virginia.

The Farmville dike is different from most of the dikes described in previous studies in that it is bimodal in composition. The main dike body is fairly typical diabase while the core of dike is much more evolved and is enriched in SiO_2, alkalies and incompatible minor and trace elements, and modally is granophyre-rich. The dike shows a decrease in MgO and CaO towards the core, and it is depleted in Cr and Ni. Although the core of the dike is relatively enriched in incompatible elements, the main body of the dike can be classified as part of the incompatible element-depleted group of eastern North American diabase.

Many elements display a variation trend within the main dike which suggests that some sort of differentiation process took place within the dike. In addition, there is a distinct compositional gap or break between the main dike body and the granophyric core. This gap can be seen in the sudden increase of granophyre from less than 20 modal percent in the main dike body to greater than 30 modal percent in the core. This gap is also seen in the variation of oxides and trace elements, and in the Mg#. This gap represents an abrupt change in dike composition.

The large size of the Farmville dike may have allowed a variety of petrogenetic processes to operate to modify magma chemistry. These processes are generally not observed in smaller dikes and are rarely observed or described in these dikes in general. Because of the limitations set by the data, many petrogenetic processes could not be directly addressed, but compositional differences between the main dike body and the granophyric core was used in an attempt to put some constraints on possible petrogenetic processes. Possible processes identified were fractional crystallization, crustal contamination, magma mixing, and multiple intrusion.

Each process has its associated problems and no single process can explain the chemical variation within the dike. Fractional crystallization can explain some of the chemical variation but cannot explain the amount of enrichment of SiO_2 in the core or the total variation of incompatible elements.

Magma mixing is difficult to envision because the required felsic magma does not approach a granitic composition and must be TiO_2-enriched, and there is a problem with a source area for the magma. Also, modeling showed that 20-25 percent mixing would be required to model the main dike body composition, and 55-60 percent mixing would be required to produce the granophyric core.

Problems with crustal contamination by a granite minimum melt include the amount of melt required versus what may be realistic, and again the need for TiO_2-enrichment. Also, none of these processes can explain the compositional gap.

The results indicate that fractional crystallization of an assemblage of plagioclase + clinopyroxene + minor pigeonite can explain much of the chemical variation, but fractional crystallization alone cannot explain the amount of SiO_2 enrichment or the total variation of incompatible elements, or the compositional gap. Also, neither magma mixing nor crustal contamination can explain the variation within the dike. It therefore seems likely that a combination of fractional crystallization and some other process is needed to explain the variation within the dike. The other possible process is multiple intrusion. A second pulse of more evolved magma could produce the required increase in SiO_2 and create the observed compositional gap, and has the added benefit that it would not be required to be as Ti-enriched as required by the magma mixing model.

One pervasive problem with any of the models is the need for at least some TiO_2-enrichment. Crystallization of TiO_2-bearing phases such as magnetite and ilmenite should deplete TiO_2 in residual liquids. This problem cannot be satisfactorily resolved in this study, but a possible explanation is that, at least initially or within the compositional range of the Farmville dike, the crystallizing oxide is a TiO_2-poor magnetite. This could explain why TiO_2 continues to increase while iron remains relatively constant or decreases slightly. However, there is no compositional data on the oxides in the Farmville dike and this hypothesis cannot be addressed in this study.

Future studies could be extremely helpful in clarifying the processes that occurred in this dike and similar dikes in the North Carolina and Virginia Piedmonts. A study of opaque mineral compositions could explain the observed behavior of iron and TiO_2. More detailed sampling along the trend of the Farmville dike would be useful to investigate chemical variation along the trend of the dike. Also, there is another, apparently larger, granophyre-cored dike near Drake's Branch, Virginia. Study of this dike would greatly add to the understanding of the processes that affected these dikes.

CONCLUSIONS

The Farmville dike is different from the majority of diabase dikes described in previous studies in North Carolina and Virginia in that it is bimodal and possesses a granophyre-rich core. The composition of the main body of the dike is a fairly typical high-iron, high-TiO_2, quartz-normative tholeiite, while the granophyric core is enriched in SiO_2, alkalies and incompatible minor and trace elements. Although these elements are relatively enriched within the dike core, the dike itself can be grouped with the broader incompatible element-depleted diabase group of eastern North America.

