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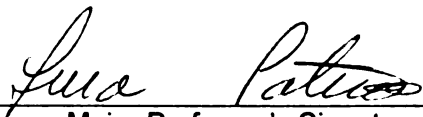
**Petrogenesis of Distinct Silicic Magma Types from the Lower
Pleistocene Guachipelin Caldera, NW Costa Rica: Extensive
Magma Mixing and Protracted Subvolcanic Residence**

presented by

Chad Daniel Deering

has been accepted towards fulfillment
of the requirements for the

 M.S degree in Geological Sciences


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**Petrogenesis of Distinct Silicic Magma Types from the Lower Pleistocene
Guachipelin Caldera, NW Costa Rica: Extensive Magma Mixing and
Protracted Subvolcanic Residence**

By

Chad Daniel Deering

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ABSTRACT

Petrogenesis of Distinct Silicic Magma Types from the Lower Pleistocene Guachipelin Caldera, NW Costa Rica: Extensive Magma Mixing and Protracted Subvolcanic Residence

By

Chad Daniel Deering

Lower Pleistocene ash-flow deposits in NW Costa Rica represent sequential eruptions of high-silica (69-79% SiO₂) magmas from the Guachipelin Caldera. Silicic magmatism such as this is uncommon in areas void of continental crust. However, the chemical variations within this suite of ash-flows are consistent with results from several different studies (i.e. Tamura and Tatsumi, 2002; Sisson et al., 2005) suggesting that partial melting of crystalline, calc-alkaline andesite or high-K basalts could produce these silicic magmas. Chemical heterogeneities were discovered through evaluation of incompatible trace element ratios. Seven units were defined using the Nb/Ta ratio, which have a significantly wide range, from 3.8 to 29.4.

Polytopic vector analysis (PVA), a multivariate statistical method, was used to characterize the relationship among individual units. The program defined four different end member or initial melts, which contributed to the generation of the seven units associated with the Guachipelin Caldera. This requires extended periods when the initial melts reside in subvolcanic zones prior to the inception of a particular eruptive event. Considering the temporal (<0.5Ma) and spatial (single caldera) constraints of this sequence of eruptions, significant chemical variations of the magmas have occurred, which require processes to operate on relatively short time scales.

ACKNOWLEDGEMENTS

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Page 171: Figure 32. The general trends of magma evolution within individual units are indicated as Nb and Ta would be partitioned proportional to one another. Shifts in Ta concentration are influenced by mixing with end-member magmas with higher or lower initial Ta concentrations. Black dots represent the compositions of the four initial melts generated that would mix to produce the hybrid magmas (Salitral East: purple diamonds, Pijije: red circles, and Virginia: black crosses). Individual symbols represent pumice fragments as follows: Green Layer: purple dotted area, Santa Fe: black diagonal area, Buena Vista: green dashed vertical lines, and Liberia: blue dashed vertical lines.

Page 172: Figure 33. Dehydration melting of three distinct crystalline calc-alkaline andesites produce the IM 2, IM 3, and IM 4 magmas. Partial melting of an anhydrous calc-alkaline source generates the IM 1 magma. Nb/Ta ratios for each initial melt (IM) are provided in the lower right corner of each box.

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I. INTRODUCTION

A long-term problem is the origin of silicic magmas in geologic settings absent of old, evolved continental crust (for a review see: Vogel et al., 2004; Tamura and Tatsumi, 2002). If old, evolved continental crust were present, simply assimilating and/or melting that crust could produce silicic magmas. The southern part of the Central American arc is void of continental crust, but silicic volcanic products are common. Some have suggested that the generation of these magmas actually represents the development of new continental crust (Vogel et al., 2004).

Several models have been presented to account for the presence of high silica volcanic products in arc settings. Tamura and Tatsumi (2002) have shown that slab-derived fluids induce the formation of mantle melts that would eventually pond at the base of the crust. Subsequent melting at the base of the crust could produce intermediate hydrous magmas that later stall within the crust, reaching neutral buoyancy. Described as calc-alkaline andesites, partial melting of these previously emplaced crystalline magmas could produce silicic melts. Sisson et al. (2005) have shown through high pressure-temperature experiments that silicic magma could be produced by partial melting or extreme fractional crystallization of K-rich basalts. In another study of arc volcanism, Hildreth and Fierstein (2000) conclude that either partial remelting of already silicic crystalline rock with expulsion of the interstitial liquid or extensive settling of phenocrysts dominated by low-silica phases was required to produce the high-silica rhyolite of the 1912 Katmai eruption.

The silicic pyroclastic ash-flow and fall deposits associated with the Guachipelin Caldera, Costa Rica (Figure 1), also display distinct chemical heterogeneities. Different

University of Costa Rica
Central American School of Geology
Geomorphologic Map

Topographic
Curubandé 3148 III IGN
Scale 1:50,000

Volcanic facies

	Atravesado lavas		Aguacatales subfacies
	Cañas Dulces dacitic domes		Von Seebach subfacies
	Paleo-Rincón de la Vieja		Pyroclastic flow facies
	Pacayaes subfacies		San Jorge subfacies
	Coyol subfacies		Curubandé subfacies
	Rincón de la Vieja facies		Alcántaro
	Colonia Blanca subfacies		Fluvial-lacustrine facies
	Santa Maria subfacies		Guachipelin debris flow facies

Symbols

	Interpreted contact		Source
	Inferred contact		Avalanche scarp
	Inferred alignment		Fluid movement
	Observed alignment		Avalanche movement
	Crater		Caldera border
	Inferred strike/dip		Escarpment slip
	Dome		Rivers
	Cone		Fan
			Shear zone

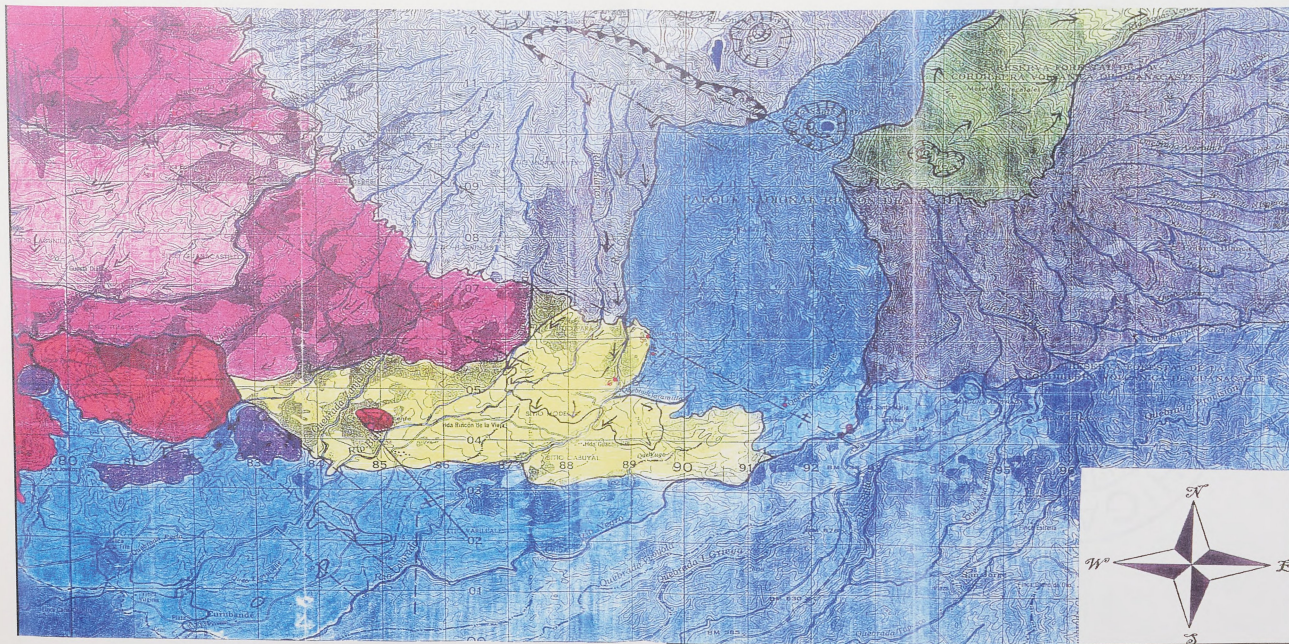


Figure 1. Geologic map taken from Acuna et al. (2000). Deposits in yellow represent pyroclastic flows related to the Guachipelin Caldera.

processes have been proposed to account for these chemical heterogeneities in other silicic deposits: 1) large-scale differentiation of an originally homogeneous magma body (Mittlefehldt and Miller, 1983; Baker and McBirney, 1985; McBirney et al., 1986; de Silva and Wolff, 1995); 2) discrete magma batches that represent partial melting or melt extraction from chemically discrete sources (Marsh, 1984; Bergantz, 1989; Sawyer, 1994; Eichelberger and Izbekov, 2000; Eichelberger et al., 2000); 3) magma chamber recharge (Eichelberger et al., 2000); and 4) further modification by magma mixing/ mingling, assimilation (Eichelberger et al., 2000).

The objectives of this study are to define the stratigraphic sequence of pyroclastic flows associated with the Guachipelin Caldera based on variations in field relationships, petrography, mineralogy, and geochemistry. Based on these data develop a model that accounts for the origin and evolution of the magma. Along with petrographic analyses, whole-rock geochemical and mineral chemical analyses, and oxygen isotope analyses, polytopic vector analysis (PVA) is used to analyze the whole-rock chemical data.

II. GEOLOGIC SETTING

The tectonic evolution of the Costa Rican region is marked by the emplacement of several different magmatic components, which are collectively known as the Caribbean Large Igneous Province (CLIP). This structure consists of compositionally distinct constituents: mid-ocean ridge basalts (MORB), ocean island basalts (OIB), arc basalts, and flood basalts with a total thickness of approximately 40 km (Salleres and Danobeitia, 2001). Beginning in the Jurassic and Early Cretaceous (150 Ma), the first component, normal oceanic basalts (N-MORB), were generated at a spreading ridge between North and South America (Meschede and Frisch, 1998). This complex was later intruded, 90 Ma, by a large volume of basalt associated with the Galapagos hot spot which thickened the pre-existing oceanic lithosphere to ~15-20 km (Pindell and Barrett, 1990). Following the emplacement of the Caribbean flood basalts in the Late Cretaceous, subduction of the Farallon plate beneath the Caribbean plate was initiated, caused by the collision and suture of the Caribbean plateau and Lesser Antilles island arc (Burke, 1988). This convergence resulted in the production of arc related magmas.

Emplacement or underplating of arc related mafic melts followed by crystallization of basaltic magmas is suggested to account for the heterogeneities in the upper mantle and lower crust, indicated by seismic refraction studies in the region (Salleres and Danobeitia, 2001). Seismic heterogeneities found throughout the upper crustal regime are consistent with the presence of crystallized magmas, which have been emplaced at various depths throughout the province (Figure 2a). Price et al. (2005) call this process preconditioning of the early crust by andesitic magmatism generated as a result of interaction between arc magmas and the lower crust.

a)

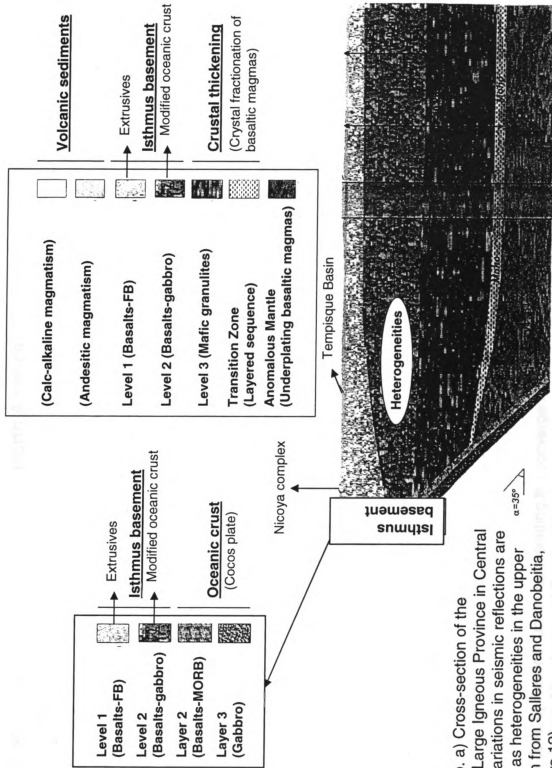


Figure 2a,b. a) Cross-section of the Caribbean Large Igneous Province in Central America. Variations in seismic reflections are interpreted as heterogeneities in the upper crust (taken from Salleres and Danobeitia, 2001; Figure 12).

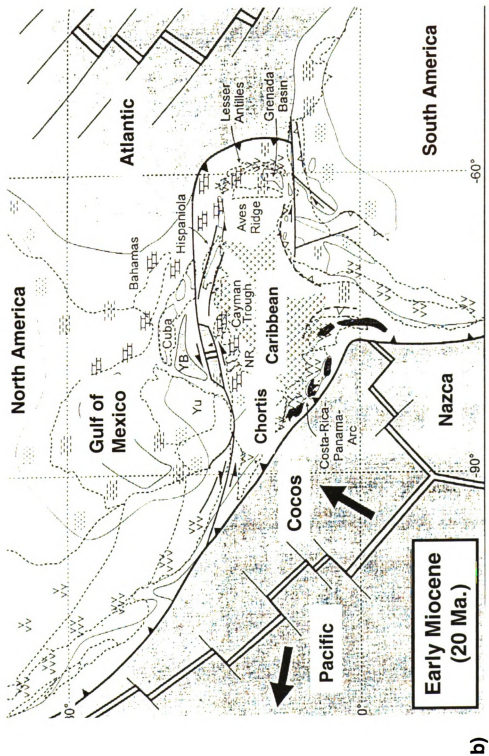


Figure 2 cont. b) Reconstruction representing the convergence of the Cocos plate oblique to the Caribbean plate (taken from Meschede and Frisch, 1998; Figure 13).

The modern tectonic configuration began during the Late Oligocene to Early Miocene, when the Farallon plate separates into the Cocos and Nazca plates (Figure 2b). As the Cocos plate to the north moves in a NNE direction converging with the Caribbean plate, subduction is occurring $\sim 20^\circ$ oblique to the margin. The down dip angle increases with depth from 10° at 15 km, to 25° at 15-38 km, and to 43° beyond 38 km in depth (Norabuena et al., 2004).

III. GUACHIPELIN IGNIMBRITE STRATIGRAPHY

Ignimbrites associated with the Guachipelin Caldera are a direct result of the modern subduction zone magmatism and are between 2.06 and 1.31 Ma (Vogel et al, 2004). These deposits are crystal-poor, poorly welded tuffs extending 3500–4000 km² from the caldera margin, with a total eruptive volume of 25 km³ (Chiesa, 1991). A geologic map of the region is provided in Figure 1 (Acuna et al., 2000). The caldera is filled with several younger deposits including some originating from an adjacent volcano, the Rincon de la Vieja (Kempter et al., 1996).

The sequence of ignimbrite deposits related to this caldera are known as the Rio Liberia Formation, which is further defined in this study using a combination of techniques including field relationships, previously acquired Ar-Ar dates, petrography, and bulk geochemical analyses. Initially, discriminations among ash-flow units were determined through field observations of physical characteristics such as mineral content. Therefore, only three units were recognized based on mineral types and abundance (i.e. biotite, amphibole, plagioclase). However, trace element ratios (Nb/Ta) reveal the presence of distinct pyroclastic units. Geochemically distinct units within the otherwise indistinguishable pyroclastic deposits provide the basis for a more comprehensive stratigraphic sequence. Identifying the stratigraphic relationship of the chemically variable ash-flow units is a prerequisite in determining systematic changes occurred. A detailed description of the chemically distinct units is covered later in the discussion.

An example of an individual outcrop stratigraphic column that is based on both physical and geochemical variables used to define the units is illustrated in Figure 3.

INDIVIDUAL OUTCROP

Location: North 10.52°

West -85.17°

Outcrop: Rd. to Santa Fe

Samples	Nb/Ta (avg.)	
040706-3(C-G)	11.15	(BIOTITE RICH) PIJJE
040706-3A,B	16.56	REWORKED
040706-2A,B	15.81	0.5-1m (BIOTITE) Green Layer/SANTA FE -high
040706-1J,K/M,N,L	24.69/15.95	5m (NO BIOTITE) SANTA FE -low
040706-1(A-i)	14.96	GREEN LAYER
		PALEOSOL
		0.1-0.25m
		0.5m
		3m
		0.2m
		6m

Figure 3. Stratigraphic column of an individual outcrop illustrating the typical sequence found among the Green Layer, Santa Fe, reworked, and Pijje.

Separate stratigraphic columns at different outcrops illustrate the variations in the units caused by differences in the lateral extent of ash-flow transport from the caldera margin. The incompatible element ratio of Niobium (Nb) and Tantalum (Ta) are used to define the units included in the stratigraphic columns. Details regarding the determination of the seven units are provided in the discussion.

The base of the Guachipelin volcanic suite is marked by a paleosol followed by a distinct pale Green Layer (Figures 3-4). The Green Layer ash-flow unit varies in thickness from 0.1 to 5.0 meters and typically consist of lapilli-sized pumice, with amphibole and plagioclase phenocrysts.

The next youngest unit is the Santa Fe-low ($\text{SiO}_2 < 72$ wt.%; Figure 4). This unit ranges in thickness from 6.0 to 15.0 meters, with tan-gray pumice distributions normally graded or in swarms, ranging in size from 2-30cm. Glomeroporphyritic mineral clots of plagioclase, amphibole, and Fe-Ti oxides and light pumice banding are also indicative of this unit.

The Salitral East is above the Santa Fe-low and this sequence is observed in only one outcrop (Figure 4). This unit is similar to the Santa Fe-low in deposit thickness (~6.0 m), pumice distribution (normal grading), color (tan-gray), and range in size from 4-20 cm. Pumice mineralogy is dominated by plagioclase and amphibole with small quantities of biotite and quartz.

The next unit in the sequence, the Santa Fe-high ($\text{SiO}_2 > 72$ wt.%; Figure 4), is also found in contact with the Santa Fe-low (Figure 3). This ash-flow sheet ranges in thickness from 0.5 to 1.0 meters with randomly distributed tan-gray pumice ranging in

contact
inferred contact
reworked

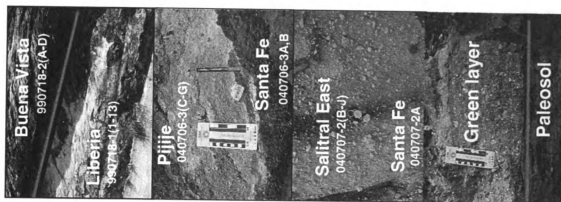
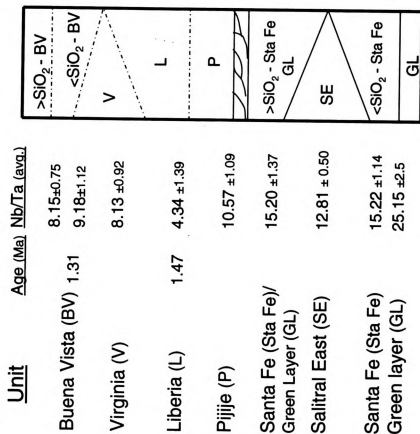


Figure 4. Composite stratigraphic column constructed based on interpretation of individual outcrop stratigraphic sequences. Nb/Ta ratios are averages for all of the pumice samples within a unit. Ar-Ar dates from Vogel et al. (2004).

size from 6 to 12 cm. Pumice mineralogy is marked by plagioclase, biotite, and quartz with small quantities of amphibole. Some Green Layer unit pumice are also found mixed within the Santa Fe-high ash-flow sheet.

Contact between the Santa Fe-high and the next youngest unit, the Pijije, is reworked, a feature consistently found where the Santa Fe-high is in contact with the Pijije (Figures 3-4). In addition to the coexistence of Pijije and Santa Fe-high pumice across this reworking contact, Green Layer unit pumice often occurs below it. The Pijije ash-flow unit is white or pink, ranging in thickness from 3 to 40 meters. Lithics are typically found in these deposits. Pumice fragments are 2 to 15 cm with mineralogy consisting primarily of plagioclase, biotite, and quartz with trace amounts of amphibole.

Pijije is followed by the Liberia (Figure 4), which is located in the sequence using inferred contacts with the Buena Vista (above) and Ar-Ar age dating. Deposit thickness and pumice size data are not available. Primary mineralogy consists of plagioclase, biotite, quartz, and small quantities of amphibole. Pumice fragments from this unit were dated at 1.47 Ma (Vogel et al., 2004).

Similar to the Liberia, the Virginia lacks any stratigraphic control, deposit thickness, or pumice size data. Only one outcrop is used to indicate the possible sequence of this unit above the Liberia unit (Figure 4), which places it below the Buena Vista. Pumice contain plagioclase and amphibole.

A distinct physical contact exists between the Liberia and Buena Vista (Figure 4), the youngest unit in the sequence (1.31 Ma) (Vogel et al., 2004). There is no deposit thickness or pumice size data. Like the Santa Fe unit, the Buena Vista unit can be divided

into two groups based on SiO₂ content (Buena Vista-low, SiO₂ <72 wt.%, and Buena Vista-high, SiO₂ >72 wt.%). These pumice samples were collected without stratigraphic control and are therefore assumed to be randomly distributed within the ash flow. Primary mineralogy consists of plagioclase and amphibole with small amounts of biotite and quartz found only in the high SiO₂ group.

The composite stratigraphic column in Figure 4 incorporates the interpretation of all the individual outcrops illustrating a possible eruptive sequence. Dating of the Monteverde Formation, below the Guachipelin sequence, at 2.06 Ma by previous workers (Alvarado et al., 1993; Gillot et al., 1994) constrains the complete eruptive sequence to less than 0.75Ma.

IV. METHODS

1. Pumice sample collection

Images in this thesis are presented in color. The collection of over 380 pumice fragments from the region S-SE of the Guachipelin Caldera by students and faculty from Michigan State University and the Universidad de Costa Rica began in July of 1999 and continued through the field season in July 2004. The locations selected for pumice sampling were chosen to encompass the region that is suggested to represent the pyroclastic deposits of the Guachipelin Caldera (Kempter et al., 1996; Acuna et al., 2000) (Figure 5). Samples were taken from a combination of road cuts, active quarries, and natural outcrop exposures near the network of roads extending away from the Caldera rim.

Samples from July 1999 to October 2003 were taken from outcrops chosen to represent the different eruptive products, but were collected without stratigraphic control within field identified units. Breaks in depositional units were determined based on the physical characteristics of the deposits as a whole and the individual phenocrysts in the pumice fragments within them. These characteristics included pumice color, distribution and frequency; mineralogy; and soil horizons. Subsequently, bulk geochemical data from these pumice samples revealed the presence of several distinct units within field identified eruptive ash-flow deposits.

During the final field season in July of 2004 a different approach to sample collection was undertaken. Pumice fragments were obtained in stratigraphic order from individual units, attempting to constrain the geochemical boundaries that were apparent within some of the field identified eruptive deposits.

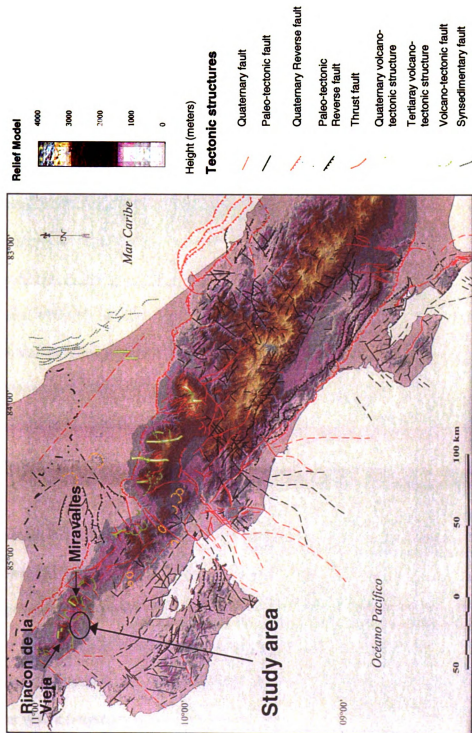


Figure 5. Field study area that lies between active arc volcanoes: Rincon de la Vieja to the Northwest and Miravalles to the East. The pumice samples were collected from road cuts and quarries along the South and Southeast Caldera margin. Map taken from Denyer et al. (2003).

2. Sample preparation/ analyses

2.1 Bulk geochemical analyses

Over 320 samples were prepared and analyzed for bulk geochemical analyses of major and trace elements. Hand samples selected for analyses were chosen based on analyzing the complete mesoscopic variation and to eliminate weathered samples. X-ray fluorescence (XRF) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) analyses at Michigan State University use fused glass disks. Samples were first trimmed of all weathered parts then rinsed in a sonic bath for ~10 min. After drying overnight, the fragments were pulverized in a chipmunk crusher and then finely powdered to $<5\mu\text{m}$ using a ceramic flat plate grinder. Three grams of this powder were thoroughly mixed with 9.0g of lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$) and 0.5g of ammonium nitrate (NH_4NO_3) as an oxidizer, all within $\pm 0.00005\text{g}$, in a platinum crucible. This mixture was then melted at $\sim 1000^\circ\text{C}$ in an oxidizing flame for $\sim 30\text{min.}$, while being stirred on an orbital mixing stage. The melt was poured into platinum molds, which are cooled on a hot plate at 400°C for approximately 5 minutes, before removing for final cooling over a 20 minute period. The fused discs were then analyzed using a Rigaku S/Max X-ray fluorescent spectrograph. XRF major element analyses were reduced by the fundamental parameter data reduction method (Criss, 1980) using XRFWIN software (Omni Instruments), while XRF trace element data were calculated using standard linear regression techniques.

For LA-ICP-MS trace element analyses, a Cetac LSX200⁺ laser ablation system was coupled with a Micromass Platform ICP-MS. The Cetac[®] LSX-200+ is a Nd:YAG laser with a frequency quadrupled to an UV wavelength of 266 nm. The analyses were

done using continuous ablation (line scan) for three minutes. Strontium, determined by XRF, was used as an internal standard. Trace element data reduction was done using MassLynx software. Prior to any calculations, the background signal was subtracted from the standards and samples. Element concentrations in the samples were calculated based on a linear regression method using BHVO, W-2, JB-1, JB-2, JB-3, JA-2, JA-3, BIR, QLO-1, AND RGM-1 standards.

2.2 Individual phase chemistry

Eighteen samples were selected for electron microprobe (EPMA) analyses at the University of Michigan. These samples represent both the bulk geochemical and physical variations observed in the deposits. Microprobe analyses were performed using a Camera SX 100 EPMA equipped with five wavelength spectrometers using an accelerating potential of 15 kV, a 6 μm beam spot size, counting time of 3 min/ mineral, and a 10 nA beam current. The following phases were analyzed for major elements: plagioclase, amphibole, biotite, Fe-Ti oxides, and glass.

Trace elements of individual mineral phases and glass analyzed by EPMA were determined using Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS). The location of each point analyzed was recorded for consistency between (EPMA) and (LA-ICP-MS) analyses. Laser ablation parameters used included a spot size of 25 μm for plagioclase and 50 μm for amphiboles and glass, and frequency of 20 Hz. The ablation mode was depth profile, where the sample stage was raised at a rate of 1 $\mu\text{m/s}$. The detector was activated before ablation to capture the transient signal. After ~0.3 min of data acquisition, ablation was initiated and continued for 5 sec. The first 0.3

min of data acquisition was used to measure the background. Once the ablated material reached the detector, the signal for the different elements was clearly observed in well-developed peaks. Results were quantified using the height of the peak above background for each element. The concentrations were calculated following Norman et al. (1996), with NIST 612 glass as the external standard and calcium determined by microprobe analysis as the internal standard.

3. Modeling: Polytopic Vector Analysis (PVA)

Polytopic Vector Analysis (PVA) is a multivariate statistical method of analyzing populations of samples that are related by mixing. There are three parameters needed to define a mixing system: 1) the number of end members, 2) the composition of each end member, and 3) the relative proportion of each end member in each sample. PVA is used to estimate all three parameters from the bulk geochemical analyses of the pumice samples (for details see appendix A).

V. RESULTS

1. Geochemistry – Bulk pumice

1.1 Major elements

Major and trace element data for pumice fragments are provided in Table 1.

Samples totaling less than 96% are excluded from the discussion. Major elements have been normalized to 100% in the figures.

The Guachipelin pumice fragments range in composition from dacitic to rhyolitic (66-76 wt.% SiO₂) (Figure 6). Variation diagrams show the chemical array for major elements as silica increases (Figure 7). The pumice samples can be divided into two groups based on SiO₂ content. First, a low silica group ranging in composition from 66 to 72 wt.% includes samples from the Green Layer, Santa Fe-low, Buena Vista-low, and Virginia units. The second group consists of high silica samples, 72 to 76 wt.% and includes Santa Fe-high, Salitral East, Pijije, Liberia, and Buena Vista-high. There is a slight overlap with a few samples from the Virginia, Pijije, Salitral East units that plot outside their respective silica group. Magnesium oxide, Fe₂O₃, CaO, Al₂O₃ and TiO₂ decrease and K₂O increases with increasing SiO₂ (Figure 7). In addition, there are three parallel Al₂O₃ trends. One trend includes samples from the Green Layer, Santa Fe-low, Virginia, and Buena Vista-low. An intermediate trend includes the Salitral East and Buena Vista-high, while another trend includes the Santa Fe-high, Pijije, and Liberia units.

Table 1 Pumice sample bulk geochemical data.(Green Layer)

Major element oxides (wt.%), trace elements (ppm).

Sample	040707-6C	040708-3B	040708-5A	040708-5B	040707-3A
<i>Location</i>					
Longitude	85.33°	85.38°	85.38°	85.38°	85.24°
Latitude	10.52°	10.69°	10.70°	10.70°	10.57°
<i>XRF analyses</i>					
SiO ₂	69.78	67.34	70.05	68.06	68.50
TiO ₂	0.49	0.53	0.48	0.49	0.51
Al ₂ O ₃	16.32	18.73	15.96	17.27	17.13
Fe ₂ O ₃	3.96	4.33	3.64	3.89	4.20
MnO	0.14	0.17	0.08	0.08	0.16
MgO	0.54	0.53	0.53	0.66	0.48
CaO	2.70	2.53	2.56	3.23	2.80
Na ₂ O	2.10	2.40	2.61	2.70	2.49
K ₂ O	3.95	3.41	4.05	3.59	3.70
P ₂ O ₅	0.03	0.03	0.04	0.03	0.03
Total	96.02	95.91	96.18	96.84	96.64
Rb	81	69	83	69	62
Sr	383	359	373	454	380
Zr	198	202	209	208	192

Laser ablation ICP-MS analyses

Y	34.21	30.16	22.22	16.93	24.79
Nb	11.69	12.65	12.30	12.40	9.52
Ba	1890	1921	1819	1696	1598
La	48.13	41.72	33.17	28.62	27.13
Ce	82.36	94.29	62.29	58.04	65.90
Pr	14.12	11.84	7.46	5.94	6.61
Nd	54.26	44.48	25.65	20.39	24.30
Sm	8.49	7.41	3.97	2.49	3.78
Eu	1.59	1.50	1.08	0.86	0.98
Tb	0.89	0.80	0.54	0.33	0.50
Dy	5.09	4.31	2.95	2.03	3.02
Ho	0.84	0.74	0.55	0.31	0.53
Er	1.84	1.74	1.38	0.56	1.27
Yb	1.99	1.96	1.93	1.29	1.62
Lu	0.24	0.27	0.28	0.15	0.22
Hf	2.97	3.55	4.33	3.43	3.34
Ta	0.43	0.54	0.60	0.49	0.36
Th	7.00	8.25	8.00	7.39	5.69
U	4.39	5.14	3.63	3.33	2.89

Table 1 cont. (Green Layer)

Sample	040707-3B	040707-3C	040706-1J	040706-1K
Location				
Longitude	85.24°	85.24°	85.17°	85.17°
Latitude	10.57°	10.57°	10.52°	10.52°
XRF analyses				
SiO ₂	70.79	67.42	69.29	69.18
TiO ₂	0.39	0.57	0.45	0.48
Al ₂ O ₃	16.30	17.33	16.37	16.20
Fe ₂ O ₃	3.19	4.33	3.29	3.52
MnO	0.06	0.11	0.08	0.09
MgO	0.51	0.99	0.67	0.76
CaO	2.28	3.23	3.10	3.03
Na ₂ O	2.81	2.98	3.03	3.01
K ₂ O	3.66	3.02	3.68	3.69
P ₂ O ₅	0.02	0.02	0.03	0.03
Total	96.58	96.77	97.17	97.19
Rb	77	51	73	74
Sr	316	382	440	430
Zr	137	221	196	193
Laser ablation ICP-MS analyses				
Y		24.99	21.19	21.70
Nb	9.15	9.69	11.51	11.94
Ba	1436	1432	1687	1728
La	22.40	26.82	32.13	33.82
Ce	45.32	55.89	58.58	62.25
Pr	5.33	6.32	7.24	7.93
Nd	19.24	22.69	25.65	27.75
Sm	2.98	3.29	3.72	3.84
Eu	0.72	0.91	1.10	1.11
Tb	0.44	0.44	0.46	0.47
Dy		2.86	2.64	2.73
Ho		0.52	0.48	0.49
Er		1.14	1.05	1.03
Yb		1.65	1.57	1.51
Lu		0.21	0.19	0.20
Hf	3.63	3.74	3.15	3.05
Ta	0.37	0.33	0.48	0.47
Th	5.56	5.66	6.55	6.62
U	2.77	2.74	3.24	3.71

Table 1 cont. (Santa Fe)

Sample	040707-6B	040706-3A	040706-3B	040708-6A	040708-2E
Location					
Longitude	85.33°	85.17°	85.17°	85.38°	85.39°
Latitude	10.52°	10.52°	10.52°	10.70°	10.69°
<i>XRF analyses</i>					
SiO ₂	70.32	74.08	70.19	73.82	73.67
TiO ₂	0.49	0.27	0.48	0.26	0.20
Al ₂ O ₃	15.71	14.46	16.01	15.03	15.73
Fe ₂ O ₃	4.00	2.23	3.48	1.82	1.38
MnO	0.18	0.05	0.08	0.07	0.06
MgO	0.65	0.34	0.67	0.39	0.19
CaO	2.53	1.87	2.60	1.65	1.82
Na ₂ O	2.04	2.59	2.61	3.00	3.12
K ₂ O	4.06	4.09	3.84	3.93	3.80
P ₂ O ₅	0.03	0.02	0.03	0.02	0.01
Total	96.09	97.51	96.82	97.60	97.63
Rb	83	95	64	88	82
Sr	358	273	344	240	277
Zr	215	133	220	133	119
<i>Laser ablation ICP-MS analyses</i>					
Y	26.90	12.97	15.46	14.82	13.17
Nb	12.55	8.70	10.36	9.39	8.79
Ba	2002	1759	1806	1766	1811
La	39.63	24.97	26.03	24.75	26.67
Ce	80.15	45.16	47.68	46.12	49.86
Pr	10.62	4.94	5.20	4.76	4.86
Nd	40.60	16.51	17.44	15.56	15.23
Sm	7.93	2.35	2.36	2.23	1.60
Eu	1.77	0.71	0.75	0.58	0.48
Tb	0.96	0.29	0.33	0.31	0.20
Dy	5.07	1.55	1.89	1.71	1.21
Ho	0.97	0.28	0.35	0.30	0.18
Er	2.89	0.71	0.79	0.75	0.33
Yb	3.06	1.38	1.39	1.56	1.07
Lu	0.49	0.19	0.19	0.24	0.13
Hf	5.48	2.64	2.98	2.80	2.23
Ta	0.83	0.57	0.58	0.59	0.58
Th	7.87	7.67	8.15	9.18	9.48
U	4.47	3.83	3.95	4.46	4.26

Table 1 cont. (Santa Fe)

Sample	040708-2J	040706-2B	040707-2A	040706-10A	040706-10B
<i>Location</i>					
Longitude	85.39°	85.17°	85.24°	85.18°	85.18°
Latitude	10.69°	10.52°	10.57°	10.62°	10.62°
<i>XRF analyses</i>					
SiO ₂	73.52	72.89	70.69	70.25	70.17
TiO ₂	0.24	0.32	0.34	0.46	0.47
Al ₂ O ₃	15.06	14.83	17.64	15.38	15.47
Fe ₂ O ₃	1.89	2.50	2.77	3.27	3.39
MnO	0.07	0.07	0.09	0.09	0.09
MgO	0.33	0.37	0.38	0.78	0.76
CaO	1.81	2.26	2.23	2.90	2.89
Na ₂ O	3.14	2.63	2.31	3.10	3.02
K ₂ O	3.92	4.11	3.52	3.70	3.70
P ₂ O ₅	0.01	0.02	0.02	0.05	0.04
Total	98.11	97.46	96.34	96.99	97.11
Rb	83	79	65	72	72
Sr	268	346	336	399	401
Zr	131	149	179	206	212
<i>Laser ablation ICP-MS analyses</i>					
Y	14.75	20.82	17.74	21.75	24.46
Nb	8.77	14.39	13.24	13.93	13.91
Ba	1803	2647	1707	1735	1742
La	27.66	39.08	33.28	30.40	29.91
Ce	46.31	73.00	60.64	59.65	58.35
Pr	5.23	7.52	7.19	7.02	6.90
Nd	16.70	24.03	24.09	24.82	25.46
Sm	2.21	3.02	3.70	4.87	5.17
Eu	0.57	0.85	1.03	1.32	1.44
Tb	0.30	0.40	0.43	0.72	0.80
Dy	1.63	2.25	2.38	3.59	3.97
Ho	0.27	0.38	0.43	0.72	0.84
Er	0.61	0.82	1.16	2.31	2.69
Yb	1.33	1.55	1.77	2.63	3.01
Lu	0.18	0.22	0.25	0.36	0.44
Hf	2.49	3.81	3.51	4.35	4.33
Ta	0.53	0.91	0.79	0.88	0.92
Th	8.62	12.86	9.12	7.22	7.02
U	3.97	6.53	3.85	3.75	3.85

Table 1 cont. (Santa Fe)

