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Petrology of Miocene volcanic rocks in the Resting Spring Range, California

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PETROLOGY OF MIOCENE VOLCANIC ROCKS IN THE RESTING SPRING
RANGE, CALIFORNIA

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Masters of Science

By

Anthony Andrew Schuetze

May 2005

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ABSTRACT

PETROLOGY OF MIOCENE VOLCANIC ROCKS IN THE RESTING SPRING RANGE, CALIFORNIA

By Anthony Schuetze

The late Miocene volcanic rocks of the Chicago Valley in the Southern Resting Spring Range consist of alternating basaltic-trachyandesite and trachyandesite lava flows and breccias, a trachydacite dome complex and lava flows, and a trachyandesite cinder cone complex. The presence of compositionally similar dikes, the dome complex, and eroded cinder cones and associated near-vent features (e.g., large bombs) indicate that volcanic rocks were erupted locally. Extensional tilting and erosion have exposed the core of this complex, allowing for a detailed look into the stratigraphy and construction of this syn-extensional magmatic system.

Field and petrographic evidence in the rocks of the study area show evidence of magma mixing. A petrogenetic model involving silicic recharge and magma mixing coupled with fractional crystallization and convective self mixing during mafic recharge best explains the geochemical data and field and petrographic observations.

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INTRODUCTION

Processes responsible for generating intermediate magmas in extension-related settings are not completely understood. Especially in regards to production of intermediate magmas, the degree to which fractional crystallization, partial melting, and mixing contribute is still unclear, although magma mixing has been favored as a dominant process in many cases (e.g., Coleman and Walker, 1990; Miller and Miller, 1991). Furthermore, the thermal role that mafic magmas play in intermediate subvolcanic magma bodies is still uncertain. They may provide heat for evolution of shallow crustal intermediate magma bodies (e.g., Murphy et al., 2000) and are increasingly implicated as eruption triggers (e.g., Pallister et al., 1996; Coombs et al., 2000).

The late Miocene volcanic rocks of the Chicago Valley in the southern Resting Spring Range, California, show spectacular and widespread evidence of complex magma mixing and mingling between rocks of widely varying composition, but the interactions are subtle and sometimes ambiguous. The rocks consist of alternating basaltic-trachyandesite and trachyandesite lava flows and breccias, trachydacite dome complex and lava flows, and trachyandesite cinder cone complex with dikes and lava flows. Extensional tilting and erosion has exposed the core of the dome complex and cinder cone vent, allowing for a detailed look into the stratigraphy and construction of this syn-extensional magmatic system.

The main objective of this study is to investigate the petrogenesis of the late Miocene Volcanic Rocks of the Chicago Valley, with particular emphasis on the origin of the trachydacites. This includes the investigation of the degree of physical and chemical hybridization and implications for understanding magma mixing processes. In particular, documenting the mineralogical and textural characteristics of widespread and diverse mafic enclaves in the intermediate rocks will provide a better understanding of their role in the chemical evolution of the magmatic system.

As outlined in this study, the petrogenesis of the volcanic rocks of the southern Resting Spring Range is best explained by mixing of compositionally diverse magmas, which are subsequently modified by fractional crystallization and convective self-mixing that accompanied mafic recharge. Mafic recharge may also have played a role in triggering eruption of the trachydacite unit.

Field area

Volcanic rocks of this study are located in the southern Resting Spring Range Mountains in Inyo County, California; between the Amargosa Valley and the Chicago Valley, just south of State Highway 178 and Resting Spring Pass (Fig. 1). The studied exposures are found from the ridgeline to the eastern flank of this range, between 35°55'N to 36°00'N latitude and 116°10'W to 116°13'W longitude. The mapping area is about 6 kilometers (km) east of Shoshone, California, within the Resting Spring 7.5' quadrangle, and comprises an area of approximately 10 km² (Fig. 2).

Figure 1. Index map of the Death Valley area. Resting Spring Range and Map Area identified. Modified from Stewart (1983). Some regional fault orientations given by arrows.

The research area consists of a homoclinally east tilted eruptive sequence consisting of mafic and intermediate lava flows and a hypabyssally rooted intermediate dome system, which is also in contact with surficial volcanic rocks, with capping mafic and intermediate lava flows. The most voluminous and interesting unit is the intermediate composition dome complex (Fig. 2).

Regional geology

The southern Resting Spring Range lies near the eastern margin of the Death Valley extensional corridor, and near the western boundary of the Basin and Range Province. The area has seen passive margin sedimentation of the Late Precambrian to Paleozoic miogeocline, Mesozoic shortening and Miocene extension and tilting (Wright et al., 1981). Most recently shallow-saline lakes existed throughout the region, which left behind mineral-rich lake deposits (Calzia and Rämö, 2000). The Lower Member of the Bonanza King Formation, lower Cambrian age, is the basement rock exposed along the western edge of the Resting Spring Range. This unit is well-exposed and documented in the greater Death Valley Region (Wright et al., 1981).

Previous work

The earliest documented study of the area was written by Rowe and published by Spurr (1903), where Rowe described stratigraphic sections through parts of the range with the most detail on the older Paleozoic sedimentary rocks. There is mention of lava

rocks that cover the Cambrian sedimentary rocks, but there is no description of the volcanic rocks and little information on the geologic map (Spurr, 1903).

Mason (1948) published a regional study of the Tecopa area, southwest of the field area, with some description of the Chicago Valley rocks. Late Tertiary volcanic rocks up to 1000 meters thick, consisting mostly of volcanic lava flows and tuffs, were mapped along the east flank of Resting Spring Range (Mason, 1948). Although little description was provided, this study helped produce the Trona Sheet of the Geologic Map of California published in 1962 (Jennings et al., 1962).

Wilhelms (1963) described the geology and structures of the central Resting Spring Range and defined the Chicago Valley Formation as the type location near Baxter Mine along the east side of the central Resting Spring Range, approximately 6 km north of the mapping location. This formation consists of a volcanoclastic unit sitting with profound unconformity on the Cambrian Bonanza King Formation. Above the basal rocks, the unit consists of greenish-yellow clastics and white tuff. The clastic unit consists of poorly sorted sand and gravel with clasts consisting of dolomite, limestone and quartzite, resembling local Paleozoic rocks. Basalt lava was noticed in the southeast corner of the Resting Spring Range.

Laibidi (1981) identified lower breccia member, middle tuff member and upper agglomerate member of the Chicago Valley Formation while investigating the structural geology of the central Resting Spring Range. The agglomerate member contains alternating layers of andesite-basalt lava flows and volcanic breccia. Laibidi (1981) noted volcanic rocks on the eastern flank of the southern Resting Spring pass, which he

described as dacite with inclusions and petrographic features indicative of magma mixing (mafic magmatic inclusions). The dacite was placed stratigraphically above these three members and was not included in the Chicago Valley Formation. The well-developed and exposed Resting Spring Pass Tuff has yielded a K/Ar age of 9.7 million years (Laibidi, 1981). The Resting Spring Pass Tuff sits stratigraphically above the late Miocene volcanic rocks of the Chicago Valley of this study. Laibidi described rock types consistent with trachydacite in the lower section of his stratigraphic sequence and reported that the dacite yielded a K/Ar age of 9.8 millions years.

Regional volcanism

Pre and syn-extensional volcanism occurred throughout the Central Death Valley Volcanic Field during the Neogene. The volcanic rocks of the Chicago Valley Formation lie on the eastern edge of this volcanic field (Fig. 1) (Calzia and Rämö, 2000). Thompson and others (1999) suggest that volcanism occurred in four eruptive stages from 12-0.7 Ma. Volcanism was accompanied by large-scale regional extension on low-angle faults, extensive footwall uplift, and significant displacements along strike-slip faults. Lava flows, domes and pyroclastic deposits were emplaced from numerous centers, mainly in the upper plate of a northwestward-migrating detachment system.

Stage I eruptions (12-8.5 Ma) are associated with the onset of extension and include minor basaltic andesite lava flows, but are dominated by calc-alkaline dacite to rhyolite lava flows. Stage II (8.5-7.5 Ma) is coincident with, and in places postdates, a period of rapid unroofing of the Black Mountains (Fig. 1). This sequence consists of

dacite to rhyolite lava flows with less voluminous basaltic lavas erupted in the southeastern and southcentral part of the field. Stage III (7.0-5.5 Ma) postdated major tectonic uplift and erosion, and consisted of basaltic to rhyolitic lava flows and small volume ash-flow and air-fall tuffs. Stage IV was restricted to basaltic and andesitic lavas in the northern part of the field (Thompson et al., 1999).

Volcanic rocks associated with rapid extension between 14-5 Ma are intermediate to felsic in composition predominantly; mafic rocks were rare. Volcanic rocks that are <5 Ma are associated with slower rates of extension and are mafic in composition predominantly with lower volumes of felsic rocks (Asmerom et al., 1994).

Structures-bedding

Bedding orientation and other structural data were collected where applicable throughout the field area, generally in the tuffs and sandstone rocks of the Chicago Valley Formation or strata of the Bonanza King Formation. Bedding attitudes in the Bonanza King Formation range between strikes from 311° to 321° , and dip to the northeast ranging from 38° to 50° , while bedding attitudes in the Chicago Valley Formation range between strikes from 300° to 015° , and dip to the northeast ranging from 23° to 33° (Fig. 2). Variation in bedding dips suggests multiple periods of extension and tilting. Available age data for these rocks show they fall within Thompson et al.'s. (1999) Stage I volcanism, which these authors suggest occurred at the onset of regional extension.

Method of investigation

Field mapping of bedrock geology and stratigraphy was performed on a 1:12,000 scale topographic base using air photos to help determine the lithologic units and volcanic geomorphic features. Eruptive centers were identified by both field relations and map characteristics. A stratigraphic section through the center of the map area was constructed. Characteristics (such as composition, size, shape, outcrop abundance) of mafic magmatic enclaves throughout the field area were documented in an attempt to characterize variation and their implications. Rock samples were collected throughout the volcanic field and vertically through the stratigraphy to help determine lithologic distribution, and compositional evolution of the magma system.

Systematic petrographic evaluation of thin sections was completed to determine general mineralogy and also document textures indicative of mixing. Attention was focused on plagioclase because numerous studies have shown it to be a particularly sensitive compositional and textural recorder of magmatic processes (see Bacon, 1986; Nelson and Montana, 1992; Coombs et al., 2000). Documentation of plagioclase phenocryst textures aid in the determination of the petrogenesis of magmas.

Geochemical analysis was performed on representative samples to characterize their major and trace element variability. These data were used to determine chemical and petrogenetic processes that modified these magmas. Major and trace element data were used especially to help evaluate the role of fractionation and mixing. Field and petrographic evidence helped to provide a model for the petrogenesis and volcanic development of this poorly studied part of the southern Death Valley Volcanic Field.