Problems exist with all of the petrogenetic processes investigated. However, chemical constraints show that the granophyric core cannot have been formed by *in situ* crystal fractionation of the dike magma or magma mixing, and a combination of processes is required to explain the chemical and mineralogical variation within the dike. Because of its sampling limitations, this study was unable to conclusively determine what process or set of processes produced the granophyric core, but it is speculated that a combination of early crystal fractionation of dominantly plagioclase + clinopyroxene + minor pigeonite within the dike followed by intrusion of a second pulse of more evolved magma, possibly derived by fractionation of a basaltic magma at depth, is responsible for the mineralogical and chemical variation within the Farmville dike.

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APPENDIX A

Analytical Methods

Twenty samples were prepared for chemical analysis. Only the visibly freshest samples were used. Only fairly large, fresh samples were used; smaller samples were generally discarded because enough fresh material could not be obtained. Also, spheroidally weathered samples and samples with thick weathering rinds were generally not used. Exceptions included fairly large spheroidally weathered boulders where fresh material could be obtained from the middle. In all, the samples chosen represent a good cross section across the dike.

Each sample chosen for analysis was cut into several slabs approximately 1/4 inch thick. Enough slabs were cut to provide at least 200 g of material. Each slab was then cleansed of oil and dirt, rinsed, and heated slightly to evaporate residual saw oil. The slabs were then ground on a rotating lap to remove saw marks and metal, and marking ink, and then rinsed and dried again. Each slab was then broken and pieces with altered or weathered edges were removed leaving what were visually the freshest samples. Slabs for each sample were broken into small pieces and pulverized in a shatter box for 5 minutes.

All samples were analyzed for SiO_2, TiO_2, Al_2O_3, Fe_2O_3*, MnO, MgO, CaO, Na_2O, K_2O, Zr, Y, Sr, Zn, Cu, Sc, Ni, V, Cr, and Ba. The samples were analyzed on the JY 70P Type II ICP at the Carnegie Institution of Washington. Sample were prepared using a $LiBO_2$ fusion technique (Medlin, et al., 1969) following the CIW ICP sample preparation outline with the exception that loss on ignition was not determined. Allowing for water and other volatiles, totals between 96 and 101% were accepted.

All major elements were analyzed using the ICP polychromator. All trace elements were analyzed using the ICP monochromator. Strontium and phosphorus were analyzed on both the polychromator and the monochromator. Strontium gave strong and consistent results on both. Phosphorus is subject to various interferences and reliable results could not be obtained.

Curves were constructed using rock standards BR and AGV-1 as the high standards for various elements. Calibration curves were constructed by linear regression of working values against recommended values for Rock standards BR, AGV-1, DNC-1, NBS-688, BHVO-1, BIR-1, Loihi and W-2. Analytical precision for the major and trace elements was determined by replicate analyses of standard W-2. Precision estimates for the major and trace elements are presented in Table 2.

Based on precision data, the reporting conventions adopted are: SiO_2, Al_2O_3, Fe_2O_3* (total iron reported as Fe_2O_3) are reported to the nearest 0.1%. All other major elements are reported to 0.01%; Zn is reported to the nearest 20 ppm; Zr, Cu, Ni and V are reported to the nearest 10 ppm; Sr, Cr, and Ba is reported to the nearest 5 ppm; and Y and Sc are reported to the nearest 1 ppm.

Data for FV-10, FV-24 and FV-25 are considered unreliable due to unidentified errors in sample handling; data for FV-33 are considered unreliable due to a known dilution error. Data for these four samples are not included in dike averages, although these samples are shown on al figures and the data are presented in the tables.

APPENDIX B

Major Oxide analyses

Results of major element analyses for the Farmville dike. All oxides are reported in weight percent. Fe2O3* is total iron as Fe2O3. FeO was calculated using an Fe2O3/Fe2O3* ratio of 0.15.