Sample	040706-10C	040706-10D	040706-10E	040706-10F	040706-10G
Location					
Longitude	85.18°	85.18°	85.18°	85.18°	85.18°
Latitude	10.62°	10.62°	10.62°	10.62°	10.62°
XRF analyses					
SiO ₂	70.18	70.33	70.18	70.10	69.61
TiO ₂	0.48	0.49	0.46	0.49	0.49
Al ₂ O ₃	15.36	15.19	15.60	15.36	15.52
Fe ₂ O ₃	3.33	3.47	3.11	3.45	3.63
MnO	0.09	0.09	0.08	0.09	0.09
MgO	0.85	0.85	0.80	0.87	0.90
CaO	2.93	2.80	2.93	2.85	3.04
Na ₂ O	3.20	2.96	2.96	3.11	3.18
K ₂ O	3.54	3.76	3.84	3.65	3.48
P ₂ O ₅	0.04	0.04	0.04	0.04	0.05
Total	96.82	97.28	96.39	96.56	97.31
Rb	69	73	74	68	69
Sr	403	387	408	395	425
Zr	210	220	211	221	202
Laser ablation ICP-MS analyses					
Y	24.38	23.57	22.68	21.45	27.67
Nb	12.17	14.01	13.42	14.42	11.56
Ba	1651	1723	1671	1734	1635
La	31.72	30.22	28.72	29.39	33.62
Ce	54.85	58.36	55.08	59.25	54.40
Pr	6.53	6.77	6.53	6.64	6.76
Nd	23.94	23.76	22.93	23.19	25.12
Sm	4.63	4.61	4.57	4.62	4.76
Eu	1.25	1.35	1.31	1.34	1.32
Tb	0.73	0.74	0.69	0.71	0.81
Dy	3.83	3.68	3.67	3.59	4.29
Ho	0.89	0.77	0.78	0.79	1.02
Er	2.74	2.40	2.45	2.57	3.23
Yb	2.90	2.71	2.69	2.73	3.27
Lu	0.44	0.43	0.41	0.43	0.55
Hf	5.44	4.49	4.45	4.74	5.70
Ta	0.89	0.93	0.86	0.95	0.85
Th	8.58	7.20	7.18	7.15	8.88
U	3.06	3.79	3.59	3.75	2.98

Table 1 cont. (Santa Fe)

Sample	040706-10i	040706-10J	040706-10K	040706-10L	040706-4A
Location					
Longitude	85.18°	85.18°	85.18°	85.18°	85.15°
Latitude	10.62°	10.62°	10.62°	10.62°	10.55°
<i>XRF analyses</i>					
SiO ₂	70.39	70.63	70.13	69.84	69.30
TiO ₂	0.48	0.48	0.50	0.48	0.48
Al ₂ O ₃	15.35	14.94	15.02	15.57	15.96
Fe ₂ O ₃	3.35	3.57	3.90	3.61	3.42
MnO	0.09	0.09	0.09	0.09	0.09
MgO	0.74	0.84	0.89	0.76	0.82
CaO	2.85	2.68	2.75	2.95	3.10
Na ₂ O	2.84	3.14	3.03	3.20	3.04
K ₂ O	3.85	3.57	3.65	3.46	3.69
P ₂ O ₅	0.05	0.05	0.04	0.03	0.10
Total	97.47	97.18	97.10	97.29	97.68
Rb	73	72	70	67	72
Sr	411	374	385	421	432
Zr	216	220	219	213	210
<i>Laser ablation ICP-MS analyses</i>					
Y	22.17	20.90	23.36	23.15	21.99
Nb	14.16	13.84	12.89	12.78	12.31
Ba	1859	1774	1759	1701	1725
La	28.43	28.83	30.28	29.03	34.30
Ce	58.27	59.26	55.37	55.10	65.75
Pr	6.37	6.46	6.42	6.27	7.65
Nd	22.23	22.79	22.94	22.66	27.78
Sm	4.47	4.27	4.28	4.31	5.14
Eu	1.26	1.21	1.23	1.26	1.34
Tb	0.61	0.61	0.64	0.64	0.73
Dy	3.31	3.13	3.50	3.41	3.67
Ho	0.84	0.74	0.86	0.86	0.78
Er	2.52	2.28	2.51	2.53	2.42
Yb	2.68	2.50	2.62	2.72	2.59
Lu	0.44	0.38	0.42	0.42	0.39
Hf	4.54	4.62	5.43	5.06	4.45
Ta	0.91	0.92	0.90	0.86	0.78
Th	7.01	7.16	7.75	7.64	7.60
U					3.50

Table 1 cont. (Santa Fe)

Sample	040706-4B	040706-4C	040706-4D	040706-4E	040706-4F
Location					
Longitude	85.15°	85.15°	85.15°	85.15°	85.15°
Latitude	10.55°	10.55°	10.55°	10.55°	10.55°
<i>XRF analyses</i>					
SiO ₂	68.95	67.93	69.73	69.16	68.34
TiO ₂	0.46	0.50	0.43	0.48	0.52
Al ₂ O ₃	15.89	15.90	15.86	15.63	15.76
Fe ₂ O ₃	3.55	4.29	3.27	3.78	4.17
MnO	0.10	0.09	0.07	0.08	0.10
MgO	0.86	1.06	0.69	0.90	1.10
CaO	3.07	3.37	2.91	2.93	3.22
Na ₂ O	3.13	2.96	2.96	3.09	2.83
K ₂ O	3.86	3.77	3.99	3.83	3.84
P ₂ O ₅	0.11	0.12	0.09	0.11	0.12
Total	97.30	97.91	97.28	97.33	97.46
Rb	73	71	79	75	74
Sr	436	465	429	411	437
Zr	204	188	198	204	199
<i>Laser ablation ICP-MS analyses</i>					
Y	22.06	24.37	22.01	21.99	20.98
Nb	12.34	11.58	12.48	12.78	12.37
Ba	1740	1668	1754	1699	1693
La	33.92	34.18	34.66	33.41	32.86
Ce	65.31	62.82	62.59	63.87	64.46
Pr	7.46	8.04	7.55	7.56	7.30
Nd	27.34	29.62	27.54	27.41	26.48
Sm	5.19	5.49	5.06	4.97	5.03
Eu	1.35	1.49	1.37	1.27	1.27
Tb	0.74	0.79	0.77	0.78	0.74
Dy	3.66	3.91	3.60	3.70	3.58
Ho	0.78	0.84	0.77	0.78	0.79
Er	2.53	2.70	2.45	2.51	2.40
Yb	2.66	2.74	2.66	2.67	2.58
Lu	0.39	0.42	0.39	0.41	0.39
Hf	4.27	3.91	4.55	4.60	4.06
Ta	0.78	0.70	0.86	0.86	0.79
Th	7.63	6.93	8.07	8.06	7.34
U	3.75	3.30	4.46	3.78	3.89

Table 1 cont. (Santa Fe)

Sample	040706-1A	040706-1B	040706-1C	040706-1D	040706-1E	040706-1F
Location						
Longitude	85.17°	85.17°	85.17°	85.17°	85.17°	85.17°
Latitude	10.52°	10.52°	10.52°	10.52°	10.52°	10.52°
<i>XRF analyses</i>						
SiO ₂	69.65	69.04	68.11	68.46	68.84	69.81
TiO ₂	0.46	0.48	0.50	0.49	0.51	0.51
Al ₂ O ₃	16.15	16.43	17.99	17.90	16.89	16.29
Fe ₂ O ₃	3.42	3.62	3.76	3.56	3.69	3.68
MnO	0.08	0.09	0.08	0.08	0.09	0.12
MgO	0.76	0.75	0.58	0.44	0.65	0.48
CaO	2.91	3.08	2.78	2.76	2.88	2.59
Na ₂ O	2.73	2.78	2.41	2.81	2.55	2.38
K ₂ O	3.81	3.68	3.76	3.46	3.86	4.10
P ₂ O ₅	0.03	0.03	0.03	0.03	0.03	0.03
Total	96.58	96.96	96.11	96.69	96.40	96.17
Rb	81	77	76	74	81	84
Sr	420	448	404	413	416	375
Zr	199	193	211	209	200	206
<i>Laser ablation ICP-MS analyses</i>						
Y	25.31	24.46	37.89	32.49	23.90	28.07
Nb	12.08	12.21	13.18	13.23	12.38	13.49
Ba	1716	1714	1690	1719	1811	1879
La	32.90	33.29	53.80	40.52	34.52	39.04
Ce	58.83	61.09	65.82	68.94	63.71	74.13
Pr	7.47	7.56	13.38	9.53	7.65	9.07
Nd	27.38	28.35	49.79	34.63	27.88	33.23
Sm	5.35	5.52	9.16	6.62	5.07	6.22
Eu	1.51	1.66	2.33	1.88	1.48	1.60
Tb	0.78	0.77	1.14	0.94	0.70	0.87
Dy	4.19	4.20	6.28	5.17	3.88	4.44
Ho	0.91	0.91	1.31	1.16	0.80	0.94
Er	2.82	2.74	4.02	3.58	2.39	2.80
Yb	3.49	3.58	5.08	4.40	2.96	3.30
Lu	0.53	0.53	0.72	0.67	0.42	0.46
Hf	5.02	4.74	4.75	5.38	4.78	4.76
Ta	0.86	0.81	0.83	0.95	0.83	0.85
Th	8.26	7.83	8.38	9.19	8.24	8.18
U	3.85	3.82	4.15	4.58	3.67	3.75

Table 1 cont. (Santa Fe)

Sample	040706-1G	040706-1H	040706-1i	040706-1L	040706-1M	040706-1N
Location						
Longitude	85.17°	85.17°	85.17°	85.17°	85.17°	85.17°
Latitude	10.52°	10.52°	10.52°	10.52°	10.52°	10.52°
<i>XRF analyses</i>						
SiO ₂	67.98	69.56	68.50	69.44	68.67	68.76
TiO ₂	0.51	0.50	0.51	0.47	0.48	0.48
Al ₂ O ₃	17.34	16.09	16.49	16.13	17.71	16.66
Fe ₂ O ₃	3.76	3.69	4.01	3.49	3.67	3.70
MnO	0.15	0.10	0.11	0.09	0.07	0.10
MgO	0.75	0.67	0.80	0.71	0.46	0.71
CaO	3.14	2.78	3.12	2.91	2.68	3.00
Na ₂ O	2.83	2.55	2.88	2.93	2.60	2.74
K ₂ O	3.51	4.01	3.56	3.78	3.64	3.82
P ₂ O ₅	0.03	0.03	0.03	0.03	0.03	0.03
Total	96.36	96.40	96.61	97.13	96.56	96.31
Rb	78	82	77	74	74	79
Sr	485	395	432	415	397	440
Zr	204	205	195	198	202	197
<i>Laser ablation ICP-MS analyses</i>						
Y	28.45	24.59	24.11	21.38	19.79	23.53
Nb	12.06	11.85	11.54	12.50	13.35	12.71
Ba	1895	1797	1740	1715	1709	1773
La	40.26	35.85	35.96	32.52	30.25	37.29
Ce	76.89	66.53	65.47	59.19	60.54	66.64
Pr	9.44	7.80	8.02	7.57	6.73	8.66
Nd	35.22	28.60	29.83	27.19	23.21	31.58
Sm	6.58	5.36	5.42	5.25	4.62	5.82
Eu	1.82	1.45	1.50	1.48	1.38	1.54
Tb	0.88	0.77	0.74	0.69	0.62	0.76
Dy	4.67	3.87	3.86	3.61	3.17	3.90
Ho	0.96	0.81	0.80	0.76	0.65	0.79
Er	2.79	2.44	2.48	2.26	2.14	2.32
Yb	3.31	3.01	2.97	2.56	2.54	2.90
Lu	0.46	0.43	0.42	0.42	0.42	0.40
Hf	4.81	4.71	4.58	4.96	5.04	4.58
Ta	0.80	0.81	0.76	0.78	0.86	0.78
Th	8.11	7.93	7.70	7.15	7.98	7.70
U	3.64	3.57	3.47	3.67	3.91	3.48

Table 1 cont. (Santa Fe)

Sample	040707-4	040707-8A	040707-8D	040707-8F	031021-1a	031021-1d
<i>Location</i>						
Longitude	85.23°	85.33°	85.33°	85.33°	85.17°	85.17°
Latitude	10.61°	10.52°	10.52°	10.52°	10.52°	10.52°
<i>XRF analyses</i>						
SiO ₂	69.45	73.69	73.73	73.42	70.23	69.04
TiO ₂	0.53	0.23	0.25	0.24	0.42	0.47
Al ₂ O ₃	16.14	15.78	14.80	15.14	16.49	17.46
Fe ₂ O ₃	3.70	1.84	1.83	1.70	2.80	3.18
MnO	0.10	0.06	0.06	0.06	0.06	0.08
MgO	0.78	0.23	0.37	0.30	0.36	0.39
CaO	3.01	1.61	1.92	1.90	2.61	2.65
Na ₂ O	2.76	2.17	2.69	3.22	2.95	2.86
K ₂ O	3.49	4.38	4.34	4.03	4.04	3.84
P ₂ O ₅	0.03	0.01	0.01	0.01	0.03	0.03
Total	96.97	96.60	97.64	97.84	96.00	96.20
Rb	65	85	89	90	85	76
Sr	389	227	273	274	194	194
Zr	206	125	117	114	381	397
<i>Laser ablation ICP-MS analyses</i>						
Y	25.04	16.58	19.83	18.63	19.44	20.80
Nb	10.44	9.28	8.91	9.27	12.62	12.78
Ba	1531	1703	1688	1754	1764	1770
La	26.43	25.10	26.34	27.63	31.72	33.70
Ce	58.55	44.50	44.00	44.65	62.82	58.98
Pr	6.27	4.79	5.17	5.61	7.43	7.50
Nd	23.88	16.23	17.35	18.60	25.69	25.76
Sm	5.29	1.99	2.39	2.48	4.65	4.41
Eu	1.49	0.53	0.66	0.68	1.26	1.35
Tb	0.74	0.28	0.34	0.31	0.61	0.64
Dy	4.23	1.63	1.97	1.88	2.90	3.06
Ho	0.92	0.28	0.37	0.34	0.69	0.64
Er	2.78	0.58	0.88	0.67	2.02	2.14
Yb	2.99	1.33	1.53	1.44	2.21	2.26
Lu	0.52	0.17	0.21	0.19	0.34	0.36
Hf	5.29	2.34	2.26	1.91	3.85	4.17
Ta	0.71	0.56	0.49	0.50	0.88	0.87
Th	6.55	8.79	8.08	8.15	7.05	7.42
U	3.59	4.42	3.99	4.52	3.24	3.33

Table 1 cont. (Santa Fe)

Sample	031021-1g	031021-1k-2	031022-1a	031022-1b	031022-1c	031022-1d
Location						
Longitude	85.17°	85.17°	85.24°	85.24°	85.24°	85.24°
Latitude	10.52°	10.52°	10.61°	10.61°	10.61°	10.61°
<i>XRF analyses</i>						
SiO ₂	69.15	70.18	69.83	70.10	68.48	70.05
TiO ₂	0.46	0.48	0.47	0.48	0.55	0.44
Al ₂ O ₃	16.26	15.77	15.68	15.10	15.91	15.76
Fe ₂ O ₃	3.53	3.51	3.33	3.60	4.12	3.32
MnO	0.07	0.07	0.08	0.09	0.11	0.10
MgO	0.69	0.63	0.86	1.02	0.95	0.65
CaO	2.73	2.32	2.98	2.89	3.16	2.89
Na ₂ O	2.76	2.73	3.08	3.00	3.20	3.10
K ₂ O	4.23	4.27	3.67	3.68	3.46	3.67
P ₂ O ₅	0.11	0.03	0.03	0.03	0.06	0.03
Total	95.90	95.50	96.50	97.50	97.00	97.60
Rb	77	82	58	59	55	59
Sr	206	212	348	346	403	364
Zr	391	339	203	203	196	204
<i>Laser ablation ICP-MS analyses</i>						
Y	19.59	20.39	22.57	19.78	20.45	20.92
Nb	13.30	14.18	9.63	10.10	10.23	10.01
Ba	1762	1790	1479	1550	1531	1604
La	32.38	30.74	24.93	21.51	23.87	25.29
Ce	69.03	59.95	52.54	48.31	54.35	60.19
Pr	7.39	6.82	6.43	5.12	5.76	6.44
Nd	25.54	23.14	24.13	18.85	20.81	23.00
Sm	4.65	4.21	4.94	3.80	4.15	4.88
Eu	1.21	1.22	1.39	1.21	1.25	1.35
Tb	0.63	0.58	0.70	0.55	0.60	0.62
Dy	3.05	2.95	3.55	2.87	3.02	3.38
Ho	0.63	0.61	0.83	0.69	0.72	0.84
Er	2.15	1.93	2.40	2.11	2.42	2.40
Yb	2.11	2.14	2.54	2.35	2.42	2.55
Lu	0.39	0.41	0.42	0.35	0.36	0.40
Hf	4.34	4.14	3.82	3.84	3.62	4.11
Ta	0.86	0.95	0.63	0.69	0.64	0.66
Th	7.35	7.23	4.69	4.74	4.71	5.20
U	3.48	4.78	2.85	2.97	2.86	3.31

Table 1 cont. (Santa Fe)

Sample	031022-1e	031022-1f	031022-1g	031022-1h-1	031022-1h-2
<i>Location</i>					
Longitude	85.24°	85.24°	85.24°	85.24°	85.24°
Latitude	10.61°	10.61°	10.61°	10.61°	10.61°
<i>XRF analyses</i>					
SiO ₂	71.09	69.51	70.84	70.22	69.25
TiO ₂	0.42	0.48	0.46	0.45	0.47
Al ₂ O ₃	15.07	15.46	15.39	15.31	16.16
Fe ₂ O ₃	3.01	3.70	3.31	3.32	3.46
MnO	0.08	0.09	0.07	0.09	0.09
MgO	0.72	0.93	0.55	0.85	0.73
CaO	2.69	3.03	2.58	2.95	3.05
Na ₂ O	2.90	3.39	2.74	3.07	3.01
K ₂ O	3.96	3.36	4.03	3.71	3.70
P ₂ O ₅	0.05	0.03	0.03	0.03	0.07
Total	96.70	96.90	96.70	97.40	96.70
Rb	62	56	65	61	58
Sr	324	366	332	349	382
Zr	201	203	211	202	201
<i>Laser ablation ICP-MS analyses</i>					
Y	23.49	19.18	19.70	21.73	21.72
Nb	9.71	9.59	10.65	10.43	9.67
Ba	1621	1492	1627	1556	1517
La	27.17	21.97	25.44	23.51	25.47
Ce	56.84	48.80	53.20	50.61	56.06
Pr	6.63	5.27	6.04	5.62	6.19
Nd	24.23	19.18	20.73	20.61	22.18
Sm	4.66	3.88	3.98	4.29	4.32
Eu	1.29	1.17	1.19	1.26	1.26
Tb	0.68	0.59	0.56	0.63	0.69
Dy	3.69	3.00	2.82	3.28	3.37
Ho	0.84	0.73	0.70	0.77	0.84
Er	2.56	2.16	2.09	2.41	2.41
Yb	2.75	2.27	2.19	2.48	2.60
Lu	0.42	0.37	0.36	0.38	0.38
Hf	4.04	3.66	3.98	3.98	3.67
Ta	0.68	0.66	0.76	0.66	0.73
Th	5.40	4.80	5.47	5.02	4.93
U	3.33	2.89	3.45	2.86	2.87

Table 1 cont. (Santa Fe)

Sample	031022-1h-3	031022-1i-1	031022-1i-2	031022-1i-3	031022-1J-1
Location					
Longitude	85.24°	85.24°	85.24°	85.24°	85.24°
Latitude	10.61°	10.61°	10.61°	10.61°	10.61°
XRF analyses					
SiO ₂	70.20	70.76	69.33	69.27	67.86
TiO ₂	0.46	0.48	0.50	0.49	0.57
Al ₂ O ₃	15.72	14.97	15.98	16.26	16.72
Fe ₂ O ₃	3.23	3.34	3.81	3.59	3.99
MnO	0.07	0.10	0.09	0.09	0.11
MgO	0.76	0.89	0.70	0.64	1.08
CaO	2.83	2.78	2.97	2.97	3.37
Na ₂ O	3.01	2.65	2.82	2.91	3.01
K ₂ O	3.68	3.98	3.75	3.75	3.26
P ₂ O ₅	0.03	0.05	0.04	0.03	0.03
Total	97.20	96.80	97.20	96.80	96.80
Rb	59	76	68	73	60
Sr	348	326	390	386	402
Zr	213	209	204	207	215
Laser ablation ICP-MS analyses					
Y	23.46	29.51	27.54	32.54	31.09
Nb	10.16	8.35	8.43	8.61	8.15
Ba	1545	1535	1531	1528	1380
La	26.55	30.49	33.20	33.35	31.09
Ce	50.74	56.38	55.00	56.90	54.03
Pr	6.93	7.01	7.26	7.91	6.99
Nd	24.74	27.43	28.59	31.38	27.40
Sm	4.87	5.94	5.27	6.25	5.42
Eu	1.36	1.37	1.37	1.47	1.45
Tb	0.73	0.82	0.78	0.93	0.84
Dy	3.58	4.66	4.10	5.06	4.54
Ho	0.84	1.08	0.94	1.20	1.04
Er	2.44	3.26	2.89	3.36	3.01
Yb	2.85	3.42	3.00	3.74	3.13
Lu	0.42	0.52	0.47	0.58	0.48
Hf	4.18	5.12	5.03	4.98	5.06
Ta	0.70	0.62	0.59	0.62	0.52
Th	5.15	6.16	6.16	6.48	5.74
U	3.06	2.58	2.22	2.59	2.29

Table 1 cont. (Santa Fe)

Sample	031022-1J-2	031022-1J-3	010627-1c	010627-6b	010627-6c
<i>Location</i>					
Longitude	85.24°	85.24°	85.42°	85.45°	85.45°
Latitude	10.61°	10.61°	10.71°	10.77°	10.77°
<i>XRF analyses</i>					
SiO ₂	70.13	69.38	69.06	71.35	70.84
TiO ₂	0.46	0.48	0.43	0.38	0.40
Al ₂ O ₃	16.03	16.44	15.58	14.85	14.77
Fe ₂ O ₃	3.42	3.49	4.27	2.87	3.20
MnO	0.12	0.12	0.12	0.09	0.08
MgO	0.64	0.86	1.00	0.76	0.81
CaO	2.74	2.90	2.31	2.83	2.86
Na ₂ O	2.62	2.75	3.00	2.86	3.13
K ₂ O	3.80	3.55	4.19	3.89	3.79
P ₂ O ₅	0.03	0.03	0.04	0.10	0.10
Total	97.40	96.60	97.00	97.00	96.00
Rb	71	64	127	68	66
Sr	366	355	213	328	334
Zr	215	208	209	200	190
<i>Laser ablation ICP-MS analyses</i>					
Y	32.99	34.38	22.46	22.69	21.91
Nb	9.04	8.31	14.37	8.67	9.38
Ba	1623	1509	832	1495	1467
La	35.84	35.56	29.31	25.95	24.69
Ce	64.54	63.51	60.26	53.93	51.61
Pr	8.46	8.31	6.28	5.96	5.74
Nd	33.13	31.61	20.47	21.72	20.74
Sm	6.48	6.07	4.13	4.35	4.13
Eu	1.50	1.49	0.75	1.17	1.13
Tb	0.92	0.89	0.66	0.62	0.62
Dy	4.87	4.87	3.34	3.36	3.32
Ho	1.13	1.17	0.71	0.69	0.67
Er	3.29	3.34	2.15	2.03	1.96
Yb	3.44	3.41	3.71	3.27	3.24
Lu	0.55	0.57	0.45	0.38	0.37
Hf	5.45	5.08	4.77	4.33	4.23
Ta	0.62	0.57	0.98	0.61	0.61
Th	6.81	6.57	11.60	5.54	5.55
U	2.60	2.38	9.05	3.62	3.84

Table 1 cont. (Santa Fe)

Sample	010627-6d	010627-6e	010627-6f	010627-6g	010629-21a
<i>Location</i>					
Longitude	85.45°	85.45°	85.45°	85.45°	85.33°
Latitude	10.77°	10.77°	10.77°	10.77°	10.52°
<i>XRF analyses</i>					
SiO ₂	68.13	71.15	70.81	69.95	72.68
TiO ₂	0.52	0.42	0.41	0.44	0.25
Al ₂ O ₃	15.10	14.46	14.85	15.16	16.68
Fe ₂ O ₃	4.49	3.35	3.14	3.41	1.88
MnO	0.10	0.09	0.08	0.09	0.07
MgO	1.40	0.89	0.80	0.89	0.28
CaO	3.99	2.80	3.02	3.29	1.64
Na ₂ O	2.83	2.84	3.00	3.16	2.31
K ₂ O	3.32	3.89	3.78	3.50	4.17
P ₂ O ₅	0.11	0.10	0.10	0.10	0.04
Total	97.00	97.00	97.00	98.00	97.00
Rb	63	67	66	63	86
Sr	382	316	355	377	223
Zr	177	194	188	194	134
<i>Laser ablation ICP-MS analyses</i>					
Y	20.81	22.34	21.75	22.23	22.99
Nb	9.44	8.61	8.62	8.21	12.32
Ba	1324	1461	1493	1438	1759
La	23.53	24.80	25.28	24.32	28.87
Ce	50.17	51.73	52.73	51.30	50.57
Pr	5.62	5.81	5.72	5.73	6.09
Nd	20.39	20.91	21.30	20.90	20.81
Sm	4.21	4.29	4.24	4.34	3.93
Eu	1.20	1.16	1.19	1.32	0.99
Tb	0.59	0.64	0.63	0.62	0.57
Dy	3.16	3.48	3.29	3.46	3.07
Ho	0.66	0.71	0.66	0.69	0.71
Er	1.87	2.10	1.99	2.01	2.08
Yb	2.93	3.31	3.16	3.25	2.88
Lu	0.35	0.41	0.39	0.38	0.42
Hf	3.70	4.27	4.32	4.13	2.69
Ta	0.49	0.64	0.62	0.53	0.85
Th	4.64	5.52	5.33	4.85	8.79
U	3.20	3.65	3.51	3.32	5.77

Table 1 cont. (Santa Fe)

Sample	010629-21b	010629-21c	010629-21d	010629-21f	010629-21g
Location					
Longitude	85.33°	85.33°	85.33°	85.33°	85.33°
Latitude	10.52°	10.52°	10.52°	10.52°	10.52°
XRF analyses					
SiO ₂	73.48	73.10	72.61	73.06	73.95
TiO ₂	0.23	0.25	0.25	0.27	0.23
Al ₂ O ₃	15.71	15.52	17.30	15.71	15.06
Fe ₂ O ₃	1.74	1.88	2.03	2.22	1.85
MnO	0.07	0.08	0.07	0.10	0.06
MgO	0.28	0.35	0.28	0.42	0.28
CaO	1.61	1.82	1.46	1.54	1.61
Na ₂ O	2.44	2.65	2.03	2.45	2.15
K ₂ O	4.40	4.30	3.92	4.19	4.77
P ₂ O ₅	0.04	0.04	0.04	0.04	0.04
Total	97.00	97.00	97.00	96.00	97.00
Rb	94	92	84	87	108
Sr	228	259	199	259	227
Zr	129	129	140	157	145
Laser ablation ICP-MS analyses					
Y	18.25	16.42	23.40	24.85	15.22
Nb	11.96	10.99	11.83	15.35	11.25
Ba	1826	1794	1681	2315	1812
La	27.09	27.57	29.46	38.03	28.96
Ce	51.05	49.15	52.57	75.25	50.81
Pr	5.33	5.75	6.72	8.66	5.79
Nd	17.53	18.66	23.20	28.67	18.18
Sm	3.17	3.34	4.37	5.13	3.14
Eu	0.87	0.93	1.09	1.22	0.86
Tb	0.47	0.45	0.59	0.68	0.42
Dy	2.39	2.33	3.27	3.53	2.22
Ho	0.54	0.51	0.72	0.78	0.48
Er	1.68	1.62	2.14	2.39	1.49
Yb	2.28	2.29	2.93	3.31	2.31
Lu	0.33	0.31	0.44	0.45	0.29
Hf	2.57	2.62	2.80	3.88	2.72
Ta	0.85	0.72	0.85	1.04	0.80
Th	8.55	7.77	8.49	11.12	8.44
U	5.84	5.44	5.89	7.47	5.75

Table 1 cont. (Santa Fe)

Sample	010629-21h	010629-21k	010629-21j	010629-21L	010629-21m
<i>Location</i>					
Longitude	85.33°	85.33°	85.33°	85.33°	85.33°
Latitude	10.52°	10.52°	10.52°	10.52°	10.52°
<i>XRF analyses</i>					
SiO ₂	73.77	71.62	73.43	74.21	74.22
TiO ₂	0.23	0.29	0.24	0.25	0.23
Al ₂ O ₃	15.25	17.33	15.23	14.24	15.17
Fe ₂ O ₃	1.93	2.19	1.79	2.07	1.79
MnO	0.06	0.07	0.07	0.09	0.06
MgO	0.28	0.35	0.34	0.36	0.28
CaO	1.59	1.64	1.81	1.73	1.56
Na ₂ O	2.08	2.18	2.67	2.53	2.33
K ₂ O	4.78	4.29	4.38	4.47	4.32
P ₂ O ₅	0.04	0.04	0.04	0.04	0.04
Total	97.00	96.00	96.00	97.00	97.00
Rb	102	90	96	95	88
Sr	259	233	256	239	210
Zr	134	145	129	157	125
<i>Laser ablation ICP-MS analyses</i>					
Y	17.56	17.00	20.27	15.95	17.17
Nb	12.39	11.28	12.66	10.99	10.82
Ba	2017	1795	1720	1793	1647
La	32.92	29.26	30.29	28.12	27.25
Ce	57.63	52.13	56.37	53.20	45.60
Pr	6.76	6.31	6.64	5.57	5.57
Nd	21.19	20.44	22.26	17.89	18.48
Sm	3.75	3.63	4.10	3.15	3.38
Eu	0.96	0.93	0.96	0.83	0.89
Tb	0.49	0.48	0.56	0.45	0.47
Dy	2.55	2.44	2.85	2.34	2.44
Ho	0.54	0.53	0.61	0.52	0.55
Er	1.80	1.66	1.82	1.57	1.71
Yb	2.46	2.25	2.73	2.21	2.32
Lu	0.35	0.32	0.37	0.30	0.33
Hf	2.96	2.56	2.81	2.91	2.68
Ta	0.86	0.79	0.86	0.77	0.79
Th	9.27	8.51	10.29	8.10	8.63
U	6.26	5.65	6.08	5.04	5.43

Table 1 cont. (Santa Fe)

Sample	010629-21n	010630-4a	010630-4b	010630-4c	010630-4d
Location					
Longitude	85.33°	85.33°	85.33°	85.33°	85.33°
Latitude	10.52°	10.57°	10.57°	10.57°	10.57°
<i>XRF analyses</i>					
SiO ₂	73.71	70.08	70.54	68.38	66.29
TiO ₂	0.23	0.45	0.49	0.50	0.56
Al ₂ O ₃	15.39	15.83	15.45	17.54	19.27
Fe ₂ O ₃	1.88	3.40	3.70	3.66	4.17
MnO	0.06	0.07	0.08	0.08	0.09
MgO	0.27	0.74	0.61	0.73	0.89
CaO	1.52	2.79	2.45	2.82	2.96
Na ₂ O	1.96	2.89	2.59	2.80	2.75
K ₂ O	4.93	3.72	4.06	3.45	2.99
P ₂ O ₅	0.04	0.03	0.04	0.03	0.03
Total	97.00	97.40	97.40	96.40	96.70
Rb	105	62	71	62	50
Sr	214	346	339	348	355
Zr	131	207	213	232	256
<i>Laser ablation ICP-MS analyses</i>					
Y	16.79	23.69	22.56	33.57	31.18
Nb	11.57	10.32	11.28	11.29	11.36
Ba	1808	1616	1648	1565	1412
La	30.79	27.69	27.65	42.45	28.88
Ce	50.79	58.01	58.17	65.33	47.90
Pr	6.41	6.73	6.32	10.82	6.19
Nd	20.45	24.59	22.45	38.25	22.82
Sm	3.60	5.12	4.48	7.38	4.66
Eu	0.89	1.31	1.18	1.79	1.21
Tb	0.46	0.66	0.62	0.92	0.73
Dy	2.46	3.65	3.23	5.12	4.15
Ho	0.55	0.74	0.74	1.06	0.90
Er	1.69	2.32	2.39	3.13	2.74
Yb	2.44	2.43	2.54	3.46	3.17
Lu	0.35	0.39	0.42	0.53	0.52
Hf	2.71	4.14	4.58	4.65	6.21
Ta	0.82	0.63	0.72	0.70	0.77
Th	8.98	5.27	5.65	5.95	7.40
U	5.88	3.78	3.70	4.03	3.35

Table 1 cont. (Santa Fe)

Sample	010630-4e	010630-4f	010630-4g	010630-4h	010630-4i	010630-4j
Location						
Longitude	85.33°	85.33°	85.33°	85.33°	85.33°	85.33°
Latitude	10.57°	10.57°	10.57°	10.57°	10.57°	10.57°
<i>XRF analyses</i>						
SiO ₂	67.87	67.60	68.84	68.13	67.95	71.43
TiO ₂	0.51	0.56	0.53	0.57	0.53	0.47
Al ₂ O ₃	18.04	17.39	16.58	16.10	17.33	15.32
Fe ₂ O ₃	3.85	4.17	3.68	4.47	4.16	3.63
MnO	0.07	0.12	0.10	0.11	0.09	0.12
MgO	0.82	0.84	0.96	1.12	0.70	0.70
CaO	2.91	3.17	3.12	3.12	2.96	2.69
Na ₂ O	2.65	2.97	2.83	3.04	2.99	2.46
K ₂ O	3.25	3.15	3.30	3.30	3.25	3.15
P ₂ O ₅	0.03	0.03	0.04	0.03	0.04	0.03
Total	96.60	97.20	97.50	97.90	97.00	97.70
Rb	56	61	58	58	55	54
Sr	356	397	372	366	399	338
Zr	219	224	215	210	211	198
<i>Laser ablation ICP-MS analyses</i>						
Y	22.53	29.92	30.46	39.51	32.84	17.75
Nb	11.02	10.83	10.39	9.34	10.06	9.30
Ba	1452	1322	1404	1393	1488	1309
La	24.97	28.81	40.50	36.54	35.87	19.67
Ce	50.58	58.57	123.97	62.89	56.59	48.00
Pr	5.6	7.65	11.43	9.47	9.66	4.66
Nd	19.98	27.52	39.19	36.00	36.23	16.89
Sm	4.02	5.79	7.94	7.30	7.55	3.65
Eu	1.18	1.50	1.95	1.70	1.82	1.06
Tb	0.60	0.81	1.06	1.02	0.98	0.49
Dy	3.34	4.34	5.63	5.66	5.28	2.64
Ho	0.70	0.88	1.07	1.13	1.09	0.55
Er	2.16	2.82	3.12	3.43	3.27	1.71
Yb	2.58	3.72	3.36	3.67	3.84	1.90
Lu	0.41	0.49	0.50	0.57	0.67	0.32
Hf	4.69	4.62	4.74	4.60	4.62	4.14
Ta	0.69	0.59	0.63	0.58	0.62	0.58
Th	5.80	5.44	5.33	5.35	5.74	4.91
U	3.52	3.95	3.84	3.11	3.40	3.23

Table 1 cont. (Santa Fe)

Sample	990718-12a	990718-12b	990718-12c	990718-12d	990718-12e
<i>Location</i>					
Longitude	85.17°	85.17°	85.17°	85.17°	85.17°
Latitude	10.52°	10.52°	10.52°	10.52°	10.52°
<i>XRF analyses</i>					
SiO ₂	69.39	72.31	68.75	68.86	69.71
TiO ₂	0.49	0.45	0.53	0.50	0.45
Al ₂ O ₃	15.90	17.24	16.32	17.22	16.25
Fe ₂ O ₃	3.80	3.52	4.13	3.75	3.32
MnO	0.09	0.06	0.10	0.08	0.08
MgO	0.78	0.39	0.66	0.55	0.59
CaO	2.85	2.30	2.88	2.67	2.82
Na ₂ O	2.78	2.01	2.83	2.58	2.92
K ₂ O	3.86	1.68	3.74	3.75	3.79
P ₂ O ₅	0.05	0.05	0.05	0.05	0.05
Total	97.46	96.09	97.29	97.18	97.51
Rb	80	34	80	78	81
Sr	408	345	419	394	407
Zr	197	186	189	204	196
<i>Laser ablation ICP-MS analyses</i>					
Y	23.89	31.26	25.09	25.31	20.92
Nb	13.27	13.16	12.36	14.75	13.19
Ba	1825	1481	1757	1890	1803
La	33.51	36.56	34.77	35.46	30.87
Ce	66.53	87.43	63.24	71.71	61.66
Pr	7.84	8.86	7.78	8.55	6.97
Nd	28.06	32.81	28.59	31.81	24.05
Sm	5.27	6.47	5.37	6.19	4.39
Eu	1.45	1.56	1.35	1.57	1.22
Tb	0.71	0.83	0.69	0.76	0.57
Dy	3.70	4.38	3.78	4.10	3.17
Ho	0.79	0.94	0.79	0.85	0.67
Er	2.24	2.75	2.27	2.49	2.02
Yb	2.63	3.07	2.56	2.88	2.32
Lu	0.40	0.50	0.38	0.45	0.35
Hf	4.32	4.27	4.19	4.74	4.30
Ta	0.89	0.91	0.76	1.02	0.90
Th	7.00	6.92	6.39	8.03	6.84
U	4.07	3.31	3.51	4.44	4.04

Table 1 cont. (Santa Fe)

Sample	990718-12g
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Location

Longitude	85.17°
Latitude	10.52°

XRF analyses

SiO ₂	69.13
TiO ₂	0.48
Al ₂ O ₃	16.11
Fe ₂ O ₃	3.77
MnO	0.07
MgO	0.64
CaO	2.80
Na ₂ O	3.05
K ₂ O	3.89
P ₂ O ₅	0.05
Total	96.98
Rb	82
Sr	401
Zr	197

Laser ablation ICP-MS analyses

Y	23.94
Nb	13.93
Ba	1815
La	35.87
Ce	64.72
Pr	8.34
Nd	29.87
Sm	5.70
Eu	1.45
Tb	0.69
Dy	3.82
Ho	0.76
Er	2.20
Yb	2.54
Lu	0.39
Hf	4.39
Ta	0.95
Th	6.80
U	4.52

Table 1 cont. (Pijije)