ROCK UNITS

Southern Resting Spring Range volcanic stratigraphy

The base of the Chicago Valley Formation consists of 0 to 30 meters (m) of volcanoclastic sandstones, breccias, and thin silicic tuffs. These rocks are overlain by volcanic rocks (here included in the Chicago Valley Formation), which consist of approximately 200 m of interlayered mafic to intermediate lava flows and breccias. The section is intruded and capped by an intermediate composition dome up to 600 m thick, which has fed thick (10's to 100's of meters) intermediate lava flows. Dikes feeding flows and a partially eroded cinder cone indicate a local source for the volcanic rocks. Figure 3 is a generalized stratigraphic section through the middle of field area (Fig. 2). Rock nomenclature (Fig. 4) follows IUGS recommendations (Le Bas et al., 1986).

The northern half of the field area consists of intermediate composition lava flows, which are inferred to be underlain by or fed from the same dome complex seen in the central part of the map area. A small intermediate dome exists in the northernmost edge of the volcanic field is compositionally similar to those in the central dome area.

Multiple mafic lava flows cover the southern half of the field area and unconformably overlies the Bonanza King Formation, but these flows are not overlain by more silicic rocks seen in the central and northern sections of the field area. These flows were probably erupted from mafic cinder cones or dikes exposed in the central and southern sections of the field area.

Figure 3. Generalized stratigraphic section through central dome complex. Shown from west (bottom) to east (top). Rock sample numbers and locations are given at height in stratigraphic column with vertical distance above contact with Bonanza King.

Figure 4. Rock nomenclature. Samples plotted using the total alkalis versus silica, taken from Le Bas et al, (Fig. 2 (1986)) Note compositional gap with two general composition ranges.

Early basaltic-trachyandesite, trachyandesite and trachydacite lava flows

Basaltic-trachyandesite, trachyandesite and trachydacite lava flows are exposed on the east side and near the crest of the range through the central section of the map area (Figs. 2 and 3). The sequence generally consists of alternating lava flows and flow breccias. Up to 17 individual lava flows and associated breccias were identified (Fig. 5) in the lower part of the volcanic section. These flows range between 0.3-12 m thick, with the entire sequence measuring approximately 180 m thick (Fig. 3), and are confined to the central area along the western ridge.

In weathered outcrop these flows are generally gray to red, massive, fractured, and rounded. Fresh surface textures range from vesicular to non-vesicular and aphanitic-porphyritic to aphyric. Mafic magmatic enclaves are present in the more silicic units, are up to 4 centimeters (cm) in diameter, and range from rounded to sub-rounded. Some large phenocrysts of plagioclase are noticeable in fresh and weathered hand samples. Generally, flow breccias for each lava flow unit were identified. The contacts between lava flows and breccias range from sharp to gradational. In some cases, the flows become coarser near the top of the flow and others grade into red cinders. The groundmass is generally gray to black, with fine to felty texture (Fig. 6). Thin section examination of these rocks show they contain plagioclase, olivine (often iddingsized), hornblende, clinopyroxene, red-brown-black unrecognizable crystals (possibly hornblende pseudomorphs), and minor quartz.

Figure 5. Southern Resting Spring Range major geologic units. Field photo looking south from center of the field area.

Figure 6. Basaltic-trachyandesite lava flow sample. Photomicrograph of basaltic-trachyandesite lava flow (RS-104) under crossed polarized light. View is 3.2mm X 2.2mm. Sieve core plagioclase phenocryst in center and olivine phenocrysts in left side of photo.

Trachydacite dome

The sequence of lava flows discussed above is overlain by a trachydacite dome complex in the center of the field area (Fig. 5), which is marked by multiple rounded peaks. Additional trachydacite domes were also identified in the northern section of the field area. The central unit is approximately half the width of the range through the center of the field area. This unit appears blue-gray to blue-green, massive and rounded in weathered outcrop, and contains conspicuous mafic magmatic enclaves (see Fig. 7).

Phenocrysts of plagioclase are easily noticeable in hand samples. Thin section examination of these rocks show a typical phenocryst-rich trachydacite with subhedral to euhedral zoned plagioclase phenocrysts in gray, gray-green and gray-red cryptocrystalline groundmass (see Fig. 8). Additional phenocrysts consist of hornblende, olivine, potassium feldspar, clinopyroxene, quartz and pseudomorphed hornblende. Laibidis (1981) described a rock type consistent with this unit and reported a K/Ar age of 9.8 million years.

Trachydacite lava flows

A series of plagioclase porphyritic trachydacite lava flows were observed along the east edge of the central area and as a large scale capping lava flow in the north. The lava flows appear blue-gray to black in color and appear massive in outcrop. Some heavily weathered sections appear red-gray and fractured. Flow breccias exist between some successive lava flows (Fig. 9).

Figure 7 Trachydacite outcrop. Field photo of typical trachydacite dome unit. Rocks appear fractured and weathered in outcrop. Note darker ellipsoidal mafic magmatic enclaves. Note gray scale is 20 cm long.

Figure 8. Trachydacite sample. Photomicrograph of trachydacite (RS-119) under crossed polarized light. Plagioclase phenocrysts show euhedral crystal shape and felty-fine groundmass. Rounded partially iddingsitized olivine crystals appear in upper left corner. View is 6.5mm X 4.4mm.

Figure 9. Trachydacite outcrop. Field photo of trachydacite lava flow outcrop and weathered red flow breccia. Note gray scale is 20 cm long.

Like the trachydacite dome, this unit also has ubiquitous mafic enclaves. Thin-section examination shows dominantly felty-fine, black groundmass enclosing euhedral to subhedral plagioclase, hornblende, olivine (often iddingsized), potassium feldspar, and clinopyroxene phenocrysts.

The uppermost lava flow appears black and glassy in outcrop. This unit forms a generally laterally continuous flow over the northern half of the field area and the east edge of the central dome complex. Along the east edge of the central dome complex, lava flows decrease in thickness away from the dome complex toward the east.

Cinder cones

Cinder cones are common through the central and southern sections of the field area. Cinder cones consist of dark-red vesicular cinders, pumice and tephra (Fig. 10). Outcrops range in shape from crescent to round. Outcrops are up to 2 m high and 3 to 50 m in diameter. Pyroclastic materials such as cinders and volcanic bombs were also observed in association with these eruptive units. Volcanic bombs range in length from 0.5 to 2 m (Fig. 11). These pyroclastics are dominant in the southern section of the field area, suggesting that this area is near the location of eruptive vents.

Dikes

Mafic dikes are common through the volcanic units, dominantly in the central section through the dacite dome, but also found cutting mafic lava flows and cinder cones. Mafic dikes appear gray to red, fractured and weathered in outcrop. Fresh surface

Figure 10. Cinder cone outcrop. Field photo looking east from central dome complex at two cone shaped cinder deposits of dark red scoria. Outcrop is approximately 2 m high.

Figure 11. Volcanic bomb outcrop. Volcanic bomb sitting on red cinders in the south end of the field area and near its eruptive source due to the large size. This bomb has a glassy texture and aerodynamic shape. Rock hammer at bottom right is 11 inches high.

textures range from aphanitic-porphyritic to aphyric. The groundmass is generally gray to black, with fine to felty texture with mineralogy similar to the basaltic-trachyandesite lava flows.

Mafic magmatic enclaves

Mafic magmatic enclaves are pervasive in rocks of the Chicago Valley Formation. They are most noticeable in outcrop in the trachydacite unit (Fig. 7), probably due to the lighter color of the host and contrast with the host, although they are also found in more mafic lava flows and cinders. Mafic magmatic enclaves range from 1 millimeter (mm) to 0.5 m in diameter. Thin section examination shows many microscopic blobs of mafic magma less than 1 mm in size throughout samples (Fig. 12). Enclave borders are finer grained than the interior of the enclave showing chilled or glassy margins. Enclave borders tend to be crenulated and were noticeable on outcrop to microscopic scale (Figs. 13A and 13B).

Enclave distribution ranged from 1% to 15% in trachydacite host outcrops, and less than 5% in more mafic lava flows and cinders. Enclaves range from elliptical to rounded, with some blocky or angular shapes (Fig. 14). Some outcrops show enclaves of swirled and wispy shapes, illustrating spectacular evidence of magma mingling (Figs. 15A and 15B).

Enclaves were predominantly aphanitic, but phaneritic mafic enclaves were also observed. These two distinct basaltic and gabbroic textures were observed in outcrop and on a microscopic scale within the trachydacite (Fig. 16). Fine grained enclaves typically

Figure 12. Trachydacite sample. Photomicrograph of mafic blob in trachydacite host (RS-190) under plane-polarized light. View is 1.3mm X 0.9mm.

Figure 13A. Mafic magmatic enclave. Field photo shows typical elongated mafic magmatic enclave in trachydacite host. The crenulated and fine glass chilled margins are noticeable. Note gray scale is 20 cm long.

Figure 13B. Mafic magmatic enclave. Photomicrograph of mafic magmatic enclave in trachydacite host (RS-118B) under crossed polarized light. View is 6.5mm X 4.4mm. The enclave is in the top half of the photo. Notice cusped border with the host material.

Figure 14. Trachydacite outcrop. Field photo shows magmatic enclaves in trachydacite dome unit. While the elongate and elliptical shaped enclaves appear to be generally aligned at this outcrop (parallel to the short side of the photo), there is no evidence throughout the field area to suggest an alignment correlation exists. Gray scale is 20 cm long.

Figure 15A. Mafic magma. Field photo shows mingling of a mafic magma in trachydacite host unit. Note gray scale is 20 cm long. In lower part of photo trachydacite shows brittle behavior as it is engulfed in mafic magma (see Fig. 15B) but towards top left fine interdigitation of mafic magma and trachydacite can be seen.

Figure 15B. Mafic magma. Field photo showing intrusion of mafic magmatic enclave in trachydacite host unit; close-up of the same outcrop in 15a. Note also vesicularity of mafic magma in interior, probably indicating rapid degassing during cooling. Note gray scale is 20 cm long. Angularity of trachydacite fragments in this outcrop suggests that the trachydacite was relatively cool and capable of fracturing locally when interaction took place.

Figure 16. Mafic magmatic enclave. Photomicrograph show an aphanitic and phaneritic mafic magmatic enclave in trachydacite host (RS-97) under crossed polarized light. View is 6.5mm X 4.4mm.

have crystals that are elongate, indicative of rapid cooling; while coarse grained enclaves have crystals interlocking and more equidimensional, indicative of plutonic origin. Thin section examination of mafic magmatic enclaves shows mineralogy identical to the more mafic lava flows (basaltic-trachyandesite). Generally, subhedral to euhedral plagioclase, hornblende (also pseudomorphs), pyroxene and olivine (often iddingsized) phenocrysts were identified in enclaves.

Petrography

Plagioclase textures

In volcanic rocks, plagioclase is typically very sensitive to physical and chemical changes in magma. Plagioclase phenocrysts were examined in thin sections to statistically associate phenocryst textures with rock type to see if any trends or correlations exist. Plagioclase crystals were identified and defined as one of three phenocryst textural types, commonly observed and documented by Coombs et al. (2000) and other authors. These types are: unsieved, sieve-core, or sieve-ring (Figs. 17A, 17B and 17C). Sieve-core and sieve-ring plagioclase phenocrysts have been considered by many authors to be formed when crystals are out of equilibrium with melt (e.g., Singer et al., 1995; Coombs et al, 2000). These crystals showing disequilibrium are often considered inherited crystals resulting from magma mixing.