	FV-05	FV-08	FV-10	FV-11	FV-13	FV-15	FV-19	FV-21	FV-22	FV-24
SiO_2	52.2	52.5	50.7	52.7	53.3	53.9	53.4	53.5	52.5	50.7
TiO_2	1.18	1.37	1.19	1.19	1.18	1.03	1.15	1.34	1.21	1.05
Al_2O_3	13.1	12.6	12.7	12.9	13.3	13.9	13.5	12.6	13.0	11.5
Fe_2O_3*	13.3	13.9	15.3	13.8	13.7	13.4	13.6	13.9	13.8	14.2
MnO	0.20	0.20	0.21	0.21	0.22	0.22	0.21	0.21	0.21	0.23
MgO	4.94	4.29	4.68	4.81	4.99	5.62	5.21	4.73	4.80	5.45
CaO	9.17	8.56	9.03	8.93	9.13	9.75	9.42	9.12	8.85	9.03
Na_2O	2.05	2.10	1.99	2.26	2.28	2.36	2.30	2.35	2.16	2.35
K_2O	0.67	0.74	0.60	0.66	0.76	0.56	0.71	0.67	0.70	0.64
Total	96.80	96.31	96.49	97.48	98.82	100.81	99.50	98.42	97.23	95.26
Fe_2O_3	1.99	2.08	2.30	2.06	2.05	2.01	2.05	2.08	2.07	2.14
FeO	10.1	10.6	11.7	10.5	10.5	10.3	10.4	10.6	10.6	10.9
Mg#	46.5	41.9	41.6	44.9	45.9	49.3	47.1	44.3	44.7	47.1
Norms										
Q	8.2	9.7	6.8	8.0	7.4	6.4	6.9	8.5	8.1	5.0
or	4.0	4.4	3.5	3.9	4.5	3.3	4.2	4.0	4.1	3.8
ab	17.3	17.8	16.8	19.1	19.3	20.0	19.5	19.9	18.3	19.9
an	24.6	22.9	24.0	23.1	23.9	25.7	24.4	21.9	23.7	19.0
di	17.4	16.4	17.4	17.7	17.8	18.8	18.6	19.5	16.9	21.5
hy	19.0	18.3	20.9	19.1	19.6	20.6	19.6	17.9	19.7	19.8
mt	2.9	3.0	3.3	3.0	3.0	2.9	3.0	3.0	3.0	3.1
il	2.2	2.6	2.3	2.3	2.2	2.0	2.2	2.5	2.3	2.0
%AN	58.7	56.3	58.8	54.7	55.4	56.3	55.7	52.4	56.5	48.9

Major oxide analyses. (Continued)

	FV-27	FV-33	FV-35	FV-36	FV-38	FV-39	FV-40	FV-41	FV-45	FV-47
SiO_2	53.1	52.0	57.6	58.4	56.0	55.1	52.5	52.7	50.7	53.1
TiO_2	1.17	1.45	1.76	1.62	1.66	1.55	1.31	1.43	1.17	1.23
Al_2O_3	13.2	11.5	12.3	13.2	12.4	12.6	12.8	11.9	12.4	13.3
Fe_2O_3*	13.6	13.8	13.4	13.2	13.3	13.5	13.2	13.9	13.3	13.9
MnO	0.21	0.18	0.18	0.18	0.18	0.19	0.19	0.20	0.20	0.21
MgO	5.23	2.35	2.75	2.55	2.79	3.07	4.03	4.05	4.52	4.86
CaO	9.17	5.44	6.10	6.48	5.70	7.21	8.33	8.15	8.46	8.96
Na_2O	2.22	2.68	2.98	2.93	3.00	2.35	2.07	2.31	2.12	2.21
K_2O	0.71	1.85	1.96	2.26	2.07	1.20	0.69	0.71	0.58	0.70
Total	98.63	90.83	99.06	100.81	97.12	96.82	95.11	95.35	93.45	98.48
Fe_2O_3	2.03	2.07	2.01	1.98	2.00	2.03	1.98	2.09	2.00	2.09
FeO	10.4	10.5	10.2	10.1	10.2	10.3	10.1	10.6	10.2	10.6
Mg#	47.3	28.4	32.5	31.0	32.8	34.7	41.6	40.5	44.1	45.0
Norms										
Q	7.5	8.9	12.4	11.8	10.6	13.3	10.9	10.3	8.3	8.1
or	4.2	10.9	11.6	13.4	12.2	7.1	4.1	4.2	3.4	4.1
ab	18.8	22.7	25.2	24.8	25.4	19.9	17.5	19.5	17.9	18.7
an	24.0	13.9	14.4	16.2	14.2	20.3	23.6	20.0	22.7	24.3
di	17.9	11.2	13.4	13.5	11.9	13.1	14.9	17.2	16.1	16.9
hy	20.0	15.6	14.5	14.0	15.6	16.0	17.7	17.2	18.7	19.8
mt	2.9	3.0	2.9	2.9	2.9	2.9	2.9	3.0	2.9	3.0
il	2.2	2.8	3.3	3.1	3.2	2.9	2.5	2.7	2.2	2.3
%AN	56.1	38.0	36.4	39.5	35.9	50.5	57.4	50.5	55.9	56.5

APPENDIX C

Trace Element Analyses

Results of trace element analyses for the Farmville dike. All Trace elements are reported in parts per million (ppm).