Sample	031024-1A	031024-1B	031024-2A	031024-2B	031024-2C
<i>Location</i>					
Longitude	85.54°	85.54°	85.54°	85.54°	85.54°
Latitude	10.80°	10.80°	10.80°	10.80°	10.80°
<i>XRF analyses</i>					
SiO ₂	74.37	74.35	74.62	74.97	74.62
TiO ₂	0.23	0.22	0.20	0.20	0.19
Al ₂ O ₃	14.70	14.35	14.41	14.01	14.48
Fe ₂ O ₃	1.63	1.67	1.43	1.57	1.61
MnO	0.11	0.09	0.07	0.10	0.06
MgO	0.32	0.29	0.28	0.20	0.29
CaO	1.74	1.79	1.67	1.67	1.99
Na ₂ O	2.61	2.77	2.92	2.81	2.95
K ₂ O	4.28	4.47	4.40	4.47	3.79
P ₂ O ₅	0.01	0.01	0.01	0.01	0.01
Total	96.99	96.67	97.32	96.87	95.15
Rb	89	93	93	90	74
Sr	261	268	240	245	288
Zr	131	125	116	120	115
<i>Laser ablation ICP-MS analyses</i>					
Y	11.95	11.55	11.54	10.98	10.45
Nb	10.02	9.78	9.70	9.14	8.47
Ba	1803	1796	1721	1761	1559
La	24.22	24.92	24.79	24.40	22.26
Ce	46.56	44.25	43.32	44.30	37.41
Pr	4.46	4.56	4.54	4.36	4.09
Nd	14.54	14.36	14.35	13.77	13.54
Sm	2.58	2.57	0.42	0.40	0.42
Eu	0.81	0.83	0.42	0.40	0.42
Tb	0.42	0.40	0.38	0.39	0.37
Dy	1.88	1.88	1.80	1.72	1.70
Ho	0.44	0.43	0.43	0.39	0.43
Er	1.49	1.39	1.42	1.32	1.44
Yb	1.67	1.69	1.68	1.59	1.58
Lu	0.26	0.24	0.26	0.25	0.23
Hf	3.16	3.22	2.98	2.92	2.85
Ta	0.91	0.88	0.89	0.88	0.81
Th	8.95	8.42	9.12	8.97	8.09
U	4.36	4.64	4.70	4.43	4.00

Table 1 cont. (Pijje)

Sample	031024-2D	031024-2E	031024-2F	031024-2G	031024-2H
Location					
Longitude	85.54°	85.54°	85.54°	85.54°	85.54°
Latitude	10.80°	10.80°	10.80°	10.80°	10.80°
<i>XRF analyses</i>					
SiO ₂	74.06	73.88	74.23	73.94	74.27
TiO ₂	0.25	0.18	0.22	0.24	0.17
Al ₂ O ₃	14.64	14.99	14.22	14.65	14.49
Fe ₂ O ₃	1.91	1.37	1.76	1.81	1.31
MnO	0.08	0.08	0.08	0.08	0.11
MgO	0.34	0.13	0.30	0.39	0.19
CaO	1.83	1.75	1.90	1.80	1.91
Na ₂ O	2.56	3.11	2.96	2.63	3.28
K ₂ O	4.32	4.49	4.31	4.44	4.26
P ₂ O ₅	0.01	0.01	0.01	0.01	0.01
Total	96.52	96.41	97.17	95.64	95.15
Rb	92	94	89	90	86
Sr	285	260	273	262	281
Zr	133	125	132	131	97
<i>Laser ablation ICP-MS analyses</i>					
Y	10.97	11.31	11.17	11.06	11.07
Nb	9.43	9.93	8.57	9.25	9.22
Ba	1847	1808	1680	1716	1775
La	24.97	26.05	23.67	24.00	24.73
Ce	42.55	46.05	41.55	40.87	43.84
Pr	4.56	4.65	4.23	4.40	4.41
Nd	14.65	14.59	13.65	14.31	14.16
Sm	0.40	0.42	0.40	0.42	0.40
Eu	0.40	0.42	0.40	0.42	0.40
Tb	0.40	0.42	0.38	0.39	0.39
Dy	1.74	1.79	1.69	1.78	1.88
Ho	0.40	0.47	0.41	0.45	0.48
Er	1.37	1.43	1.31	1.44	1.55
Yb	1.62	1.66	1.58	1.68	1.66
Lu	0.26	0.26	0.25	0.26	0.25
Hf	3.36	3.25	3.08	3.25	2.59
Ta	0.91	1.01	0.76	0.89	0.93
Th	8.75	9.67	8.19	8.54	8.65
U	4.25	5.02	3.99	4.35	4.66

Table 1 cont. (Pijije)

Sample	040708-1A	040708-1B	040708-1C	040708-1D	040708-2A
Location					
Longitude	85.39°	85.39°	85.39°	85.39°	85.39°
Latitude	10.69°	10.69°	10.69°	10.69°	10.69°
<i>XRF analyses</i>					
SiO ₂	74.98	76.04	76.23	75.40	73.76
TiO ₂	0.24	0.22	0.20	0.23	0.24
Al ₂ O ₃	15.29	14.38	14.41	14.40	15.09
Fe ₂ O ₃	2.28	1.84	1.55	1.98	1.75
MnO	0.08	0.08	0.05	0.07	0.07
MgO	0.10	0.08	0.05	0.10	0.33
CaO	1.73	1.04	1.10	1.28	1.80
Na ₂ O	2.60	2.27	2.38	2.65	2.98
K ₂ O	2.69	4.04	4.02	3.87	3.98
P ₂ O ₅	0.01	0.01	0.01	0.01	0.01
Total	98.20	98.44	98.27	98.45	97.44
Rb	65	103	103	96	86
Sr	304	201	208	229	264
Zr	152	137	131	151	131
<i>Laser ablation ICP-MS analyses</i>					
Y	10.98	12.55	10.59	12.50	13.87
Nb	8.73	8.76	9.40	10.15	9.44
Ba	1686	1923	1911	1967	1759
La	21.60	25.56	23.49	25.99	26.48
Ce	39.41	39.75	38.94	44.43	48.71
Pr	4.12	4.70	4.27	4.73	5.24
Nd	13.55	15.29	13.70	15.04	17.62
Sm	2.46	2.87	2.44	2.77	3.54
Eu	0.99	0.94	0.83	0.92	0.94
Tb	0.33	0.42	0.34	0.37	0.48
Dy	1.73	1.91	1.69	1.90	2.40
Ho	0.47	0.56	0.47	0.50	0.48
Er	1.45	1.72	1.38	1.47	1.58
Yb	1.44	1.84	1.48	1.63	2.23
Lu	0.23	0.30	0.23	0.27	0.37
Hf	3.18	3.83	3.08	2.97	3.89
Ta	0.77	1.02	1.14	0.88	0.85
Th	5.57	9.25	8.26	6.87	9.33
U					4.32

Table 1 cont. (Pijije)

Sample	040708-2B	040708-2C	040708-2D	040708-2F	040708-2G
<i>Location</i>					
Longitude	85.39°	85.39°	85.39°	85.39°	85.39°
Latitude	10.69°	10.69°	10.69°	10.69°	10.69°
<i>XRF analyses</i>					
SiO ₂	73.88	73.91	73.03	73.03	72.46
TiO ₂	0.19	0.21	0.29	0.28	0.25
Al ₂ O ₃	15.54	14.92	15.30	15.14	16.36
Fe ₂ O ₃	1.46	1.61	2.07	1.86	1.74
MnO	0.06	0.07	0.07	0.07	0.07
MgO	0.12	0.27	0.46	0.43	0.34
CaO	1.61	1.71	1.92	1.92	2.12
Na ₂ O	2.78	2.95	3.08	3.26	3.25
K ₂ O	4.35	4.33	3.76	4.00	3.41
P ₂ O ₅	0.01	0.01	0.01	0.01	0.01
Total	97.51	98.04	97.90	97.81	97.81
Rb	97	96	87	92	74
Sr	259	262	278	283	310
Zr	132	126	151	141	147
<i>Laser ablation ICP-MS analyses</i>					
Y	14.34	12.89	14.87	13.78	14.57
Nb	11.72	10.41	10.66	10.41	10.87
Ba	1927	1894	1803	1950	1837
La	28.86	26.64	28.15	28.06	26.83
Ce	55.64	51.78	46.84	50.87	49.90
Pr	5.52	5.03	5.40	5.32	5.37
Nd	17.98	16.10	17.38	17.20	17.68
Sm	3.28	2.98	3.06	2.97	3.42
Eu	0.87	0.86	0.86	0.85	0.93
Tb	0.44	0.40	0.42	0.42	0.44
Dy	2.19	2.01	2.29	2.05	2.33
Ho	0.57	0.53	0.54	0.54	0.60
Er	1.76	1.55	1.65	1.61	1.78
Yb	1.90	1.90	1.78	1.81	1.96
Lu	0.30	0.30	0.29	0.29	0.32
Hf	3.39	2.96	3.36	3.27	3.39
Ta	1.15	0.99	0.90	0.93	1.00
Th	9.55	8.24	8.05	7.82	8.20
U					

Table 1 cont. (Pijije)

Sample	040708-2i	040708-6B	040708-6C	040708-6E	040706-3C
Location					
Longitude	85.39°	85.38°	85.38°	85.38°	85.17°
Latitude	10.69°	10.70°	10.70°	10.70°	10.52°
<i>XRF analyses</i>					
SiO ₂	73.13	72.63	73.21	73.57	70.28
TiO ₂	0.24	0.27	0.23	0.19	0.35
Al ₂ O ₃	16.12	16.83	15.70	15.70	18.86
Fe ₂ O ₃	1.80	1.67	1.66	1.61	2.97
MnO	0.09	0.08	0.07	0.07	0.06
MgO	0.23	0.41	0.36	0.20	0.45
CaO	1.89	1.64	1.93	1.82	1.43
Na ₂ O	2.96	2.51	3.09	2.86	2.26
K ₂ O	3.54	3.97	3.74	3.96	3.32
P ₂ O ₅	0.01	0.01	0.01	0.01	0.02
Total	97.34	97.76	98.69	98.79	96.49
Rb	72	84	79	81	80
Sr	279	247	280	269	215
Zr	137	143	126	132	145
<i>Laser ablation ICP-MS analyses</i>					
Y	14.44	16.63	13.50	14.04	16.80
Nb	10.74	10.78	10.48	10.96	10.64
Ba	1742	1847	1874	1882	1844
La	27.31	24.51	24.40	24.48	26.89
Ce	49.90	52.42	48.26	51.65	47.65
Pr	5.08	4.87	4.75	4.69	5.16
Nd	16.58	16.38	15.10	15.23	17.58
Sm	3.15	3.52	2.90	2.90	3.35
Eu	0.89	0.97	0.89	0.91	0.88
Tb	0.44	0.50	0.42	0.41	0.49
Dy	2.30	2.55	2.13	2.14	2.50
Ho	0.62	0.74	0.57	0.59	0.52
Er	1.80	2.34	1.73	1.74	1.76
Yb	2.05	2.67	2.03	2.01	2.23
Lu	0.33	0.45	0.32	0.32	0.35
Hf	3.60	3.56	2.90	2.98	3.87
Ta	0.96	1.04	0.96	1.07	0.97
Th	9.27	9.58	8.07	8.73	9.82
U					4.39

Table 1 cont. (Pijje)

Sample	040706-3D	040706-3G	031021-1b	031021-1c	031021-1e	031021-1i*
Location						
Longitude	85.17°	85.17°	85.17°	85.17°	85.17°	85.17°
Latitude	10.52°	10.52°	10.52°	10.52°	10.52°	10.52°
XRF analyses						
SiO ₂	72.94	71.27	71.09	72.42	71.22	70.07
TiO ₂	0.23	0.33	0.25	0.21	0.23	0.22
Al ₂ O ₃	15.49	16.75	15.08	14.49	13.86	14.70
Fe ₂ O ₃	1.86	2.72	1.78	1.50	1.66	1.60
MnO	0.13	0.08	0.05	0.05	0.05	0.05
MgO	0.32	0.63	0.34	0.23	0.29	0.17
CaO	2.09	1.79	1.58	1.93	1.51	1.46
Na ₂ O	3.13	2.72	2.58	3.05	2.45	2.48
K ₂ O	3.80	3.70	4.15	3.95	4.72	4.19
P ₂ O ₅	0.01	0.02	0.02	0.01	0.01	0.01
Total	97.88	96.84	96.92	97.84	96.00	94.95
Rb	78	91	102	93	105	97
Sr	302	247	242	295	238	233
Zr	125	165	127	115	131	120
Laser ablation ICP-MS analyses						
Y	15.51	24.37	13.88	10.23	12.97	13.58
Nb	8.24	10.21	10.39	9.55	10.02	9.68
Ba	1876	1820	1860	1754	1865	1697
La	28.00	35.25	27.99	23.97	25.29	26.94
Ce	46.79	52.78	46.21	45.13	45.13	45.89
Pr	5.21	7.40	5.19	4.60	4.83	5.14
Nd	17.91	26.82	16.52	14.09	15.80	16.38
Sm	3.31	4.89	2.86	2.39	2.64	2.81
Eu	0.99	1.18	0.85	0.91	0.71	0.84
Tb	0.48	0.73	0.36	0.35	0.40	0.42
Dy	2.38	3.74	1.82	1.56	1.74	1.95
Ho	0.51	0.80	0.46	0.41	0.40	0.44
Er	1.75	2.39	1.45	1.27	1.38	1.44
Yb	2.16	3.04	1.57	1.36	1.59	1.63
Lu	0.32	0.45	0.27	0.24	0.29	0.35
Hf	3.46	4.41	2.93	2.51	3.14	3.19
Ta	0.74	0.90	1.04	0.85	0.95	0.88
Th	8.89	10.42	8.00	6.81	8.75	9.44
U	3.95	4.22	3.88	4.01	3.95	5.21

Table 1 cont. (Pijije)

Sample	031021-1J	031021-1k-1	031021-1k-3*	031021-1l-1	031021-1l-2*
Location					
Longitude	85.17°	85.17°	85.17°	85.17°	85.17°
Latitude	10.52°	10.52°	10.52°	10.52°	10.52°
XRF analyses					
SiO ₂	70.29	71.23	69.54	71.52	77.79
TiO ₂	0.26	0.21	0.27	0.23	0.26
Al ₂ O ₃	14.70	14.44	14.61	13.69	11.46
Fe ₂ O ₃	1.98	1.51	2.11	1.64	1.48
MnO	0.04	0.06	0.07	0.06	0.04
MgO	0.26	0.22	0.39	0.31	0.31
CaO	1.80	1.70	1.57	1.41	0.93
Na ₂ O	2.63	2.80	2.97	2.81	1.36
K ₂ O	4.05	4.26	3.95	4.35	1.73
P ₂ O ₅	0.02	0.01	0.01	0.01	0.02
Total	96.03	96.44	95.49	96.03	95.38
Rb	99	98	94	103	59
Sr	286	266	236	212	160
Zr	129	119	146	126	95
Laser ablation ICP-MS analyses					
Y	14.09	12.25	12.04	12.98	9.74
Nb	9.63	9.99	10.93	10.78	9.45
Ba	1752	1823	1811	1823	1582
La	26.00	25.33	23.93	26.08	16.18
Ce	48.77	47.82	44.58	47.57	33.76
Pr	5.40	5.21	4.55	5.27	3.77
Nd	16.43	15.26	13.78	16.00	11.34
Sm	2.91	2.76	2.41	2.94	2.20
Eu	1.09	1.14	0.83	0.91	0.93
Tb	0.49	0.48	0.35	0.42	0.42
Dy	1.91	1.70	1.63	1.86	1.57
Ho	0.43	0.43	0.35	0.47	0.38
Er	1.40	1.33	1.32	1.59	1.15
Yb	1.54	1.41	1.42	1.57	1.13
Lu	0.31	0.32	0.28	0.34	0.29
Hf	3.03	2.68	3.16	2.86	2.36
Ta	0.91	0.90	0.99	0.97	1.09
Th	8.17	7.79	8.59	8.02	5.38
U	4.40	4.65	5.26	4.89	6.71

Table 1 cont. (Pijije)

Sample	010627-1a	010627-1b	010627-1d	010627-3d	010629-1b	010629-1c
<i>Location</i>						
Longitude	85.42°	85.42°	85.42°	85.42°	85.35°	85.35°
Latitude	10.71°	10.71°	10.71°	10.71°	10.54°	10.54°
<i>XRF analyses</i>						
SiO ₂	73.97	72.00	74.73	73.74	74.53	74.62
TiO ₂	0.24	0.32	0.21	0.23	0.28	0.26
Al ₂ O ₃	15.09	15.31	14.37	15.72	13.97	13.87
Fe ₂ O ₃	1.81	2.81	1.61	1.65	1.75	1.78
MnO	0.09	0.07	0.07	0.08	0.08	0.07
MgO	0.35	0.55	0.27	0.27	0.52	0.46
CaO	1.67	1.92	1.58	1.58	1.71	1.75
Na ₂ O	2.32	2.85	2.45	2.37	2.82	2.88
K ₂ O	4.42	4.13	4.66	4.32	4.29	4.27
P ₂ O ₅	0.04	0.05	0.05	0.04	0.05	0.04
Total	97.00	98.00	98.00	97.00	98.00	98.00
Rb	94	125	102	93	99	115
Sr	236	289	234	227	233	247
Zr	136	154	121	133	133	138
<i>Laser ablation ICP-MS analyses</i>						
Y	13.78	13.90	10.94	15.07	17.30	16.89
Nb	10.21	10.18	9.49	10.04	10.89	10.11
Ba	1831	1733	1872	1709	1942	1908
La	25.77	23.88	25.63	31.19	29.62	28.74
Ce	51.08	44.16	51.92	56.47	48.46	44.97
Pr	4.70	4.39	4.50	5.55	5.84	5.66
Nd	14.76	13.74	13.48	17.28	18.56	18.31
Sm	2.60	2.62	2.34	3.12	3.35	3.33
Eu	0.77	0.89	0.72	0.78	0.83	0.88
Tb	0.42	0.45	0.40	0.50	0.48	0.48
Dy	2.01	2.09	1.69	2.33	2.37	2.44
Ho	0.40	0.41	0.33	0.47	0.51	0.55
Er	1.29	1.36	1.11	1.47	1.59	1.57
Yb	2.71	2.70	2.48	3.15	2.51	2.56
Lu	0.28	0.30	0.24	0.35	0.32	0.34
Hf	3.02	3.69	3.01	3.31	3.02	3.06
Ta	0.98	0.84	1.00	1.00	0.98	0.92
Th	8.74	8.10	8.68	9.92	8.29	7.98
U	7.42	5.71	6.08	5.92	6.19	6.69

Table 1 cont. (Pijije)

Sample	010629-1d	990719-5b	990720-1a	990720-1b	990720-1c	990720-1e
Location						
Longitude	85.35°	85.37°	85.57°	85.57°	85.57°	85.57°
Latitude	10.54°	10.69°	10.85°	10.85°	10.85°	10.85°
<i>XRF analyses</i>						
SiO ₂	74.75	74.45	70.73	73.75	72.05	74.49
TiO ₂	0.24	0.22	0.28	0.25	0.26	0.20
Al ₂ O ₃	14.47	14.19	17.55	14.75	17.15	14.20
Fe ₂ O ₃	1.48	1.66	2.27	2.45	2.66	2.03
MnO	0.06	0.07	0.33	0.10	0.07	0.08
MgO	0.39	0.30	0.40	0.37	0.28	0.25
CaO	1.80	1.82	1.90	1.54	1.47	1.74
Na ₂ O	2.85	2.88	2.38	2.17	1.98	2.45
K ₂ O	3.92	4.37	4.11	4.58	4.03	4.54
P ₂ O ₅	0.04	0.04	0.04	0.04	0.04	0.04
Total	97.00	97.40	93.10	93.00	95.90	96.80
Rb	94	91	103	108	84	96
Sr	261	264	276	221	198	239
Zr	127	128	153	132	149	142
<i>Laser ablation ICP-MS analyses</i>						
Y	12.14	12.52	18.28	14.02	15.37	12.93
Nb	11.36	8.66	11.04	9.76	11.48	9.00
Ba	1954	1778	2550	1822	1661	1684
La	25.46	25.33	27.84	25.57	24.52	25.04
Ce	42.01	46.52	51.33	45.09	45.30	44.07
Pr	4.55	4.47	5.26	4.55	4.48	4.63
Nd	13.88	14.24	17.36	14.90	14.53	14.99
Sm	2.44	2.51	3.17	2.66	2.65	2.70
Eu	0.72	0.73	0.99	0.76	0.72	0.78
Tb	0.37	0.37	0.44	0.35	0.39	0.35
Dy	1.69	1.91	2.43	1.94	2.04	1.77
Ho	0.36	0.34	0.51	0.38	0.43	0.36
Er	1.17	1.11	1.52	1.24	1.31	1.16
Yb	2.01	2.33	2.74	2.27	2.43	2.15
Lu	0.22	0.28	0.33	0.27	0.32	0.27
Hf	2.90	3.26	3.73	3.33	3.63	3.17
Ta	1.02	0.86	1.08	0.96	1.19	0.88
Th	7.96	7.97	10.08	8.93	10.32	7.82
U	6.99	4.78	5.32	5.70	5.78	5.03

Table 1 cont. (Pijije)

Sample	990719-5a	990719-5b
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Location

Longitude	85.37°	85.37°
Latitude	10.69°	10.69°

XRF analyses

SiO ₂	74.03	74.45
TiO ₂	0.22	0.22
Al ₂ O ₃	14.57	14.19
Fe ₂ O ₃	1.47	1.66
MnO	0.06	0.07
MgO	0.30	0.30
CaO	1.94	1.82
Na ₂ O	3.47	2.88
K ₂ O	3.90	4.37
P ₂ O ₅	0.04	0.04
Total	96.90	97.40
Rb	88	91
Sr	286	264
Zr	119	128

Laser ablation ICP-MS analyses

Y	11.82	12.52
Nb	8.75	8.66
Ba	1832	1778
La	26.15	25.33
Ce	46.77	46.52
Pr	4.56	4.47
Nd	14.10	14.24
Sm	2.56	2.51
Eu	0.81	0.73
Tb	0.35	0.37
Dy	1.65	1.91
Ho	0.34	0.34
Er	1.04	1.11
Yb	2.17	2.33
Lu	0.24	0.28
Hf	2.92	3.26
Ta	0.83	0.86
Th	7.40	7.97
U	5.00	4.78

Table 1 cont. (Salitral East)

Sample	990717-4a	990717-4d	990717-4e	990717-4f	990717-4g	990717-4h
Location						
Longitude	85.17°	85.17°	85.17°	85.17°	85.17°	85.17°
Latitude	10.61°	10.61°	10.61°	10.61°	10.61°	10.61°
<i>XRF analyses</i>						
SiO ₂	72.36	72.29	71.55	73.58	73.20	72.77
TiO ₂	0.34	0.36	0.37	0.32	0.31	0.34
Al ₂ O ₃	14.75	15.42	16.38	14.52	15.10	14.82
Fe ₂ O ₃	2.84	2.79	2.78	2.39	2.23	2.48
MnO	0.06	0.06	0.08	0.08	0.06	0.07
MgO	0.57	0.38	0.37	0.38	0.35	0.45
CaO	2.39	2.17	2.13	1.95	2.01	2.26
Na ₂ O	2.70	2.36	2.40	2.41	2.67	2.57
K ₂ O	3.96	4.15	3.91	4.36	4.06	4.22
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02	0.02
Total	97.40	97.00	96.90	98.00	97.40	97.00
Rb	80	77	74	80	78	78
Sr	349	326	330	312	317	344
Zr	159	165	180	154	151	156
<i>Laser ablation ICP-MS analyses</i>						
Y	13.82	26.01	20.35	15.7	18.28	15.96
Nb	12.28	11.25	14.51	12.99	12.28	11.76
Ba	1701	1625	1802	1852	1790	1804
La	24.04	31.85	29.25	28.42	28.46	28.37
Ce	46.75	42.41	53.53	57.96	48.8	52.62
Pr	4.75	7.27	6.5	5.73	6.73	5.67
Nd	15.7	25.82	23.75	18.76	22.08	19.6
Sm	2.9	3.94	4.49	3.15	3.36	3.47
Eu	0.91	0.91	1.22	0.87	0.95	1
Tb	0.38	0.52	0.53	0.37	0.41	0.41
Dy	1.85	3.06	2.7	2.09	2.28	2.17
Ho	0.49	0.78	0.69	0.53	0.57	0.55
Er	1.47	2.28	2.24	1.68	1.78	1.62
Yb	1.67	2.54	2.41	1.78	2.03	1.86
Lu	0.28	0.46	0.46	0.34	0.35	0.31
Hf	3	4.01	3.83	3.37	3.4	3.4
Ta	0.91	0.82	1.12	1	1.02	0.96
Th	6.77	8.74	8.54	7.85	8	7.36
U	2.97	2.64	3.99	3.46	3.4	3.06

Table 1 cont. (Salitral East)

Sample	990717-4i	990717-4J	990717-4k	010630-2a	010630-2b	010630-2c
Location						
Longitude	85.17°	85.17°	85.17°	85.34°	85.34°	85.34°
Latitude	10.61°	10.61°	10.61°	10.71°	10.71°	10.71°
<i>XRF analyses</i>						
SiO ₂	69.84	72.78	73.36	73.76	73.78	74.16
TiO ₂	0.39	0.37	0.34	0.41	0.41	0.39
Al ₂ O ₃	17.54	14.92	14.20	14.86	14.98	14.63
Fe ₂ O ₃	3.07	2.74	2.50	2.86	2.85	2.69
MnO	0.09	0.07	0.06	0.08	0.09	0.08
MgO	0.47	0.48	0.46	0.59	0.57	0.52
CaO	2.49	2.09	2.10	1.95	2.06	1.89
Na ₂ O	2.64	2.48	2.61	1.84	1.58	1.77
K ₂ O	3.45	4.05	4.35	3.60	3.62	3.83
P ₂ O ₅	0.02	0.02	0.02	0.05	0.05	0.05
Total	96.50	97.10	97.70	96.00	96.00	96.00
Rb	57	75	83	77	81	82
Sr	378	311	321	273	281	265
Zr	189	161	148	222	225	212
<i>Laser ablation ICP-MS analyses</i>						
Y	16.48	16.12	15.39	21.47	21.3	20.6
Nb	14.1	12.86	10.13	10.58	10.94	9.69
Ba	1689	1823	1712	1832	1944	1740
La	30.31	27.99	28.03	30.78	31.93	29.07
Ce	61.26	59.64	45.67	55.35	57.46	51.78
Pr	6.65	5.72	4.84	6.28	6.55	6.11
Nd	23.01	19.13	17	21.94	22.44	21.2
Sm	4.16	3.48	2.92	4.02	4.12	3.92
Eu	1.28	0.99	0.77	1.12	1.14	1.1
Tb	0.49	0.43	0.35	0.59	0.57	0.57
Dy	2.49	2.17	2.12	3.1	3.01	2.94
Ho	0.64	0.56	0.51	0.64	0.62	0.63
Er	1.97	1.71	1.6	1.95	1.88	1.85
Yb	2.31	1.96	1.8	3.18	3.2	3.16
Lu	0.42	0.37	0.32	0.38	0.38	0.37
Hf	3.93	3.42	3.62	4.85	4.87	4.66
Ta	1.06	1.02	0.8	0.86	0.93	0.76
Th	8.54	7.77	8.21	7.2	7.62	6.69
U	3.48	3.35	2.47	4.63	4.84	4.09

Table 1 cont. (Salitral East)

Sample	010630-2d	010630-2e	010630-2f	010630-2g	010630-2h
<i>Location</i>					
Longitude	85.34°	85.34°	85.34°	85.34°	85.34°
Latitude	10.71°	10.71°	10.71°	10.71°	10.71°
<i>XRF analyses</i>					
SiO ₂	72.80	72.12	72.16	73.08	72.15
TiO ₂	0.42	0.48	0.45	0.42	0.46
Al ₂ O ₃	15.65	16.08	15.13	15.55	16.98
Fe ₂ O ₃	2.95	3.62	3.55	2.90	3.33
MnO	0.08	0.08	0.09	0.09	0.08
MgO	0.58	0.55	0.67	0.59	0.48
CaO	2.17	2.08	2.37	2.11	1.96
Na ₂ O	1.70	1.53	1.94	1.61	1.17
K ₂ O	3.59	3.38	3.56	3.62	3.34
P ₂ O ₅	0.05	0.07	0.06	0.05	0.05
Total	94.00	95.00	95.00	94.00	94.00
Rb	78	73	73	76	76
Sr	309	282	317	295	282
Zr	222	216	206	224	230
<i>Laser ablation ICP-MS analyses</i>					
Y	20.24	24.77	24.24	19.53	21.34
Nb	10.38	10.15	10.91	9.66	10.55
Ba	1909	1811	2054	1773	1838
La	29.58	33.66	31.85	28.25	29.75
Ce	54.93	54.72	57.8	53.4	57.02
Pr	6.18	6.9	7.04	5.8	6.38
Nd	21.74	24.15	25.55	19.93	22.11
Sm	4.04	4.79	5.13	3.79	4.12
Eu	1.21	1.39	1.39	1.16	1.17
Tb	0.57	0.66	0.67	0.55	0.6
Dy	2.96	3.54	3.56	2.93	3.12
Ho	0.61	0.72	0.74	0.58	0.64
Er	1.76	2.16	2.18	1.71	1.89
Yb	3.07	3.69	3.48	3	3.14
Lu	0.35	0.45	0.42	0.35	0.37
Hf	4.87	4.71	4.92	4.4	4.72
Ta	0.81	0.88	0.93	0.74	0.84
Th	6.87	6.76	7.54	6.29	7.09
U	4.5	4.26	4.49	4.34	4.48

Table 1 cont. (Salitral East)

Sample	010630-3a	010630-3d	010630-3e	010630-3f	010630-3g*
Location					
Longitude	85.30°	85.30°	85.30°	85.30°	85.30°
Latitude	10.66°	10.66°	10.66°	10.66°	10.66°
<i>XRF analyses</i>					
SiO ₂	73.61	73.61	72.79	72.22	73.61
TiO ₂	0.38	0.41	0.41	0.41	0.40
Al ₂ O ₃	14.72	14.82	15.08	16.29	14.90
Fe ₂ O ₃	2.63	2.83	3.00	2.86	3.01
MnO	0.12	0.09	0.14	0.08	0.09
MgO	0.55	0.55	0.53	0.48	0.44
CaO	2.15	2.22	2.28	2.30	1.99
Na ₂ O	2.03	1.62	2.08	1.95	1.55
K ₂ O	3.76	3.81	3.64	3.36	3.97
P ₂ O ₅	0.04	0.04	0.05	0.05	0.04
Total	96.20	96.30	95.90	94.50	95.60
Rb	81	83	76	76	93
Sr	301	313	318	322	306
Zr	231	228	222	230	216
<i>Laser ablation ICP-MS analyses</i>					
Y	17.92	17.82	18.94	21.32	21.20
Nb	10.82	10.90	11.05	10.92	11.40
Ba	1914	1853	1863	1784	1960
La	29.28	28.25	28.04	29.47	32.23
Ce	65.65	59.79	71.49	61.46	69.41
Pr	6.37	6.39	6.21	6.80	7.39
Nd	21.76	21.61	20.98	23.51	25.45
Sm	4.03	4.07	4.20	4.70	4.83
Eu	1.14	1.16	1.18	1.35	1.41
Tb	0.54	0.53	0.57	0.64	0.64
Dy	2.71	2.63	2.80	3.29	3.09
Ho	0.66	0.66	0.70	0.81	0.79
Er	2.01	1.88	2.10	2.35	2.29
Yb	2.13	2.19	2.42	2.58	2.44
Lu	0.36	0.34	0.38	0.42	0.40
Hf	4.57	4.42	4.36	4.51	4.37
Ta	0.84	0.81	0.83	0.87	0.95
Th	6.76	6.51	6.43	6.70	7.27
U	3.34	3.29	3.56	3.48	4.12

Table 1 cont. (Salitral East)

Sample	010630-3h	040706-5B	040706-5C	040706-5E	040706-6A
Location					
Longitude	85.30°	85.15°	85.15°	85.15°	85.15°
Latitude	10.66°	10.56°	10.56°	10.56°	10.56°
<i>XRF analyses</i>					
SiO ₂	72.51	73.64	73.47	73.01	73.54
TiO ₂	0.42	0.29	0.33	0.32	0.33
Al ₂ O ₃	15.73	14.45	14.19	14.59	14.36
Fe ₂ O ₃	3.09	2.25	2.41	2.63	2.60
MnO	0.08	0.07	0.08	0.08	0.08
MgO	0.49	0.35	0.55	0.41	0.48
CaO	2.27	2.22	2.26	2.27	2.03
Na ₂ O	1.83	2.60	2.60	2.48	2.10
K ₂ O	3.53	4.11	4.08	4.18	4.45
P ₂ O ₅	0.04	0.02	0.02	0.02	0.02
Total	95.20	96.90	97.32	97.05	97.44
Rb	86	80	83	82	89
Sr	331	346	330	343	314
Zr	227	143	155	153	154
<i>Laser ablation ICP-MS analyses</i>					
Y	18.09	13.66	15.71	17.39	17.06
Nb	12.60	11.29	12.54	11.24	12.02
Ba	1862	1820	1792	1785	1840
La	29.21	27.69	28.78	29.93	28.93
Ce	66.19	48.87	50.85	52.19	52.89
Pr	6.58	5.44	5.61	6.16	5.92
Nd	22.10	17.68	18.74	21.12	19.98
Sm	4.23	3.43	3.47	4.26	4.00
Eu	1.26	1.06	1.02	1.19	1.14
Tb	0.60	0.46	0.53	0.54	0.54
Dy	2.68	2.28	2.41	2.78	2.78
Ho	0.69	0.47	0.50	0.57	0.58
Er	2.08	1.57	1.62	1.87	1.88
Yb	2.22	2.19	1.91	2.44	2.41
Lu	0.36	0.35	0.30	0.40	0.41
Hf	4.70	3.97	3.43	4.15	4.32
Ta	0.93	0.87	0.96	0.86	0.92
Th	7.15	7.83	7.46	7.99	8.26
U	4.20	3.62	3.76	3.67	3.85

Table 1 cont. (Salitral East)

Sample	040706-7A	040706-7B	040706-7C	040706-7D	040706-7E
Location					
Longitude	85.15°	85.15°	85.15°	85.15°	85.15°
Latitude	10.56°	10.56°	10.56°	10.56°	10.56°
<i>XRF analyses</i>					
SiO ₂	73.44	73.21	72.66	73.24	73.33
TiO ₂	0.32	0.32	0.35	0.31	0.30
Al ₂ O ₃	14.20	14.37	14.52	14.44	14.51
Fe ₂ O ₃	2.49	2.53	2.84	2.48	2.28
MnO	0.08	0.09	0.09	0.07	0.07
MgO	0.55	0.52	0.59	0.47	0.39
CaO	2.24	2.22	2.31	2.22	2.25
Na ₂ O	2.55	2.56	2.29	2.30	2.45
K ₂ O	4.12	4.15	4.33	4.45	4.42
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02
Total	98.10	97.50	97.61	97.83	97.55
Rb	83	76	86	83	83
Sr	334	328	343	340	349
Zr	150	150	168	147	151
<i>Laser ablation ICP-MS analyses</i>					
Y	16.13	16.66	17.77	15.44	14.34
Nb	12.22	12.89	12.59	12.61	12.56
Ba	1805	1854	1894	1870	1841
La	27.92	28.57	29.88	27.98	26.66
Ce	50.73	52.32	55.33	52.53	51.27
Pr	5.64	5.74	6.17	5.58	5.24
Nd	18.50	19.09	20.61	18.12	17.10
Sm	3.31	3.58	3.94	3.26	3.07
Eu	1.00	1.08	1.13	1.02	0.98
Tb	0.53	0.52	0.58	0.51	0.49
Dy	2.47	2.49	2.78	2.41	2.27
Ho	0.50	0.56	0.55	0.54	0.52
Er	1.60	1.77	1.82	1.73	1.68
Yb	2.00	2.16	2.23	2.07	1.88
Lu	0.30	0.33	0.34	0.31	0.31
Hf	3.37	3.38	3.67	3.40	3.39
Ta	0.94	1.02	0.93	1.05	1.05
Th	7.58	7.64	7.65	7.92	7.57
U	3.77	4.23	3.91	4.39	4.29

Table 1 cont. (Salitral East)

Sample	040706-7F	040706-7G	040706-7H	040706-7i	040706-7J
Location					
Longitude	85.15°	85.15°	85.15°	85.15°	85.15°
Latitude	10.56°	10.56°	10.56°	10.56°	10.56°
<i>XRF analyses</i>					
SiO ₂	73.31	73.38	74.30	73.19	73.26
TiO ₂	0.31	0.28	0.27	0.30	0.29
Al ₂ O ₃	14.31	14.51	13.97	14.66	14.49
Fe ₂ O ₃	2.49	2.34	2.14	2.19	2.27
MnO	0.07	0.07	0.07	0.06	0.06
MgO	0.41	0.37	0.35	0.37	0.42
CaO	2.21	2.21	1.92	2.26	2.22
Na ₂ O	2.48	2.31	2.22	2.67	2.66
K ₂ O	4.39	4.51	4.74	4.27	4.30
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02
Total	97.85	98.09	97.64	98.07	98.03
Rb	85	83	94	79	78
Sr	350	347	305	352	350
Zr	149	143	144	140	141
<i>Laser ablation ICP-MS analyses</i>					
Y	15.68	15.72	15.95	14.29	15.58
Nb	12.11	12.01	12.51	12.46	11.97
Ba	1858	1869	1938	1832	1847
La	28.46	28.35	29.86	27.63	28.56
Ce	51.63	53.47	53.89	51.64	51.56
Pr	5.53	5.45	5.73	5.39	5.67
Nd	18.62	17.94	19.22	17.39	18.76
Sm	3.40	3.26	3.42	3.03	3.40
Eu	0.98	1.01	0.98	0.99	1.02
Tb	0.53	0.52	0.52	0.49	0.53
Dy	2.35	2.32	2.41	2.29	2.49
Ho	0.49	0.49	0.52	0.49	0.49
Er	1.72	1.67	1.65	1.62	1.68
Yb	2.03	1.98	2.04	2.01	1.96
Lu	0.32	0.31	0.31	0.28	0.32
Hf	3.29	3.19	3.23	3.24	3.22
Ta	0.95	1.01	1.07	1.02	0.95
Th	7.70	7.67	8.20	7.67	7.60
U	3.78	3.85	3.93	4.19	3.71