Plagioclase phenocrysts were examined in rock types through the field area, to determine which plagioclase texture types were present. Some thin sections contained multiple rock types (host and enclave) and point counts included variation of plagioclase

Figure 17A. Unsieved and sieve-core plagioclase phenocrysts. Photomicrograph shows unsieved plagioclase phenocryst (left) and sieve-core plagioclase phenocryst in trachydacite host (RS-97) under crossed polarized light. View is 6.5mm X 4.4mm.

Figure 17B. Sieve-core plagioclase phenocryst. Photomicrograph shows sieve-core plagioclase phenocryst in trachydacite host (RS-129A) under crossed polarized light. View is 3.2mm X 2.2mm.

Figure 17C. Sieve-ring plagioclase phenocryst. Photomicrograph shows sieve-ring plagioclase phenocryst in basaltic trachyandesite host (RS-130B) under crossed polarized light. View is 3.2mm X 2.2mm.

textures within each rock type. Point count analysis of plagioclase phenocrysts of selected samples is shown in Figure 18.

Phenocryst data Distribution of the three plagioclase phenocryst textural types within rocks of the field area was evaluated to determine if any correlation exists. Unsieved plagioclase phenocrysts are most abundant type of phenocryst within all volcanic rocks. Unsieved plagioclase phenocryst totals within a standard thin section range from 30% to 90% of all plagioclase phenocrysts within trachydacite rocks. Unsieved plagioclase phenocrysts are up to three times more common than other plagioclase phenocrysts within the more mafic (basaltic-trachyandesite to trachyandesite) rocks, but found in lower abundance overall than in trachydacite rocks. Unsieved plagioclase phenocrysts were less common in mafic magmatic enclaves, but crystals were smaller and harder to identify, and generally mafic enclaves have a lower vol. % of phenocrysts compared to host rocks.

Sieve-core plagioclase phenocrysts are the second most prominent phenocryst type. They occur slightly more than sieve-ring plagioclase phenocrysts throughout trachydacite rocks and lava flow rocks, but are substantially less common than unsieved plagioclase phenocrysts. Sieve-core plagioclase phenocrysts were only identified in two of the 17 mafic magmatic enclave samples.

Sieve-ring plagioclase phenocrysts are the least common phenocryst type, occurring slightly less than sieve-core plagioclase phenocrysts throughout host rocks and

Figure 18. Bar graphs showing plagioclase phenocryst point counts for host, lava and enclaves

lava flows, but slightly more in mafic magmatic enclave samples. Sieve-ring plagioclase phenocrysts were only identified in five of the 17 mafic magmatic enclave samples.

Most samples of mafic magmatic enclaves used to determine plagioclase phenocryst types were from trachydacite host samples that were also evaluated to determine plagioclase phenocryst types. Fewer sieve-ring plagioclase phenocrysts were identified in mafic magmatic enclaves compared to the host rock of the same sample. This phenomena might be related to the overall small size of the phenocrysts in mafic magmatic enclaves, compared with host sample.

Plagioclase composition data Distribution of the plagioclase composition variations within rocks of the field area was determined to help identify if any correlation exists. Plagioclase compositions variations were determined for many unsieved crystals and some sieve-ring crystals in a variety of rock types using the Michel-Levy method to determine if any correlation exists. Although somewhat imprecise in comparison to measurement of plagioclase composition by microprobe, particularly for plagioclase crystals that also show compositional zoning, the Michel-Levy method nevertheless provides an estimate of the degree of compositional heterogeneity among plagioclase crystal populations. Plagioclase phenocryst compositions were measured in basaltic-trachyandesite, trachyandesite and trachydacite lava flows, trachydacite host, and both fine and coarse grained enclaves found in trachydacite. These results and comparisons are displayed in Figure 19.

Figure 19. Plagioclase Composition

Generally, An_{20-60} unsieved plagioclase phenocrysts exist throughout the trachydacite hosts. An_{19-46} unsieved plagioclase exists throughout basaltic-trachyandesite and trachyandesite lava. An_{22-57} unsieved plagioclase exists throughout basaltic-trachyandesite and trachyandesite enclaves in trachydacite host rocks, and An_{19-46} unsieved plagioclase exists throughout coarse grained enclaves in trachydacite host. Some variation is noticed over comparison of rocks at this scale with multiple populations observed. Evaluation of unsieved plagioclase contents of eight trachydacite host samples (RS-5, RS-6, RS-23, RS-42, RS-45, RS-122, RS-125 and RS-129A) and their mafic magmatic enclaves show that a range of plagioclase compositions within single samples exist (Table 1). However, unsieved plagioclase in RS-129A shows similar compositions, ranging from An_{29-42} for trachydacite host and An_{23-46} for a coarse grained mafic enclave found within the host trachydacite.

Plagioclase An Range

Sample #	Dacite Host	Basalt Enclave	Gabbro Enclave
RS-5	25	-	29
RS-6	34-37	-	20
RS-23	37-45	36-40	-
RS-42	28	-	36
RS-45	23-27	36	36
RS-122	28-60	40-42	-
RS-125	20-35	22	-
RS-129A	29-42	-	23-46
Range	20-60	22-40	29-36

Table 1: Plagioclase composition data

GEOCHEMISTRY

Geochemical data

Geochemical analysis was used to help characterize volcanic rocks throughout the field area (Fig. 4) and aid in determining petrogenesis. Chemical analysis was performed on the lower sequence of basaltic-trachyandesite and trachyandesite lava flows along the western side of the project site, the trachydacite domes and associated flows in the central and northern section of the project site, basaltic-trachyandesite and trachyandesite lava flows along the south side of the project site, and basaltic-trachyandesite dikes through the central section of the mapping area. Washington State University Geo Analytical Laboratory performed X-ray fluorescence spectrometry (XRF) and inductively coupled plasma mass spectrometry (ICP-MS) to determine major and trace element geochemistry on 11 samples. These results are listed in Table 2, and major and trace element compositional data are presented on a volatile-free normalization to 100%.

Silica concentrations exist in two major ranges, (basaltic-trachyandesite) from 52.3 to 57.3 weight percent (wt.%) SiO_2 and (trachydacite) from 65.7 to 66.7 wt.% SiO_2 (Fig. 20). Only one sample (RS-67) falls between these two ranges at 60.3 wt.% SiO_2 . In addition to the observed compositional gaps, major element chemical trends show significant scatter for several elements (e.g., MgO vs SiO_2 ; Al_2O_3 vs SiO_2). Samples RS-115 and RS-116A have especially low Al_2O_3 concentrations in comparison to other analyzed rocks. These samples are from lava flows in the southern section of the field

Rock	RS-33	RS-37	RS-78	RS-87	RS-91	RS-93	RS-94	RS-97A	RS-97B	RS-115	RS-116A
Basaltic	Basaltic	Trachy	Basaltic	Basaltic	Basaltic	Trachydacite	Trachydacite	Trachydacite	Basaltic	Basaltic	Trachy
Name	Trachyandesite	Andesite	Trachyandesite	Trachyandesite	Trachyandesite				Trachyandesite	Trachyandesite	Andesite
Enclave	Enclave	Lava	Dike	Lava	Lava				Enclave	Lava	Lava
Sample	35.958° N	35.942° N	35.953° N	35.954° N	35.947° N	35.95° N	35.958° N	35.963° N	35.963° N	35.936° N	35.936° N
Location	116.18° W	116.183° W	116.183° W	116.184° W	116.172° W	116.175° W	116.18° W	116.198° W	116.198° W	116.169° W	116.167° W
SiO ₂	55.71	60.27	52.31	55.3	54.98	65.89	66.67	65.72	53.9	55.49	57.24
Al ₂ O ₃	16.57	16.06	16.59	16.63	17.12	15.87	15.95	15.89	17.03	14.58	14.66
TiO ₂	1.084	0.971	1.407	1.275	1.351	0.617	0.692	0.725	1.435	1.367	1.282
FeO*	7.89	5.56	8.08	7.01	7.39	3.52	3.77	3.98	8.03	8.49	7.56
MnO	0.146	0.106	0.133	0.128	0.128	0.077	0.077	0.071	0.157	0.139	0.15
CaO	7.85	5.14	7.86	6.76	7.5	3.53	2.88	3.3	8.61	7.23	6.85
MgO	4.23	4.46	7.49	5.99	4.66	1.79	0.92	1.62	4.95	6.65	5.77
K ₂ O	2.5	3.09	1.84	2.46	2.27	4.2	4.4	4.22	1.5	2.2	2.62
Na ₂ O	3.66	4.06	3.75	4.01	4.21	4.3	4.42	4.23	3.87	3.49	3.48
P ₂ O ₅	0.37	0.281	0.522	0.446	0.401	0.206	0.211	0.229	0.515	0.372	0.398
total alk	6.16	7.15	5.59	6.46	6.48	8.5	8.81	8.45	5.37	5.69	6.1
Normalized Results (Weight %):											
Trace Elements (ppm):											
Ba	1039	1190	823	891	867	1560	1676	1510	956	852	1076
Ce	75	74	89	65	64	87	88	81	75	77	70
Cr	186	169	239	181	152	17	10	27	220	297	230
Cu	27	24	46	36	36	8	0	12	51	49	35
Ga	19	20	18	17	20	17	21	19	18	20	19
La	52	38	49	37	45	43	48	51	41	34	48
Nb	15.5	17.5	23.6	21.2	21.5	16.3	17.3	16.6	23.7	16.7	17.7
Ni	56	115	134	113	83	10	11	18	79	166	121
Pb	21	17	7	8	13	20	24	22	12	14	11
Rb	58	76	37	47	46	105	113	113	41	55	65
Sc	22	12	22	16	22	8	13	9	28	17	14
Sr	783	488	668	605	608	501	422	440	720	556	748
Th	6	7	5	6	3	10	13	14	7	6	9
V	148	97	155	126	112	43	48	45	83	142	136
Y	22	23	25	24	25	20	22	22	27	26	26
Zn	117	59	78	68	60	53	48	50	110	88	88
Zr	214	248	234	234	228	268	297	276	243	203	229
Analyses by XRF											
Ba	1081	1167	783	881	857	1559	1591	1427	824	820	1001
Ce	83.87	79.76	80.72	76.45	71.73	88.82	92.92	90.25	85.65	76.28	97.73
Ca	2.33	1.49	1.15	0.6	1.08	1.51	1.98	1.92	1.84	1.25	1.38
Dy	4.41	4.35	4.84	4.75	4.91	3.69	4.02	3.89	5.24	4.98	5.06
Er	2.29	2.32	2.54	2.52	2.57	2.01	2.14	2.06	2.75	2.56	2.47
Eu	1.7	1.58	1.91	1.8	1.79	1.45	1.5	1.54	2.03	1.87	2.11
Gd	5.28	4.99	5.61	5.27	5.31	4.26	4.65	4.52	5.97	5.9	6.48
Hf	5.18	6.06	4.99	5.18	5.07	6.59	6.97	6.29	5.25	4.94	5.35
Ho	0.85	0.87	0.96	0.94	0.95	0.72	0.8	0.77	1.02	0.95	0.94
La	47.51	45.91	45.03	43.16	39.99	52.69	54.77	52.66	49.99	40.74	49.41
Lu	0.33	0.33	0.36	0.36	0.36	0.3	0.32	0.3	0.38	0.32	0.31
Nb	16.79	17.71	24.35	21.82	20.82	16.14	17	17.48	23.89	16.15	19
Nd	34.61	30.91	33.4	31.14	29.69	31.68	33.71	32.48	36.34	33.48	42.49
Pb	17.28	15.88	9.07	15.01	10.52	20.77	20.95	19.53	12.81	10.48	13.04
Pr	9.13	8.35	8.71	8.2	7.79	8.98	9.52	9.15	9.59	8.65	10.84
Rb	57.7	76.8	36.3	47.7	40.5	102.5	105	102.2	25.8	54.7	54.3
Sc	21	15.7	23.5	20.2	21.3	7.7	7.8	9.6	24.9	20.4	22.6
Sm	6.61	5.89	6.67	6.16	6.12	5.66	6.1	5.86	7.15	6.82	8.22
Sr	788	484	647	602	602	463	418	475	727	553	743
Ta	0.86	1.08	1.43	1.31	1.28	1.1	1.11	1.09	1.35	0.97	1.06
Tb	0.77	0.75	0.84	0.83	0.83	0.64	0.71	0.69	0.91	0.89	0.92
Th	7.13	9.71	6.05	6.46	6.25	12.76	13.27	11.93	5.93	6.74	7.64
Tm	0.33	0.34	0.36	0.36	0.38	0.29	0.32	0.3	0.39	0.34	0.34
U	1.66	1.75	1.19	1.41	1.3	2.22	2.31	2.09	1	1.28	1.53
Y	22.98	23.45	25.97	25.62	25.68	20.17	21.74	21.17	27.99	25.85	25.5
Yb	2.04	2.07	2.26	2.21	2.27	1.82	1.98	1.89	2.42	2.13	2.04
Zr	205	248	223	229	215	266	279	253	227	194	211
Analyses by ICP-MS											
Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO.											