	FV-05	FV-08	FV-10	FV-11	FV-13	FV-15	FV-19	FV-21	FV-22	FV-24
Zr	90	134	102	104	112	82	111	124	91	93
Sr	149	138	150	143	153	153	149	149	145	129
Y	28	32	29	31	25	25	25	28	28	30
Zn	101	143	104	102	129	93	140	146	105	112
Cu	45	66	66	46	56	40	58	62	47	48
Sc	46	50	49	50	52	50	53	52	45	55
Ni	8	-1	20	4	11	18	13	9	11	17
Cr	15	9	30	12	14	23	17	11	14	18
V	389	415	405	411	403	384	417	417	369	446
Ba	177	201	177	152	162	135	158	174	178	142

	FV-27	FV-33	FV-35	FV-36	FV-38	FV-39	FV-40	FV-41	FV-45	FV-47
Zr	103	149	157	165	167	164	110	129	102	98
Sr	149	140	145	142	128	137	147	140	138	154
Y	31	42	44	45	46	45	32	38	32	32
Zn	94	113	121	118	122	113	107	107	96	105
Cu	49	80	63	61	64	62	56	55	47	46
Sc	51	38	40	38	41	41	43	48	48	49
Ni	10	15	1	-1	-5	0	16	4	8	11
Cr	16	15	3	1	3	4	8	9	10	13
V	390	339	345	339	375	359	373	399	377	402
Ba	200	358	360	325	323	278	225	199	153	178

APPENDIX D

ICP Raw Intensity Data

Raw intensity data for Farmville samples and reference standards listed by run number.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O
Run 1 Calibration									
AGV-1	46732.7	12474.3	19077.7	42136	3125	19772	8324	22419	13647.2
BR	29438.3	31018.3	11320	77874.7	6014	173276	22912.7	15006.3	6462.2
BLNK	330.7	194	615.7	66.3	228	26	-297.3	146	200
Run 1 samples									
W-2(1)*	39503.5	12262	16738	64045.5	4947.5	82427.5	17970	10916.5	2963.5
FV-15	41453	12175	15614.5	79753	6295.5	72748	16562	11566	2653.5
FV-39	42382.5	18207.5	14193	80264	5474.5	39066.5	12134.5	11470.5	5498
DNC-1	36078.5	5828	20714	58710.5	4373	133197	19237.5	9560	1269.5
NBS-68	36887.5	13483	19556	60235	4774	111468	20862	10284	1075.7
FV-47	40818	14501	14927	82617	6098.5	62720.5	15187.5	10778.5	3290.3
FV-22	40347	14189	14616	82100	6113.5	61986	14986.5	10490.5	3261.8
LOIHI(1)	34104	43044	16223	73949.5	4881.5	65952	17297.5	17263.5	6314.5
W-2(1)	39211.5	12286	16961	61550	4721.5	82310.5	18491	10059.5	2849
FV-8	40388.5	16049.5	14236	82331.5	5813.5	55223.5	14484	10223.5	3435.8
BR(2)	29148.5	30865.5	11527.5	73533.5	5610	172817	23958	13394	5948.5
FV-5	40136.5	13913	14760.5	78682.5	5884	63784	15538.5	9937.5	3149.3
BHVO-1	38111	32018	15384	70085.5	4786.5	94184.5	19895	10068.5	2469
BIR(1)	36485	11255	17462.5	65154.5	4902	126997	23554.5	7895	483
FV-40(1)	40377	15421.5	14393.5	78225	5454.5	51764	14081	10064.5	3206.5
FV-40(2)	40457.5	15441.5	14478	78357.5	5444.5	51760	14156	10099	3191.5
BLANK	281.5	192	704.5	58.5	231	32.5	-352.5	151.5	251
FV-10	38996	14040.5	14314.5	91044	6135.5	60285.5	15297.5	9660.5	2818.5
W-2(1)	39236.5	12259	16931	60756	4644	82429	18902	9575.5	2726.7
BR(1)	28448.5	29919	11232.5	71051.5	5420	168247	23692.5	12078	5445.5
AGV-1(1)	45277.5	12111	18854.5	37911	2801	19190	8716.5	16993.5	10920.5