Table 1 cont. (Salitral East)

Sample	040706-7K	040706-7L	040706-7M	040706-7N	040706-7o
<i>Location</i>					
Longitude	85.15°	85.15°	85.15°	85.15°	85.15°
Latitude	10.56°	10.56°	10.56°	10.56°	10.56°
<i>XRF analyses</i>					
SiO ₂	73.56	73.40	72.82	72.30	72.28
TiO ₂	0.30	0.29	0.31	0.35	0.34
Al ₂ O ₃	14.24	14.43	14.96	15.26	15.10
Fe ₂ O ₃	2.32	2.31	2.39	2.67	2.43
MnO	0.06	0.06	0.09	0.08	0.08
MgO	0.44	0.39	0.35	0.46	0.49
CaO	2.16	2.26	2.26	2.27	2.40
Na ₂ O	2.50	2.66	2.59	2.79	2.83
K ₂ O	4.41	4.19	4.21	3.81	4.02
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02
Total	98.03	98.23	97.63	97.98	97.76
Rb	82	78	76	67	72
Sr	335	355	356	344	363
Zr	139	141	151	177	156
<i>Laser ablation ICP-MS analyses</i>					
Y	16.58	17.08	18.48	21.26	19.28
Nb	12.19	11.43	12.25	12.83	11.94
Ba	1817	1815	1801	1722	1697
La	29.01	28.54	31.43	34.88	29.29
Ce	50.59	50.73	66.18	57.96	51.84
Pr	5.86	5.43	6.44	7.19	5.84
Nd	19.66	18.85	23.21	25.49	20.58
Sm	3.62	3.48	4.49	4.92	3.81
Eu	1.04	0.99	1.21	1.24	1.09
Tb	0.54	0.50	0.61	0.65	0.58
Dy	2.51	2.45	2.88	3.27	2.90
Ho	0.54	0.53	0.61	0.72	0.65
Er	1.74	1.70	2.03	2.17	2.07
Yb	2.11	2.06	2.46	2.79	2.47
Lu	0.34	0.36	0.39	0.48	0.40
Hf	3.22	3.02	3.17	3.92	3.19
Ta	0.97	0.89	0.96	1.00	0.94
Th	7.57	7.28	7.69	8.32	7.62
U	3.72	3.55	3.88	3.96	3.67

Table 1 cont. (Salitral East)

Sample	040706-7P	040706-7Q	040707-2B	040707-2C	040707-2D
Location					
Longitude	85.15°	85.15°	85.24°	85.24°	85.24°
Latitude	10.56°	10.56°	10.57°	10.57°	10.57°
<i>XRF analyses</i>					
SiO ₂	72.46	71.61	74.01	73.12	73.49
TiO ₂	0.33	0.36	0.26	0.31	0.28
Al ₂ O ₃	14.94	15.76	15.23	14.52	14.62
Fe ₂ O ₃	2.50	2.81	2.01	2.44	2.16
MnO	0.08	0.08	0.09	0.13	0.08
MgO	0.54	0.47	0.30	0.42	0.40
CaO	2.35	2.32	1.57	2.24	2.10
Na ₂ O	2.59	2.73	2.59	2.45	2.24
K ₂ O	4.20	3.84	3.93	4.35	4.61
P ₂ O ₅	0.02	0.02	0.01	0.02	0.02
Total	97.95	97.84	97.08	97.80	97.06
Rb	74	64	89	84	87
Sr	348	355	230	343	327
Zr	159	168	128	149	143
<i>Laser ablation ICP-MS analyses</i>					
Y	23.91	24.71	11.07	16.46	15.30
Nb	12.39	13.35	7.47	11.52	11.24
Ba	1743	1738	1199	1952	1914
La	36.23	43.63	22.27	30.18	28.88
Ce	56.86	60.95	35.40	62.46	53.26
Pr	7.34	8.77	4.72	5.90	5.81
Nd	27.21	30.81	16.14	20.20	19.69
Sm	5.22	5.57	3.20	3.57	4.04
Eu	1.36	1.38	0.90	1.03	1.14
Tb	0.73	0.78	0.42	0.51	0.51
Dy	3.72	3.66	2.07	2.64	2.62
Ho	0.80	0.75	0.42	0.55	0.54
Er	2.61	2.38	1.35	1.85	1.69
Yb	2.96	2.95	1.92	2.06	2.28
Lu	0.49	0.46	0.30	0.31	0.38
Hf	3.45	3.73	2.85	3.19	4.22
Ta	1.01	0.96	0.61	0.89	0.89
Th	7.93	8.24	5.11	7.89	8.21
U	3.93	4.05	2.30	3.81	3.70

Table 1 cont. (Salitral East)

Sample	040707-2E	040707-2F	040707-2G	040707-2H	040707-2i
Location					
Longitude	85.24°	85.24°	85.24°	85.24°	85.24°
Latitude	10.57°	10.57°	10.57°	10.57°	10.57°
XRF analyses					
SiO ₂	72.89	72.68	73.12	73.15	73.26
TiO ₂	0.34	0.33	0.30	0.31	0.31
Al ₂ O ₃	14.47	14.65	14.67	14.61	14.43
Fe ₂ O ₃	2.67	2.62	2.36	2.27	2.38
MnO	0.07	0.07	0.09	0.06	0.08
MgO	0.44	0.44	0.32	0.34	0.44
CaO	2.34	2.28	2.27	2.29	2.29
Na ₂ O	2.59	2.50	2.27	2.52	2.75
K ₂ O	4.18	4.40	4.59	4.43	4.03
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02
Total	97.81	97.25	97.43	97.10	97.76
Rb	74	82	80	80	75
Sr	352	338	352	354	345
Zr	148	147	140	144	149
Laser ablation ICP-MS analyses					
Y	16.12		14.85	15.33	16.37
Nb	11.19	11.27	11.27	11.83	11.02
Ba	1782	1770	1878	1847	1792
La	29.65	30.18	29.40	30.81	30.00
Ce	48.74	49.23	53.97	49.77	54.70
Pr	6.10	6.24	6.01	6.33	6.28
Nd	21.05	21.53	20.45	21.52	21.38
Sm	4.22	4.13	3.98	4.14	4.19
Eu	1.16	1.20	1.16	1.16	1.18
Tb	0.54	0.57	0.53	0.53	0.54
Dy	2.77		2.55	2.68	2.74
Ho	0.57		0.52	0.55	0.57
Er	1.79		1.69	1.76	1.87
Yb	2.34		2.27	2.35	2.37
Lu	0.38		0.37	0.37	0.37
Hf	4.17	4.09	3.86	4.07	4.18
Ta	0.84	0.87	0.86	0.89	0.83
Th	7.76	7.86	7.79	7.84	7.87
U	3.45	3.67	3.74	3.92	3.44

Table 1 cont. (Salitral East)

Sample	040707-2J	040706-9A	040706-9B	040706-9C	040706-8A
<i>Location</i>					
Longitude	85.24°	85.16°	85.16°	85.16°	85.16°
Latitude	10.57°	10.60°	10.60°	10.60°	10.60°
<i>XRF analyses</i>					
SiO ₂	73.56	72.36	70.91	71.13	72.60
TiO ₂	0.30	0.31	0.34	0.34	0.35
Al ₂ O ₃	14.24	15.17	16.72	16.37	14.97
Fe ₂ O ₃	2.38	2.50	2.55	2.51	2.68
MnO	0.06	0.06	0.07	0.07	0.08
MgO	0.37	0.44	0.42	0.53	0.62
CaO	2.14	2.33	2.54	2.54	2.18
Na ₂ O	2.47	2.59	2.70	2.86	2.36
K ₂ O	4.46	4.21	3.72	3.64	4.14
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02
Total	97.23	96.89	96.95	97.36	98.25
Rb	79	83	69	67	79
Sr	322	355	398	390	319
Zr	148	153	171	163	163
<i>Laser ablation ICP-MS analyses</i>					
Y	16.19	15.66	16.95	19.62	18.18
Nb	11.26	12.11	13.09	13.73	12.82
Ba	1775	1786	1854	1774	1743
La	29.91	29.43	33.19	31.94	28.04
Ce	47.60	49.20	54.96	51.17	50.66
Pr	5.98	6.21	6.77	7.29	5.81
Nd	20.21	20.95	22.33	23.40	19.87
Sm	3.97	3.91	3.94	3.90	3.80
Eu	1.09	1.14	1.19	1.21	1.05
Tb	0.50	0.57	0.60	0.62	0.61
Dy	2.70	2.73	2.87	3.08	2.97
Ho	0.56	0.53	0.56	0.62	0.61
Er	1.80	1.74	1.83	2.07	2.04
Yb	2.40	2.02	2.39	2.57	2.46
Lu	0.39	0.32	0.36	0.39	0.41
Hf	4.16	3.37	3.66	3.59	3.80
Ta	0.88	0.96	1.03	1.01	0.99
Th	8.14	7.70	8.56	8.58	8.23
U	3.56	3.76	4.22	4.17	4.05

Table 1 cont. (Salitral East)

Sample	040706-8B	040706-8C	040706-8D	040706-8E	040707-5
Location					
Longitude	85.16°	85.16°	85.16°	85.16°	85.23°
Latitude	10.60°	10.60°	10.60°	10.60°	10.63°
<i>XRF analyses</i>					
SiO ₂	71.58	71.79	71.73	72.22	72.13
TiO ₂	0.32	0.33	0.35	0.32	0.35
Al ₂ O ₃	16.20	15.94	15.66	15.31	15.37
Fe ₂ O ₃	2.54	2.53	2.69	2.48	3.04
MnO	0.09	0.07	0.10	0.12	0.10
MgO	0.57	0.58	0.56	0.46	0.50
CaO	2.38	2.24	2.41	2.33	2.22
Na ₂ O	2.53	2.46	2.67	2.50	2.32
K ₂ O	3.77	4.03	3.80	4.24	3.95
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02
Total	97.33	96.43	97.04	96.68	96.90
Rb	67	81	76	88	79
Sr	351	337	370	362	328
Zr	165	171	169	163	164
<i>Laser ablation ICP-MS analyses</i>					
Y	16.46	19.40	15.73	14.11	18.47
Nb	12.57		12.62	12.59	13.04
Ba	1726	1711	1850	1931	1790
La	27.33	30.57	27.60	27.60	31.02
Ce	56.56	51.35	53.54	54.73	62.36
Pr	5.60	5.97	5.66	5.40	6.70
Nd	19.03	20.46	18.76	18.13	23.03
Sm	3.58	4.10	3.63	3.25	4.09
Eu	1.23	1.21	1.11	1.05	1.15
Tb	0.51	0.59	0.56	0.45	0.55
Dy	2.55	3.00	2.63	2.21	2.83
Ho	0.62	0.85	0.52	0.57	0.71
Er	1.83	2.60	1.74	1.67	2.02
Yb	2.06	2.72	1.96	1.80	2.26
Lu	0.34	0.44	0.30	0.29	0.38
Hf	3.68		3.63	3.46	3.59
Ta	1.02		0.96	0.95	1.01
Th	8.11		7.70	7.49	7.57
U			4.03		

Table 1 cont. (Virginia)

Sample	010627-3f	010629-1a	020709-3c	020709-3d	020709-3g
Location					
Longitude	85.42°	85.35°	85.38°	85.38°	85.38°
Latitude	10.72°	10.54°	10.75°	10.75°	10.75°
<i>XRF analyses</i>					
SiO ₂	73.12	78.73	73.81	73.85	72.43
TiO ₂	0.23	0.21	0.36	0.40	0.44
Al ₂ O ₃	16.41	11.89	14.63	14.75	14.95
Fe ₂ O ₃	1.74	1.50	2.39	2.71	3.30
MnO	0.08	0.04	0.08	0.08	0.08
MgO	0.26	0.39	0.46	0.51	0.61
CaO	1.61	1.67	2.02	1.98	2.25
Na ₂ O	2.65	2.36	1.83	1.69	2.35
K ₂ O	3.86	3.16	4.35	3.97	3.52
P ₂ O ₅	0.04	0.05	0.05	0.05	0.07
Total	96.00	98.00	95.32	95.03	96.12
Rb	85	78	92	86	76
Sr	238	252	290	278	307
Zr	140	104	221	224	222
<i>Laser ablation ICP-MS analyses</i>					
Y	19.25	12.45	15.88	17.21	23.86
Nb	10.31	8.56	9.19	9.53	8.2
Ba	3687	2328	1767	1797	1671
La	28.3	27.21	29.04	29.63	30.16
Ce	51.76	37.82	53.12	53.81	52.85
Pr	5.12	4.76	5.97	6.07	7.05
Nd	16.23	14.92	19.8	20.45	27.54
Sm	2.91	2.65	3.58	3.69	4.89
Eu	0.99	0.79	1.01	1.02	1.37
Tb	0.47	0.37	0.51	0.55	0.79
Dy	2.4	1.82	2.65	2.76	3.96
Ho	0.53	0.38	0.49	0.54	0.77
Er	1.69	1.15	1.59	1.67	2.33
Yb	3.26	1.94	2.15	2.19	2.87
Lu	0.42	0.23	0.31	0.33	0.45
Hf	3.4	2.54	4.89	5.15	5.25
Ta	1.34	1.12	1.14	1.05	1.11
Th	9.14	6.25	8.42	8.58	8.41
U	6.14	5.49	5.41	5.37	5.06

Table 1 cont. (Virginia)

Sample	020709-3h	020709-4a	020709-4b	020709-4c	020712-1b	020712-1c
<i>Location</i>						
Longitude	85.38°	85.42°	85.42°	85.42°	85.46°	85.46°
Latitude	10.75°	10.72°	10.72°	10.72°	10.70°	10.70°
<i>XRF analyses</i>						
SiO ₂	72.93	68.90	71.01	70.79	69.58	71.20
TiO ₂	0.40	0.47	0.47	0.42	0.43	0.48
Al ₂ O ₃	14.89	18.22	15.62	16.01	17.21	15.14
Fe ₂ O ₃	2.75	3.60	3.47	3.18	3.36	3.82
MnO	0.15	0.12	0.12	0.07	0.08	0.07
MgO	0.54	0.42	0.37	0.38	0.32	0.58
CaO	2.29	2.21	2.32	2.50	2.70	2.16
Na ₂ O	2.44	2.28	2.18	2.35	2.26	2.50
K ₂ O	3.57	3.73	4.38	4.24	4.01	4.00
P ₂ O ₅	0.05	0.05	0.05	0.05	0.05	0.05
Total	96.09	95.54	96.70	97.03	96.80	96.80
Rb	77	78	93	87	83	84
Sr	318	325	346	369	406	320
Zr	219	208	211	203	209	224
<i>Laser ablation ICP-MS analyses</i>						
Y	18.2	21.95	21.1	20.8	19.43	19.27
Nb	8.8	10.49	12.05	10.24	8.52	11.37
Ba	1773	1993	1964	1860	1862	1776
La	29.86	35.17	36.46	36.27	34.38	32.64
Ce	54.2	73.93	70.49	61.5	61.78	61.55
Pr	6.39	8.87	8.4	8.04	7.97	7.01
Nd	22.73	33.19	29.89	29.52	29.15	24.80
Sm	4.1	6.4	5.58	5.52	5.62	4.68
Eu	1.2	1.46	1.34	1.36	1.47	1.13
Tb	0.58	0.83	0.78	0.74	0.70	0.61
Dy	2.96	3.99	3.68	3.56	3.63	3.28
Ho	0.61	0.8	0.71	0.69	0.80	0.61
Er	1.78	2.47	2.22	2.15	2.23	1.97
Yb	2.39	3.02	2.73	2.63	2.58	2.62
Lu	0.36	0.41	0.41	0.41	0.40	0.39
Hf	5.02	5.12	5.07	4.95	4.89	5.29
Ta	1.03	1.4	1.27	1.12	1.22	1.25
Th	8.11	9.77	9.26	9.18	9.26	9.98
U	5.01	8.05	6.63	5.41	6.06	5.56

Table 1 cont. (Virginia)

Sample	020712-1d
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Location

Longitude	85.46°
Latitude	10.70°

XRF analyses

SiO ₂	70.57
TiO ₂	0.38
Al ₂ O ₃	17.10
Fe ₂ O ₃	2.88
MnO	0.07
MgO	0.29
CaO	1.99
Na ₂ O	2.31
K ₂ O	4.36
P ₂ O ₅	0.05
Total	95.60
Rb	91
Sr	305
Zr	198

Laser ablation ICP-MS analyses

Y	17.79
Nb	10.33
Ba	1936
La	31.88
Ce	59.02
Pr	6.64
Nd	23.15
Sm	4.22
Eu	1.12
Tb	0.60
Dy	3.02
Ho	0.58
Er	1.87
Yb	2.37
Lu	0.37
Hf	5.45
Ta	1.49
Th	10.92
U	5.39

Table 1 cont. (Liberia)

Sample	990718-1-1	990718-1-2	990718-1-3	990718-1-4	990718-1-5
Location					
Longitude	85.26°	85.26°	85.26°	85.26°	85.26°
Latitude	10.56°	10.56°	10.56°	10.56°	10.56°
<i>XRF analyses</i>					
SiO ₂	72.23	74.77	72.96	73.78	74.12
TiO ₂	0.29	0.21	0.25	0.26	0.22
Al ₂ O ₃	17.13	14.04	16.03	15.53	14.80
Fe ₂ O ₃	2.00	1.56	1.61	1.78	1.59
MnO	0.04	0.07	0.06	0.06	0.07
MgO	0.49	0.35	0.41	0.44	0.37
CaO	1.57	1.64	1.69	1.53	1.72
Na ₂ O	2.32	2.40	2.51	2.18	2.45
K ₂ O	3.92	4.93	4.45	4.42	4.64
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02
T _{total}	98.00	98.00	97.00	98.00	98.00
R _b	94	104	110	109	115
S _r	241	249	257	239	263
N _r	150	133	135	146	127
<i>Laser ablation ICP-MS analyses</i>					
Y	13.87	10.62	14.17	10.87	19.9
Z _b	8.98	7.45	6.9	8.17	6.6
B _a	1591	1660	1651	1779	1579
F _a	24.67	20.91	26.25	22.23	34.1
O _e	50.25	36.87	46.56	43.74	
T _r	5.49	4.1	4.93	4.23	
Z _d	19.78	12.85	16.34	14.51	
M _m	3.73	2.46	2.67	2.44	
U _u	1.06	1.09	0.63	0.87	
B _b	0.46	0.36	0.33	0.37	
Y _y	2.47	1.84	1.95	1.81	
O _o	0.45	0.35	0.42	0.34	
R _r	1.37	0.91	1.32	1.22	
B _b	2.11	1.87	1.58	1.87	
U _u	0.31	0.24	0.26	0.2	
F _f	4.23	3.14	3.45	3.99	
A _a	2.07	1.68	1.12	2.1	
H _h	9.46	7.53	9.47	8.07	
C	3.51	3.22	5.8	3.83	

Table 1 cont. (Liberia)

Sample	990718-1-6	990718-1-7	990718-1-8	990718-1-9	990718-1-10
Location					
Longitude	85.26°	85.26°	85.26°	85.26°	85.26°
Latitude	10.56°	10.56°	10.56°	10.56°	10.56°
XRF analyses					
SiO ₂	74.29	73.61	76.10	73.51	74.19
TiO ₂	0.24	0.24	0.22	0.27	0.24
Al ₂ O ₃	14.26	15.12	13.44	14.99	14.49
Fe ₂ O ₃	1.70	1.86	1.38	1.91	1.64
MnO	0.06	0.05	0.05	0.07	0.06
MgO	0.48	0.35	0.34	0.52	0.41
CaO	1.83	1.76	1.65	1.70	1.73
Na ₂ O	2.76	2.62	2.57	2.43	2.82
K ₂ O	4.36	4.38	4.22	4.58	4.40
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02
T _{total}	99.00	98.00	100.00	98.00	97.00
R _b	115	92	101	121	89
S _r	281	274	262	256	264
N _r	138	142	113	142	144
Laser ablation ICP-MS analyses					
Y _b	9.54	12.13	9.33	11	9.54
Z _b	7.1	7.64	7.61	7.66	7.63
B _a	1721	1749	1545	1820	1793
L _a	21.53	23.65	19.11	23.21	22.08
C _e	38.16	42.88	33.33	40.28	39.83
T _r	4.25	4.58	3.71	4.39	4.16
Z _d	13.59	16.48	11.01	14.45	13.36
M _m	2.17	2.73	2.28	2.15	2.08
U _u	0.95	1.1	1.1	0.92	1
B _b	0.36	0.38	0.31	0.39	0.32
Y _y	1.75	1.98	1.31	1.89	1.76
I _o	0.29	0.38	0.3	0.34	0.29
R _r	0.97	1.11	0.92	1.09	0.9
B _b	1.86	2.04	1.59	2.12	1.73
U _u	0.18	0.3	0.21	0.23	0.21
I _i	3.6	3.74	2.72	4.01	3.49
A _a	1.54	1.74	1.5	1.98	1.84
T _t	7.19	7.59	6.49	8.35	7.79
C _c	3.45	3.64	2.92	3.37	3.86

Table 1 cont. (Liberia)

Sample	990718-1-11	990718-1-12	990718-1-13	020712-1b	020712-1c
<i>Location</i>					
Longitude	85.26°	85.26°	85.26°	85.46°	85.46°
Latitude	10.56°	10.56°	10.56°	10.70°	10.70°
<i>XRF analyses</i>					
SiO ₂	72.75	73.98	73.69	69.58	71.20
TiO ₂	0.29	0.22	0.28	0.43	0.48
Al ₂ O ₃	16.22	15.02	14.63	17.21	15.14
Fe ₂ O ₃	2.05	1.61	2.05	3.36	3.82
MnO	0.05	0.05	0.06	0.08	0.07
MgO	0.47	0.35	0.65	0.32	0.58
CaO	1.66	1.66	1.82	2.70	2.16
Na ₂ O	2.62	2.39	2.76	2.26	2.50
K ₂ O	3.87	4.69	4.05	4.01	4.00
P ₂ O ₅	0.02	0.02	0.02	0.05	0.05
Total	97.00	98.00	98.00	96.80	96.80
Rb	86	108	120	83	84
Sr	253	251	257	406	320
Zr	160	143	167	209	224
<i>Laser ablation ICP-MS analyses</i>					
Y	13.06	12.07	14.45	19.43	19.27
Nb	8.22	7.55	7.4	8.52	11.37
Ba	1701	1744	1608	1862	1776
La	26.14	25.59	25.62	34.38	32.64
Ce	48.83	46.43	44.62	61.78	61.55
Pr	5.56	5.45	5.53	7.97	7.01
Nd	19.22	18.77	19.84	29.15	24.8
Sm	3.61	3.27	3.67	5.62	4.68
Eu	1.13	1.08	1.07	1.47	1.13
Tb	0.45	0.4	0.5	0.7	0.61
Dy	2.45	2.12	2.45	3.63	3.28
Ho	0.41	0.37	0.46	0.8	0.61
Er	1.34	1.25	1.41	2.23	1.97
Yb	2.01	1.9	2.02	2.58	2.62
Lu	0.32	0.27	0.27	0.4	0.39
Hf	3.82	3.55	4.16	4.89	5.29
Ta	1.99	1.95	1.66	1.22	1.25
Th	8.39	8.21	7.91	9.26	9.98
U	3.6	3.82	3.3	6.06	5.56

Table 1 cont. (Liberia)

Sample	020712-1d	020712-1e	020712-1f	020712-1g	020712-1g #1
Location					
Longitude	85.46°	85.46°	85.46°	85.46°	85.46°
Latitude	10.70°	10.70°	10.70°	10.70°	10.70°
<i>XRF analyses</i>					
SiO ₂	70.57	73.74	74.31	73.43	74.38
TiO ₂	0.38	0.20	0.20	0.22	0.21
Al ₂ O ₃	17.10	15.48	15.30	16.34	14.83
Fe ₂ O ₃	2.88	1.57	1.56	1.52	1.57
MnO	0.07	0.06	0.07	0.06	0.06
MgO	0.29	0.24	0.18	0.26	0.23
CaO	1.99	1.49	1.35	1.24	1.48
Na ₂ O	2.31	2.35	2.30	2.13	2.35
K ₂ O	4.36	4.82	4.71	4.76	4.86
P ₂ O ₅	0.05	0.05	0.04	0.05	0.04
Total	95.60	97.40	97.10	96.30	96.60
Rb	91	109	104	108	110
Sr	305	214	197	198	225
Zr	198	116	144	135	136
<i>Laser ablation ICP-MS analyses</i>					
Y	17.79		11.82		11.24
Nb	10.33		8.47		7.11
Ba	1936		1985		1936
La	31.88		26.84		26.6
Ce	59.02		52.34		49.57
Pr	6.64		4.8		4.67
Nd	23.15		15.65		15.16
Sm	4.22		2.6		2.19
Eu	1.12		0.72		0.74
Tb	0.6		0.36		0.36
Dy	3.02		1.91		1.82
Ho	0.58		0.4		0.36
Er	1.87		1.3		1.18
Yb	2.37		1.9		1.84
Lu	0.37		0.27		0.27
Hf	5.45		3.71		3.55
Ta	1.49		1.8		1.59
Th	10.92		11.96		10.69
U	5.39		7.13		6.89

Table 1 cont. (Liberia)

Sample	020712-1g #2	020712-1g #4
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Location

Longitude	85.46°	85.46°
Latitude	10.70°	10.70°

XRF analyses

SiO ₂	73.81	75.09
TiO ₂	0.19	0.15
Al ₂ O ₃	15.31	14.61
Fe ₂ O ₃	1.51	1.24
MnO	0.07	0.06
MgO	0.22	0.08
CaO	1.76	1.47
Na ₂ O	3.08	2.57
K ₂ O	4.01	4.68
P ₂ O ₅	0.04	0.04
Total	97.60	98.10
Rb	94	98
Sr	262	230
Zr	127	118

Laser ablation ICP-MS analyses

Y	13.09	11.42
Nb	4.85	4.88
Ba	2326	1918
La	28.89	26.81
Ce	50.71	46.95
Pr	4.67	4.48
Nd	15.56	15.04
Sm	2.54	2.35
Eu	0.8	0.66
Tb	0.38	0.36
Dy	2.05	1.84
Ho	0.47	0.4
Er	1.6	1.31
Yb	1.89	1.8
Lu	0.32	0.27
Hf	3.73	3.34
Ta	1.42	1.39
Th	10.72	11.44
U	5.72	6.6

Table 1 cont. (Buena Vista)

Sample	990718-2b-1	990718-2b-2	990718-2c	990718-2d-1	990718-2d-2
Location					
Longitude	85.24°	85.24°	85.24°	85.24°	85.24°
Latitude	10.62°	10.62°	10.62°	10.62°	10.62°
<i>XRF analyses</i>					
SiO ₂	69.79	70.03	67.92	72.33	68.49
TiO ₂	0.52	0.50	0.53	0.32	0.53
Al ₂ O ₃	15.46	15.52	16.72	15.18	16.53
Fe ₂ O ₃	3.92	3.55	4.07	2.52	4.19
MnO	0.11	0.15	0.11	0.08	0.07
MgO	0.70	0.65	1.04	0.61	0.52
CaO	3.01	2.78	3.35	2.28	3.14
Na ₂ O	2.97	2.84	2.90	2.77	2.61
K ₂ O	3.46	3.93	3.32	3.89	3.86
P ₂ O ₅	0.05	0.05	0.03	0.02	0.05
Total	98.00	97.00	98.00	98.00	98.00
Rb	60	71	58	77	74
Sr	416	377	404	370	427
Zr	206	215	212	158	204
<i>Laser ablation ICP-MS analyses</i>					
Y	17.63	20.21	20.99	17.18	18.35
Nb	9.01	8.63	8.87	10.46	8.68
Ba	1699	1690	1455	1721	1548
La	24.94	25.86	25	31.89	24.43
Ce	61.16	56.63	55.32	56.23	47.71
Pr	5.91	6.47	6.56	6.61	5.42
Nd	22.05	22.51	26.21	22.17	20.27
Sm	4.35	4.75	5.61	3.89	3.77
Eu	1.22	1.61	1.69	1.25	1.28
Tb	0.56	0.68	0.71	0.49	0.58
Dy	2.82	3.45	3.41	2.71	2.67
Ho	0.45	0.64	0.72	0.52	0.44
Er	1.95	1.86	1.98	1.56	2.16
Yb	2.29	2.68	2.74	2.28	2.23
Lu	0.34	0.38	0.39	0.36	0.34
Hf	3.79	4.81	3.61	3.95	3.73
Ta	0.96	1.2	0.9	1.42	0.92
Th	4.16	5.86	4.05	8.27	4.31
U	2.69	2.74	2.61	2.73	2.16

Table 1 cont. (Buena Vista)

Sample	990718-2d-3	990718-2d-4	990718-2d-5	990718-3a	990718-3-1
Location					
Longitude	85.24°	85.24°	85.24°	85.23°	85.23°
Latitude	10.62°	10.62°	10.62°	10.62°	10.62°
<i>XRF analyses</i>					
SiO ₂	72.90	69.97	68.79	72.48	73.05
TiO ₂	0.32	0.49	0.50	0.33	0.30
Al ₂ O ₃	14.71	15.87	16.95	14.62	14.42
Fe ₂ O ₃	2.41	3.82	3.50	2.63	2.50
MnO	0.07	0.08	0.10	0.07	0.07
MgO	0.65	0.34	0.71	0.67	0.54
CaO	2.28	2.74	3.11	2.28	2.21
Na ₂ O	2.81	2.41	2.74	2.87	2.55
K ₂ O	3.81	4.22	3.59	4.03	4.32
P ₂ O ₅	0.03	0.04	0.03	0.02	0.02
Total	98.00	97.00	98.00	98.00	99.00
Rb	85	80	58	80	84
Sr	368	379	385	368	357
Zr	160	212	219	166	156
<i>Laser ablation ICP-MS analyses</i>					
Y	11.6	23.14	18.58	13.26	14.67
Nb	10.15	8.78	8.98	10.15	10.2
Ba	1735	1624	1310	1733	1807
La	28.23	28.73	25.8	30.04	35.68
Ce	47.68	54.32	53.34	51.33	61.24
Pr	5.13	6.59	5.83	5.86	7.09
Nd	17.3	26.12	21.69	20.1	24.25
Sm	2.85	5.02	4.34	3.32	4.08
Eu	0.96	1.34	1.16	1.05	1.14
Tb	0.36	0.66	0.58	0.42	0.46
Dy	1.77	3.41	3.36	2.15	2.36
Ho	0.21	0.62	0.67	0.34	0.36
Er	1.08	2.19	2.07	1.45	1.51
Yb	1.58	2.71	2.4	2.01	2.03
Lu	0.22	0.44	0.38	0.31	0.33
Hf	3.05	4.5	5.73	3.42	3.31
Ta	1.32	1	0.86	1.26	1.38
Th	6.24	4.94	5.93	6.51	6.39
U	2.52	2.33	2.35	2.62	2.84

Table 1 cont. (Buena Vista)

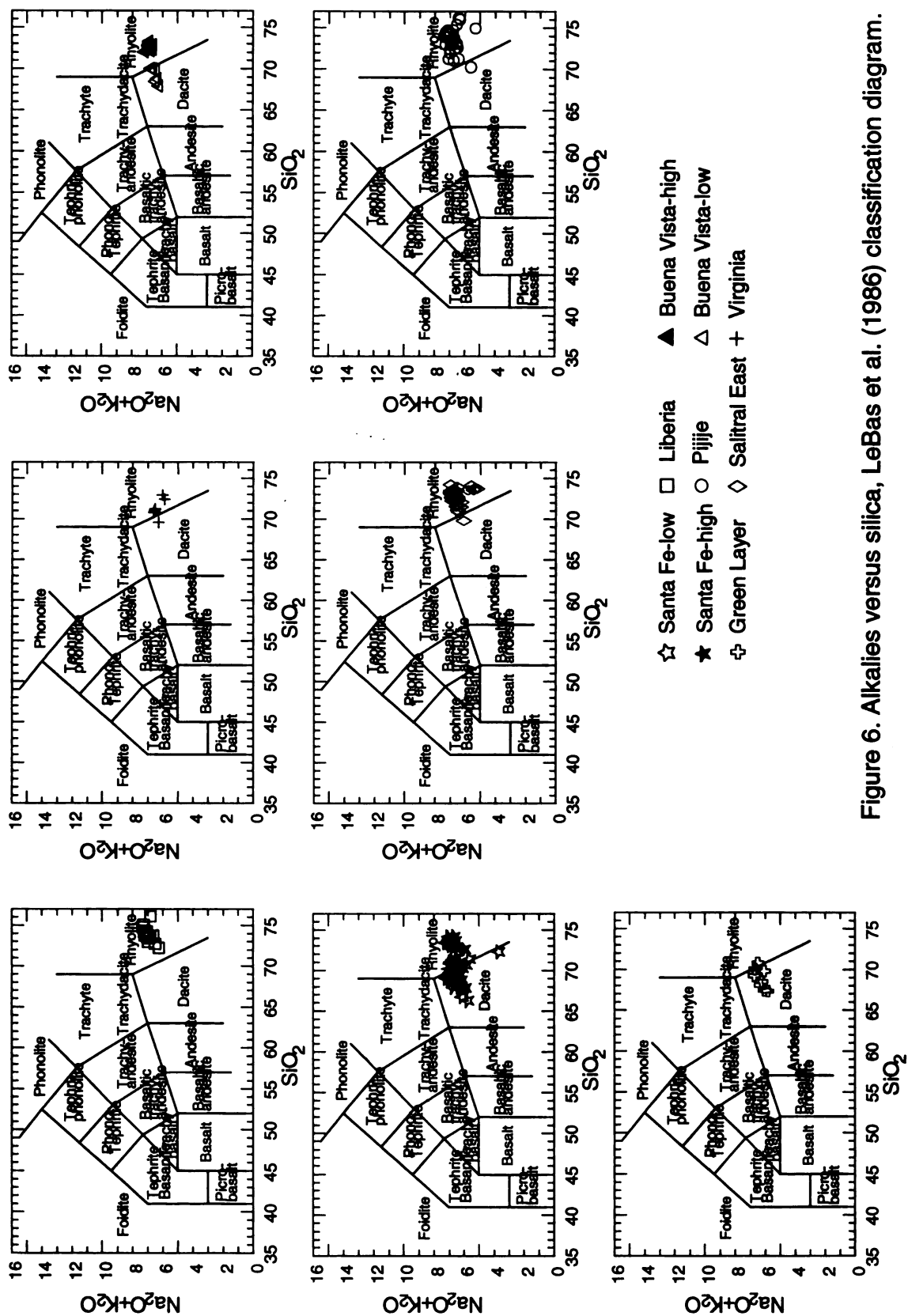
Sample	990718-3-2	990718-3-3	990718-3-4	990718-3-5	990718-3-6
Location					
Longitude	85.23°	85.23°	85.23°	85.23°	85.23°
Latitude	10.62°	10.62°	10.62°	10.62°	10.62°
<i>XRF analyses</i>					
SiO ₂	72.04	72.71	72.83	73.34	72.18
TiO ₂	0.32	0.33	0.31	0.31	0.31
Al ₂ O ₃	14.88	14.37	14.63	14.12	15.00
Fe ₂ O ₃	2.52	2.61	2.36	2.44	2.49
MnO	0.07	0.07	0.06	0.07	0.07
MgO	0.61	0.77	0.60	0.65	0.67
CaO	2.33	2.23	2.28	2.17	2.42
Na ₂ O	3.05	2.68	2.53	2.58	2.74
K ₂ O	4.14	4.23	4.38	4.31	4.09
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02
Total	100.00	98.00	98.00	99.00	99.00
Rb	86	90	82	81	78
Sr	395	350	373	347	401
Zr	155	166	160	154	164
<i>Laser ablation ICP-MS analyses</i>					
Y	14.73	15.22	14.16	13.32	14.88
Nb	11.14	9.59	9.66	10.7	9.72
Ba	1743	1709	1798	1679	1765
La	37.26	32.44	32.33	34.62	33
Ce	60.38	52.29	48.11	52.63	55.57
Pr	7.76	6.17	6.01	6.53	6.46
Nd	28.58	21.92	21.23	23.04	22.71
Sm	4.87	3.7	3.58	3.52	3.87
Eu	1.26	1.09	1.07	1.04	1.13
Tb	0.55	0.46	0.43	0.47	0.47
Dy	2.82	2.3	2.21	2.46	2.31
Ho	0.58	0.39	0.32	0.49	0.38
Er	1.74	1.45	1.38	1.57	1.56
Yb	2.26	1.87	1.89	2.15	1.95
Lu	0.35	0.3	0.32	0.31	0.32
Hf	3.73	3.79	3.59	3.66	3.24
Ta	1.23	1.21	1.24	1.27	1.29
Th	7.81	6.74	6.75	8.03	6.39
U	2.79	2.44	2.46	2.63	2.62

Table 1 cont. (Buena Vista)

Sample	990718-3-7	990718-3-8	990718-4-1	990718-4a	990718-4-2
Location					
Longitude	85.23°	85.23°	85.23°	85.23°	85.23°
Latitude	10.62°	10.62°	10.62°	10.62°	10.62°
<i>XRF analyses</i>					
SiO ₂	72.39	72.65	73.30	72.87	72.57
TiO ₂	0.33	0.32	0.31	0.32	0.34
Al ₂ O ₃	14.70	14.69	14.39	14.55	14.42
Fe ₂ O ₃	2.68	2.51	2.41	2.52	2.76
MnO	0.09	0.09	0.08	0.08	0.08
MgO	0.69	0.60	0.53	0.60	0.68
CaO	2.28	2.23	2.06	2.13	2.27
Na ₂ O	2.85	2.75	2.56	2.61	2.82
K ₂ O	3.96	4.14	4.33	4.31	4.03
P ₂ O ₅	0.02	0.02	0.02	0.02	0.02
Total	98.00	98.00	98.00	97.00	97.00
Rb	75	78	88	81	79
Sr	369		337	348	355
Zr	166	159	154	161	166
<i>Laser ablation ICP-MS analyses</i>					
Y	19.3		17.08	14.16	11.92
Nb	11.55		10.23	11.36	11.05
Ba	1745		1771	1739	1664
La	38.54		34.88	35.29	35.12
Ce	66.35		61.95	55.3	57.18
Pr	8.53		7.39	6.58	6.41
Nd	32.25		23.98	22.89	22.2
Sm	5.37		3.91	3.76	3.78
Eu	1.38		1.26	1.07	1.08
Tb	0.62		0.54	0.47	0.47
Dy	3.36		2.72	2.43	2.36
Ho	0.71		0.52	0.49	0.48
Er	2.01		1.62	1.67	1.41
Yb	2.63		2.21	2.14	2.06
Lu	0.42		0.36	0.36	0.3
Hf	3.73		3.71	3.77	3.87
Ta	1.3		1.57	1.33	1.2
Th	7.69		8.75	7.86	7.5
U	2.9		2.95	2.84	2.76

Table 1 cont. (Buena Vista)

Sample	990718-4-3	990718-4-4	990718-4-5
Location			
Longitude	85.23°	85.23°	85.23°
Latitude	10.62°	10.62°	10.62°
<i>XRF analyses</i>			
SiO ₂	72.42	72.15	72.55
TiO ₂	0.34	0.32	0.33
Al ₂ O ₃	14.72	14.86	14.58
Fe ₂ O ₃	2.61	2.54	2.58
MnO	0.07	0.07	0.08
MgO	0.67	0.76	0.70
CaO	2.31	2.50	2.37
Na ₂ O	2.64	2.71	2.66
K ₂ O	4.21	4.07	4.12
P ₂ O ₅	0.02	0.02	0.02
Total	98.00	98.00	98.00
Rb	81	77	79
Sr	372	397	374
Zr	153	158	163
<i>Laser ablation ICP-MS analyses</i>			
Y	12.31	11.62	13.03
Nb	11.09	10.42	10.35
Ba	1747	1658	1655
La	33.43	32.84	35.35
Ce	53.41	50.46	50.24
Pr	6.22	6.13	6.39
Nd	21.34	21.17	22.38
Sm	3.72	3.69	3.89
Eu	1.1	1.11	1.08
Tb	0.45	0.46	0.45
Dy	2.42	2.23	2.55
Ho	0.47	0.47	0.51
Er	1.44	1.37	1.44
Yb	1.93	1.76	2.03
Lu	0.31	0.27	0.3
Hf	3.57	3.77	3.9
Ta	1.33	1.16	1.19
Th	7.29	7.23	7.46
U	2.81	2.52	2.49



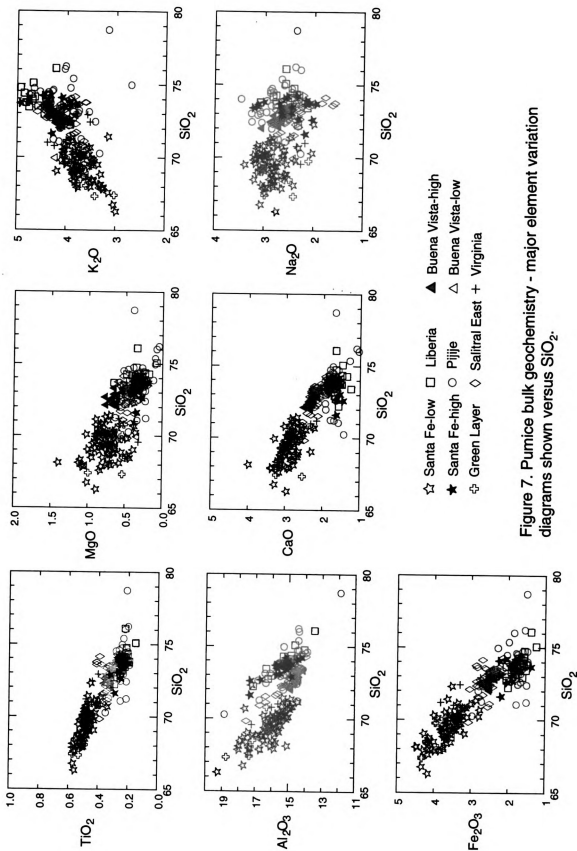


Figure 7. Pumice bulk geochemistry - major element variation diagrams shown versus SiO₂.