Table 2. Geochemical data. Geochemical data of selected samples from field area. Rock type and sample location given.

Figure 20. Major Elements vs SiO₂ Harker diagram plots. Low Aluminum samples (RS-115 & RS-116A) are represented by larger square symbols.

area (unconformably overlying the Bonanza King Formation), and are unlikely to be related to the other rocks comprising the main eruptive center that is the subject of this study.

Trace element compositional data are shown for samples plotted versus SiO_2 (Fig. 21). Nickel vs SiO_2 has the greatest scatter; samples ranging in SiO_2 from 54.98 to 55.49 wt.% range in Ni from 83 to 166 ppm (Fig. 21). The highest Ni concentration is from sample RS-115, basaltic-trachyandesite lava from the southern section of the field area. Additional trace element plots showing compatible-compatible; compatible-incompatible and incompatible-incompatible element relations were completed (Fig. 22). Generally, compatible-incompatible element plots (e.g., Ni vs. Rb) show the most scatter. Incompatible-incompatible element relations are most interesting in that for some element pairs (e.g., Ba vs. Th) a fairly good positive linear variation is observed, whereas for both of these elements vs. Rb the trends appear to show inflections at about 60 ppm Rb.

Trace element normalized plots (normalized N-MORB from Sun and McDonough (1989)) show that all rocks have LREE and LIL enrichment and high field strength element “depletions” (e.g., Th, Nb and Ti). Similar and overlapping patterns exist for basaltic-trachyandesite to trachydacite (Figs. 23 and 24).

Rare earth element data (normalized to chondrite) for all samples are also remarkably similar, showing overall LREE enrichment and complete overlap between rock types spanning the observed compositional range (Figs. 25, 26 and 27). All samples also lack Europium anomalies.

Figure 21. Trace elements vs SiO₂ Harker diagram plots. Low Aluminum samples (RS-115 & RS-116A) are represented by larger square symbols.

Figure 22. Trace element Harker diagram plots. Low Aluminum samples (RS-115 & RS-116A) are represented by larger square symbols.

Figure 23. Trace element normalization of low silica (<66 wt.%) rocks.

Figure 24. Trace element normalization of high silica (>66 wt.%) rocks.

Figure 25. Rare earth element normalization plots-all rocks

Figure 26. Rare earth element normalization-mafic rocks.

Figure 27. Rare earth element normalization plots-host rocks

CIPW Norm calculations are included in Appendix A, along with calculated Mg numbers. Mg numbers greater than 60 are calculated for samples RS-67, RS-78, RS-87, RS-115 and RS-116A (61.4, 64.7, 62.9, 60.8 and 60.2, respectively). Dike sample RS-78, with an Mg number of 64.7 is the most primitive and has the lowest wt.% SiO₂. While Mg numbers greater than 60 are often considered to be fairly primitive magmas, these rocks are not likely in equilibrium with mantle, owing to their high SiO₂ concentrations. Primary mantle derived magmas have basalts with Ni contents around 400 ppm and Cr contents >800 ppm (Wilson, 1989). Dike sample RS-78 (the only basaltic rock in the data set) has 134 ppm Ni and 239 ppm Cr (Table 2), but is not the most “primitive” (based on these criteria) of the analyzed rocks. Low Al₂O₃ samples RS-115 and RS-116A have higher Ni and Cr but also have higher SiO₂.

DISCUSSION

The objective of this study is to investigate the petrogenesis of the late Miocene Volcanic Rocks of the Chicago Valley, with particular emphasis on petrogenesis of the trachydacite unit.

The stratigraphic volcanic sequence consists of alternating basaltic-trachyandesite to trachydacite lava flows, a trachydacite dome system, a cinder cone complex, and pyroclastic deposits. This volcanic system appears incompatible with one simple evolving closed magma system due to the variation and changing of compositions back and forth. Trachydacite was present early in the volcanic sequence in the early lava flows along the western edge of the central area, but after eruption, a period of more mafic magmatism ensued, as shown by a sequence of more mafic lava flows. The highly varied compositions suggest a more disorganized open magma chamber system rather than a simple single evolving magma chamber, and field and petrographic evidence documented earlier indicates a role for magma mixing processes during petrogenesis of the trachydacite unit.

The degree to which fractional crystallization, partial melting, or magma mixing contributed to the petrogenesis was tested using geochemistry in an attempt to better assess the petrogenesis of the trachydacite unit and the other volcanic rocks in the southern Resting Spring Range.

Fractional crystallization

Based on the observed Mg numbers for even the most mafic rocks, and their relatively low Ni and Cr concentrations, some olivine (with or without pyroxene) fractionation has probably affected all mafic rocks to some degree. Coarse-grained, mafic magmatic enclaves found in trachydacites may also be part of a fractionating mineral assemblage in the magma chamber that produced the trachydacites, and the overlap in unsieved plagioclase compositions between “gabbroic” enclave and host also suggest a fractionation relationship.

Major element Harker diagram plots also appear compatible with some fractional crystallization (Fig. 20), although the data are scattered enough that establishing fractional crystallization as the main mechanism for chemical variation is difficult from major element data alone. On a plot of MgO vs. SiO₂ (Fig. 20) olivine fractionation in mafic rocks could account for relatively low MgO at low SiO₂. However, data are too scattered to infer this as the predominant process. In addition, a compositional gap of silica content exists, with only one sample falling between 57.3 wt.% SiO₂ and 66 wt.% SiO₂, which is difficult to reconcile with a continuous “liquid line of descent” from basaltic-trachyandesite to trachydacite.

The general trend of Ni vs. Rb might be compatible with fractionation of mafic silicates and plagioclase, showing decreasing Ni content and increasing Rb during magma evolution (Fig. 28). However, the sample with the lowest SiO₂ and highest Ni and Cr concentrations (RS-78) does not have the lowest Rb concentration. In addition, no europium anomaly exists in rocks of the study area (Figs 25, 26, and 27), which might

Figure 28. Trace element Harker diagram plots. Low Aluminum samples (RS-115 & RS-116A) are represented by larger square symbols.

indicate plagioclase fractionation. Europium anomalies are absent in the entire suite of samples, suggesting plagioclase fractionation did not play a major role in evolution of magmas. Coleman and Walker (1990) observed similar REE patterns in calc-alkaline volcanic rocks in the Death Valley area, which these authors suggested were related by fractional crystallization. Coleman and Walker (1990) explain the lack of a negative Eu anomaly as high oxygen fugacity, which would have lowered the distribution coefficient of Eu during plagioclase fractionation.

Ba vs. Rb and Th vs. Rb show general trends consistent with fractionation at higher Rb concentrations (above approximately 60 ppm), and the linear positive increase on the Th vs. Ba plot, with the line passing through the origin, would be consistent with fractional crystallization of incompatible elements (Fig. 28). However, the Ni vs. Cr plot is not compatible with fractionation from a single parent. Fractional crystallization could therefore produce part of the above mentioned trends, particularly at high SiO₂, but cannot be the only or primary mechanism of petrogenesis for the entire suite.

Magma mixing

The degree to which magma mixing influenced magmatic evolution in development of rocks was evaluated by viewing field and petrographic evidence presented in more detail below. The close proximity of vents of mafic rocks (cinder cones and dikes) with the trachydacite complex argues ascending magmas utilized the same conduit systems and therefore could have mixed. However, the degree to which

mixing is responsible for the observed chemical variation must be evaluated with geochemical tests as well.

Scatter in compatible-incompatible elements (e.g., Ni vs. Rb) and compatible-compatible elements (e.g., Cr vs. Ni) may be indicative of multi-component mixing (Fig. 28), although fractionation of different parents might also explain these trends. However, flat trends on Ba vs. Rb and Th vs. Rb plots (Fig. 28) cannot be explained by any conceivable fractional crystallization sequence, because for two incompatible elements their ratio in the evolving liquid should remain constant (e.g., Ba vs. Th; Fig. 28). The flatness of Ba vs. Rb and Th vs. Rb for low Rb (and generally low SiO₂) coupled with the good linear coordination observed on Ba vs. Th, would require mixing magmas to have variable Rb concentrations but fairly constant Ba/Th ratios (Fig. 28). At higher Rb (higher SiO₂), the positive incompatible-incompatible trend could be produced primarily by fractionation.

Injection of silicic magma into mafic magma can explain scatter in major elements trends, as well as on compatible-incompatible plots and compatible-compatible plots. However, the general scatter on element-element plots indicates binary mixing between two single magmatic end members did not occur.