* Number in parentheses indicates replicate sample number.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O
Run 2 calibration									
AGV-1	45883.3	12171.3	18813	38474	2855.7	19549	8935.3	17605.3	11025.7
BR	28687.7	29701.7	10994.7	71873.3	5575.3	169356	23859.3	11645.7	4997
BLNK	254	190	716.3	72	234.7	24.7	-347.7	112	289.3
Run 2 samples									
W-2(2)*	39264	12084.5	16402	61345.5	4807.5	82454.5	18952	8913	2529.2
BR(3)	30380	31874	11665	76840.5	5928	180341	25247	13194.5	5869
FV-33	39459.5	17025	12883	81612	5129	30599	9551.5	11214.5	6936
NBS-68	36795	13250	19229	58847	4704	111829	21611.5	8815	983
BIR	37475	11510	17573	67905.5	5157.5	130894	24278.5	8027.5	480.2
FV-38	43374.5	19471.5	13843	78799.5	5162.5	36414.5	10030	12522	7729.3
DNC-1	36753.5	5907	20727	59001.5	4390.5	136897	20408.5	8214.5	1194
FV-27	41128.5	13663	14737	80355	6217	68761	16298.5	9331.5	2858.3
W-2(1)	40087	12394.5	16859	63110.5	4927	84816.5	19404.5	9002	2516.5
FV-19	41295	13464	15067	80850.5	6232.5	68380.5	16752	9637	2843.3
BLANK	241	169	671.5	144.5	217.5	38.5	-350	116	259
LOIHI(1)	35098.5	43698.5	16185	76042	5099	68032.5	18216.5	15783.5	5758
FV-13	41225.5	13867.5	14878.5	80998.5	6250	65571	16218	9557	3009.2
FV-40(3)	42563.5	15986	14669	83615.5	5938.5	54717.5	15054	9888.5	3082.3
BHVO(1)	39542	32948.5	15461	73812	5099	98352.5	20990	9693.5	2366.8
FV-45	39212.5	13738	13907.5	78778	5741.5	59330	15022	8893.5	2375.8
FV-36	45197	18952.5	14733	78165	5301.5	33198	11433.5	12245.5	8439.2
FV-11	40829	14006.5	14410	81537.5	6151	63174.5	15861.5	9467.5	2679
W-2(2)	40672	12333	16775	63598	4938.5	84984.5	19482.5	9061.5	2500
W-2(1)	40720	12512	16904	64308.5	5005	85918.5	19622	8991	2529.8
BR(1)	29395	30539	11171.5	74714.5	5851.5	174297	24460	11815	5129.7

* Number in parentheses indicates replicate sample number.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O
Run 3 calibration									
AGV-1	45442.3	11929.3	18352.7	38538.3	2880.7	19181	8712	16404	10358.7
BR	29078.3	19875	10992.7	73512	5731.7	170984	24033.3	11489.7	5022.3
BLNK	247.3	177.3	647	68.7	228	25.7	-336.7	109	306.2
Run 3 samples									
W-2(1)*	39819	12161.5	16362	62504.5	4925.5	83221.5	19052.5	8637.5	2421.3
RCCG-1	41564	12009.5	17905	72763	5001	36467.5	13718.5	12732.5	6353
FV-40(5)	41891.5	15565.5	14248.5	82146.5	5820	53197	14652	9304.5	2871.5
NBS-68	36967.5	13108.5	18669	59191	4786.5	111060	21550	8352.5	935
BIR	37438.5	11260.5	16969	67479.5	5212.5	128994	24180	7207	441.3
FV-35	44137	18207.5	12965	77786.5	5353	34280.5	10643	12026.5	6885.7
DNC-1	35934	5478.5	18512	56350	4391	129780	20340	8024.5	996.5
FV-41	40394	14901.5	12523.5	80751.5	5784.5	51292	14345.5	9347	2620.8
W2(1)	39557	11550	15139.5	60986	4844.5	80649	19224	9457.5	2320.3
BLANK	242.5	189	668	76.5	236	35.5	-312.5	132.5	263.8
AGV-1(1)	45142.5	11288	16874	37525.5	2897	18615	8786.5	17295.5	9547.2
LOIHI(1)	34049.5	39702	14265.5	72304	4956.5	64052	17945	16083.5	5035.3
FV-40(4)	39793.5	14061	12612	76505	5560	49234	14078	9426	2568.7
LOIHI(2)	33385.5	38697	14024	70561.5	4896.5	62445	17486.5	15438.5	4905.5
BHVO-1	37949.5	29389.5	13493.5	69212	4913.5	91195.5	20331	9373	1959.7
BR(3)	29371	28549	10291	72712.5	5808	168405	24644	12371	4716.3
FV-21	41013	13934	13276	80486	6219	60237	16086.5	9497.5	2497.5
FV-24	38886	11031.5	12164.5	82652	6687.5	69636.5	15931.5	9505	2389.5
BR(2)	29539.5	25933	10703.5	74738	5861	172326	24591	13516	5258.7
W-2(1)	40607	12207	15930.5	63976.5	5003.5	83990	19601	10116	2518.8
BR(1)	29406	29855	10612.5	74588	5902.5	171263	24474	13273.5	5260.3