1.2 Trace elements

Trace element variations with respect to SiO_2 are illustrated in Figure 8. The units show little variation with respect to (High field strength elements) HFSE: Nb-Ta with increasing SiO_2 content. The Nb remains constant, while there is a slight increase in Ta among units. The Liberia unit is an outlier in regards to both HFSE, it has lower Nb and higher Ta than the other units. There are slight decreases in middle rare earth elements (MREE), heavy rare earth elements (HREE), and Sr with increasing SiO_2 content. However, the Green Layer unit is a notable outlier in HREE, displaying lower values than the other samples from the same SiO_2 range. Light rare earth elements (LREE) content remains relatively constant between the two SiO_2 groups.

Spider diagrams for each of the seven geochemical units are depicted in Figures 9 and 10. Figure 9 (normalized to primitive mantle) displays enrichment in large ion lithophiles (LIL) and depletion in the HFSE and Phosphorus. The first two patterns are similar to magmas generated in subduction zone environments. Figure 10 (normalized to chondrite) shows all of the units are enriched in LREE and some units are depleted in MREE relative to the HREE. The Green Layer and some selected samples of the Santa Fe-high/low do not display the HREE depletion. The Santa Fe unit range of REE trends encompass all of those displayed by the other units. The units defined in this study have slight positive and negative anomalies (Eu/Eu^* range 1.57-0.55) and all have slight negative anomalies (Eu/Eu^* 0.5-0.8).

The cumulative frequency distribution of incompatible trace element ratios aided in identifying compositional distinctions among the set of ash-flow sheets (Figure 11). This type of statistical data analysis can separate the data set based on the frequency

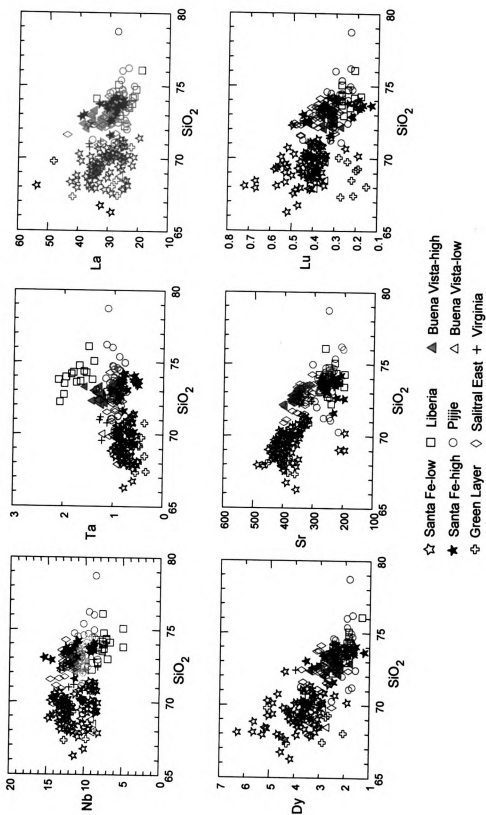


Figure 8. Pumice bulk geochemistry – trace element variation shown versus SiO_2 .

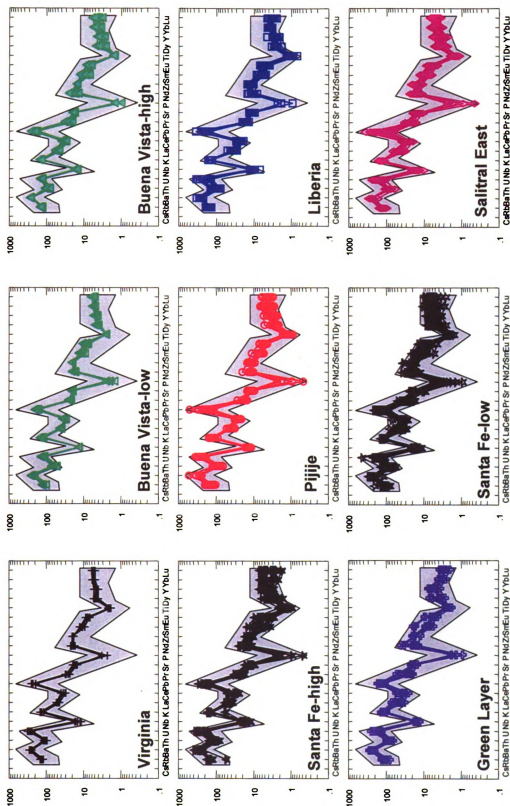


Figure 9. Spider diagrams of representative pumice fragments from each of the seven depositional units of the Guachipelin Caldera. Samples normalized to primitive mantle value of Sun and McDonough (1989). Gray area represents entire set of Guachipelin pumice fragments sampled.

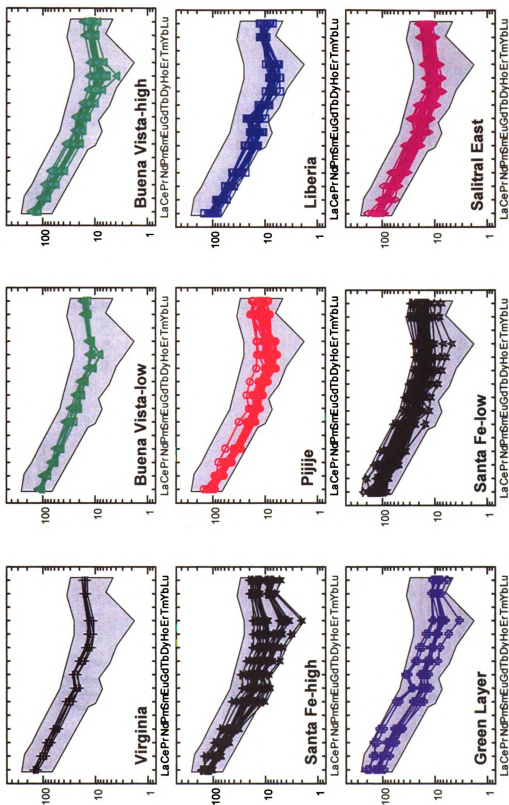


Figure 10. REE normalized diagrams of representative pumice fragments from each of the seven depositional units of the Guachipelin Caldera. Note the wide range of values the Santa Fe unit encompasses relative to the other units. Samples normalized to chondrite value of Sun and McDonough (1989). The symbols are the same as previous figures.

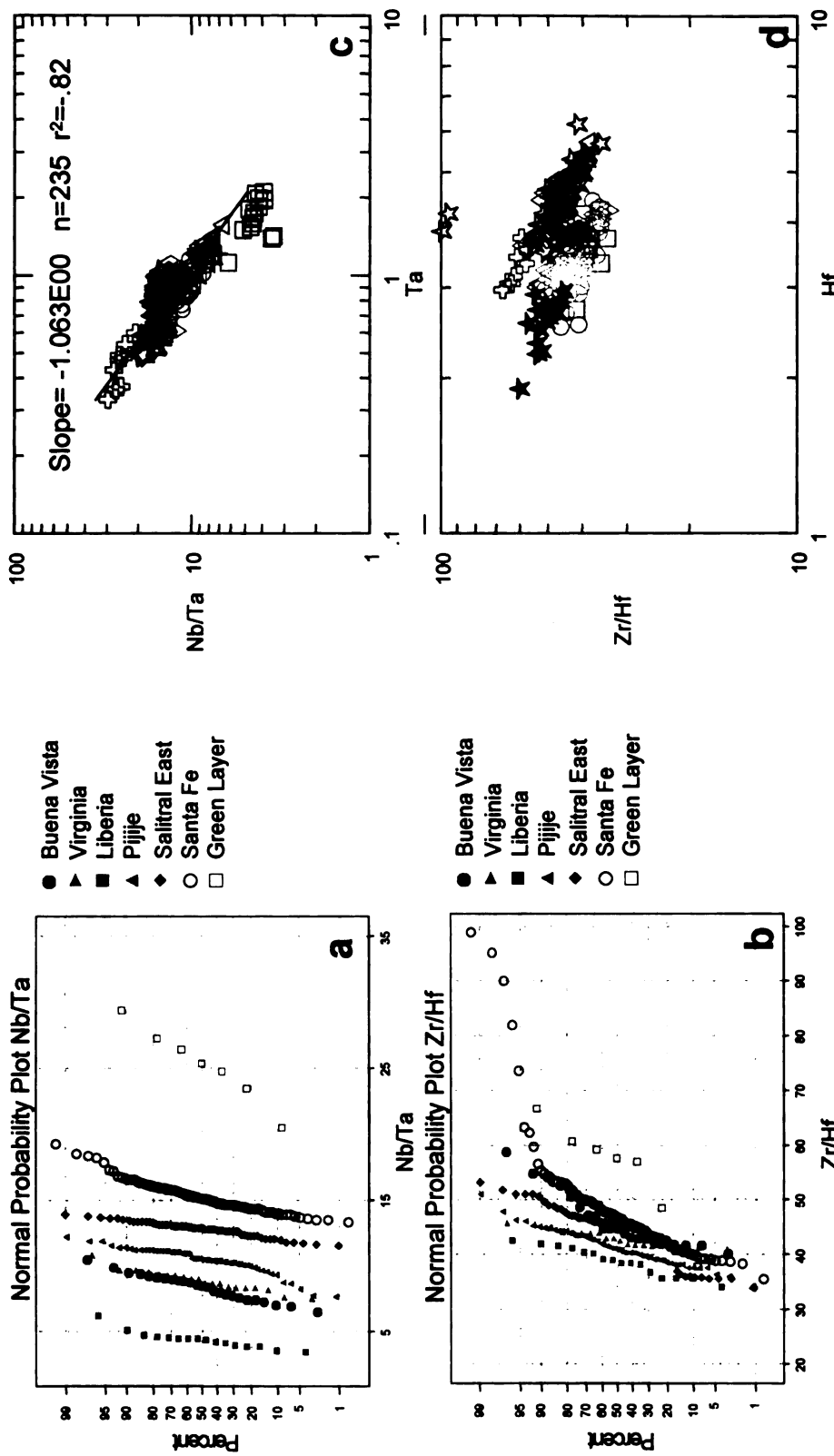


Figure 11a-d. a) and b) are cumulative frequency plots of incompatible trace element ratios Nb/Ta and Zr/Hf, respectively. Both a) and c) display distinct variations among units. The Nb/Ta ratio demonstrates that clear compositional breaks exist within the Guachipelin pyroclastic deposits; however, Zr/Hf ratios do not separate the units as clearly. The Log-Log plots c) and d) are used to illustrate systematic variations among units based on the aforementioned ratios. A slope closer to one indicates a systematic control of the ratios by the element plotted on the X-axis, while slopes much less than one suggest less of a control by that element. d) Slope is not given, but the Hf control on two parallel trending groups is evident.

distribution of samples. The slope of the cumulative frequency distribution represents the standard deviation from the mean. Breaks in the sample distribution can indicate the presence of a compositionally distinct “unit” based on the element ratio used. A more vertical slope indicates less variance from the mean within an individual unit (Figure 11a). Equally incompatible elements would not be affected by processes of differentiation such as fractional crystallization or low degrees of partial melting. Therefore, these types of element ratios are used to discriminate among ash-flow sheets from independent sources.

Figure 11a,b displays two incompatible trace element ratios that could be affected by processes related to melting processes in subduction zones. Nb/Ta ratios were used to distinguish among the seven compositionally distinct ash-flow sheets (Figure 11a). These ash-flow sheets display a wide range of Nb/Ta values from 4 to 29. The seven units, including high and low silica subgroups of the Santa Fe and Buena Vista, with corresponding Nb/Ta averages (± 1 standard deviation) are as follows: Green Layer (25.15 ± 2.5), Santa Fe-low (15.22 ± 1.14), Santa Fe-high (15.20 ± 1.37), Salitral East (12.81 ± 0.50), Pijije (10.57 ± 1.09), Liberia (4.34 ± 1.39), Virginia (8.13 ± 0.92), Buena Vista-low (9.18 ± 1.12), Buena Vista-high (8.15 ± 0.75). The high and low silica groups of Santa Fe have very similar Nb/Ta ratios with little deviation from the mean. In comparison the Buena Vista groups are within their respective standard deviations from one another, but the Buena Vista-high appears to be more similar to the Virginia unit. In comparison to other ignimbrite deposits from the Central American arc, the Nb/Ta ratios in these samples cover a wider range than all the other samples (Figure 12). In contrast,

the Zr/Hf ratios show significant overlaps and breaks in unit cumulative frequency (Figure 11b).

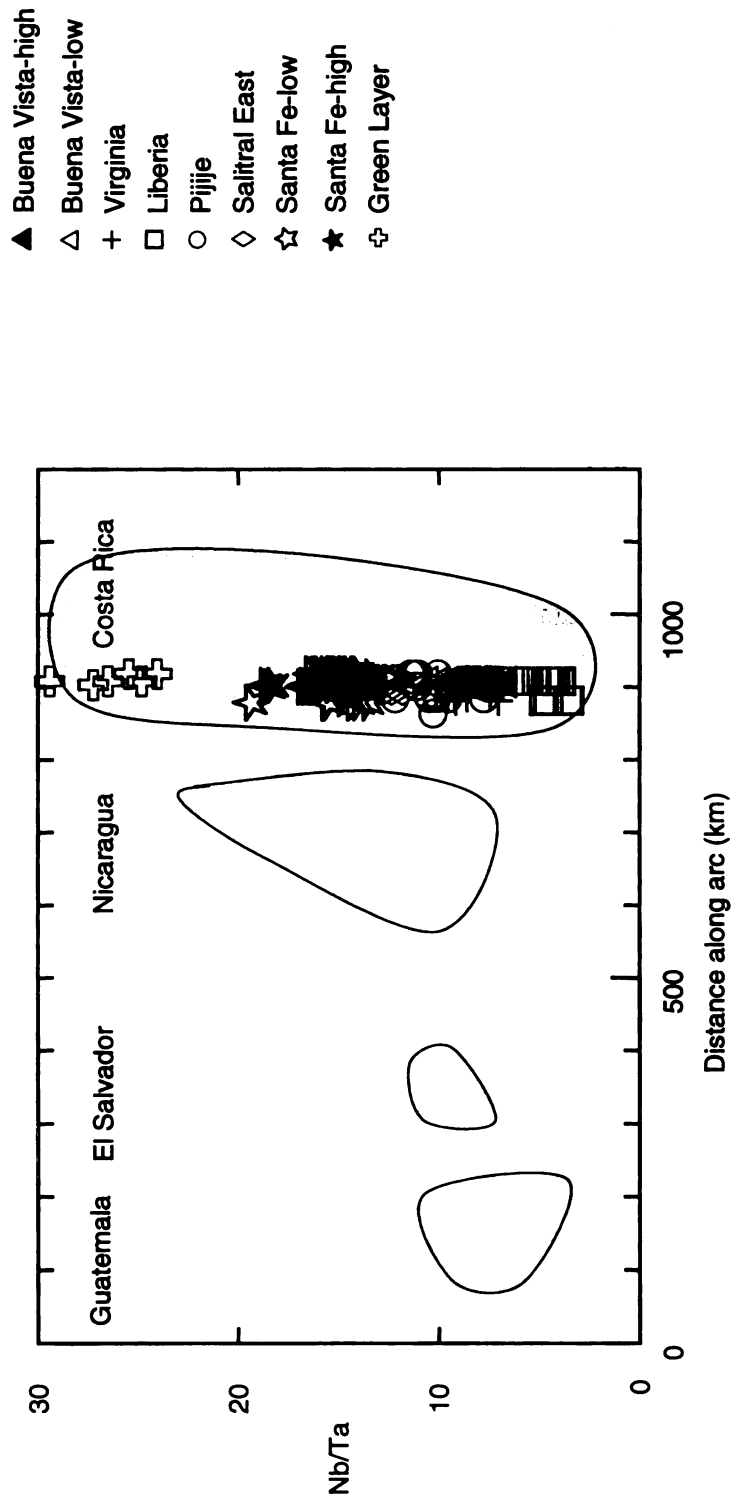
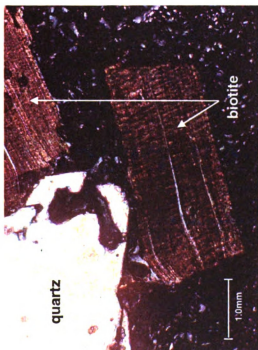


Figure 12. The range of Nb/Ta from high-silica pumice of the Guachipelin caldera encompasses all of the high silica ($\text{SiO}_2 > 65 \text{ wt\%}$) samples along the arc. Distance along the arc is measured from Mexico-Guatemala border to central Costa Rica. Gray area represents high silica samples found along the arc other than those from the Guachipelin caldera.

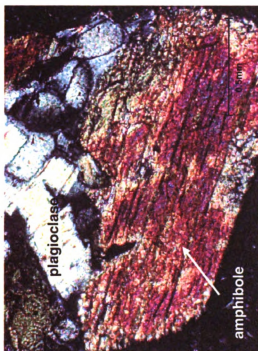
Variation diagrams that plot incompatible trace element ratios with one of the elements on a log scale are used to compare the compatibility of the two elements and determine systematic relationships among units. The slope of the trends displayed in Figures 11c,d indicate a systematic control of Ta and Hf over their respective ratios. This variation could be due to the same phase controlling the trace element (e.g. Ta) partitioning (e.g. amphibole) among the units.

2. Petrographic analyses

Petrographic analyses were performed on thirty-six thin sections representing pumice samples from each of the seven units (Appendix B). Pumice are hypocrySTALLINE with degrees of crystallinity typically between 7% and 20%, although several thin sections have crystallinity values as high as 50%. Most samples display a glassy groundmass, but some samples have plagioclase microlites. Some of the pumice samples with the plagioclase microlites display an intermediate to strong trachytic texture (i.e. Pijije, Santa Fe-low/high). Primary mineralogy consists of plagioclase, (low/high-Mg) amphiboles, biotite, and quartz with trace amounts of Fe-Ti oxides (magnetite and ilmenite), zircon, and apatite (Figure 13). Table 2 lists the representative averages of mineral abundances for each of the units given as estimated modal percentages. An estimated average of the mineral sizes is also provided. Twinning is common among both plagioclase and amphibole, and many of the plagioclase grains display oscillatory zoning. Melt inclusions are abundant in plagioclase and amphibole - many are completely devitrified. Several disequilibrium textures (i.e. resorption, embayment, corroded plagioclase cores) are



(a)



(b)

Figure 13a,b. Photomicrographs (XPL) of pumice fragments showing representative minerals of the different units in the field area. Plagioclase, amphibole, biotite and quartz are the most common minerals. Note the resorbed quartz in (a), more than 90% of the quartz found in these pumice samples exhibit this disequilibrium texture. b) Typical amphibole and plagioclase grains at the edge of a glomeroporphyritic clot.

Table 2 Petrographic summary

Unit/ Sample	Plagioclase	Amphibole	Biotite	Quartz	Opaques
	Modal %	Modal %	Modal %	Modal %	Modal %
Buena Vista-low					
990718-2c	15	2			3
Size (mm)	0.05-2.875	0.125-1.5			0.025-0.75
Buena Vista-high					
990718-2D-1	15	2			2
990718-2D-3	10	1			2
990718-3a	15	1	<<1	2	1
990718-3-1	10	1	<1	1	1
990718-3-4	7	2	<1		<1
990718-3-5	7	<1	<1	<1	1
990718-3-6r	10	2	<1	1	1
990718-4-5	15	2		4	2
Size (mm)	0.05-2.875	0.075-2.25	0.125-.625	0.05-2.5	0.025-1.0
Virginia					
020709-3a	4	<1			1
020709-4c	3	<1			1
Size (mm)	0.05-3.75	0.05-1.25			0.025-0.375
Liberia					
990718-1-1	8	<1	7	<1	<1
990718-1-3	7	<1	5	2	<1
Size (mm)	0.05-3.625	0.075-1.5	0.025-1.875	0.125-4.5	0.025-1.25
Pijje					
010627-1a	6	1	1	2	<1
010627-1c	20	<1	6	1	<1
010629-1c	15	<1	7	10	3
040706-3e	10		5	5	<1
040708-2a	40	10	1		1
040708-6d	10	5	2	5	1
010629-1a	15	<1	2	3	1
Size (mm)	0.05-5.0	0.175-1.5	0.05-2.5	0.075-3.75	0.025-0.75
Salitral East					
040706-7f	5	4	<<1	1	1
040707-2d	5	2	<1	<1	1
040707-2j	5	2		<1	1
Size (mm)	0.075-2.5	0.075-2.0	0.05-0.875	0.25-3.375	0.025-0.75

Table 2 cont.

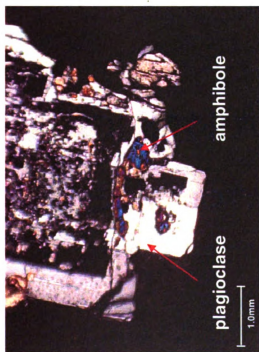
Unit/ Sample	Plagioclase	Amphibole	Biotite	Quartz	Opagues
	Modal %	Modal %	Modal %	Modal %	Modal %
Santa Fe-low					
990718-12g	6	2			<1
040706-1a	15	2			<1
040706-1m	15	2			1
040706-2a	10	1			1
040707-2a	15	2		1	1
<i>Size (mm)</i>	0.025-2.5	0.125-2.5			0.025-0.5
Santa Fe-high					
040706-3a	5	<<1	1	2	<1
040707-8f	5	<1	2	3	1
010629-21f	7		2		<1
010629-21g	3	<<1	2	2	<1
<i>Size (mm)</i>	0.05-3.75	0.15-1.625	0.125-2.125	0.25-5.0	0.025-0.6
Green Layer					
040706-1j	7	2			1
040707-3c	7	4			1
040708-5a	5	<1			1
<i>Size (mm)</i>	0.25-4.0	0.25-2.75			0.025-0.5

found throughout the sample collection (Figures 13 and 14). Plagioclase and quartz are typically the minerals displaying these textures; however, some amphibole grains display a “brush-like” texture that may be related to disequilibrium or a result of phenocryst dehydration during the eruption (Figure 14b).

Although the petrography of the seven units is similar, meaningful variations among units do exist. The size, distribution (i.e. glomeroporphytic clots, bi-modal), and modal abundance of minerals and groundmass are features that differ between units. Most notably, biotite and quartz are only present in pumice fragments with $\text{SiO}_2 \geq 72$ wt.%. Mineral distribution also varies considerably. Bi-modal size distributions of plagioclase and amphibole are observed in samples from the Green Layer and Virginia units. Some samples have glomeroporphyritic clots of several or all of the primary minerals present (Figure 14b). Another distinct difference is the presence of both dark and light colored glass, found in the Green layer, Santa Fe-high, Buena Vista-low, and Pijije units (Figure 15).

3. Mineral composition

Individual mineral phase and glass chemistry of eighteen samples representing all of the seven units and sub-groups are provided in Table 3. Major element data are normalized to 100% and given in wt.% oxides. Trace element data acquired by LA-ICP-MS are given in ppm.



(a)



(b)

Figure 14a,b. a) Photomicrograph (XPL) of corroded plagioclase core with amphibole inclusions. This disequilibrium texture is found in plagioclase from nearly all of the representative units from the Guachipelin pumice deposits. b) Photomicrograph (XPL) of a glomerophyritic clotted and resorbed plagioclase from the Santa Fe unit. These clots generally include the presence of all of the primary minerals represented in a particular pumice fragment. The brush-like texture seen here along the margin of these amphibole were also common among units.

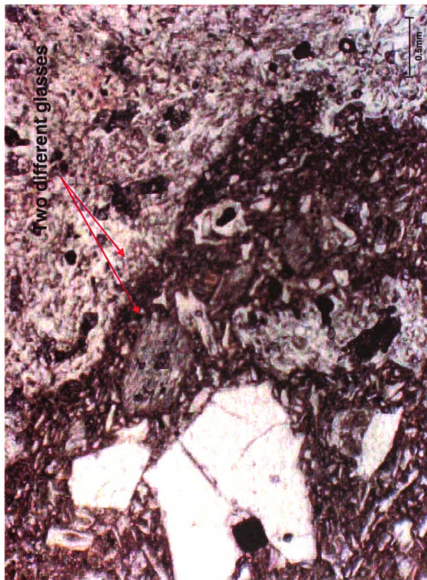


Figure 15. Photomicrograph (PPL) illustrating the presence of two distinct glasses in a single pumice fragment from the Pijije unit. Note the difference in crystallinity between the two apparently different magmas. This compositional variation is consistent with the presence of banded pumice fragments identified in the field.

Table 3 Phase chemistry (AMPHIBOLE)

b.d (bad data)

Microprobe analyses

Unit	Buena Vista		Buena Vista		Buena Vista		Buena Vista	
Sample	990718-2C amph 1	990718-2C amph 2	990718-2C amph 3	990718-2C amph 4	990718-3-6r amph2			
SiO ₂	48.53	48.54	49.20	48.86	49.79			
TiO ₂	1.68	1.76	1.65	1.81	1.27			
Al ₂ O ₃	6.88	7.12	6.86	8.04	6.46			
FeO	12.86	13.11	12.76	11.38	12.38			
MnO	0.51	0.46	0.52	0.40	0.73			
MgO	15.46	15.06	15.37	15.73	16.02			
CaO	11.48	11.44	11.12	10.77	11.11			
Na ₂ O	1.59	1.63	1.58	1.88	1.39			
K ₂ O	0.37	0.42	0.37	0.41	0.39			
F					0.30			
Cl	0.11	0.14	0.12	0.12	0.13			
Cr ₂ O ₃	bd	bd	bd	bd	0.01			
Total	97.58	96.16	97.85	89.38	98.11			

Laser ablation ICP-MS analyses

Ta
Hf
Yb
Er
Ho
Dy
La
Nb
Y

Table 3 cont.

Microprobe analyses

Unit	Buena Vista	Buena Vista	Buena Vista	Buena Vista	Buena Vista
Sample	990718-3-6r amph3	990718-4-5 amph3	990718-4-5 amph2	990718-4-5 amph2a	990718-3a amph3
SiO ₂	51.59	50.27	50.74	48.96	50.06
TiO ₂	1.07	1.18	1.25	1.26	1.26
Al ₂ O ₃	5.01	5.96	5.75	7.11	6.11
FeO	11.61	12.00	11.81	12.27	11.98
MnO	0.69	0.62	0.69	0.70	0.60
MgO	16.99	16.70	16.40	16.20	16.63
CaO	11.17	11.20	11.20	11.13	11.30
Na ₂ O	1.14	1.26	1.20	1.40	1.23
K ₂ O	0.32	0.40	0.40	0.45	0.34
F	0.31	0.29	0.41	0.38	0.38
Cl	0.11	0.13	0.14	0.14	0.11
Cr ₂ O ₃	bd	bd	0.01	bd	bd
Total	97.49	98.57	99.07	99.01	99.02

Laser ablation ICP-MS analyses

Ta	0.45
Hf	1.70
Yb	11.77
Er	11.55
Ho	4.12
Dy	20.75
La	20.86
Nb	12.06
Y	52.31

Table 3 cont.

Microprobe analyses

Unit	Buena Vista		Liberia		Virginia	
Sample	990718-2d-1 amph 2	990718-2d-1 amph 4	990718-1-1 amph 4	990718-1-1 amph 1	020709-3a amph 1b	020709-3a amph 2a
SiO ₂	49.92	50.24	50.47	48.62	46.66	
TiO ₂	1.28	1.33	1.14	1.53	2.05	
Al ₂ O ₃	6.15	6.34	6.18	6.94	8.09	
FeO	12.36	11.81	12.40	11.89	12.50	
MnO	0.70	0.66	0.79	0.56	0.47	
MgO	16.21	16.15	15.73	16.58	15.84	
CaO	11.31	11.23	11.26	11.50	11.68	
Na ₂ O	1.32	1.34	1.27	1.49	1.75	
K ₂ O	0.37	0.38	0.37	0.37	0.49	
F	0.24	0.35	0.26	0.42	0.37	
Cl	0.12	0.13	0.12	0.10	0.09	
Cr ₂ O ₃	0.02	0.02	bd	0.01	bd	
Total	98.48	97.28	96.38	96.39	97.08	

Laser ablation ICP-MS analyses

Ta	0.46	0.43	0.44
Hf	2.26	2.99	2.66
Yb	18.82	14.47	11.88
Er	18.06	14.00	11.33
Ho	6.55	5.07	4.06
Dy	30.24	25.40	20.34
La	22.89	19.06	15.50
Nb	11.27	12.72	11.57
Y	51.25	102.70	90.73

Table 3 cont.

Microprobe analyses

Unit	Virginia	Virginia	Virginia	Virginia	Virginia	Virginia
Sample	020709-3a amph2b	020709-4C amph3a	020709-4C amph3b	020709-4C amph3c	020709-4C amph3d	020709-4C amph3d
SiO ₂	47.56	53.01	52.71	52.89	52.39	52.39
TiO ₂	1.95	0.11	0.11	0.10	0.15	0.15
Al ₂ O ₃	7.51	0.49	0.49	0.36	0.85	0.85
FeO	12.12	20.06	20.07	20.03	20.56	20.56
MnO	0.43	1.31	1.26	1.18	1.27	1.27
MgO	16.19	23.91	24.32	24.38	23.78	23.78
CaO	11.65	0.93	1.01	1.01	0.97	0.97
Na ₂ O	1.71	0.03	0.00	0.03	0.03	0.03
K ₂ O	0.49	0.00	0.00	0.00	0.00	0.00
F	0.28	0.14	bd	bd	bd	bd
Cl	0.10	bd	bd	bd	bd	bd
Cr ₂ O ₃	0.01	0.01	0.01	bd	bd	bd
Total	96.57	98.81	98.86	98.77	98.94	98.94

Laser ablation ICP-MS analyses

Ta	bd
Hf	bd
Yb	bd
Er	bd
Ho	bd
Dy	1.42
La	3.19
Nb	0.93
Y	18.14

Table 3 cont.

Microprobe analyses

Unit	Salitral East	Salitral East	Pijje	Pijje	Pijje	Pijje	Pijje
Sample	040706-7F amph 1	040706-7F amph 3	010629-1A amph 1	010629-1C amph 3	010629-1C amph 3	010629-1C amph 3	010629-1C amph 6
SiO ₂	49.71	50.05	47.68	50.22	51.08	80.70	
TiO ₂	1.37	1.36	1.46	1.12	1.14	0.12	
Al ₂ O ₃	6.88	6.05	8.03	6.07	5.92	12.35	
FeO	11.86	12.44	13.34	12.86	11.69	0.20	
MnO	0.63	0.78	0.63	0.92	0.87	0.06	
MgO	16.13	16.28	14.78	15.34	15.67	0.03	
CaO	11.23	10.98	11.52	11.31	11.63	0.39	
Na ₂ O	1.38	1.22	1.65	1.28	1.18	1.20	
K ₂ O	0.41	0.39	0.45	0.47	0.45	4.80	
F	0.29	0.32	0.36	0.28			
Cl	0.12	0.14	0.09	0.12	0.11	0.08	
Cr ₂ O ₃	0.00	0.00	bd	bd	0.01	0.01	
Total	98.73	96.92	98.34	98.70	96.29	96.89	

Laser ablation ICP-MS analyses

Ta	0.41	bd
Hf	2.03	bd
Yb	13.52	bd
Er	13.52	bd
Ho	4.59	bd
Dy	21.63	bd
La	21.42	0.37
Nb	12.42	0.15
Y	54.10	8.18

Table 3 cont.

Microprobe analyses

Unit	Santa Fe	Santa Fe	Santa Fe	Santa Fe	Green Layer	Green Layer
Sample	990718-12g amph 3a	990718-12g amph 3b	040707-8F amph 4	040706-1J amph2	040706-1J amph5	
SiO ₂	53.03	53.39	49.68	53.74	53.77	
TiO ₂	0.22	0.17	1.22	0.11	0.12	
Al ₂ O ₃	0.95	0.56	6.15	0.52	0.62	
FeO	19.74	19.49	13.04	19.37	19.63	
MnO	1.17	1.14	0.88	1.22	1.28	
MgO	23.81	24.08	15.63	23.99	23.55	
CaO	1.04	1.13	11.37	1.03	0.99	
Na ₂ O	0.02	0.02	1.32	0.02	0.00	
K ₂ O	0.00	0.01	0.45	0.00	0.00	
F	bd	bd	0.16			
Cl	bd	bd	0.11	bd	0.02	
Cr ₂ O ₃	bd	bd	bd	bd	bd	
Total	100.27	100.25	97.99	99.89	96.93	

Laser ablation ICP-MS analyses

Ta	bd	0.42	bd
Hf	bd	1.89	bd
Yb	bd	14.68	bd
Er	bd	14.90	bd
Ho	bd	5.51	bd
Dy	7.78	29.76	bd
La	9.32	28.31	bd
Nb	bd	13.85	bd
Y	bd	42.08	6.20

Table 3 cont. (BIOTITE)

Microprobe analyses

Unit	Buena Vista	Liberia	Liberia	Liberia	Pijje	Pijje	Pijje
Sample	990718-2D-1 bio4	990718-1-1 bio2a	990718-1-1 bio2b	010629-1A bio1b	010629-1A bio3	010629-1C bio1	
SiO ₂	40.15	38.16	38.63	39.77	39.07	40.11	
TiO ₂	5.18	4.93	5.06	5.07	5.00	4.97	
Al ₂ O ₃	14.54	14.46	14.49	14.59	14.53	14.42	
FeO	14.29	16.17	16.13	15.08	15.92	15.97	
MnO	0.20	0.44	0.37	0.32	0.29	0.45	
MgO	15.37	14.88	14.38	14.36	14.47	14.77	
CaO	0.10	0.01	0.00	0.06	0.03	0.09	
Na ₂ O	0.44	0.55	0.52	0.38	0.57	0.36	
K ₂ O	8.71	9.55	9.66	9.36	9.24	8.35	
F	0.74	0.56	0.44	0.68	0.63	0.21	
Cl	0.27	0.30	0.31	0.30	0.24	0.31	
Total	96.20	96.37	95.19	95.23	96.81	93.36	

Table 3 cont.

Microprobe analyses

Unit	Pijje	Pijje	Santa Fe
Sample	010629-1C bio2	010629-1C bio8	040707-8F bio1a
SiO ₂	40.38	39.68	39.99
TiO ₂	4.76	4.86	4.84
Al ₂ O ₃	14.56	14.64	14.91
FeO	16.29	16.10	17.57
MnO	0.39	0.37	0.20
MgO	14.57	14.80	13.47
CaO	0.12	0.14	0.11
Na ₂ O	0.31	0.42	0.31
K ₂ O	8.32	8.35	8.01
F	0.00	0.37	0.34
Cl	0.30	0.28	0.25
Total	94.86	94.82	94.59

Table 3 cont.