Petrographic evidence of mixing

Multiple studies (e.g., Tsuchiyama, 1985; Nelson and Montana, 1992; Coombs et al, 2000) have shown volcanic plagioclase to be sensitive to magmatic processes, particularly magma mixing. Plagioclase crystals commonly exhibit a variety of

disequilibrium textures that can include complex zoning patterns and resorption features that record changing physical conditions and evolution in magmatic systems (Nelson and Montana, 1992). Plagioclase crystals that formed, due to early crystallization in magma, can undergo resorption or re-equilibration if mixed with new magma. Depending upon the duration of interaction preceding eruption these inherited phenocrysts will begin to conform to the new physical environment and might initiate new crystal overgrowths. Plagioclase phenocrysts will begin to nucleate and new composition plagioclase can grow on old crystals.

Sieve-core phenocrysts (Fig. 17B) are interpreted to result from either magma mixing (Coombs et al, 2000), or melting due to rapid decompression during magma ascent and eruption (Nelson and Montana, 1992). Experiments have not produced these textures, although they are well documented in systems where magma mixing can otherwise be shown to have occurred (Kouchi and Sunagawa, 1983). Based on the other abundant evidence for interaction between compositionally and/or thermally contrasting magmas, I interpret these textures to result from mixing processes.

In studies where plagioclase composition of phenocrysts were determined by microprobe, sieve-ring or spongy phenocrysts (Fig. 17A) have clear unresorbed cores with a distinct ring of sieve texture, which are typically more An rich than the cores (i.e. reversely zoned). This spongy texture is a result of disequilibrium and represents resorption and new crystal growth on the rim of an inherited phenocryst (e.g., Miller and Miller, 1991; Coombs et al, 2000). The new growth represents the equilibrium plagioclase composition of the new host liquid. These textures were found throughout all

samples, although the highest proportion is observed in the trachydacite. Fewer sieve-ring phenocrysts were found in basaltic-trachyandesite and trachyandesite lavas and even fewer in mafic enclaves.

The lack of sieve-ring phenocrysts in mafic magmatic enclaves might suggest that mafic magma injection events preserved in these enclaves occurred when the thermal contrast between mafic magma and trachydacite was large, resulting in less mixing and little exchange of phenocrysts between trachydacite and enclave-forming magma.

Where observed, overgrowths of clear rims on the sieve-core plagioclase can be used to constrain the length of time between incorporation of the crystal in the new magma and eruption, provided one has an estimate of the plagioclase growth rate. This can give a clue to the amount of time that the two magmas interacted before eruption, and whether magma mixing plays a role in eruption. Crystal growth rates range from 10^{-9} cm/s to 10^{-12} cm/s for plagioclase in mafic to intermediate magmas (Cashman, 1990; Singer et al., 1995; Larson, 2005). The thickness of three overgrowth rims on sieve-core plagioclase in three different trachydacite hosts was measured and found to range from 0.0025 cm to 0.0077 cm. Using the range of reported crystal growth rates above, these overgrowth thicknesses indicate growth time of 3 days to 81 years since mixing.

Assimilation of local basement rocks with magma might also produce intermediate magmas. However, local shallow basement rocks consist of Paleozoic Bonanza King carbonates and quartzites. The chemistry of the study rocks is not consistent with assimilation of carbonate rocks, and no xenocrysts of quartz were observed within volcanic rocks. Deeper crustal assimilation is possible, but the relatively

short post-mixing crystal residence time measured in this study of 3 days to 81 years would make this less likely.

Mafic magmatic enclaves

Mafic magmatic enclaves are common and well documented in both plutonic and volcanic intermediate to felsic host rocks and are representative of magma mixing or mingling. Bacon (1986) states that enclaves are magmas from deeper levels that coexisted with the host in the same magma system. If viscosities of the two components are low and similar, mixing may form a homogeneous hybrid. Formation of magmatic enclaves may occur by either forcible injection of mafic magma or dispersion of mafic dikes (Bacon, 1986) and may also be caused by convective mixing or stirring of silicic magma induced by mafic magma injection (e.g., Pallister et al., 1996).

In contrast, Kouchi and Sunagawa (1985) experimentally mixed basalt and dacites at 1250°C, and noticed dacite dissolving into basalt to form a hybrid of andesite composition, but that blobs of basalt were unchanged and incorporated into the dacite host as enclaves. These experiments point out that even at high temperatures where silicic magma has minimal chilling effect, mafic magma has a tendency to form inclusions when stirred into silicic magma, and that silicic magma stirred into mafic magma produces a very thoroughly homogenized hybrid, although evidence of mixing still may be preserved as disequilibrium textures in crystals. Bacon (1986), also states that enclaves can be found as sub-mm sized blobs, and that these are more widespread than currently recognized.

Enclaves in this study are rarely angular and most show crenulated or cusped margins, bent or convex toward the host. The finer-grained (chilled) margins observed in larger enclaves clearly indicate quenching of hotter mafic magma in the cooler host has occurred. They range in size from 1cm to 0.5m, commonly 20 cm, but also occur commonly as sub-mm sized mafic blobs. The common occurrence of the sub-mm mafic blobs in the trachydacites suggests that mafic magma was injected repeatedly and that very effective dispersal by stirring occurred within the trachydacite chamber.

Field, chemical and petrographic evidence presented above argues that magma mixing played a critical overall petrogenetic role in Miocene volcanic rocks in the southern Resting Spring Range, and that mixing may also have played a role in the dynamics of the trachydacite magma chamber.

Origin of trachydacite

Any model for the origin of trachydacite must explain the following: (1) presence of unsieved plagioclase crystals with appreciable range of An contents; (2) similarity in composition of unsieved plagioclase between coarse and fine-grained mafic enclaves and the trachydacite host; (3) incompatible elemental trends that are indicative of fractional crystallization at high SiO₂ concentrations; (4) sieve-textured plagioclase that is indicative of mixing processes in the magma chamber; and (5) ubiquitous presence of mafic input, from dismembered dikes and large enclaves to sub-mm mafic blobs.

Frost and Mahood (1987) showed that a rheologic barrier exists between common basaltic and granitic magmas limiting maximum silica content for hybrid magmas to ~63

wt.% SiO₂. Thus, producing the trachydacite unit by injection of basaltic magma into rhyolitic magma to produce an intermediate composition hybrid magma is difficult to explain. Analyzed trachydacites in the Miocene volcanic rocks in the southern Resting Spring Range vary from 65.7 to 66.7 wt.% SiO₂ and yet still show textural evidence of widespread mixing. In addition, the mafic magma blobs observed in thin sections at sub-mm scale and sieve-ring plagioclase are also indicative of mixing.

Eichelberger et al. (2000) suggest that silicic replenishment or recharge of a basaltic system results in chemical mixing in the chamber. Such a process would help overcome problems with the rheological barriers at a silica content of ~63 wt.% SiO₂ and create the trachydacite unit. In this way, the trachydacite chamber would be built up progressively by modest injections of silicic magma into mafic magma that produce compositional hybrids (e.g., Kouchi and Sunagawa, 1983) that also preserve evidence of hybridization in crystals.

An alternative mechanism to produce the features in the trachydacite might be convective self-mixing (Couch et al., 2001). These authors propose that a crystal-rich magma displaying a range of disequilibrium features, resorption surfaces, wide ranges of mineral compositions, and minerals not in equilibrium with surrounding rock matrix in lavas can be explained by convective self-mixing of the magma if the chamber is heated from below and cooled from above. As outlined by Couch et al. (2001), hot mafic magma intrudes the base of a more silicic magma chamber, forming a layer of hot siliceous magma at the boundary and allowing for local crystal resorption. This hot boundary layer becomes buoyant, and results in development of convective plumes. The

plumes rise and mix with the cooler interior, resulting in crystal rim growth on resorbed crystals from deeper in the chamber. Mixing these crystals throughout the magma chamber should also occur, but direct mixing of basalt and silicic magma to produce a hybrid intermediate magma need not be invoked to produce the disequilibrium features. This mechanism is attractive in the case of the trachydacites because it can generally explain all features of the data including petrographic evidence for disequilibrium and chemical evidence for fractionation at high SiO_2 , as well as the widespread evidence for mafic input in the form of disrupted mafic dikes, mafic enclaves and smaller blobs.

As mentioned previously, for rocks with greater than 60 wt.% SiO_2 , fractionation best explains the general linear increase in incompatible elements with trends passing through the origin. However, magma mixing of compositionally distinct magmas is hard to reconcile with these incompatible element trends (Fig. 28). Self-mixing of the magma chamber should not produce scatter in the trends because all liquids along with them *are* part of a common “liquid line of descent.” Further tests of this model using radiogenic isotopes may help to better quantify the role of open versus closed system chemical evolution of the trachydacites.

CONCLUSIONS

Late Miocene volcanic rocks in the southern Resting Spring Range show clear evidence of open system magmatism. The petrogenetic model for the trachydacite unit is consistent with a petrogenetic model of magmas evolving by fractional crystallization, silicic recharge, magma mixing and convective self mixing. The volcanic history of the assemblage is interpreted here to comprise five phases in its evolution as documented by field exposures, stratigraphic relationships, petrographic relations and geochemical trends (Fig. 29).

Phase 1

The initial event in the magmatic and volcanic sequence of the late Miocene Volcanic Rocks of the Chicago Valley Formation is development of a mafic magma chamber. While there is evidence for randomness throughout the eruptive sequence, there is some support for fractional crystallization occurring, in that no mafic magmas are primitive, and even the most mafic dike appears to have experienced some fractionation of mafic silicates.

Phase 2

Injection of silicic and mafic magma into mafic magma chamber caused eruption of the western sequence of dominantly basaltic-trachyandesite and trachyandesite lava

MAGMATIC/VOLCANIC SEQUENCE

Phase 1: The initial event in the magmatic and volcanic sequence of the late Miocene Volcanic Rocks of the Chicago Valley Formation is development of a mafic magma chamber. While there is evidence for randomness throughout the eruptive sequence, there is some support for fractional crystallization occurring, in that no mafic magmas are primitive, and even the most mafic dike appears to have experienced some fractionation of mafic silicates.

Phase 2: Injection of silicic and mafic magma into mafic magma chamber and eruption of the western sequence of dominantly basaltic-trachyandesite and trachyandesite lava flows and breccias. The most chemically primitive of the rocks (basaltic-trachyandesite) erupted within the sequence near a trachydacite lava. Some initial mixing of silicic and mafic magmas took place early in the sequence of flows and then the compositional trend moved back toward more mafic for the remaining flows in the sequence.

Phase 3: Silicic replenishment of mafic magma chamber and fractional crystallization begin to shift the magma chamber toward an intermediate composition. This allows exchange of plagioclase phenocrysts from silicic and mafic magmas into the evolving magma chamber to occur, resulting in the highly varied plagioclase composition of phenocrysts measured in this study.

Phase 4: Injection of mafic magma into silicic magma chamber allows self-mixing to occur. This permits further crystal mixing and development of disequilibrium features previously documented, while the chamber continues to evolve by fractional crystallization to higher silica values. This continued intrusion of mafic magma into the intermediate composition magma chamber and convective self-mixing allowed for very effective dispersal of mafic blobs down to mm scale. Mafic replenishments probably also triggered eruptions, given the relatively short time scales recorded by estimates of rim growth times on sieve-ring and sieve-core plagioclase.