* Number in parentheses indicates replicate sample number.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O
Run 4 calibration									
AGV-1	46436	12009	17849.7	39460.7	3000.7	19399.7	8931.7	19213.7	10663.8
BR	29459.3	29791.7	10632.7	74546.3	5889.7	171266	24514	13182.7	5123.2
BLNK	240	195.3	628.7	63.3	236	29.3	-311.7	132.7	347
Run 4 samples									
W-2(1)*	40348	12111.5	15716	63297	5029	83052	19465.5	10011	2480.2
DNC-1	36382	5659.5	18962.5	58002	4472.5	131867	20212	7868	1045.5
BIR(2)	35990	10740.5	15991	63163.5	4853	122039	23838	7396	438.5
LOIHI(1)	34206	41575	15013	72166	4872.5	65003	18251	15766.5	5183.5
BIR	37029	11001	16177	65078	5023.5	126126	24497.5	7437	475.5
BLANK	234.5	183.5	687.5	141.5	249	58	-332	129	301.7
AGV-1(2)	44730	11623.5	17334.5	37046.5	2824	18726.5	8800	16477	9289.7
BHVO-1	39081.5	31846.5	14684	71343	5027	96080	21115.5	9385.5	2087
NBS-68	37178	13135.5	18316	58627	4759	111654	22284	8925	954.5
W-2(1)	40342	12227	16109	62300	4927.5	84165	19948	9158.5	2338.2
BR(1)	28862.5	29395	10643	71755.5	5627.5	169425	24531	11729	4741.7

* Number in parentheses indicates replicate sample number.

APPENDIX E

Accepted Rock Standard Values

Accepted Values for rock standards (from Govindaraju, 1989).

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3*	MnO	MgO	CaO	Na_2O	K_2O
AGV-1	58.79	1.05	17.14	6.76	0.092	1.53	4.94	4.26	2.91
BR	38.2	2.6	10.2	12.88	0.2	13.28	13.8	3.05	1.4
W-2	52.44	1.06	15.35	10.74	0.163	6.37	10.87	2.14	0.627
DNC-1	47.04	0.48	18.3	9.93	0.149	10.05	11.27	1.87	0.229
NBS-68	48.35	1.168	17.35	10.34	0.167	8.46	12.17	2.16	0.19
BHVO-1	49.94	2.71	13.8	12.23	0.168	7.23	11.4	2.26	0.52
BIR	47.77	0.96	15.35	11.26	0.171	9.68	13.24	1.75	0.027
LOIHI	44.7	3.74	14.6	12.04	0.17	5.52	10.5	3.69	1.61

	Zr	Sr	Y	Zn	Cu	Sc	Ni	Cr	V	Ba
AGV-1	227	662	20	88	60	12.2	16	10.1	121	1226
BR	250	1320	30	160	72	25	260	380	235	1050
W-2	94	194	24	77	103	35	70	93	262	182
DNC-1	41	145	18	66	96	31	247	285	148	114
NBS-68	60.6	169.2	17	58	96	38.1	150	332	250	200
BHVO-1	179	403	27.6	105	136	31.8	121	289	317	139
BIR	22	108	16	71	126	44	166	382	313	7.7
LOIHI	245	822	22	--	--	18.3	95	100	380	397