Microprobe analyses

Unit	Santa Fe	Santa Fe	Santa Fe	Santa Fe	Santa Fe	Santa Fe
Sample	040707-8F glass6	010629-21F glass4a	010629-21F glass4b	010629-21F glass4c	010629-21F glass4d	Santa Fe
SiO ₂	76.70	77.32	77.55	77.47	76.69	
TiO ₂	0.11	0.10	0.12	0.17	0.15	
Al ₂ O ₃	12.36	12.45	12.43	12.12	12.63	
FeO	0.82	0.69	0.75	0.63	0.80	
MnO	0.06	0.13	0.14	0.03	0.01	
MgO	0.11	0.09	0.05	0.07	0.12	
CaO	0.84	0.68	0.71	0.74	0.78	
Na ₂ O	3.77	3.12	2.71	3.51	2.97	
K ₂ O	4.80	5.14	5.24	4.92	5.55	
F		0.03	0.06	0.05	0.03	
Cl	0.39	0.21	0.24	0.26	0.26	
Cr ₂ O ₃	0.04	0.04		0.04	0.01	
Total	98.84	97.14	97.12	97.84	97.88	

Laser ablation ICP-MS analyses

Sr
 Ba
 Ta
 Hf
 Yb
 Er
 Ho
 Dy
 La
 Nb
 Y

Table 3 cont.

Microprobe analyses

Unit	Santa Fe	Santa Fe	Santa Fe	Santa Fe	Santa Fe
Sample	010629-21F glass5a	010629-21F glass5b	010629-21F glass3b	990718-12G glass4a	
SiO ₂	76.60	77.38	77.34	75.47	
TiO ₂	0.12	0.05	0.11	0.25	
Al ₂ O ₃	13.34	12.28	12.61	13.23	
FeO	0.70	0.64	0.81	1.20	
MnO	0.03	0.04	0.08	0.07	
MgO	0.07	0.08	0.03	0.10	
CaO	0.75	0.70	0.75	1.11	
Na ₂ O	2.98	2.95	2.49	3.63	
K ₂ O	5.15	5.59	5.56	4.67	
F		0.04	0.00		
Cl	0.26	0.25	0.20	0.26	
Cr ₂ O ₃			0.02	0.01	
Total	99.59	97.66	95.90	97.38	

Laser ablation ICP-MS analyses

Sr	5.78	9.85
Ba	83.22	86.34
Ta	bd	bd
Hf	bd	bd
Yb	bd	bd
Er	bd	bd
Ho	bd	bd
Dy	0.27	bd
La	1.88	1.08
Nb	0.44	0.42
Y	18.62	29.74

Table 3 cont. (GLASS)

Microprobe analyses

Unit	Buena Vista		Buena Vista		Buena Vista		Buena Vista		Buena Vista	
Sample	990718-3a glass 3a	990718-3a glass 3b	990718-3a glass 2a	990718-3a glass 2b	990718-3-6R glass 1b					
SiO ₂	76.88	77.20	77.08	77.57	77.07					
TiO ₂	0.17	0.16	0.11	0.18	0.18					
Al ₂ O ₃	12.70	12.41	12.60	12.48	12.56					
FeO	0.91	0.78	0.79	0.74	0.84					
MnO	0.04	0.07	0.04	0.04	0.12					
MgO	0.26	0.15	0.20	0.15	0.13					
CaO	0.80	0.72	0.87	0.82	0.88					
Na ₂ O	3.37	3.36	3.22	3.10	3.42					
K ₂ O	4.52	4.82	4.83	4.66	4.50					
F	0.06	0.04	0.00	0.00						
Cl	0.30	0.29	0.24	0.26	0.29					
Cr ₂ O ₃										
Total	97.41	97.86	96.46	98.74	97.78					

Laser ablation ICP-MS analyses

Sr	
Ba	
Ta	0.21
Hf	0.82
Yb	1.54
Er	1.12
Ho	0.33
Dy	2.28
La	21.20
Nb	3.24
Y	46.41

Table 3 cont.

Microprobe analyses

Unit	Buena Vista		Buena Vista		Buena Vista		Buena Vista	
Sample	990718-3-6R	glass 2	990718-3-6R	glass 6a	990718-4-5	glass2a	990718-4-5	glass2b
SiO ₂	77.94		77.56	76.94	77.53		77.11	
TiO ₂	0.06		0.19	0.20	0.13		0.13	
Al ₂ O ₃	12.55		12.46	12.20	12.53		12.60	
FeO	0.65		1.07	1.17	0.69		0.98	
MnO	0.05		0.06	0.06	0.09		0.06	
MgO	0.06		0.15	0.23	0.20		0.15	
CaO	0.83		0.81	0.75	0.85		0.84	
Na ₂ O	2.24		2.74	3.42	2.03		3.49	
K ₂ O	5.16		4.61	4.70	5.68		4.40	
F	0.19		0.06	0.03	0.00			
Cl	0.26		0.27	0.27	0.24		0.25	
Cr ₂ O ₃			0.03	0.05	0.03			
Total	97.02		97.53	98.53	97.95		98.44	

Laser ablation ICP-MS analyses

Sr
 Ba
 Ta
 Hf
 Yb
 Er
 Ho
 Dy
 La
 Nb
 Y

Table 3 cont.

Microprobe analyses

Unit	Buena Vista		Buena Vista		Buena Vista		Buena Vista		Liberia	
Sample	990718-2D-1 glass2	990718-2D-1 glass3	990718-2D-1 glass4a	990718-2D-1 glass4b	990718-1-1 glass7					
SiO ₂	77.18	77.46	77.48	77.29	77.46					
TiO ₂	0.19	0.17	0.12	0.16	0.11					
Al ₂ O ₃	12.36	12.44	12.58	12.53	12.63					
FeO	0.94	0.87	0.96	0.88	0.39					
MnO	0.08	0.00	0.11	0.08						
MgO	0.19	0.12	0.14	0.17	0.04					
CaO	0.81	0.94	0.82	0.83	0.36					
Na ₂ O	3.13	3.23	3.34	3.36	2.31					
K ₂ O	4.86	4.50	4.20	4.35	6.61					
F			0.05	0.04						
Cl	0.25	0.27	0.22	0.24	0.09					
Cr ₂ O ₃		0.01		0.07	0.01					
Total	98.10	96.21	100.82	97.36	98.74					

Laser ablation ICP-MS analyses

Sr	7.13
Ba	93.68
Ta	0.15
Hf	0.47
Yb	bd
Er	bd
Ho	0.09
Dy	0.54
La	2.63
Nb	0.70
Y	16.25

Table 3 cont.

Microprobe analyses

Unit	Virginia	Virginia	Virginia	Virginia	Virginia	Virginia
Sample	020709-3a glass 1a	020709-3a glass 1b	020709-3a glass 2a	020709-3a glass 2b	020709-4c glass 4a	020709-4c glass 4a
SiO ₂	74.56	75.49	74.76	75.84	76.01	76.01
TiO ₂	0.30	0.29	0.27	0.29	0.24	0.24
Al ₂ O ₃	13.52	14.32	13.75	13.98	13.45	13.45
FeO	1.62	1.45	1.52	1.48	1.13	1.13
MnO	0.12	0.04	0.05	0.13	0.04	0.04
MgO	0.29	0.42	0.36	0.28	0.21	0.21
CaO	1.62	1.40	1.61	1.39	1.05	1.05
Na ₂ O	4.03	2.22	3.37	2.02	1.35	1.35
K ₂ O	3.64	4.17	4.01	4.35	6.23	6.23
F	0.09	0.01	0.06	0.23	0.28	0.28
Cl	0.20	0.18	0.24		0.01	0.01
Cr ₂ O ₃						
Total	95.56	98.38	95.58	95.04	96.98	96.98

Laser ablation ICP-MS analyses

Sr	91.08	
Ba	619.88	
Ta	bd	bd
Hf	0.68	1.17
Yb	bd	bd
Er	bd	bd
Ho	bd	bd
Dy	bd	1.39
La	1.84	7.06
Nb	0.52	2.15
Y	39.45	92.67

Table 3 cont.

Microprobe analyses

Unit	Virginia	Virginia	Salitral East	Salitral East	Pijje
Sample	020709-4c glass 3a	020709-4c glass 3b	040706-7F glass 1	040706-7F glass 3	010629-1A glass3a
SiO ₂	75.86	75.32	77.21	77.37	77.73
TiO ₂	0.28	0.28	0.16	0.18	0.15
Al ₂ O ₃	12.88	13.17	13.19	12.36	12.43
FeO	1.13	1.41	0.77	0.91	0.27
MnO	0.03	0.05		0.08	0.07
MgO	0.22	0.22	0.11	0.15	0.06
CaO	1.12	1.04	0.84	0.76	0.52
Na ₂ O	3.47	3.04	3.09	3.37	2.45
K ₂ O	4.74	4.95	4.39	4.45	6.13
F		0.17		0.15	0.03
Cl	0.27	0.27	0.20	0.23	0.12
Cr ₂ O ₃		0.07	0.02		0.06
Total	96.88	97.97	97.87	98.79	97.84

Laser ablation ICP-MS analyses

Sr	130.40	5.96
Ba	1372.27	55.81
Ta	bd	bd
Hf	bd	bd
Yb	bd	bd
Er	bd	bd
Ho	bd	bd
Dy	bd	bd
La	0.38	0.40
Nb	bd	bd
Y	22.02	17.30

Table 3 cont.

Microprobe analyses

Unit	Pijje	Pijje	Pijje	Pijje	Pijje	Pijje
Sample	010629-1A glass3b	010629-1A glass5a	010629-1C glass2	010629-1C glass6a	010629-1C glass6b	
SiO ₂	77.95	77.05	77.52	77.62	78.48	
TiO ₂	0.16	0.12	0.08	0.05	0.14	
Al ₂ O ₃	13.08	12.45	12.31	12.92	12.64	
FeO	0.91	0.71	0.31	0.48	0.67	
MnO	0.06	0.07	0.06		0.08	
MgO	0.04	0.11	0.06	0.01	0.08	
CaO	1.59	0.57	0.61	0.40	1.20	
Na ₂ O	5.18	3.07	2.82	3.28	5.92	
K ₂ O	0.80	5.51	6.08	5.04	0.58	
F	0.12	0.08		0.18	0.22	
Cl	0.11	0.26	0.16	0.02		
Cr ₂ O ₃						
Total	99.60	98.43	98.64	97.10	99.36	

Laser ablation ICP-MS analyses

Sr						
Ba						
Ta						0.34
Hf				bd	bd	1.20
Yb				bd	bd	bd
Er				bd	bd	0.67
Ho				bd	bd	bd
Dy				bd	bd	1.00
La				0.40	6.98	
Nb				0.23	2.29	
Y				8.88	48.90	

Table 3 cont.

Microprobe analyses

Unit	Pijje	Pijje	Pijje	Pijje	Santa Fe	Santa Fe
Sample	010629-1C glass6c	010629-1C glass6d	010629-1C glass8	040707-8F glass1	040707-8F glass5	
SiO ₂	77.15	77.38	77.70	76.81	77.17	
TiO ₂	0.08	0.13	0.09	0.14	0.13	
Al ₂ O ₃	12.90	12.63	12.32	12.63	12.38	
FeO	0.36	0.48	0.74	0.75	0.73	
MnO	0.03	0.05	0.07	0.11	0.04	
MgO	0.04	0.03	0.28	0.07	0.19	
CaO	0.62	0.65	0.36	0.79	0.64	
Na ₂ O	3.21	3.23	3.13	3.53	3.61	
K ₂ O	5.30	5.22	5.05	4.91	4.79	
F	0.12				0.09	
Cl	0.18	0.19	0.27	0.24	0.23	
Cr ₂ O ₃				0.02		
Total	98.47	98.31	97.76	99.77	98.53	

Laser ablation ICP-MS analyses

Sr	9.41
Ba	169.43
Ta	bd
Hf	bd
Yb	bd
Er	bd
Ho	bd
Dy	bd
La	1.16
Nb	0.43
Y	14.51

Table 3 cont.

Microprobe analyses

Unit	Santa Fe	Santa Fe	Santa Fe	Santa Fe	Santa Fe	Santa Fe
Sample	040707-8F glass6	010629-21F glass4a	010629-21F glass4b	010629-21F glass4c	010629-21F glass4d	
SiO ₂	76.70	77.32	77.55	77.47	76.69	
TiO ₂	0.11	0.10	0.12	0.17	0.15	
Al ₂ O ₃	12.36	12.45	12.43	12.12	12.63	
FeO	0.82	0.69	0.75	0.63	0.80	
MnO	0.06	0.13	0.14	0.03	0.01	
MgO	0.11	0.09	0.05	0.07	0.12	
CaO	0.84	0.68	0.71	0.74	0.78	
Na ₂ O	3.77	3.12	2.71	3.51	2.97	
K ₂ O	4.80	5.14	5.24	4.92	5.55	
F		0.03	0.06	0.05	0.03	
Cl	0.39	0.21	0.24	0.26	0.26	
Cr ₂ O ₃	0.04	0.04		0.04	0.01	
Total	98.84	97.14	97.12	97.84	97.88	

Laser ablation ICP-MS analyses

Sr
 Ba
 Ta
 Hf
 Yb
 Er
 Ho
 Dy
 La
 Nb
 Y

Table 3 cont.

Microprobe analyses

Unit	Santa Fe	Santa Fe	Santa Fe	Santa Fe
Sample	010629-21F glass5a	010629-21F glass5b	010629-21F glass3b	990718-12G glass4a
SiO ₂	76.60	77.38	77.34	75.47
TiO ₂	0.12	0.05	0.11	0.25
Al ₂ O ₃	13.34	12.28	12.61	13.23
FeO	0.70	0.64	0.81	1.20
MnO	0.03	0.04	0.08	0.07
MgO	0.07	0.08	0.03	0.10
CaO	0.75	0.70	0.75	1.11
Na ₂ O	2.98	2.95	2.49	3.63
K ₂ O	5.15	5.59	5.56	4.67
F		0.04	0.00	0.26
Cl	0.26	0.25	0.20	0.01
Cr ₂ O ₃			0.02	
Total	99.59	97.66	95.90	97.38

Laser ablation ICP-MS analyses

Sr	5.78	9.85
Ba	83.22	86.34
Ta	bd	bd
Hf	bd	bd
Yb	bd	bd
Er	bd	bd
Ho	bd	bd
Dy	0.27	bd
La	1.88	1.08
Nb	0.44	0.42
Y	18.62	29.74

Table 3 cont.

Microprobe analyses

Unit	Green Layer	Green Layer	Green Layer
Sample	040706-1J glass4	040707-3C glass1	040708-5A glass3
SiO ₂	75.66	76.27	75.76
TiO ₂	0.31	0.20	0.24
Al ₂ O ₃	13.13	12.62	13.18
FeO	1.32	1.60	1.36
MnO	0.02	0.04	0.01
MgO	0.25	0.13	0.14
CaO	1.15	1.13	1.12
Na ₂ O	3.50	3.73	3.35
K ₂ O	4.38	3.97	4.51
F		0.06	0.06
Cl	0.28	0.25	0.25
Cr ₂ O ₃	0.00		0.03
Total	98.92	97.31	97.14

Laser ablation ICP-MS analyses

Sr	
Ba	
Ta	bd
Hf	bd
Yb	bd
Er	bd
Ho	bd
Dy	bd
La	0.92
Nb	0.27
Y	24.53
	bd
	bd
	bd
	bd
	bd
	bd
	bd
	0.34
	27.50

Table 3 cont. (PLAGIOCLASE)

Microprobe analyses

Unit	Buena Vista		Buena Vista		Buena Vista		Buena Vista	
Sample	990718-3-6r	plag 1	990718-3-6r	plag 1	990718-3-6r	plag 1	990718-3-6r	plag 1
SiO ₂	59.41		60.06		60.03		60.50	
TiO ₂	0.01		0.00		0.01		0.00	
Al ₂ O ₃	25.59		25.18		24.92		24.33	
FeO	0.22		0.24		0.27		0.28	
MgO	0.16		0.00		0.81		0.25	
CaO	7.21		6.75		6.33		6.41	
Na ₂ O	6.75		6.88		6.90		7.20	
K ₂ O	0.58		0.59		0.57		0.75	
SrO	0.00		0.16		0.00		0.00	
BaO	0.06		0.14		0.15		0.28	
Total	98.42		99.35		99.80		99.43	
								100.28

LA- ICP-MS analyses

Sr
Ba

Table 3 cont.

Microprobe analyses

Unit	Buena Vista		Buena Vista		Buena Vista		Buena Vista	
Sample	990718-3-6r	plag 1	990718-3-6r	plag 1	990718-3-6r	plag 1	990718-3-6r	plag 1
SiO ₂	58.44	59.40	60.16	58.76	58.98			
TiO ₂	0.00	0.00	0.01	0.00	0.00			
Al ₂ O ₃	25.24	25.21	24.97	25.61	25.56			
FeO	0.32	0.15	0.33	0.20	0.33			
MgO	1.20	0.63	0.08	0.31	0.06			
CaO	7.80	7.42	6.70	7.81	7.59			
Na ₂ O	6.45	6.64	6.95	6.71	6.73			
K ₂ O	0.45	0.52	0.57	0.47	0.58			
SrO	0.00	0.00	0.20	0.00	0.00			
BaO	0.10	0.03	0.03	0.13	0.17			
Total	99.70	99.49	98.40	98.68	97.47			

LA- ICP-MS analyses

Sr
Ba

Table 3 cont.

Microprobe analyses

Unit	Buena Vista 990718-3-6r plag 1a	Buena Vista 990718-3a plag1	Buena Vista 990718-3a plag1	Buena Vista 990718-3a plag1	Buena Vista 990718-3a plag1
Sample	58.46	57.37	57.35	58.52	57.63
SiO ₂	0.00	0.01	0.00	0.00	0.00
TiO ₂	25.65	26.60	26.46	25.62	26.39
Al ₂ O ₃	0.25	0.21	0.24	0.26	0.22
FeO	0.16	0.00	0.00	0.00	0.00
MgO	7.70	8.51	8.71	7.57	8.41
CaO	7.10	6.73	6.76	7.11	6.73
Na ₂ O	0.56	0.44	0.41	0.49	0.47
K ₂ O	0.00	0.04	0.00	0.31	0.00
SrO	0.11	0.08	0.06	0.12	0.16
BaO	98.90	99.17	98.50	99.53	98.82
Total					

LA- ICP-MS analyses

Sr	1420.97	1343.03
Ba	1172.09	1036.82

Table 3 cont.

Microprobe analyses

Unit	Buena Vista		Buena Vista		Buena Vista		Buena Vista		Buena Vista	
Sample	990718-3a plag1	990718-3a plag1	990718-3a plag1	990718-3a plag1	990718-3a plag1	990718-3a plag1	990718-3a plag1	990718-3a plag1	990718-3a plag2	990718-3a plag2
SiO ₂	57.75	60.33	59.86	59.83	58.36	58.45				
TiO ₂	0.00	0.01	0.00	0.00	0.01	0.03				
Al ₂ O ₃	25.99	24.59	24.82	24.68	26.04	25.64				
FeO	0.33	0.20	0.30	0.29	0.29	0.28				
MgO	0.02	0.00	0.00	0.00	0.00	0.01				
CaO	8.06	6.40	6.40	7.16	7.85	7.96				
Na ₂ O	7.09	7.77	7.62	7.30	6.76	6.90				
K ₂ O	0.49	0.65	0.65	0.55	0.47	0.51				
SrO	0.16	0.00	0.19	0.00	0.00	0.14				
BaO	0.11	0.05	0.15	0.19	0.20	0.08				
Total	97.99	98.33	99.01	98.81	98.76	98.74				

LA- ICP-MS analyses

Sr	1261.06
Ba	1354.39

Table 3 cont.

Microprobe analyses

Unit	Buena Vista		Buena Vista		Buena Vista		Buena Vista		Buena Vista	
Sample	990718-3a	plag2	990718-3a	plag2	990718-3a	plag2	990718-3a	plag2	990718-3a	plag2
SiO ₂	59.05		59.00		56.56		57.82		60.14	
TiO ₂	0.01		0.00		0.01		0.00		0.00	
Al ₂ O ₃	25.28		25.10		27.33		26.12		24.74	
FeO	0.31		0.22		0.19		0.28		0.14	
MgO	0.00		0.46		0.00		0.21		0.00	
CaO	7.37		7.25		9.18		8.13		6.82	
Na ₂ O	7.21		7.20		6.30		6.78		7.45	
K ₂ O	0.48		0.51		0.36		0.52		0.55	
SrO	0.14		0.11		0.00		0.00		0.04	
BaO	0.14		0.15		0.06		0.12		0.13	
Total	98.56		99.61		99.72		100.22		98.58	

LA- ICP-MS analyses

Sr
Ba

Table 3 cont.

Microprobe analyses

Unit	Buena Vista	Buena Vista	Buena Vista	Buena Vista	Buena Vista
Sample	990718-3a plag2	990718-4-5 plag 1	990718-4-5 plag 1	990718-4-5 plag 1	990718-4-5 plag 1
SiO ₂	60.34	61.19	57.95	57.99	59.59
TiO ₂	0.02	0.00	0.02	0.01	0.00
Al ₂ O ₃	24.83	24.38	26.22	26.01	25.25
FeO	0.24	0.25	0.23	0.34	0.26
MgO	0.00	0.14	0.34	0.52	0.00
CaO	6.68	6.05	8.27	8.07	7.24
Na ₂ O	7.20	7.04	6.29	6.54	7.13
K ₂ O	0.63	0.68	0.45	0.41	0.48
SrO	0.00	0.14	0.11	0.00	0.00
BaO	0.05	0.12	0.13	0.09	0.07
Total	99.55	100.09	100.37	100.08	98.88

LA- ICP-MS analyses

Sr

Ba

Table 3 cont.

Microprobe analyses

Unit	Buena Vista		Buena Vista		Buena Vista		Buena Vista	
Sample	990718-4-5	plag 1	990718-4-5	plag 1	990718-4-5	plag 1	990718-4-5	plag 1
SiO ₂	57.39	60.18	59.25	56.85	57.83			
TiO ₂	0.01	0.00	0.00	0.00	0.00			
Al ₂ O ₃	26.58	24.83	25.32	26.96	24.98			
FeO	0.29	0.35	0.25	0.29	0.28			
MgO	0.08	0.00	0.42	0.01	0.75			
CaO	9.11	7.02	7.28	8.81	7.26			
Na ₂ O	6.07	6.92	6.82	6.53	8.27			
K ₂ O	0.40	0.55	0.59	0.42	0.47			
SrO	0.00	0.00	0.00	0.00	0.00			
BaO	0.08	0.14	0.06	0.14	0.16			
Total	100.19	99.28	100.43	97.12	92.83			

LA- ICP-MS analyses

Sr
Ba

Table 3 cont.

Microprobe analyses

Unit	Buena Vista	Buena Vista	Buena Vista	Buena Vista	Buena Vista	Liberia
Sample	990718-4-5 plag 1	990718-2D-1 plag 3a	990718-2D-1 plag 3b	990718-2D-1 plag 3c	990718-1-1 plag 6a	
SiO ₂	59.01	58.47	57.40	58.83	62.10	
TiO ₂	0.00	0.00	0.00	0.01	0.01	
Al ₂ O ₃	25.80	25.31	26.09	25.53	23.80	
FeO	0.19	0.25	0.26	0.24	0.22	
MgO	0.36	0.87	0.28	0.26	0.04	
CaO	6.76	7.33	8.57	7.42	5.78	
Na ₂ O	7.14	7.04	6.64	7.03	7.09	
K ₂ O	0.60	0.50	0.46	0.51	0.72	
SrO	0.00	0.08	0.12	0.00	0.14	
BaO	0.14	0.15	0.19	0.16	0.11	
Total	99.74	100.65	100.63	101.11	100.43	

LA- ICP-MS analyses

Sr	859.62
Ba	1296.66

Table 3 cont.

Microprobe analyses

Unit	Liberia	Liberia	Liberia	Salitral East	Salitral East
Sample	990718-1-1 plag 6b	990718-1-1 plag 6c	040706-7F plag1a	040706-7F plag1b	
SiO ₂	61.38	62.07	58.36	57.55	
TiO ₂	0.02	0.00	0.00	0.00	
Al ₂ O ₃	23.90	23.76	26.34	26.48	
FeO	0.19	0.17	0.19	0.21	
MgO	0.48	0.18	0.01	0.35	
CaO	5.92	5.05	8.69	8.45	
Na ₂ O	7.21	7.83	5.94	6.48	
K ₂ O	0.72	0.82	0.44	0.41	
SrO	0.03	0.00	0.00	0.00	
BaO	0.15	0.14	0.04	0.07	
Total	100.38	100.88	99.66	103.54	

LA- ICP-MS analyses

Sr	921.35	812.71	1329.92	1218.59
Ba	1316.34	1615.86	835.69	813.17

Table 3 cont.

Microprobe analyses

Unit	Salitral East	Pijje	Pijje	Pijje	Pijje	Pijje
Sample	040706-7F plag1c	010629-1A plag 2a	010629-1A plag 2b	010629-1A plag 2c	010629-1C plag 5a	
SiO ₂	60.00	60.07	60.04	60.71	60.12	
TiO ₂	0.00	0.03	0.01	0.00	0.03	
Al ₂ O ₃	24.43	24.73	24.68	24.47	25.42	
FeO	0.25	0.25	0.24	0.18	0.19	
MgO	0.73	0.00	0.33	0.00	0.00	
CaO	6.59	6.40	6.45	6.36	6.28	
Na ₂ O	7.20	7.78	7.32	7.48	7.23	
K ₂ O	0.60	0.66	0.65	0.72	0.66	
SrO	0.04	0.00	0.04	0.00	0.00	
BaO	0.16	0.09	0.23	0.07	0.08	
Total	101.00	98.16	99.37	99.50	98.20	

LA- ICP-MS analyses

Sr	1255.24
Ba	1212.34

Table 3 cont.

Microprobe analyses

Unit	Pijje	Pijje	Pijje	Pijje	Pijje	Pijje
Sample	010629-1C plag 5b	010629-1C plag 5c	010629-1C plag 8a	010629-1C plag 8b	010629-1C plag 8c	
SiO ₂	60.25	61.12	59.55	60.91	60.86	
TiO ₂	0.01	0.00	0.00	0.00	0.01	
Al ₂ O ₃	24.52	23.91	24.61	24.88	24.19	
FeO	0.18	0.19	0.25	0.29	0.25	
MgO	0.03	0.60	0.87	0.30	0.00	
CaO	6.24	5.52	6.32	6.36	6.18	
Na ₂ O	7.80	7.67	7.60	6.52	7.25	
K ₂ O	0.70	0.78	0.60	0.63	0.71	
SrO	0.04	0.00	0.04	0.00	0.35	
BaO	0.22	0.22	0.15	0.11	0.20	
Total	98.90	99.91	100.28	99.30	100.22	

LA- ICP-MS analyses

Sr
Ba

Table 3 cont.

Microprobe analyses

Unit	Virginia	Virginia	Virginia	Virginia	Virginia
Sample	020709-3a plag3	020709-3a plag3	020709-3a plag3	020709-3a plag3	020709-3a plag3
SiO ₂	56.75	57.39	57.39	58.11	58.04
TiO ₂	0.01	0.01	0.00	0.01	0.00
Al ₂ O ₃	26.47	26.11	26.72	26.75	26.83
FeO	0.40	0.43	0.32	0.41	0.40
MgO	0.00	0.03	0.00	0.10	0.01
CaO	8.94	8.66	8.75	8.53	8.89
Na ₂ O	6.66	6.89	6.25	5.67	5.29
K ₂ O	0.35	0.37	0.36	0.35	0.38
SrO	0.29	0.00	0.14	0.00	0.00
BaO	0.14	0.11	0.08	0.07	0.15
Total	99.32	98.19	97.67	97.91	97.28

LA- ICP-MS analyses

Sr	1314.43
Ba	912

Table 3 cont.

Microprobe analyses

Unit	Virginia	Virginia	Virginia	Virginia	Virginia
Sample	020709-3a plag3	020709-3a plag3	020709-3a plag3	020709-3a plag3	020709-3a plag3
SiO ₂	58.78	58.49	59.17	58.90	59.40
TiO ₂	0.00	0.00	0.00	0.00	0.02
Al ₂ O ₃	26.85	26.96	26.64	27.11	27.24
FeO	0.36	0.44	0.37	0.40	0.34
MgO	0.02	0.05	0.00	0.00	0.12
CaO	8.62	8.76	8.72	8.79	8.43
Na ₂ O	4.96	4.67	4.57	4.36	4.09
K ₂ O	0.35	0.39	0.35	0.31	0.32
SrO	0.00	0.22	0.00	0.00	0.00
BaO	0.06	0.03	0.18	0.14	0.04
Total	98.12	96.81	96.36	95.61	96.52

LA- ICP-MS analyses

Sr	1288.83	1232.61
Ba	877.15	592.65

Table 3 cont.

Microprobe analyses

Unit	Virginia	Virginia	Virginia	Virginia	Virginia
Sample	020709-3a plag3a	020709-3a plag3b	020709-4C plag1	020709-4C plag1	020709-4C plag1
SiO ₂	57.14	56.80	56.31	55.91	56.67
TiO ₂	0.00	0.00	0.01	0.02	0.04
Al ₂ O ₃	26.90	27.26	27.39	27.47	28.02
FeO	0.32	0.40	0.38	0.40	0.36
MgO	0.00	0.05	0.01	0.00	0.00
CaO	9.30	9.20	9.77	10.20	9.84
Na ₂ O	5.88	5.90	5.67	5.56	4.56
K ₂ O	0.32	0.32	0.38	0.37	0.38
SrO	0.00	0.00	0.00	0.00	0.00
BaO	0.14	0.06	0.07	0.06	0.13
Total	98.22	100.80	98.10	97.34	96.89

LA- ICP-MS analyses

Sr	1476.39	1377.69	1498.61
Ba	1087.92	975.09	1082.78

Table 3 cont.

Microprobe analyses

Unit	Santa Fe		Santa Fe		Santa Fe		Santa Fe		Santa Fe	
Sample	040707-8F	plag 3a	040707-8F	plag 3b	040707-8F	plag 3c	010629-21F	plag 2a	010629-21F	plag 2b
SiO ₂	59.76		59.76		61.84		60.69		60.80	
TiO ₂	0.02		0.03		0.02		0.00		0.00	
Al ₂ O ₃	25.27		24.65		23.46		24.16		24.57	
FeO	0.27		0.17		0.28		0.22		0.22	
MgO	0.33		0.29		0.00		0.26		0.05	
CaO	7.04		7.08		5.39		5.88		6.64	
Na ₂ O	6.71		7.08		8.01		7.77		7.15	
K ₂ O	0.54		0.61		0.76		0.75		0.56	
SrO	0.00		0.14		0.00		0.18		0.00	
BaO	0.06		0.18		0.25		0.10		0.01	
Total	100.16		100.72		101.26		100.95		99.34	

LA- ICP-MS analyses

Sr	1103	1096.55	891.94	885.9	976.47
Ba	1324.41	1402.54	1938.12	1402.7	1314.42

Table 3 cont.

Microprobe analyses

Unit	Santa Fe	Santa Fe	Santa Fe	Santa Fe	Santa Fe	Green Layer
Sample	010629-21F	990718-12g	990718-12g	990718-12g	990718-12g	040706-1J
	plag 2c	plag 2a	plag 2b	plag 2c	plag 5a	
SiO ₂	60.84	52.69	55.64	59.03	51.38	
TiO ₂	0.00	0.02	0.02	0.01	0.00	
Al ₂ O ₃	24.02	29.37	27.39	25.33	30.14	
FeO	0.25	0.32	0.39	0.32	0.44	
MgO	0.42	0.45	0.37	0.12	0.28	
CaO	5.66	12.15	9.79	7.68	13.49	
Na ₂ O	7.88	4.72	5.76	6.70	3.91	
K ₂ O	0.71	0.23	0.38	0.61	0.17	
SrO	0.00	0.00	0.11	0.00	0.20	
BaO	0.23	0.05	0.15	0.20	0.00	
Total	99.45	99.53	100.69	98.23	99.51	

LA- ICP-MS analyses

Sr	916.77	1466.04	1412	1346.3	1476.39
Ba	1684.61	621.35	820.72	1272.16	452.9

Table 3 cont.

Microprobe analyses

Unit	Green Layer	Green Layer
Sample	040706-1J plag 5b	040706-1J plag 5c
SiO ₂	56.97	59.21
TiO ₂	0.00	0.00
Al ₂ O ₃	26.60	25.25
FeO	0.36	0.25
MgO	0.06	0.10
CaO	9.11	7.69
Na ₂ O	6.24	6.78
K ₂ O	0.45	0.49
SrO	0.07	0.11
BaO	0.13	0.12
Total	100.49	100.65

LA- ICP-MS analyses

Sr	1240.46	1379.89
Ba	694.61	1349.06

3.1 Plagioclase

Plagioclase compositions among units range from 25-65% An, displaying oscillatory, reverse, and normal zoning (Figure 16). The Green layer represents the unit with the highest anorthite content (65%) in addition to having the widest compositional range (65-37% An; normal zoning). The plagioclase grains from the Santa Fe-low are also normally zoned with a range of 57-37% An. Santa Fe-high plagioclase samples display normal zoning (37-28% An) with core anorthite contents similar to the rim value of the Santa Fe-low plagioclase. The Salitral East plagioclases are normally zoned, with An ranging from 44-32%. The only unit that has plagioclase grains with clear reverse zoning is Virginia, the An ranges from 42 in the core to 52% in the inner rim, with a slight drop to 46% An at the outer rim. However, Virginia also has plagioclase with no zoning at ~50% An. Other units (Pijije, Liberia, Santa Fe-high) show small compositional variations from core to rim in the plagioclase grains and also represent the units with lowest anorthite content (32-25% An). The Buena Vista-high plagioclases display oscillatory zoning fluctuating between 30 and 44 An%. Plagioclase grains from the Buena Vista-low were not analyzed.

Plagioclases are sensitive indicators of melt composition, and any changes that occur throughout the melt evolution are recorded in the mineral growth. Volcanic rocks typically exhibit plagioclase with oscillatory zoning (i.e. Anderson, 1984; Kuritani, 1998; Ginibre et al., 2002; Halama et al., 2002). Although there are seven units defined based on trace element ratios, there is considerable compositional overlap among plagioclase core and rims from several different units (Figure 16).

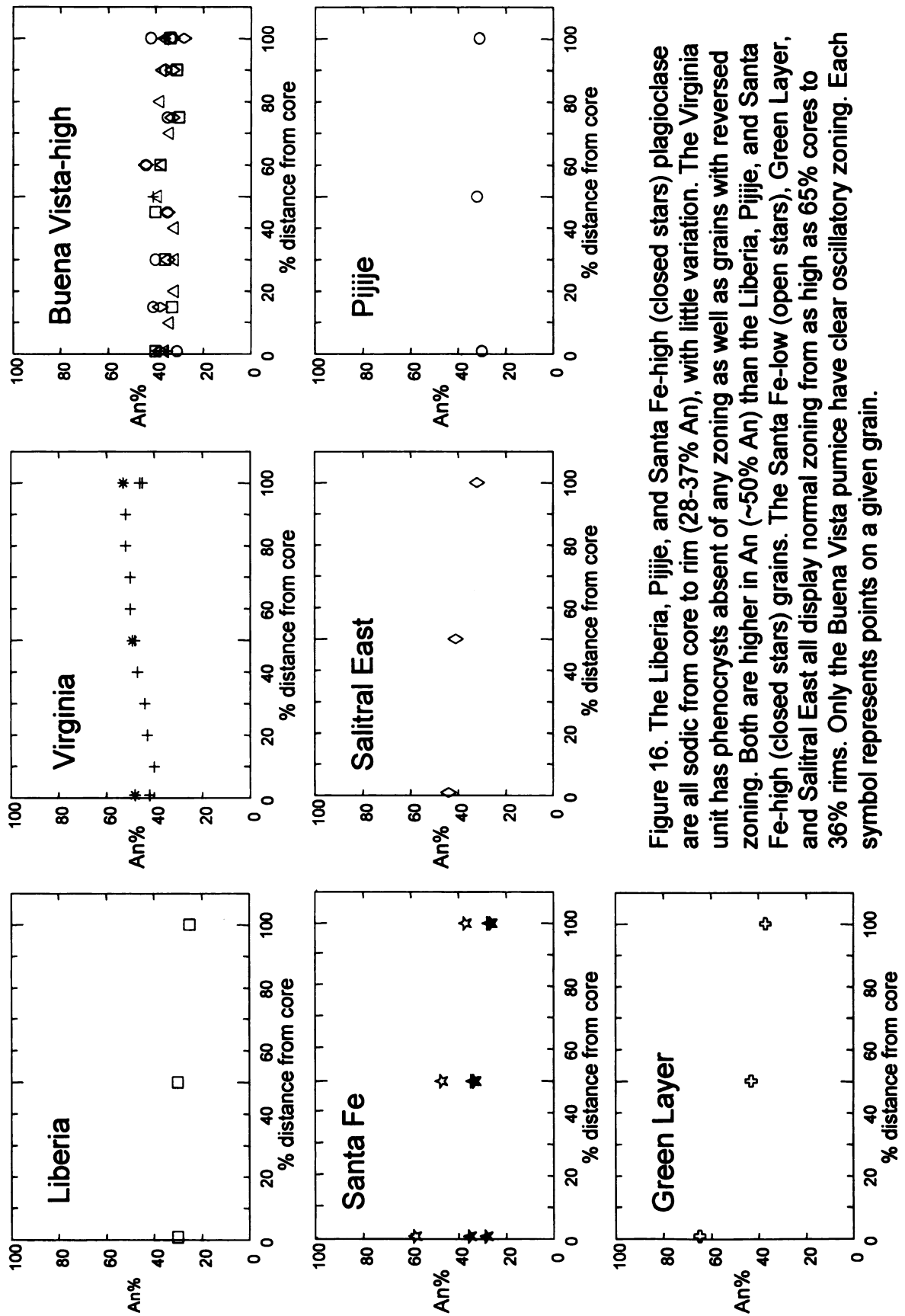


Figure 16. The Liberia, Pijije, and Santa Fe-high (closed stars) plagioclase are all sodic from core to rim (28-37% An), with little variation. The Virginia unit has phenocrysts absent of any zoning as well as grains with reversed zoning. Both are higher in An (~50% An) than the Liberia, Pijije, and Santa Fe-high (closed stars) grains. The Santa Fe-low (open stars), Green Layer, and Salitral East all display normal zoning from as high as 65% cores to 36% rims. Only the Buena Vista pumice have clear oscillatory zoning. Each symbol represents points on a given grain.