Phase 5: Mafic magmatism continued, with eruption of basaltic-trachyandesite and trachyandesite lava in the south. Chemical variations, especially in Al and Ni concentrations show these lavas to be petrologically different, from the sequence of lavas in the central area, and thus these were probably erupted from a separate magma plumbing system.

Figure 29. Volcanic history of the Miocene volcanic rocks of the southern Resting Spring Range

flows and breccias. A trachydacite lava flow was also associated with these early lava flows low in the stratigraphic sequence. The most chemically primitive of the rocks (basaltic-trachyandesite) erupted within the sequence near a trachydacite lava. Some initial mixing of silicic and mafic magmas took place early in the sequence of flows and then the compositional trend moved back toward more mafic for the remaining flows in the sequence. Eruption was likely into a paleo basin or topographic low because this sequence of flows is not laterally continuous, and is only exposed along the western side of the field area.

Phase 3

Silicic replenishment of mafic magma chamber magma, mixing and fractional crystallization begin to shift the magma chamber toward an intermediate composition. This allows exchanging plagioclase phenocrysts from silicic and mafic magmas into the evolving magma chamber to occur, resulting in the highly varied plagioclase composition of phenocrysts measured in this study.

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Injection of mafic magma into silicic magma chamber allows self-mixing to occur. This permits further crystal mixing and development of disequilibrium features previously documented, while the chamber continues to evolve by fractional crystallization to higher SiO_2 values. This continued intrusion of mafic magma into the intermediate composition magma chamber and convective self-mixing allowed for very

effective dispersal of mafic blobs down to mm scale. Mafic replenishments probably also triggered eruptions, given the relatively short time scales recorded by estimates of rim growth times on sieve-ring and sieve-core plagioclase.

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Mafic magmatism continued, with eruption of basaltic-trachyandesite and trachyandesite lava in the south. Chemical variations, especially in Al and Ni concentrations show these lavas to be petrologically different, from the sequence of lavas in the central area, and thus these were probably erupted from a separate magma plumbing system.

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APPENDIX

CIPW normalization calculations tables. Calculation of normalization utilizes program written by Dr. Kurt Hollocher , Union College, Geology Department.
(www.union.edu/PUBLIC/GEODEPT/COURSES/petrology/norms.html; site accessed December 2003).

CIPW normalization calculation RS-33 basaltic-trachyandesite enclave

Rock Analysis			Correction Factors		Corrected Analysis		Normative Minerals			Weight %	Volume %
										Norm	Norm
SiO ₂	55.71	%	Total=100%? Y/N	N	55.66		Quartz		0.97	1.05	
TiO ₂	1.08	%	Fe ³⁺ /(Total Iron)	0.1	1.08		Plagioclase		52.34	56.37	
Al ₂ O ₃	16.57	%			16.56		Orthoclase		14.77	16.63	
Fe ₂ O ₃		%	Total Fe as FeO	7.89	0.88		Nepheline				
FeO	7.89	%	Desired Fe ₂ O ₃	0.88	7.09		Leucite				
MnO	0.15	%	Desired FeO	7.10	0.15		Kalsilite				
MgO	4.23	%	Weight corr. factor	0.999	4.23		Corundum				
CaO	7.85	%			7.84		Diopside	12.89		11.02	
Na ₂ O	3.66	%			3.66		Hypersthene	14.93		12.15	
K ₂ O	2.50	%	Zero values not shown		2.50		Wollastonite				
P ₂ O ₅	0.37	%			0.37		Olivine				
CO ₂		%					Larnite				
SO ₃		%					Acmite				
S		%					K ₂ SiO ₃				
F		%					Na ₂ SiO ₃				
Cl		%	Norm calculation checks: Norm seems OK				Rutile				
Sr	788	ppm			0.09		Ilmenite	2.05		1.24	
Ba	1081	ppm			0.12		Magnetite	1.28		0.71	
Ni	56	ppm			0.01		Hematite				
Cr	186	ppm	More of the norm below		0.03		Apatite	0.86		0.77	
Zr	205	ppm			0.03		Zircon	0.04		0.03	
Total	100.01				100.30		Perovskite				
							Chromite	0.04		0.03	
							Sphene				
							Pyrite				
							Halite				
							Fluorite				
							Anhydrite				
							Na ₂ SO ₄				
							Calcite				
							Na ₂ CO ₃				
							Total	100.17		100.00	
							Fe ³⁺ /(Total Fe) in rock	10.0		10.0	
							Mg/(Mg+Total Fe) in rock	48.9		48.9	
							Mg/(Mg+Fe ²⁺) in rock	51.5		51.5	
							Mg/(Mg+Fe ²⁺) in silicates	56.2		56.2	
							Ca/(Ca+Na) in rock	54.2		54.2	
							Ca/(Ca+Na) in plagioclase	39.4		39.4	
							Differentiation Index	68.1		74.1	
							Calculated density, g/cc	2.89		2.89	
							Calculated liquid density	2.59		2.59	
							Calculated viscosity, dry	3.5		3.5	
							Calculated viscosity, wet	3.3		3.3	
							Estimated liquidus temp.	1113		1113	
							Estimated H ₂ O content	0.90		0.90	

Table A1.

CIPW normalization calculation RS-67 trachy andesite
lava

Rock Analysis			Correction Factors		Corrected Analysis	Normative Minerals	Weight % Norm	Volume % Norm
SiO ₂	60.27	%	Total=100%? Y/N	N	60.23	Quartz	6.05	6.42
TiO ₂	0.97	%	Fe ³⁺ /(Total Iron)	0.1	0.97	Plagioclase	50.80	53.62
Al ₂ O ₃	16.06	%			16.05	Orthoclase	18.26	20.06
Fe ₂ O ₃		%	Total Fe as FeO	5.56	0.62	Nepheline		
FeO	5.56	%	Desired Fe ₂ O ₃	0.62	5.00	Leucite		
MnO	0.11	%	Desired FeO	5.00	0.11	Kalsilite		
MgO	4.46	%	Weight corr. factor	0.999	4.46	Corundum		
CaO	5.14	%			5.14	Diopside	6.22	5.25
Na ₂ O	4.06	%			4.06	Hypersthene	15.34	12.47
K ₂ O	3.09	%	Zero values not shown		3.09	Wollastonite		
P ₂ O ₅	0.28	%			0.28	Olivine		
CO ₂		%				Larnite		
SO ₃		%				Acmite		
S		%				K ₂ SiO ₃		
F		%				Na ₂ SiO ₃		
Cl		%	Norm calculation checks: Norm seems OK			Rutile		
Sr	484	ppm			0.06	Ilmenite	1.84	1.09
Ba	1167	ppm			0.13	Magnetite	0.90	0.49
Ni	115	ppm	More of the norm below		0.01	Hematite		
Cr	169	ppm			0.02	Apatite	0.65	0.57
Zr	248	ppm			0.03	Zircon	0.04	0.03
Total	100.00				100.26	Perovskite		
						Chromite	0.03	0.02
						Sphene		
						Pyrite		
						Halite		
						Fluorite		
						Anhydrite		
						Na ₂ SO ₄		
						Calcite		
						Na ₂ CO ₃		
						Total	100.13	100.02
Fe ³⁺ /(Total Fe) in rock							10.0	10.0
Mg/(Mg+Total Fe) in rock							58.9	58.9
Mg/(Mg+Fe ²⁺) in rock							61.4	61.4
Mg/(Mg+Fe ²⁺) in silicates							66.7	66.7
Ca/(Ca+Na) in rock							41.2	41.2
Ca/(Ca+Na) in plagioclase							31.1	31.1
Differentiation Index							75.1	80.1
Calculated density, g/cc							2.82	2.82
Calculated liquid density							2.53	2.53
Calculated viscosity, dry							4.6	4.6
Calculated viscosity, wet							4.1	4.1
Estimated liquidus temp.							1029	1029
Estimated H ₂ O content							1.52	1.52

Table A2.

CIPW normalization calculation RS-78 basaltic-trachyandesite dike

Rock Analysis		Correction Factors		Corrected Analysis	Normative Minerals	Weight % Norm	Volume % Norm
SiO ₂	52.31 %	Total=100%? Y/N	N	52.26	Quartz		
TiO ₂	1.41 %	Fe ³⁺ /(Total Iron)	0.1	1.41	Plagioclase	54.70	59.47
Al ₂ O ₃	16.59 %			16.58	Orthoclase	10.87	12.36
Fe ₂ O ₃	%	Total Fe as FeO	8.09	0.90	Nepheline		
FeO	8.09 %	Desired Fe ₂ O ₃	0.90	7.27	Leucite		
MnO	0.13 %	Desired FeO	7.28	0.13	Kalsilite		
MgO	7.49 %	Weight corr. factor	0.999	7.48	Corundum		
CaO	7.86 %			7.85	Diopside	10.52	9.22
Na ₂ O	3.75 %			3.75	Hypersthene	4.70	3.98
K ₂ O	1.84 %	Zero values not shown		1.84	Wollastonite		
P ₂ O ₅	0.52 %			0.52	Olivine	14.06	11.45
CO ₂	%				Larnite		
SO ₃	%				Acmite		
S	%				K ₂ SiO ₃		
F	%				Na ₂ SiO ₃		
Cl	%				Rutile		
Sr	647 ppm	Norm calculation checks: Norm seems OK		0.08	Ilmenite	2.68	1.64
Ba	783 ppm			0.09	Magnetite	1.30	0.73
Ni	134 ppm	More of the norm below		0.02	Hematite		
Cr	239 ppm			0.03	Apatite	1.20	1.10
Zr	223 ppm			0.03	Zircon	0.04	0.03
Total	99.99			100.24	Perovskite		
					Chromite	0.04	0.03
					Sphene		
					Pyrite		
					Halite		
					Fluorite		
					Anhydrite		
					Na ₂ SO ₄		
					Calcite		
					Na ₂ CO ₃		
					Total	100.11	100.01
					Fe ³⁺ /(Total Fe) in rock	10.0	10.0
					Mg/(Mg+Total Fe) in rock	62.3	62.3
					Mg/(Mg+Fe ²⁺) in rock	64.7	64.7
					Mg/(Mg+Fe ²⁺) in silicates	69.9	69.9
					Ca/(Ca+Na) in rock	53.6	53.6
					Ca/(Ca+Na) in plagioclase	40.6	40.6
					Differentiation Index	65.6	71.8
					Calculated density, g/cc	2.91	2.91
					Calculated liquid density	2.63	2.63
					Calculated viscosity, dry	2.6	2.6
					Calculated viscosity, wet	2.5	2.5
					Estimated liquidus temp.	1174	1174
					Estimated H ₂ O content	0.56	0.56