In particular, the sodic rim (38% An) of the Santa Fe-low is within analytical error ($\pm 10\%$ of the actual value) of the Santa Fe-high core (36% An). Also of note is the composition of the Salitral East plagioclase core, (44% An) which falls within the range (57-37% An) of the Santa Fe-low plagioclase.

Trace elements Barium (Ba) and Strontium (Sr) have a high partition coefficient with respect to plagioclase and provide strong additional evidence for a co-genetic relationship among evolving melts at various stages. Figure 17 shows the Ba/Sr overlap among units (Santa Fe-low, Green Layer, Salitral East, Virginia, Buena Vista-high), with lower Ba/Sr ratios, whereas Liberia and Santa Fe-high have a higher Ba/Sr ratio.

3.2 Amphibole

Two distinct amphibole groups (high/low-Mg) have been identified using petrographic analyses and EMPA analyses. These two groups are identified by differences in interference colors and pleochroism using a polarized microscope and distinct major-trace element groupings (Figure 18). Several of the trace elements display variations consistent with the two groups. Notably the Nb and Dy are found in two distinct concentrations, high in the low-Mg amphiboles and low in the high-Mg amphiboles. All other trace elements analyzed show overlap between the two types of amphibole. High-Mg amphibole are found in the Virginia, Santa Fe-low, Green Layer and low-Mg amphibole are found in the Virginia, Santa Fe-high, Green Layer, Pijje, Salitral East, Buena Vista-high/low, and Liberia.

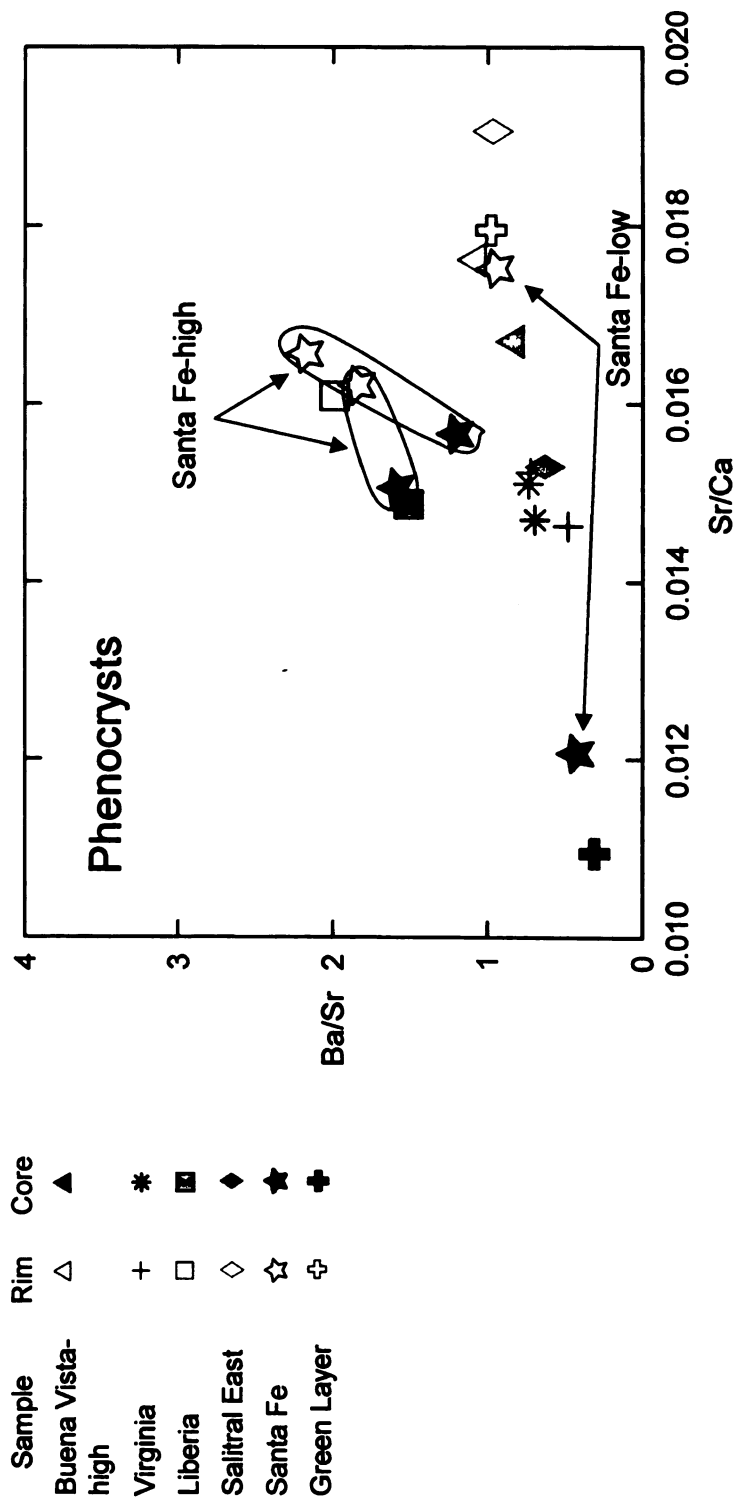


Figure 17. Ba/Sr vs. Sr/Ca plot for the plagioclase phenocrysts. All units are represented here with the exception of Pijje. Two separate trends are evident from core to rim of the phenocrysts. The upper group includes the Liberia and Santa Fe-high (stars). The lower trend includes the Green Layer, Santa Fe-low (stars), Salitral East, Virginia, and Buena Vista, which display considerable overlap between cores and rims.

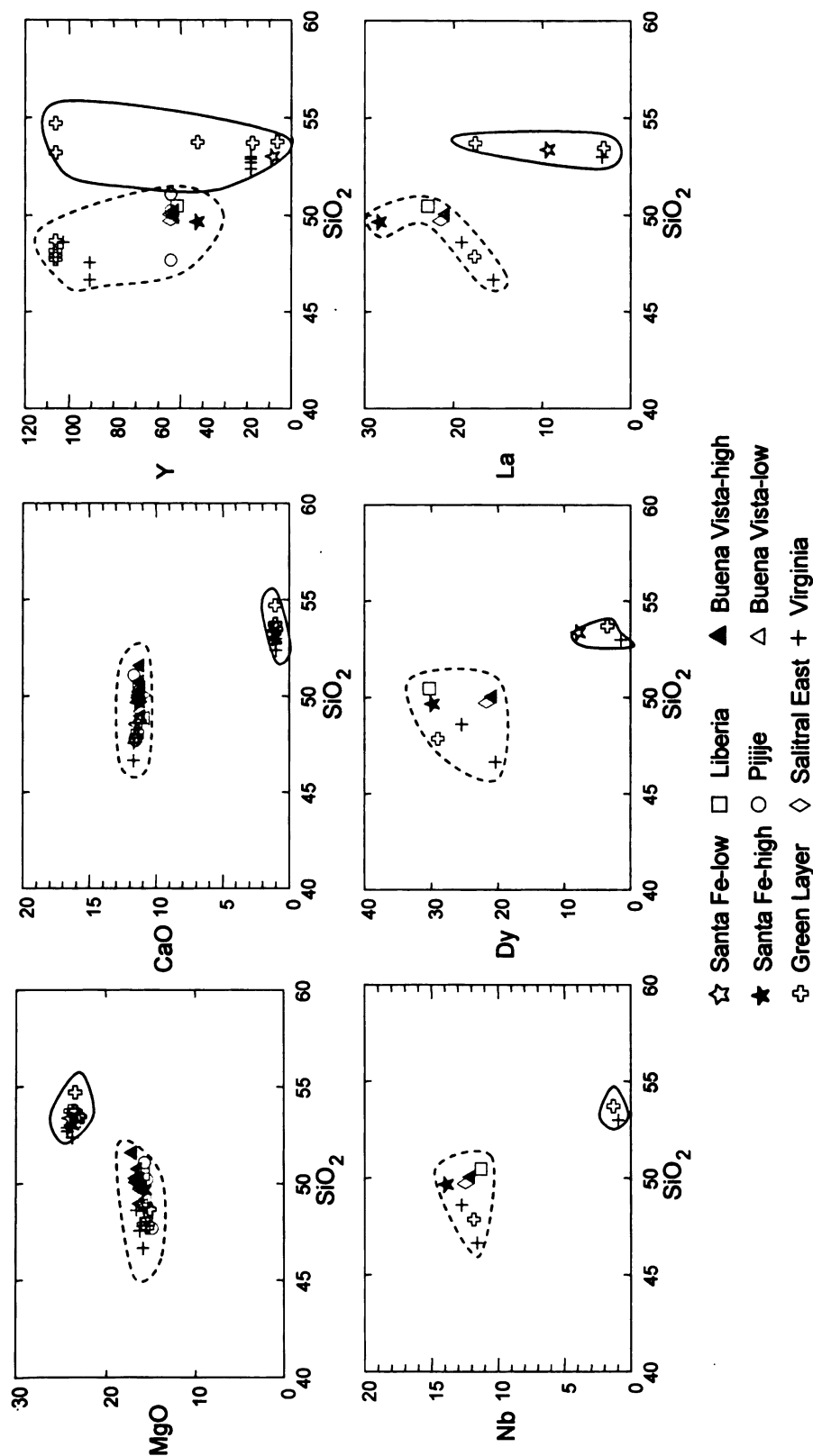


Figure 18. Major and trace element variation diagrams for the amphibole. Two distinct amphibole groups are clearly distinguishable. These are termed high and low-Mg amphiboles in the text. High-Mg amphiboles are encircled by a black solid line, low-Mg amphiboles are encircled by a black dashed line. The low and high silica groups within the Buena Vista unit are both represented and contain only the low-Mg amphibole. The Santa Fe-low and Santa Fe high silica groups contain high-Mg amphibole and low-Mg amphibole, respectively.

3.3 Biotite

Major element data for biotite are displayed in variation diagrams with respect to SiO_2 (Figure 19). The biotite analyzed represent four of the five units that contain biotite. Pijije and Liberia biotites have intermediate FeO and MgO content relative to the Santa Fe-high and Buena Vista-high. The Santa Fe-high has higher FeO and lower MgO, while the Buena Vista-high has lower FeO and higher MgO than the Pijije/Liberia. Trace element data for the biotite grains was not acquired.

3.4 Glass

Glass chemistry for the pumice samples includes all of the major elements (Figure 20) and select trace element analyses (Figure 21). As a whole, the major elements of the glasses display a linear relationship with an increase in SiO_2 (Figure 20). The glass analyses can be divided into two groups: low-silica (<76.5 wt.%) and high-silica (>76.5 wt.%). The low silica group is represented by samples from the Green layer, Santa Fe-low, and Virginia. The high silica group is represented by samples from Santa Fe-low/high, Salitral East, Pijije, Liberia, and Buena Vista-high. The units within these two groups also correspond to the low and high-silica groups identified by bulk geochemistry with the exception of the Santa Fe-low unit, which is represented in both the high and low silica glass groups.

Glass trace element data displayed are restricted by a lack of data for some of the representative units (Figure 21). The Green Layer, Santa Fe-low/high, Salitral East, Pijije, and Liberia, when represented, display relatively similar concentrations for the trace

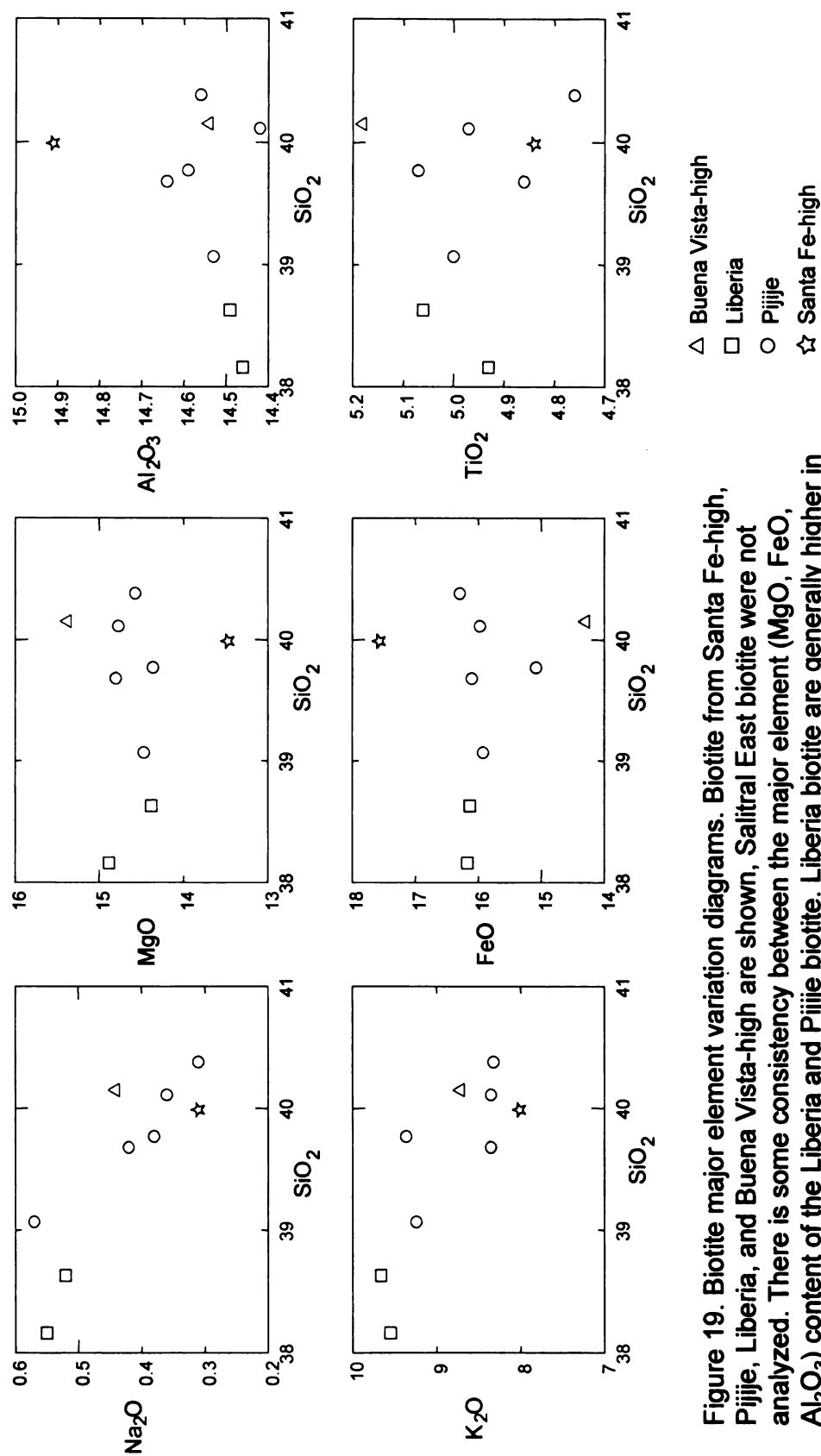


Figure 19. Biotite major element variation diagrams. Biotite from Santa Fe-high, Pijije, Liberia, and Buena Vista-high are shown, Salitral East biotite were not analyzed. There is some consistency between the major element (MgO, FeO, Al₂O₃) content of the Liberia and Pijije biotite. Liberia biotite are generally higher in K₂O, Na₂O, and TiO₂ than the Pijije biotite. Biotite from the Salitral East were not analyzed.

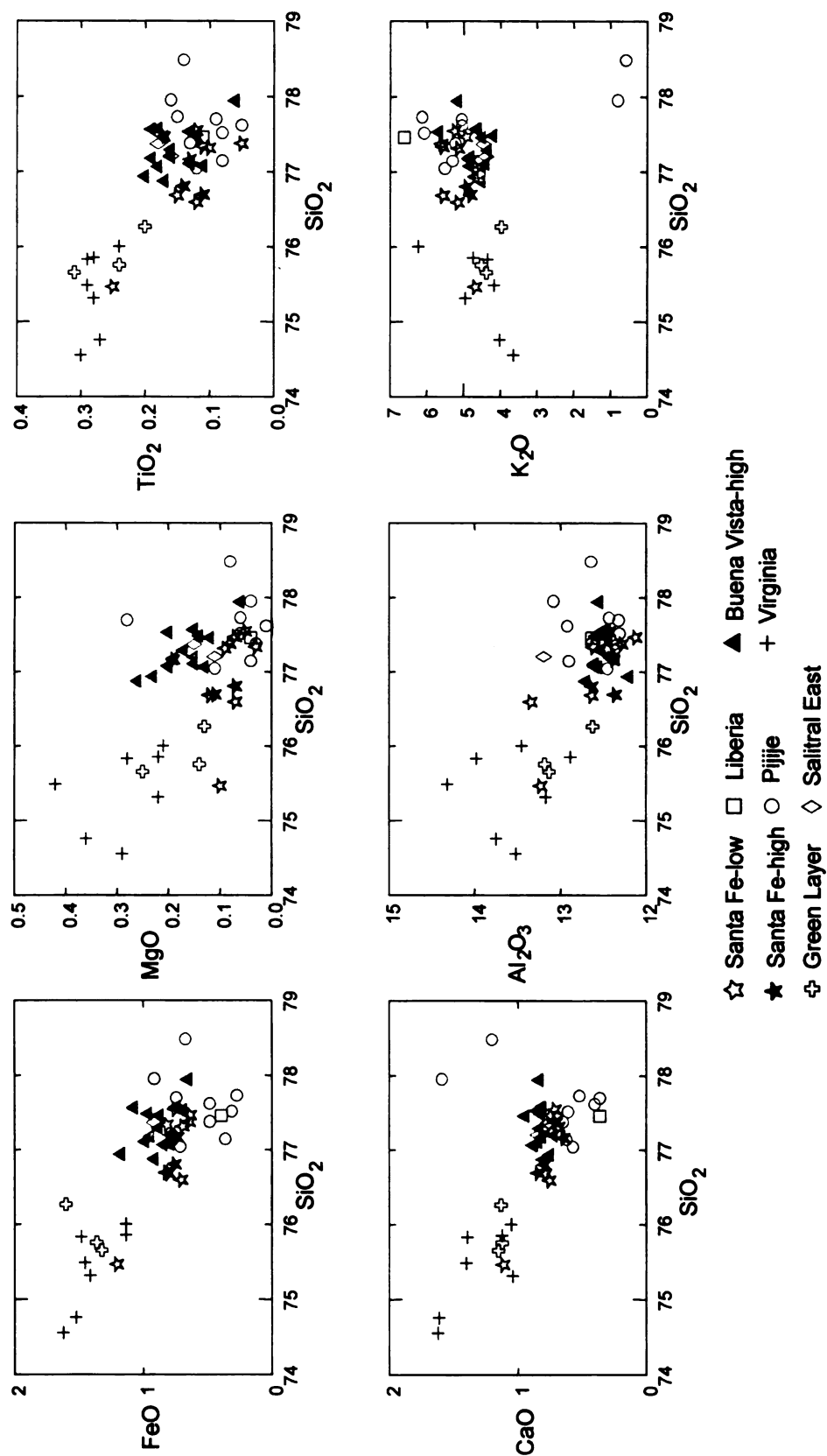


Figure 20. Major element variation diagrams showing the chemical array of the glass from individual pumice. FeO, CaO, Al₂O₃, Na₂O (not shown), and TiO₂ all show a negative correlation with increasing SiO₂. MgO displays two sub-parallel negative trends and K₂O shows the only positive correlation with increasing SiO₂.

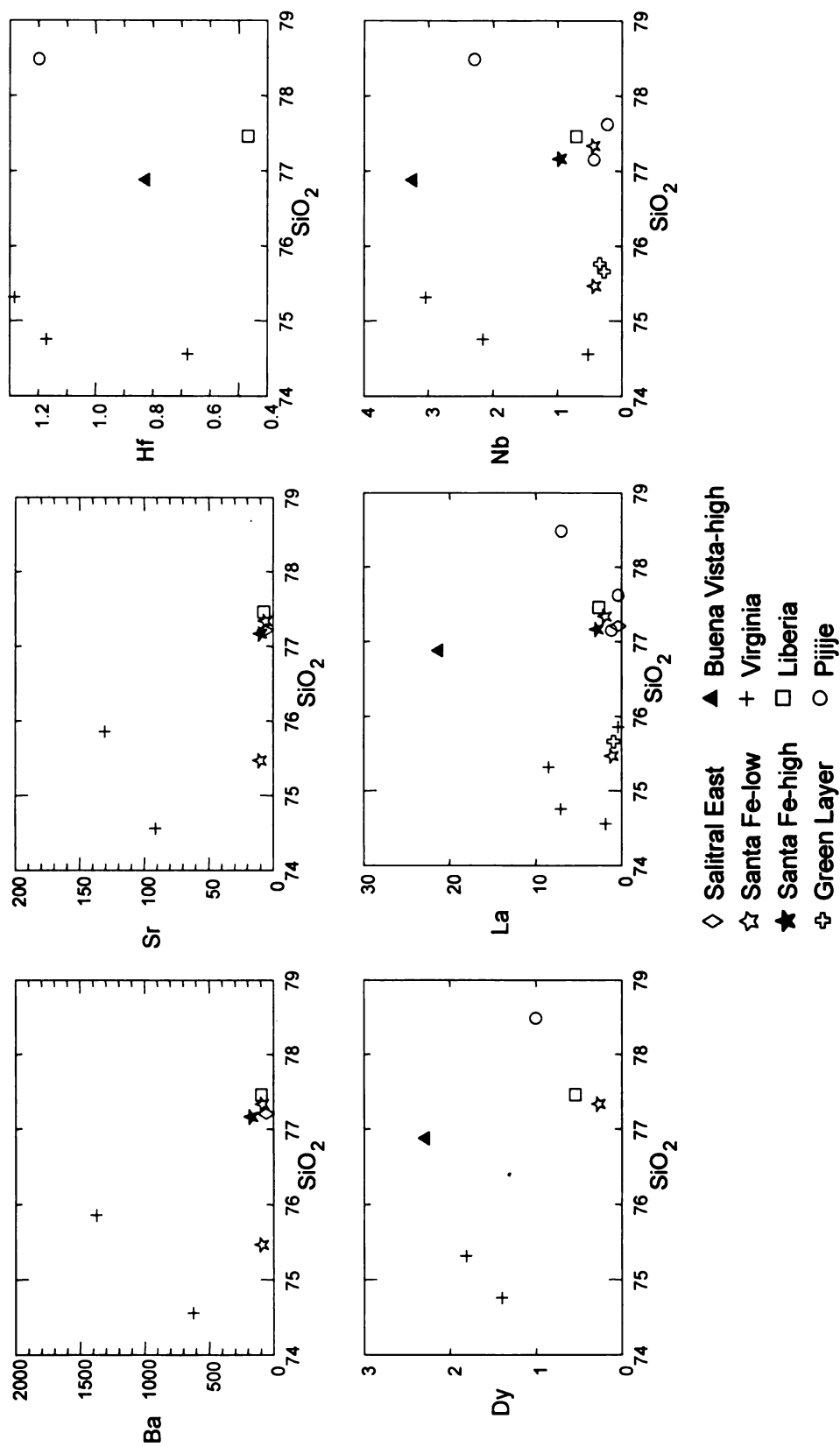


Figure 21. Trace element variation diagrams displaying the glass chemistry of selected individual pumice fragments. All of the units are not represented for each of the trace element diagrams due to lack of usable data.

elements analyzed. However, the Virginia and Buena Vista-high units display higher concentrations of each of the trace elements shown.

VI. DISCUSSION

1. Origin of silicic magma: Partial melting/ extreme fractional crystallization of calc-alkaline andesite

A review of experimental studies (Patino Douce and McCarthy, 1998; Patino Douce, 1999) concluded that generation of silicic magmas with high K_2O/Na_2O in subduction zone environments is not feasible through fractional crystallization or partial melting of a low-K basaltic source rock. More recently, Sisson et al. (2005) present results from an experimental study supporting a process of either a low degree of partial melting or a high degree of fractional crystallization of high K_2O/Na_2O basalts could produce the high K_2O/Na_2O silicic melts.

Tamuri and Tatsumi (2002) proposed a model to explain the origin of silicic melts in arc settings based on petrologic and geochemical evidence. A mantle-derived intermediate melt, hydrous magnesian andesite in composition, is generated at the slab-mantle interface. This intermediate hydrous melt at the base of the crust then ascends to shallower depths where it stalls and crystallizes as it reaches a buoyant equilibrium. Dehydration melting of this intermediate, calc-alkaline andesite could produce partial melts of silicic magma compositions similar to those found in this study. An alternative to melting a solidified calc-alkaline andesite is extraction of the silicic interstitial liquid from a medium to high- K_2O basaltic melt that undergoes a high degree of fractional crystallization or partial melting of a crystalline medium to high- K_2O basalt (Sisson et al., 2005).

Geochemical evidence from the Guachipelin volcanic suite is consistent with the results from Tamura and Tatsumi (2002) and Sisson et al. (2005). First, Tamura and

Tatsumi (2002) define the intermediate crystalline bodies that have stalled in the crust as hydrous and calc-alkaline in composition. A depletion of middle rare-earth elements (MREE) in all samples, with the exception of the Green Layer, indicates a hydrous source based on the presence of residual amphibole (Figure 22). The relative enrichment in MREE of the Green Layer unit could be a result of a higher degree of partial melting that consumed the residual amphibole of the source rock, increasing the MREE. In addition, the patterns in Figure 9 clearly relate the silicic volcanic products to processes related to arc magmatism. Second, the high alkali content of these magmas is also consistent with Sisson et al. (2005) experimental results indicating partial melting of amphibole rich calc-alkaline sources could produce these silicic melts. The Guachipelin suite is within this range of elevated alkalis shown in Figure 23. The experiments of Sisson et al. (2005) involved melting of gabbros with medium to high-K content similar to those found in basaltic lavas from Costa Rica. In addition, the starting products Sisson et al. (2005) used also contained amphibole, which is a proposed component of the Guachipelin source rocks.

Although the Guachipelin ash-flow sheets may share similar types of source, distinct trace element variations exist among the separate ash-flow sheets implying that the sources were not identical. It is therefore necessary to further evaluate possible processes of magma differentiation. The following are several of these processes that will be evaluated: 1) different degrees of partial melting of a single source, 2) partial melting of several distinct sources, 3) fractional crystallization, and 4) assimilation. Before these processes are evaluated, the behavior of the HFSE, used to differentiate between chemically distinct units, will be addressed.

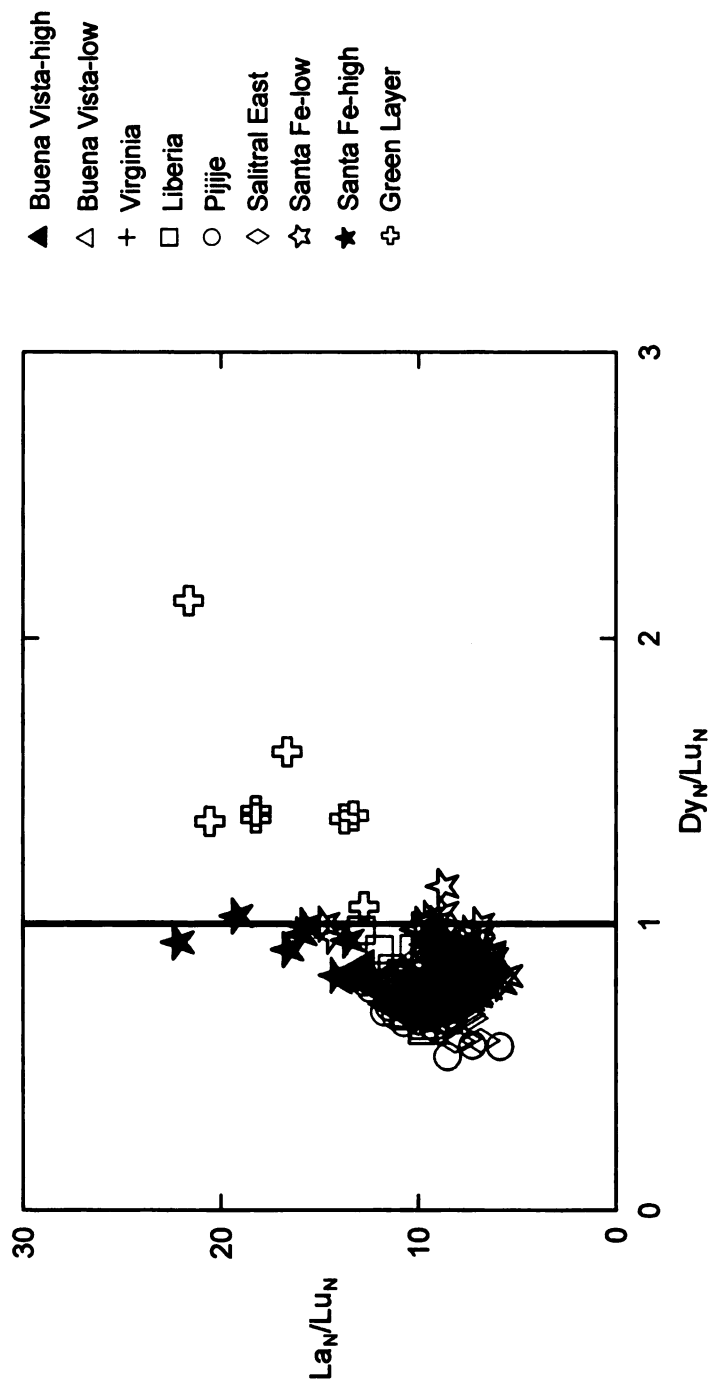


Figure 22. Plot illustrating the variation in MREE (Dy) relative to the LREE (La) and HREE (Lu). Pumice samples with values of $Dy_N/Lu_N < 1$ could be the result of sequestering of the MREE by amphibole in the source. The subscript N denotes normalization to chondrite value of Sun and McDonough, 1989.

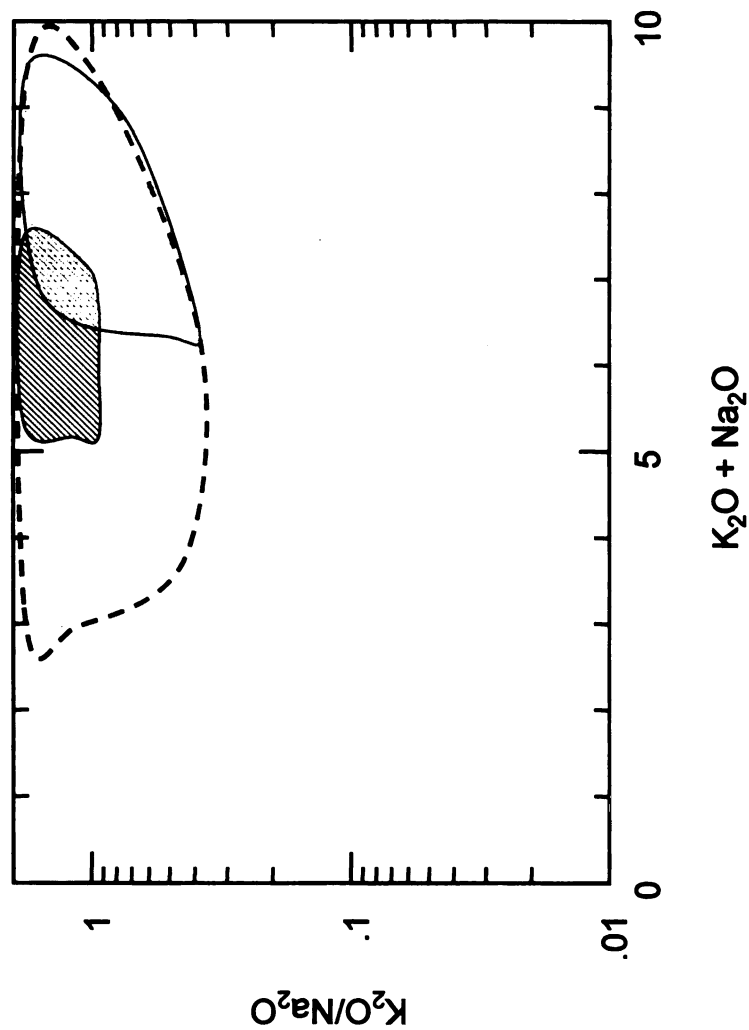


Figure 23. Modified from Vogel et al. (in press). Blue dotted area represents experimental results from melting of high K-basalts, Sisson et al. (2005). Red diagonal lined area represents the Guachipelin silicic pumice fragments. Dashed line encompasses the silicic pumice samples ($\text{SiO}_2 > 65\text{wt. \%}$) from the entire Central American Arc.

2. Sources (HFSE: Nb, Ta, Zr, Hf systematics)

Incompatible trace element ratios are used to differentiate between chemically distinct magma batches. The trace element behavior is controlled by the composition of the source, distribution coefficient, and the degree of melting. Therefore, the individual element contributions from possible subduction zone components (i.e. slab melting) could influence the overall mass flux and/ or partitioning into phases prior to eruption. High field strength elements (HFSE: Nb, Ta, Zr, and Hf) are of particular interest in studies involving subduction zone magmatism because of their different behavior in this setting compared to other settings. HFSE are characteristically depleted relative to REE and large ion lithophile elements (LILE) in magmas from subduction zone settings. This depletion is related to the mass flux processes associated with the subducting slab to the mantle (Munker et al., 2004). Yet, their behavior in this tectonic setting is still not well understood (i.e. Barth et al., 2000; Munker et al., 2004; Schmidt et al., 2004).

It has been shown using the Nb/Ta ratio cumulative frequency plots for the Guachipelin pumice samples that discrete heterogeneities occur within this suite of volcanic deposits (Figure 11). Distinct breaks and/ or differences in the slope of the sample distribution indicate for the most part that a process other than fractional crystallization has governed the chemical differentiation among units (Figure 11a). Specifically in the case of Nb/Ta, the distinct variation displayed among units is not only abrupt, but systematic with respect to Ta (Figure 11c). This systematic control over the ratio by Ta could be a result of a common single phase partitioning within each unit. The compositional overlap among several units displayed by Zr/Hf (Figure 11b), could be a result of chemical “overprinting” by some late stage process such as mixing or

assimilation. The distribution coefficients, crystallization history, and timing of the mixing events relative to the mineral crystallization could influence the degree of overlap found among units. Therefore, other trace element ratios may not reflect the differences among the sources of units. This requires specific attention be given to the behavior of Nb and Ta in determining the differentiation processes.

There are several different stages involved in magma generation in subduction zones that may affect the HFSE composition of the igneous products: slab dehydration, slab melting, and mantle composition. First, fractionation of the HFSE through slab melting and dehydration at the slab-mantle wedge interface is considered. Munker et al. (2004) and Schmidt et al. (2004) have suggested that residual rutile in the slab could account for variations in Nb/Ta. However, these samples show no correlation between ratios used to infer slab melt (Sr/Y) and Nb/Ta variation (Figure 24a). Nb is more incompatible than Ta during an ilmenite-, clinopyroxene-, and rutile- controlled melting process, which would cause variations in mantle wedge depletions. Therefore, a correlation of Nb/Ta with other mantle wedge depletion parameters (Zr/Nb, Zr/Hf, Lu/Hf) is expected (Munker et al., 2004). Yet these magmas show no correlation with mantle wedge depletion parameters (Figure 24b). In addition, with respect to slab dehydration in fluid dominated subduction zone environments, Nb-Ta are thought to otherwise behave conservatively (Elliot et al., 1997). Consequently, partitioning of these elements during a later stage of melt evolution is required to account for the trace element variations of the Guachipelin volcanic suite.

Further work regarding HFSE partitioning suggests crustal level differentiation could be responsible for the Nb/Ta variations (Barth et al., 2000). Barth et al. (2000)

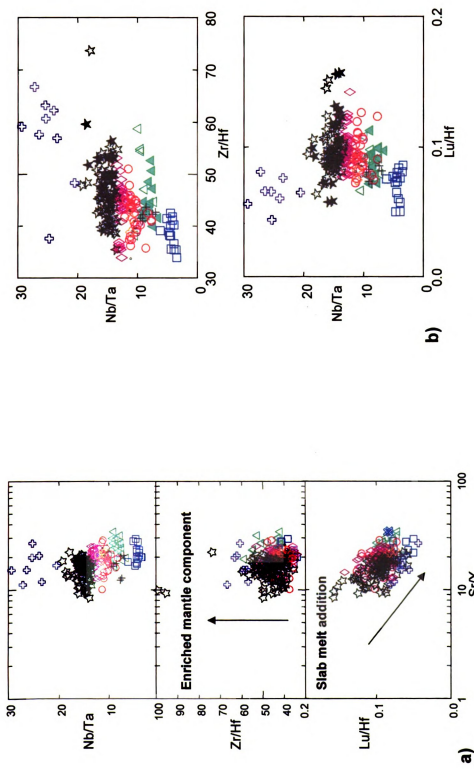


Figure 24a,b. Modified from Munker et. al. (2004). a) Interaction of slab melt with the mantle would generate magmas with high Sr/Y . Key incompatible element ratio Nb/Ta shows no correlation with slab melt addition. Zr/Hf and Lu/Hf can be used as indicators of contribution of an enriched mantle component and slab melt addition, respectively. b) Illustrates the lack of a strong correlation between Nb/Ta and other mantle depletion parameters (e.g. Zr/Hf , Lu/Hf , and Zr/Nb (not shown)). This suggests variable degrees of mantle wedge depletion are not controlling the Nb/Ta ratio.

propose a process of intracrustal differentiation of basaltic magma to form evolved melts. The HFSE differences among the calc-alkaline sources could be a result of the presence of several key minerals. These minerals determine the final mineral-melt partitioning and therefore the composition of any liquid produced in subsequent melting events. In particular, the following minerals fractionate Nb and Ta to different degrees: magnetite (D_{Nb}/D_{Ta} ca. 0.7-0.9), amphibole (D_{Nb}/D_{Ta} ca. 0.7-1.9), ilmenite (D_{Nb}/D_{Ta} ca. 0.7-0.9), and clinopyroxene (D_{Nb}/D_{Ta} ca. 0.3-1.0) (Munker et al., 2004). These minerals are found in peridotite, basalts, eclogites, or amphibolites. The presence of Mg-amphibole in the source could decrease the Nb/Ta ratio in the melt, accounting for the melts with distinct Nb/Ta ratios below the chondritic ratio of 19.9 ± 0.6 (Munker et al., 2004). All of the units have ratios lower than chondrite with the exception of the Green Layer. In contrast, the presence of ilmenite and/ or clinopyroxene increases the melt in Nb/Ta with respect to chondrite.