Table A3

CIPW normalization calculation RS-87 basaltic-trachyandesite lava

Rock Analysis			Correction Factors		Corrected Analysis		Normative Minerals		Weight %	Volume %
									Norm	Norm
SiO ₂	55.30	%	Total=100%? Y/N	N	55.26		Quartz			
TiO ₂	1.28	%	Fe ³⁺ /(Total Iron)	0.1	1.27		Plagioclase	54.01	58.07	
Al ₂ O ₃	16.63	%			16.62		Orthoclase	14.54	16.30	
Fe ₂ O ₃		%	Total Fe as FeO	7.01	0.78		Nepheline			
FeO	7.01	%	Desired Fe ₂ O ₃	0.78	6.30		Leucite			
MnO	0.13	%	Desired FeO	6.31	0.13		Kalsilite			
MgO	5.99	%	Weight corr. factor	0.999	5.99		Corundum			
CaO	6.76	%			6.75		Diopside	8.82	7.61	
Na ₂ O	4.01	%			4.01		Hypersthene	13.88	11.56	
K ₂ O	2.46	%	Zero values not shown		2.46		Wollastonite			
P ₂ O ₅	0.45	%			0.45		Olivine	4.22	3.38	
CO ₂		%					Larnite			
SO ₃		%					Acmite			
S		%					K ₂ SiO ₃			
F		%					Na ₂ SiO ₃			
Cl		%	Norm calculation checks: Norm seems OK				Rutile			
Sr	602	ppm			0.07		Ilmenite	2.41	1.46	
Ba	881	ppm			0.10		Magnetite	1.13	0.62	
Ni	113	ppm	More of the norm below		0.01		Hematite			
Cr	181	ppm			0.03		Apatite	1.04	0.94	
Zr	229	ppm			0.03		Zircon	0.04	0.03	
Total	100.01				100.26		Perovskite			
							Chromite	0.04	0.02	
							Sphene			
							Pyrite			
							Halite			
							Fluorite			
							Anhydrite			
							Na ₂ SO ₄			
							Calcite			
							Na ₂ CO ₃			
							Total	100.13	99.99	
Fe ³⁺ /(Total Fe) in rock								10.0	10.0	
Mg/(Mg+Total Fe) in rock								60.4	60.4	
Mg/(Mg+Fe ²⁺) in rock								62.9	62.9	
Mg/(Mg+Fe ²⁺) in silicates								68.4	68.4	
Ca/(Ca+Na) in rock								48.2	48.2	
Ca/(Ca+Na) in plagioclase								35.8	35.8	
Differentiation Index								68.6	74.4	
Calculated density, g/cc								2.88	2.88	
Calculated liquid density								2.59	2.59	
Calculated viscosity, dry								3.3	3.3	
Calculated viscosity, wet								3.1	3.1	
Estimated liquidus temp.								1120	1120	
Estimated H ₂ O content								0.85	0.85	

Table A4.

CIPW normalization calculation RS-91 basaltic-trachyandesite lava

Rock Analysis			Correction Factors		Corrected Analysis	Normative Minerals	Weight % Norm	Volume % Norm
SiO ₂	54.98	%	Total=100%? Y/N	N	54.93	Quartz		
TiO ₂	1.35	%	Fe ³⁺ /(Total Iron)	0.1	1.35	Plagioclase	56.71	60.93
Al ₂ O ₃	17.12	%			17.11	Orthoclase	13.41	15.03
Fe ₂ O ₃		%	Total Fe as FeO	7.39	0.82	Nepheline		
FeO	7.39	%	Desired Fe ₂ O ₃	0.82	6.65	Leucite		
MnO	0.13	%	Desired FeO	6.65	0.13	Kalsilite		
MgO	4.66	%	Weight corr. factor	0.999	4.66	Corundum		
CaO	7.50	%			7.49	Diopside	11.37	9.73
Na ₂ O	4.21	%			4.21	Hypersthene	9.33	7.65
K ₂ O	2.27	%	Zern value not shown		2.27	Wollastonite		
P ₂ O ₅	0.40	%			0.40	Olivine	4.57	3.57
CO ₂		%				Larnite		
SO ₃		%				Acmite		
S		%				K ₂ SiO ₃		
F		%				Na ₂ SiO ₃		
Cl		%	Norm calculation checks:			Rutile		
Sr	602	ppm	Norm seems OK		0.07	Ilmenite	2.56	1.55
Ba	857	ppm			0.10	Magnetite	1.19	0.66
Ni	83	ppm	More of the norm below		0.01	Hematite		
Cr	152	ppm			0.02	Apatite	0.93	0.83
Zr	215	ppm			0.03	Zircon	0.04	0.03
Total	100.01				100.25	Perovskite		
						Chromite	0.03	0.02
						Sphene		
						Pyrite		
						Halite		
						Fluorite		
						Anhydrite		
						Na ₂ SO ₄		
						Calcite		
						Na ₂ CO ₃		
						Total	100.14	100.00
						Fe ³⁺ /(Total Fe) in rock	10.0	10.0
						Mg/(Mg+Total Fe) in rock	52.9	52.9
						Mg/(Mg+Fe ²⁺) in rock	55.5	55.5
						Mg/(Mg+Fe ²⁺) in silicates	61.5	61.5
						Ca/(Ca+Na) in rock	49.6	49.6
						Ca/(Ca+Na) in plagioclase	35.8	35.8
						Differentiation Index	70.1	76.0
						Calculated density, g/cc	2.87	2.87
						Calculated liquid density	2.59	2.59
						Calculated viscosity, dry	3.3	3.3
						Calculated viscosity, wet	3.1	3.1
						Estimated liquidus temp.	1126	1126
						Estimated H ₂ O content	0.82	0.82

Table A5.

CIPW normalization calculation RS-93 trachy-dacite

Rock Analysis			Correction Factors		Corrected Analysis		Normative Minerals	Weight % Norm	Volume % Norm
SiO ₂	65.89	%	Total=100%? Y/N	N	65.85		Quartz	14.10	14.47
TiO ₂	0.62	%	Fe ³⁺ /(Total Iron)	0.15	0.62		Plagioclase	47.95	49.18
Al ₂ O ₃	15.87	%			15.86		Orthoclase	24.82	26.37
Fe ₂ O ₃		%	Total Fe as FeO	3.52	0.59		Nepheline		
FeO	3.52	%	Desired Fe ₂ O ₃	0.59	2.99		Leucite		
MnO	0.08	%	Desired FeO	2.99	0.08		Kalsilite		
MgO	1.79	%	Weight corr. factor	0.999	1.79		Corundum		
CaO	3.53	%			3.53		Diopside	4.14	3.35
Na ₂ O	4.30	%			4.30		Hypersthene	6.54	5.06
K ₂ O	4.20	%	Zero values not shown		4.20		Wollastonite		
P ₂ O ₅	0.21	%			0.21		Olivine		
CO ₂		%					Larnite		
SO ₃		%					Acmite		
S		%					K ₂ SiO ₃		
F		%					Na ₂ SiO ₃		
Cl		%	Norm calculation checks: Norm seems OK				Rutile		
Sr	463	ppm			0.05		Ilmenite	1.18	0.67
Ba	1559	ppm			0.17		Magnetite	0.86	0.45
Ni	10	ppm	More of the norm below				Hematite		
Cr	17	ppm					Apatite	0.49	0.41
Zr	266	ppm					Zircon	0.06	0.04
Total	100.00				0.04		Perovskite		
					100.28		Chromite		
							Sphene		
							Pyrite		
							Halite		
							Fluorite		
							Anhydrite		
							Na ₂ SO ₄		
							Calcite		
							Na ₂ CO ₃		
							Total	100.14	100.00
							Fe ³⁺ /(Total Fe) in rock	15.1	15.1
							Mg/(Mg+Total Fe) in rock	47.5	47.5
							Mg/(Mg+Fe ²⁺) in rock	51.6	51.6
							Mg/(Mg+Fe ²⁺) in silicates	58.7	58.7
							Ca/(Ca+Na) in rock	31.2	31.2
							Ca/(Ca+Na) in plagioclase	23.1	23.1
							Differentiation Index	86.9	90.0
							Calculated density, g/cc	2.72	2.72
							Calculated liquid density	2.46	2.46
							Calculated viscosity, dry	6.5	6.5
							Calculated viscosity, wet	5.4	5.4
							Estimated liquidus temp.	926	926
							Estimated H ₂ O content	2.49	2.49

Table A6.

CIPW normalization calculation RS-94 trachy-dacite

Rock Analysis			Correction Factors		Corrected Analysis	Normative Minerals	Weight % Norm	Volume % Norm
SiO ₂	66.67	%	Total=100%? Y/N	N	66.63	Quartz	15.49	15.83
TiO ₂	0.69	%	Fe ³⁺ /(Total Iron)	0.15	0.69	Plagioclase	48.06	49.11
Al ₂ O ₃	15.95	%			15.94	Orthoclase	26.00	27.50
Fe ₂ O ₃		%	Total Fe as FeO	3.77	0.63	Nepheline		
FeO	3.77	%	Desired Fe ₂ O ₃	0.63	3.20	Leucite		
MnO	0.08	%	Desired FeO	3.20	0.08	Kalsilite		
MgO	0.92	%	Weight corr. factor	0.999	0.92	Corundum		
CaO	2.88	%			2.88	Diopside	2.30	1.82
Na ₂ O	4.42	%			4.42	Hypersthene	5.49	4.07
K ₂ O	4.40	%	Zero values not shown		4.40	Wollastonite		
P ₂ O ₅	0.21	%			0.21	Olivine		
CO ₂		%				Larnite		
SO ₃		%				Acmite		
S		%				K ₂ SiO ₃		
F		%				Na ₂ SiO ₃		
Cl		%	Norm calculation checks: Norm seems OK			Rutile		
Sr	418	ppm			0.05	Ilmenite	1.31	0.75
Ba	1591	ppm			0.18	Magnetite	0.91	0.48
Ni	11	ppm	More of the norm below			Hematite		
Cr	10	ppm				Apatite	0.49	0.41
Zr	279	ppm			0.04	Zircon	0.06	0.04
Total	99.99				100.27	Perovskite		
						Chromite		
						Sphene		
						Pyrite		
						Halite		
						Fluorite		
						Anhydrite		
						Na ₂ SO ₄		
						Calcite		
						Na ₂ CO ₃		
						Total	100.11	100.01
Fe ³⁺ /(Total Fe) in rock							15.0	15.0
Mg/(Mg+Total Fe) in rock							30.3	30.3
Mg/(Mg+Fe ²⁺) in rock							33.9	33.9
Mg/(Mg+Fe ²⁺) in silicates							40.8	40.8
Ca/(Ca+Na) in rock							26.5	26.5
Ca/(Ca+Na) in plagioclase							21.2	21.2
Differentiation Index							89.6	92.4
Calculated density, g/cc							2.71	2.71
Calculated liquid density							2.45	2.45
Calculated viscosity, dry							6.9	6.9
Calculated viscosity, wet							5.7	5.7
Estimated liquidus temp.							912	912
Estimated H ₂ O content							2.64	2.64

Table A7.

CIPW normalization calculation RS-97A trachy-dacite

Rock Analysis			Correction Factors		Corrected Analysis		Normative Minerals	Weight % Norm	Volume % Norm
SiO ₂	65.72	%	Total=100%? Y/N	N	65.68		Quartz	14.51	14.92
TiO ₂	0.73	%	Fe ³⁺ /(Total Iron)	0.15	0.72		Plagioclase	47.67	48.94
Al ₂ O ₃	15.89	%			15.88		Orthoclase	24.94	26.54
Fe ₂ O ₃		%	Total Fe as FeO	3.98	0.66		Nepheline		
FeO	3.98	%	Desired Fe ₂ O ₃	0.66	3.38		Leucite		
MnO	0.07	%	Desired FeO	3.38	0.07		Kalsilite		
MgO	1.62	%	Weight corr. factor	0.999	1.62		Corundum		
CaO	3.30	%			3.30		Diopside	2.86	2.31
Na ₂ O	4.23	%			4.23		Hypersthene	7.21	5.52
K ₂ O	4.22	%	Zero values not shown		4.22		Wollastonite		
P ₂ O ₅	0.23	%			0.23		Olivine		
CO ₂		%					Larnite		
SO ₃		%					Acmite		
S		%					K ₂ SiO ₃		
F		%					Na ₂ SiO ₃		
Cl		%	Norm calculation checks: Norm seems OK				Rutile		
Sr	475	ppm			0.06		Ilmenite	1.37	0.78
Ba	1427	ppm			0.16		Magnetite	0.96	0.50
Ni	18	ppm	More of the norm below				Hematite		
Cr	27	ppm					Apatite	0.53	0.45
Zr	253	ppm			0.03		Zircon	0.04	0.03
Total	99.99				100.24		Perovskite		
							Chromite		
							Sphene		
							Pyrite		
							Halite		
							Fluorite		
							Anhydrite		
							Na ₂ SO ₄		
							Calcite		
							Na ₂ CO ₃		
							Total	100.09	99.99
							Fe ³⁺ /(Total Fe) in rock	14.9	14.9
							Mg/(Mg+Total Fe) in rock	42.1	42.1
							Mg/(Mg+Fe ²⁺) in rock	46.1	46.1
							Mg/(Mg+Fe ²⁺) in silicates	53.5	53.5
							Ca/(Ca+Na) in rock	30.1	30.1
							Ca/(Ca+Na) in plagioclase	23.8	23.8
							Differentiation Index	87.1	90.4
							Calculated density, g/cc	2.73	2.73
							Calculated liquid density	2.46	2.46
							Calculated viscosity, dry	6.5	6.5
							Calculated viscosity, wet	5.4	5.4
							Estimated liquidus temp.	929	929
							Estimated H ₂ O content	2.46	2.46

Table A8.

CIPW normalization calculation RS-97B basaltic
trachyandesite enclave

Rock Analysis			Correction Factors		Corrected Analysis		Normative Minerals		Weight %	Volume %
									Norm	Norm
SiO ₂	53.90	%	Total=100%? Y/N	N	53.85		Quartz			
TiO ₂	1.44	%	Fe ³⁺ /(Total Iron)	0.1	1.43		Plagioclase	57.36	62.26	
Al ₂ O ₃	17.03	%			17.01		Orthoclase	8.86	10.07	
Fe ₂ O ₃		%	Total Fe as FeO	8.03	0.89		Nepheline			
FeO	8.03	%	Desired Fe ₂ O ₃	0.89	7.22		Leucite			
MnO	0.16	%	Desired FeO	7.23	0.16		Kalsilite			
MgO	4.95	%	Weight corr. factor	0.999	4.95		Corundum			
CaO	8.61	%			8.60		Diopside	12.45	10.79	
Na ₂ O	3.87	%			3.87		Hypersthene	14.90	12.36	
K ₂ O	1.50	%	Zero values not shown		1.50		Wollastonite			
P ₂ O ₅	0.52	%			0.51		Olivine	1.28	1.01	
CO ₂		%					Larnite			
SO ₃		%					Acmite			
S		%					K ₂ SiO ₃			
F		%					Na ₂ SiO ₃			
Cl		%	Norm calculation checks: Norm seems OK				Rutile			
Sr	727	ppm			0.09		Ilmenite	2.72	1.66	
Ba	824	ppm			0.09		Magnetite	1.29	0.72	
Ni	79	ppm	More of the norm below		0.01		Hematite			
Cr	220	ppm			0.03		Apatite	1.18	1.07	
Zr	227	ppm			0.03		Zircon	0.04	0.03	
Total	100.00				100.24		Perovskite			
							Chromite	0.04	0.03	
							Sphene			
							Pyrite			
							Halite			
							Fluorite			
							Anhydrite			
							Na ₂ SO ₄			
							Calcite			
							Na ₂ CO ₃			
							Total	100.12	100.00	
							Fe ³⁺ /(Total Fe) in rock	10.0	10.0	
							Mg/(Mg+Total Fe) in rock	52.4	52.4	
							Mg/(Mg+Fe ²⁺) in rock	55.0	55.0	
							Mg/(Mg+Fe ²⁺) in silicates	60.8	60.8	
							Ca/(Ca+Na) in rock	55.1	55.1	
							Ca/(Ca+Na) in plagioclase	41.5	41.5	
							Differentiation Index	66.2	72.3	
							Calculated density, g/cc	2.91	2.91	
							Calculated liquid density	2.62	2.62	
							Calculated viscosity, dry	3.1	3.1	
							Calculated viscosity, wet	2.9	2.9	
							Estimated liquidus temp.	1145	1145	
							Estimated H ₂ O content	0.71	0.71	

Table A9.

CIPW normalization calculation RS-115 basaltic-trachyandesite lava

Rock Analysis			Correction Factors		Corrected Analysis		Normative Minerals			Weight %	Volume %
										Norm	Norm
SiO ₂	55.49	%	Total=100%? Y/N	N	55.44		Quartz		0.59	0.65	
TiO ₂	1.37	%	Fe ³⁺ /(Total Iron)	0.1	1.37		Plagioclase		47.12	51.66	
Al ₂ O ₃	14.58	%			14.57		Orthoclase		13.00	14.87	
Fe ₂ O ₃		%	Total Fe as FeO	8.49	0.94		Nepheline				
FeO	8.49	%	Desired Fe ₂ O ₃	0.94	7.63		Leucite				
MnO	0.14	%	Desired FeO	7.64	0.14		Kalsilite				
MgO	6.65	%	Weight corr. factor	0.999	6.64		Corundum				
CaO	7.23	%			7.22		Diopside	13.20	11.59		
Na ₂ O	3.49	%			3.49		Hypersthene	21.32	18.01		
K ₂ O	2.20	%	Zero values not shown		2.20		Wollastonite				
P ₂ O ₅	0.37	%			0.37		Olivine				
CO ₂		%					Larnite				
SO ₃		%					Acmite				
S		%					K ₂ SiO ₃				
F		%	Norm calculation checks:				Na ₂ SiO ₃				
Cl		%	Norm seems OK				Rutile				
Sr	553	ppm			0.07		Ilmenite	2.60	1.60		
Ba	820	ppm			0.09		Magnetite	1.36	0.77		
Ni	166	ppm	More of the norm below		0.02		Hematite				
Cr	297	ppm			0.04		Apatite	0.86	0.78		
Zr	194	ppm			0.03		Zircon	0.04	0.03		
Total	100.01				100.26		Perovskite				
							Chromite	0.06	0.03		
							Sphene				
							Pyrite				
							Halite				
							Fluorite				
							Anhydrite				
							Na ₂ SO ₄				
							Calcite				
							Na ₂ CO ₃				
							Total	100.15	99.99		
							Fe ³⁺ /(Total Fe) in rock	10.0	10.0		
							Mg/(Mg+Total Fe) in rock	58.3	58.3		
							Mg/(Mg+Fe ²⁺) in rock	60.8	60.8		
							Mg/(Mg+Fe ²⁺) in silicates	65.9	65.9		
							Ca/(Ca+Na) in rock	53.3	53.3		
							Ca/(Ca+Na) in plagioclase	36.0	36.0		
							Differentiation Index	60.7	67.2		
							Calculated density, g/cc	2.93	2.93		
							Calculated liquid density	2.61	2.61		
							Calculated viscosity, dry	3.2	3.2		
							Calculated viscosity, wet	3.0	3.0		
							Estimated liquidus temp.	1116	1116		
							Estimated H ₂ O content	0.88	0.88		

Table A10.

CIPW normalization calculation RS-116A trachy andesite
lava

Rock Analysis		Correction Factors		Corrected Analysis	Normative Minerals	Weight % Norm	Volume % Norm
SiO ₂	57.24 %	Total=100%? Y/N	N	57.19	Quartz	3.30	3.60
TiO ₂	1.28 %	Fe ³⁺ /(Total Iron)	0.1	1.28	Plagioclase	46.06	49.90
Al ₂ O ₃	14.66 %			14.65	Orthoclase	15.48	17.49
Fe ₂ O ₃	%	Total Fe as FeO	7.56	0.84	Nepheline		
FeO	7.56 %	Desired Fe ₂ O ₃	0.84	6.80	Leucite		
MnO	0.15 %	Desired FeO	6.80	0.15	Kalsilite		
MgO	5.77 %	Weight corr. factor	0.999	5.77	Corundum		
CaO	6.85 %			6.84	Diopside	12.38	10.73
Na ₂ O	3.48 %			3.48	Hypersthene	18.28	15.24
K ₂ O	2.62 %	Zero values not shown		2.62	Wollastonite		
P ₂ O ₅	0.40 %			0.40	Olivine		
CO ₂	%				Larnite		
SO ₃	%				Acmite		
S	%				K ₂ SiO ₃		
F	%				Na ₂ SiO ₃		
Cl	%	Norm calculation checks: Norm seems OK			Rutile		
Sr	743 ppm			0.09	Ilmenite	2.43	1.48
Ba	1001 ppm			0.11	Magnetite	1.22	0.68
Ni	121 ppm	More of the norm below		0.02	Hematite		
Cr	230 ppm			0.03	Apatite	0.93	0.84
Zr	211 ppm			0.03	Zircon	0.04	0.03
Total	100.01			100.30	Perovskite		
					Chromite	0.04	0.03
					Sphene		
					Pyrite		
					Halite		
					Fluorite		
					Anhydrite		
					Na ₂ SO ₄		
					Calcite		
					Na ₂ CO ₃		
					Total	100.16	100.02
				Fe ³⁺ /(Total Fe) in rock		10.0	10.0
				Mg/(Mg+Total Fe) in rock		57.6	57.6
				Mg/(Mg+Fe ²⁺) in rock		60.2	60.2
				Mg/(Mg+Fe ²⁺) in silicates		65.5	65.5
				Ca/(Ca+Na) in rock		52.1	52.1
				Ca/(Ca+Na) in plagioclase		34.7	34.7
				Differentiation Index		64.8	71.0
				Calculated density, g/cc		2.90	2.90
				Calculated liquid density		2.59	2.59
				Calculated viscosity, dry		3.7	3.7
				Calculated viscosity, wet		3.4	3.4
				Estimated liquidus temp.		1085	1085
				Estimated H ₂ O content		1.09	1.09

Table A11.