Zr/Hf ratios in the melts are controlled primarily by magnetite (D_{Zr}/D_{Hf} ca. 1.0-2.3), pyroxenes (D_{Zr}/D_{Hf} ca. 0.45-0.98), and amphibole (D_{Zr}/D_{Hf} ca. 0.3-0.6) (Munker et al., 2004). The presence of magnetite in the source would decrease the Zr/Hf in the melt, whereas pyroxenes and amphibole would increase the ratio.

It has now been shown that the differences in HFSE can be accounted for by different mineral compositions of the sources. Although we have determined the existence of seven distinct magmas, this does not necessarily require seven sources. These magmas could be related by a high degree of fractional crystallization (Sisson et al., 2005) of a single source rock. However, considering that in order to maintain the systematic increase in Ta among units, as the Nb/Ta decreases, a single source must

produce melts progressively enriched in Ta, it is expected that the sequence of eruptions would display this change. This is not supported by the depositional sequence in this study or a relationship between Nb/Ta and SiO₂ (Figure 25).

An oxygen isotope study of ignimbrites from Costa Rica by Eaton (2004), concluded that major element correlations with $\delta^{18}\text{O}$ were not consistent with crystal fractionation. Instead he postulated that variations in the $\delta^{18}\text{O}$ might be explained by assimilation of crustal rocks that have been affected by surface waters low in $\delta^{18}\text{O}$. It is important to note that at most three of the seven units described in this study were represented in that interpretation. Nevertheless, there is no evidence to support fractional crystallization (FC) as the primary process of differentiation relating these magmas. Eaton (2004) also demonstrated that the Guanacaste region, that includes the Guachipelin, displayed lower $\delta^{18}\text{O}$ values than the rest of Costa Rica (Figure 26).

An alternative process to fractional crystallization is different degrees of partial melting of a single source rock. However, as a whole these units lack any significant difference in the degree of partial melting (Figure 22), assuming amphibole is in the source for all of the magmas.

There is no evidence of assimilation of the Caribbean Large Igneous Province (CLIP), the multi-component crustal material these magmas intrude. Mineral composition analyses of over ninety pumice samples from the Guachipelin units alone revealed no evidence of xenoliths or xenocrysts. Second, the bulk geochemistry does not support the assimilation of a more mafic component that may have been completely melted during an event. Furthermore, multiple trials using PVA on data from Hauff et al. (2000) that

included samples of each of the individual components of the CLIP, failed to show any geochemical relationship between the pumice from the Guachipelin and the CLIP.

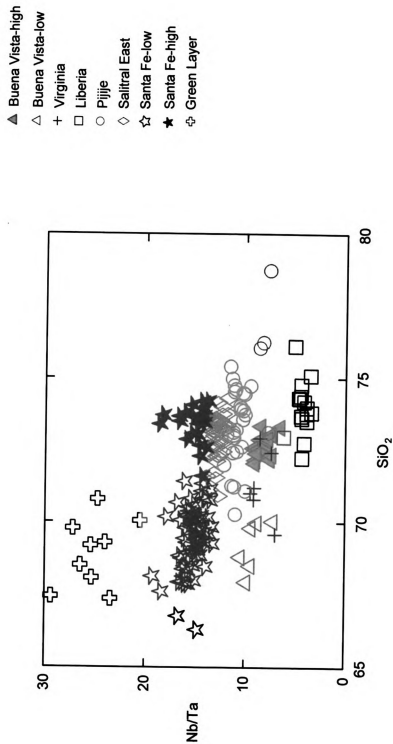


Figure 25. Variation diagram of Nb/Ta ratio versus SiO₂ illustrating that fractional crystallization of a silicate mineral is not controlling the Nb/Ta ratio.

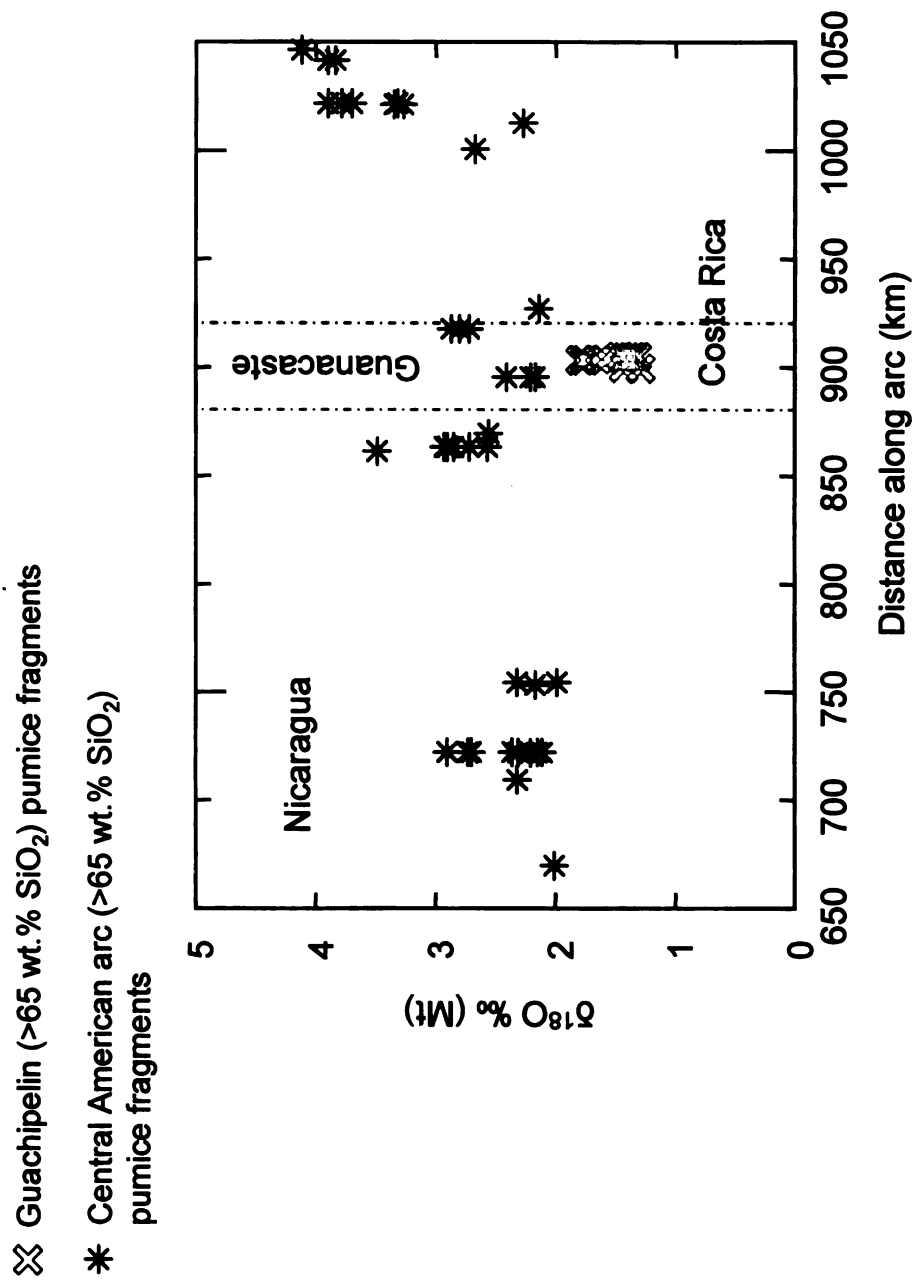
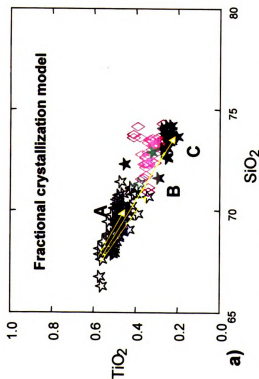


Figure 26. From Eaton (2004). Although there is an overall increase along arc of approximately 2.0‰ $\delta^{18}\text{O}$ from the magnetite(Mt) analyzed, the Guanacaste (specifically the Guachipelin), are anomalously low.

3. Limited fractional crystallization and melt segregation

Although the process of fractional crystallization (FC) fails to account for the chemical variation among the units, multiple linear regression modeling supports limited FC during the evolution of the Santa Fe unit from the low to high silica group (Figure 27). The presence of the compositional gap between the two Santa Fe groups (Figure 7) and distinct differences in the degree of crystallinity requires these deposits to follow separate evolutionary trends. The two sub-groups Santa Fe-low and -high were originally defined as one unit based on the similar Nb/Ta ratios 15.22 and 15.20, respectively, and the fact that they occur in stratigraphic contact with one another. Therefore, explaining the compositional gap by different sources is rejected.

Major elements from the Santa Fe vary systematically, decreasing in MgO, Fe₂O₃, and CaO with an increase in SiO₂ and are consistent with FC trends. Several different parent/daughter combinations were used in the model to test FC, first within the Santa Fe-low, then from the low to an intermediate, and finally to the Santa Fe-high (Figure 27a). Table 4 shows the results of this three part model. The sum of the squares (Σr^2) of the residual provides a measure of the similarity between measured and theoretical chemical parameters tested. The 0.023 and 0.05 Σr^2 residual determined in this modeling is well below acceptable limits that other workers have established. In addition, the liquid/ melt predictions correspond well with the actual pumice crystallinity and mineral abundances. Theoretical predictions of trace element compositions for the daughter were estimated using a combination of partition coefficients from Rollison (1993) and the GERM on-line database (<http://www.earthref.org/GERM/index.html?main.htm>). Figure 27b displays a comparison of the trace element concentrations of the predicted daughter



a) Figure 27a,b. a) Fractional crystallization (FC) modeling using multiple linear regressions. Model is testing FC between the Santa Fe-low and Santa Fe-high. Yellow arrows used to indicate the pathways for Steps A-C. Step A represents the modeling within the Santa Fe-low (Parent: 010630-4h, Daughter: 010630-4a). Step B shows the model from one of the least evolved Santa Fe-low samples to an intermediate Santa Fe sample (Parent: 010630-4e, Daughter: 040707-2a). Step C represents modeling extending across the compositional gap *within* the Santa Fe unit from low to high (Parent: 010630-4h, Daughter: 040708-6a). b) Spider diagrams comparing the observed and calculated trace element trends for each step. **Note:** Symbols used in spider diagrams are not consistent with coding used to identify individual units.

b)

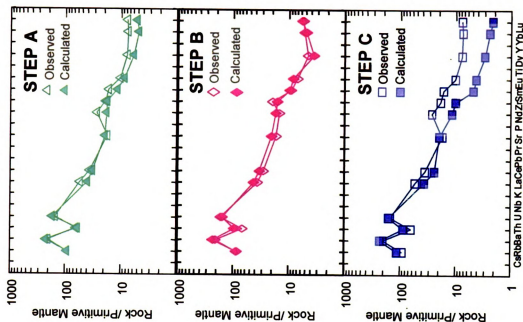


Table 4 Multiple linear regressions

STEP A

PARENT	010630-4h
DAUGHTER	010630-4a
%	Min/rock
1.7	Homblende
5.0	Plagioclase
0.2	ilmenite
0.8	Magnetite
0.923	Liquid remaining

Sum of the squares of the residual = 0.05

Analyte	Daughter	Obs: 010630-4h	Calc: 010630-4h	Residual
SiO ₂	70.32	68.43	68.41	0.01
TiO ₂	0.45	0.57	0.57	0
Al ₂ O ₃	15.88	16.17	16.15	0.01
FeO	3.07	4.04	4.04	0
MnO	0.07	0.11	0.09	0.02
MgO	0.74	1.13	1.13	0
CaO	2.8	3.13	3.21	0.08
Na ₂ O	2.9	3.06	2.91	0.15
K ₂ O	3.73	3.31	3.45	0.14
P ₂ O ₅	0.03	0.03	0.03	0

Prediction based on distribution coefficients

RB	61.9	58	58.4	0.47
SR	347	367.5	402.5	34.98
ZR	207.7	210.8	195.7	15.1
BA	1621.8	1399.2	1543.5	144.31
LA	27.8	36.7	26.8	9.91
CE	58.2	63.2	56.3	6.85
ND	24.7	36.2	24.3	11.9
SM	5.14	7.33	5.1	2.23
EU	1.31	1.71	1.44	0.26
TB	0.66	1.02	0.63	0.39
DY	3.66	5.69	4.32	1.36
ER	2.33	3.45	2.66	0.78
YB	2.44	3.69	2.37	1.32
LU	0.39	0.57	0.38	0.19
HF	4.15	4.62	3.91	0.71
TA	0.63	0.58	0.76	0.18
TH	5.29	5.37	4.98	0.39
U	3.79	3.12	3.54	0.42

Table 4 cont.

STEP B

PARENT	010630-4e
DAUGHTER	040707-2a
%	Min/rock
2.2	Hornblende
6.4	Plagioclase
0.3	ilmenite
0.9	Magnetite
90.2	Liquid remaining

Sum of the squares of the residual = 0.09

Analyte	Daughter	Obs: 010630-4e	Calc: 010630-4e	Residual
SiO ₂	70.89	68.13	68.36	0.09
TiO ₂	0.34	0.51	0.53	0.02
Al ₂ O ₃	17.69	18.11	18.03	0.04
FeO	2.5	3.48	3.5	0.02
MnO	0.09	0.07	0.1	0.03
MgO	0.38	0.82	0.75	0.07
CaO	2.24	2.92	3.05	0.13
Na ₂ O	2.32	2.66	2.43	0.23
K ₂ O	3.53	3.26	3.21	0.05
P ₂ O ₅	0.02	0.03	0.02	0.01

Prediction based on distribution coefficients

RB	0.29	56.5	60.6	4.05
SR	2.87	356.9	409.3	52.4
ZR	0.27	219.9	166	54
BA	0.39	1457.5	1607.8	150.3
LA	0.55	25.1	31.9	6.8
CE	0.65	50.8	58.6	7.87
ND	1.08	20.1	24.4	4.31
SM	1.31	4.04	3.83	0.2
EU	2.32	1.18	1.18	0
TB	0.4	0.6	0.41	0.2
DY	1.62	3.35	2.54	0.81
ER	1.41	2.17	1.21	0.96
YB	1.33	2.59	1.84	0.75
LU	1.21	0.41	0.26	0.16
HF	0.25	4.71	3.26	1.45
TA	0.32	0.69	0.74	0.05
TH	0.3	5.82	8.51	2.68
U	0.16	3.53	3.54	0.01

Table 4 cont.

STEP C

PARENT	010630-4h
DAUGHTER	040708-6A
%	Min/rock
4.2	Hornblende
11.2	Plagioclase
0.3	ilmenite
2.2	Magnetite
82.1	Liquid remaining

Sum of the squares of the residual = 0.02

Analyte	Daughter	Obs: 010630-4h	Calc: 010630-4h	Residual
SiO ₂	73.96	68.44	68.57	0.05
TiO ₂	0.26	0.57	0.58	0.01
Al ₂ O ₃	15.06	16.17	16.04	0.07
FeO	1.64	4.04	4.05	0.01
MnO	0.07	0.11	0.1	0.01
MgO	0.39	1.13	1.08	0.04
CaO	1.65	3.13	3.21	0.07
Na ₂ O	3.01	3.05	3.07	0.02
K ₂ O	3.94	3.32	3.28	0.04
P ₂ O ₅	0.02	0.03	0.02	0.01

Prediction based on distribution coefficients

RB	0.28	58	76.7	18.72
SR	2.76	367.6	339.9	27.7
ZR	0.27	210.9	115.4	95.5
BA	0.38	1399.3	1566.5	167.22
LA	0.47	36.7	22.3	14.4
CE	0.51	63.2	42	21.2
ND	0.73	36.2	14.8	21.4
SM	0.87	7.33	2.18	5.15
EU	2.15	1.71	0.73	0.98
TB	0.36	1.02	0.27	0.75
DY	3.17	5.69	2.63	3.06
ER	2.82	3.45	1.08	2.37
YB	0.6	3.69	1.45	2.24
LU	0.58	0.57	0.22	0.35
HF	0.22	4.62	2.41	2.22
TA	2.04	0.58	0.73	0.14
TH	0.17	5.37	7.81	2.43
U	0.11	3.12	3.75	0.63

and the actual pumice sample for steps A-C. Steps A and B display a good correlation between the observed and calculated trace element quantities as the melt fractionates out key minerals: amphibole, plagioclase, ilmenite, and magnetite. The lack of a good correlation between some of the M- HREE in Step C could be the result fractionation of biotite, quartz, zircon, or apatite related to the Santa Fe-high magma. Trace element partitioning in these minerals were not considered in this model due to the lack of mineral composition data available.

The compositional gap between the Santa Fe-low and high requires fractional crystallization to occur with melt segregation/ extraction from the crystallizing magma. The higher degree of crystallinity of the low-silica Santa Fe group (up to 17%) could represent a longer residence time in a shallow magma chamber with subsequent extractions of interstitial melt to produce two other identified units. First, Step A involves the fractional crystallization within the Santa Fe-low magma. Second, the Salitral East, a hybrid magma, is proposed to be the product of melt extraction from the evolving Santa Fe-low initial melt at some intermediate point of crystallization. This is represented by Step B in the multiple linear regressions in Figure 27. However, the Salitral East, which is defined as a distinct magma, also requires some process that would change the Nb/Ta ratio (see section below for further explanation). Third, Step C models extraction of a melt from the Santa Fe-low magma reservoir, after the extraction of the melt involved in producing the Salitral East magma, which could produce the Santa Fe-high. This unit is characterized by a lower degree of crystallinity than the Santa Fe-low (up to 10%) and the core plagioclase compositions correspond to the rim compositions of the Santa Fe-low (Figure 16).

4. Mixing/Mingling

4.1 Geochemical and petrologic evidence

The distinct geochemical variations between the Guachipelin ash-flow deposits require one or more of several magma differentiation processes. Limited fractional crystallization (FC) of the Santa Fe-low with subsequent extractions of the Salitral East and Santa Fe-high magmas represents one of these processes involved in the magma evolution, but several factors limit this interpretation to only two of the seven units. First, the Santa Fe unit, including both low and high sub-groups, is defined based on having the same average Nb/Ta. Crystal fractionation of amphibole, plagioclase, magnetite, ilmenite, zircon, and apatite would not change the incompatible element ratio among these samples if both elements are behaving equally incompatible with respect to the mineral-melt system. In Figure 11c it is evident that the individual Santa Fe and Salitral East units have nearly horizontal trends, indicating that the Nb and Ta are behaving equally incompatible. Second, although the Salitral East has a distinct Nb/Ta ratio, the samples fall within the major element compositional gap between the Santa Fe groups and the plagioclase core compositions are within the intermediate compositional range of the Santa Fe-low. However, the remaining units - defined by distinct differences in incompatible elements - require some other process to account for the chemical variations.

There are both geochemical and petrologic evidence of mixing/ mingling in most of the representative ash-flow units. The geochemical evidence includes 1) the presence of two amphibole types (High and Low-Mg) in a single pumice, 2) bulk compositional overlap among units, 3) the presence of two different glass compositions in a single pumice, 4) compositional similarities of glasses between units, 5) compositional

similarities between plagioclase, amphibole, or biotite, 6) plagioclase with reverse and/or oscillatory zoning. Petrographic evidence includes disequilibrium textures in plagioclase and amphibole.

4.2 Polytopic vector analysis (PVA); (See appendix A for description of method)

The polytopic vector analyses of pumice major and trace elements from the units, yields a basis of geochemical relationships among samples and are useful in determining the presence of mixing/ fractional crystallization trends. Data output displayed on a scatterplot matrix show compositional trends that might occur among samples. A correlation determined by this method provides support for mixing and fractionation processes as the primary controls in chemical differentiation. PVA mixing trends generated by analysis of all of the data are consistent with those inferred by evaluating the parallel to sub-parallel Al_2O_3 variation with increasing SiO_2 (Figure 28). PVA involves co-analyses of the various units that display chemical and petrologic evidence of mixing from the entire data set.

Four end-members or initial melts (IM) were required to characterize all of the units. Initial melt compositions are provided in Table 5. These initial melts (IM) are compositionally similar to eruptive deposits (e.g. Santa Fe-low) and are distinguished in the subsequent discussion as: IM 1, IM 2, IM 3, and IM 4. The initial melt (IM 2) is also evolving throughout the proposed sequences of mixing. Any composition more evolved than that initial melt (IM 2) is referred to as an evolved melt (EV 2). The following mixing systems were identified using PVA on the bulk geochemical data: IM 2+EV 2 and IM 1; IM 2+ EV 2 and IM 3; IM 2+EV 2 and IM 4.

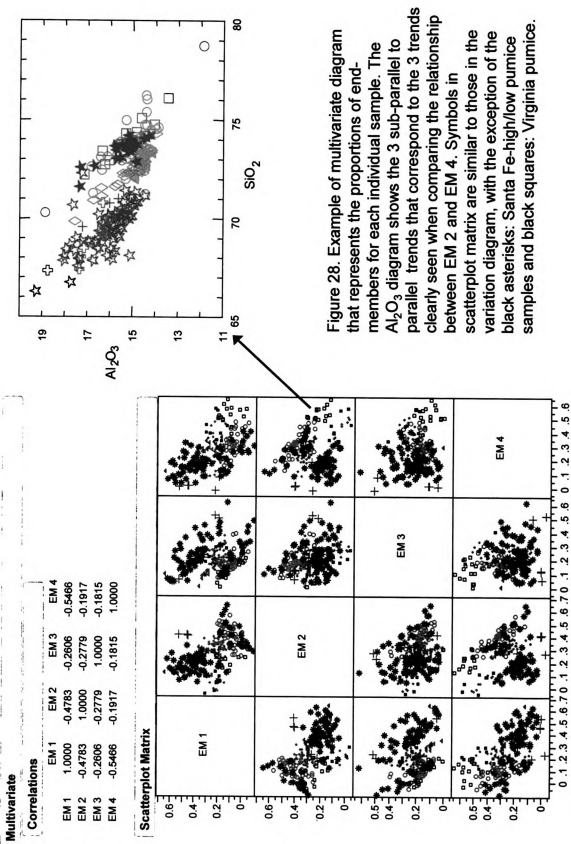


Table 5 Initial melt compositions from the four end member sources
Includes the most evolved end member of the Santa Fe (EV-2)

Analyte	IM 1	IM 2	EV 2	IM 3	IM 4
<i>SiO₂</i>	67	66.9	76.9	67.2	71.2
<i>TiO₂</i>	0.537	0.645	0.0573	0.592	0.311
<i>Al₂O₃</i>	18.8	15.7	14.1	16.9	17.1
<i>FeO</i>	4.4	4.75	0.5	4.3	2.25
<i>MnO</i>	0.177	0.11	0.0389	0.135	0.0493
<i>MgO</i>	0.546	1.22	-0.0141	0.848	0.59
<i>CaO</i>	2.5	3.92	0.913	3.43	1.72
<i>Na₂O</i>	2.38	3.49	2.52	3	2.47
<i>K₂O</i>	3.37	3.02	4.68	3.24	3.99
<i>P₂O₅</i>	0.0294	0.0633	0.0128	0.0463	0.0162
<i>Rb</i>	68.7	41.8	105	51.3	101
<i>Sr</i>	355	467	153	417	254
<i>Zr</i>	200	253	73.2	235	173
<i>Y</i>	30.7	26.7	8.1	21.9	15.2
<i>Nb</i>	12.8	8.56	9.02	8.39	8.59
<i>Ba</i>	1930	1290	1900	1440	1710
<i>La</i>	42.4	24.9	22.5	22.8	27.5
<i>Ce</i>	96.6	54.2	38.9	59.1	52.9
<i>Pr</i>	12.2	6.36	3.52	6.32	6.05
<i>Nd</i>	45.9	25.2	8.93	24.6	22.3
<i>Sm</i>	7.6	5.39	0.341	5.4	3.87
<i>Eu</i>	1.52	1.55	0.147	1.57	1.05
<i>Gd</i>	6.89	5.26	0.509	4.75	5.57
<i>Tb</i>	0.817	0.777	0.0415	0.735	0.515
<i>Dy</i>	4.39	4.27	0.218	3.74	2.79
<i>Ho</i>	0.707	0.942	-0.00463	0.755	0.478
<i>Er</i>	1.7	2.86	-0.287	2.29	1.51
<i>Yb</i>	1.99	3.01	0.703	2.79	2.16
<i>Lu</i>	0.3	0.459	0.0549	0.416	0.332
<i>Hf</i>	3.54	5.36	0.889	4.89	4.59
<i>Ta</i>	0.494	0.526	0.586	0.847	2.1
<i>Pb</i>	11.5	8.59	13.5	12.3	18.8
<i>Th</i>	8.29	3.29	9.95	4.2	8.92

Each of these mixing systems was evaluated in compositional space using both major and trace elements to illustrate the overlap among its constituents.

The first mixing system between the IM 2+ EV 2 and IM 1 produces a modified Santa Fe-low magma (Figure 29a). This interaction is extensive and ongoing as the initial Santa Fe melt evolves by fractional crystallization (EV 2). Some Santa Fe-low and Green Layer pumice fragments exhibit similarities in: 1) major element glass chemistry (Figure 21), 2) bulk geochemistry (REE patterns, Nb/Ta) (Figures 7 and 8), 3) amphibole composition (Figure 19), 4) plagioclase composition (Figure 16 and 17). Glass major element chemistry of these units shows considerable overlap (Figures 20). It is expected that sufficient mixing of the IM 2+ EV 2 with the IM 1 would elevate the Nb/Ta near that of the Green Layer. This also requires a large contribution of the IM 1, which is consistent with PVA generated proportions of IM 1 contribution, up to 58% (Figure 29a). Some of the Santa Fe samples with higher than average Nb/Ta ratios are found closest to the Green Layer-IM apex of the ternary mixing diagram (Figure 29a). The amphibole found in both of these units is the high-Mg type and plagioclase compositions are similar in both anorthite content and Ba/Sr trends (Figures 16-18). Disequilibrium textures in plagioclase from the Santa Fe-low and Green layer and the presence of two distinct glasses in Green Layer pumice identified in petrographic analyses, suggests the mixing of melts after one or both have already begun to crystallize. The preservation of this texture in itself supports a relatively short time elapsed between mixing and eruption (Nakamura, 1995).

The next mixing system is between the IM 2+EV 2 and IM 3, which produces the Salitral East magma (Figure 29b). The Salitral East, Santa Fe-low, and Buena Vista-high

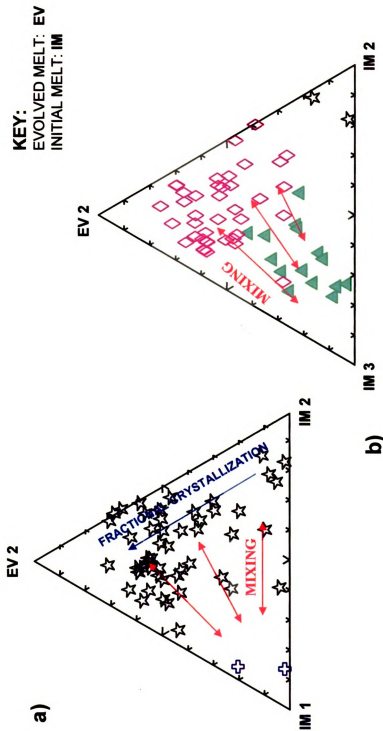


Figure 29a,b. a) Ternary diagram demonstrating mixing proportions determined by PVA among the evolving IM 2+EV 2 and IM 1. Fractional crystallization trends represent the path consistent with modeling using multiple linear regressions. Santa Fe-low pumice and open purple crosses: Green Layer pumice. b) Ternary diagram demonstrating mixing proportions determined by PVA among the melt extracted from the IM 2+EV 2 and the IM 3 producing the hybrid Salitral East magma. Open black stars: Santa Fe-low pumice, open purple diamonds: Salitral East pumice, closed green triangles: Buena Vista-high pumice.

pumice fragments exhibit similarities in: 1) glass major element chemistry (Figure 20), 2) bulk geochemistry (Figures 7 and 8); not similar, but Salitral East fall in between the Santa Fe-low and Buena Vista-high, 3) amphibole composition (Figure 18), 4) plagioclase composition (Figure 16 and 17). In regards to glass, bulk geochemistry, and amphibole composition the Salitral East is compositionally more similar to the Buena Vista-high than the Santa Fe-low. However, the Salitral East plagioclase core compositions reflect initial growth within a less evolved magma (Santa Fe-low) than the Buena Vista-high. This is consistent with melt extraction from the IM 2 after there has been some crystallization (Figure 27b) and subsequent mixing with a more evolved magma the IM 3. Mixing with this magma type would maintain the normal zoning and is consistent with the plagioclase trace element trends (Figures 16 and 17). The dominant nature of the compositional similarities between the Salitral East and Buena Vista-high pumice fragments suggests extensive input from the IM 3 rather than the IM 2+EV 2, produced the Salitral East magma. This is also consistent with PVA mixing proportions, up to 60% of IM 3 (Figure 29b). In addition, the Salitral East pumice fragments lack any signs of compositional banding in either the hand samples or the thin sections. Therefore the subordinate IM 2 magma may have reached thermal equilibrium with the interacting IM 3. Although corroded plagioclase cores indicate chemical disequilibrium exists between the two. This supports the early growth of the plagioclase from the IM 2 that came in contact with the IM 3 magma long enough to reach thermal, but not chemical, equilibrium.

The evolved EV 2 and IM 1 undergo limited mixing, modifying the magmas (Figure 30a). This mixing occurs after the Santa Fe reaches the final stage of crystal

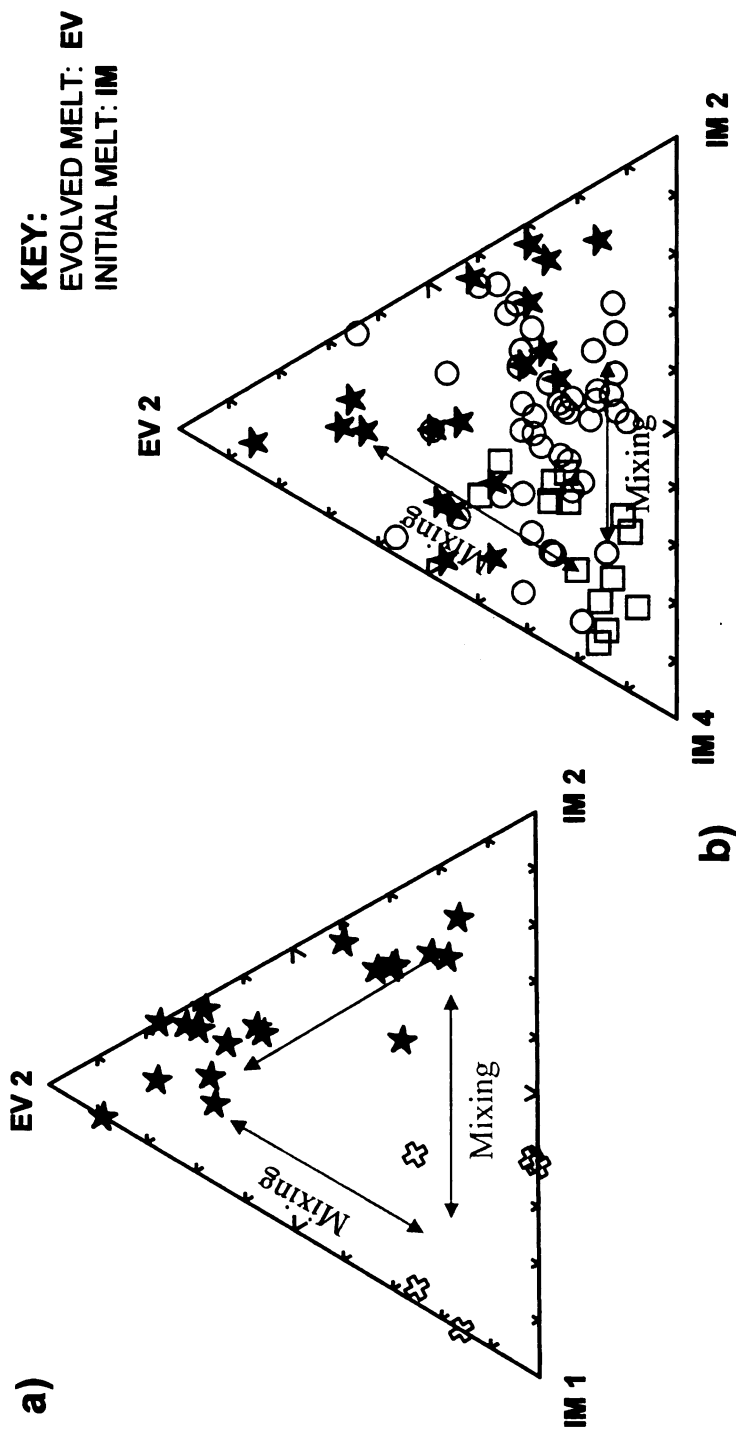


Figure 30a,b. a) Ternary diagram demonstrating mixing proportions determined by PVA among the highly evolved IM 2+EV 2 and IM 1. Fractional crystallization trends represent the path consistent with modeling using multiple linear regressions. Closed black stars: Santa Fe-high pumice and open purple crosses: Green Layer pumice. b) Ternary diagram demonstrating mixing proportions determined by PVA among the melt extracted from the IM 2+EV 2 and the IM 4 producing the hybrid Pijije magma. Open red circles: Pijije pumice, open blue boxes: Liberia pumice, and closed black stars: Santa Fe-high pumice.

fractionation (Figure 27a). At this point melt is extracted from this magma body and mixes with the IM 1. The Green Layer is influenced more in this mixing system, a contributing proportion of Santa Fe up to 50% according to the PVA results. The presence of both high and low Mg- amphiboles in a single Green Layer pumice that are not found in the Santa Fe-high pumice, is also consistent with these mixing proportions. High Mg-amphibole is only associated with the IM 1 and low Mg-amphibole only with the Santa Fe-high, or in general the low and high – silica groups, respectively. Selected Santa Fe-high and Green Layer pumice exhibit similarities in amphibole composition (Figure 18). Petrographically these Green Layer pumice fragments also display clear evidence of both a dark and light colored glass. Similar to the good correlation between the Santa Fe-low: Green Layer interaction described earlier, the Santa Fe-high with the highest Nb/Ta relative to the other Santa Fe-high samples show REE patterns that are similar to the patterns for the Green Layer pumice (Figures 9 and 10).

The evolved EV 2 and IM 4 mix to produce the hybrid Pijije magma (Figure 30b). The Santa Fe-high, Pijije, and Liberia pumice exhibit limited similarities in: 1) glass major and trace element chemistry (Figures 20 and 21), 2) bulk geochemistry (Figures 7 and 8), 3) amphibole major element composition (Figure 18), 4) plagioclase composition (Figures 16 and 17). In addition, the Na₂O and K₂O concentrations in the biotite from the Pijije fall on or between the Liberia and Santa Fe-high biotite.

The final mixing relationships are between the IM 2+EV 2 and the IM 3 to produce the hybrid Virginia and subsequently the modified Buena Vista-low magmas (Figure 31a,b). The Santa Fe-low, Virginia, and Buena Vista-low exhibit similarities in: 1) glass major and trace element chemistry of the Virginia and Santa Fe-low only

KEY:
 EVOLVED MELT: EV
 INITIAL MELT: IM

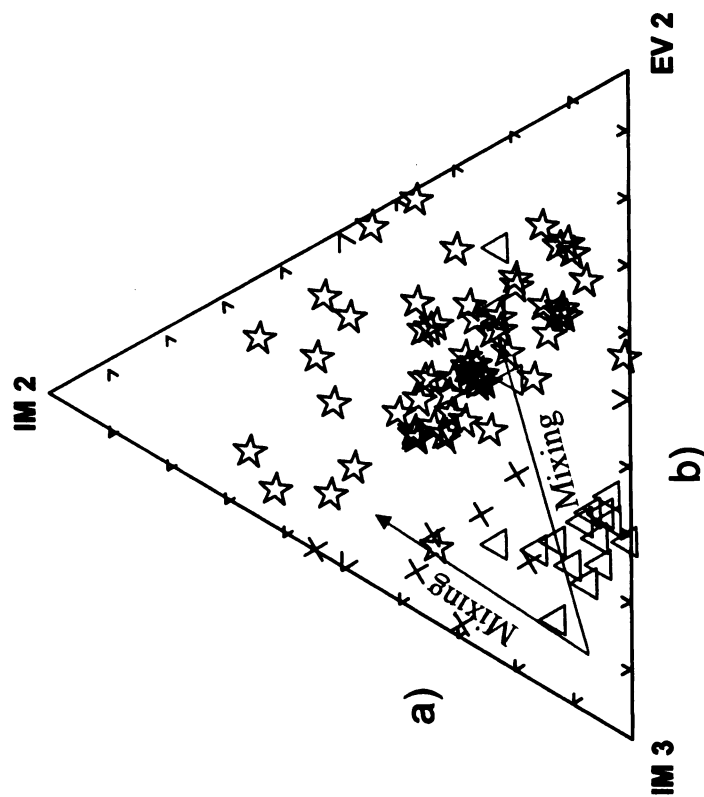


Figure 31a,b. a) Ternary diagram demonstrating mixing proportions determined by PVA among the evolving IM 2+EV 2 and IM 3. Mixing between the least evolved of the Santa Fe-low produced the hybrid Virginia magma. b) Mixing between the evolving IM 2 and IM 3 produce the Buena Vista-low magma. The Buena Vista-low/high pumice, black crosses: Virginia pumice, and green open triangles: Buena Vista-low/high pumice.

(Figures 20 and 21), 2) bulk geochemistry (Figures 7 and 8), 3) amphibole composition (Figure 18), 4) plagioclase composition (Figures 16 and 17). This final sequence of eruptions requires the protracted existence of the IM 3 and an evolving IM 2. Key petrologic evidence that supports the mixing to produce the hybrid Virginia include the presence of oscillatory and reverse zoning in the Buena Vista-high and Virginia plagioclase phenocrysts, respectively. In addition, the high and low- Mg amphibole are found in the Virginia pumice population, but not in the same sample. Both the anorthite content of the plagioclase (up to 57% rim) and presence of the high-Mg amphibole are interpreted as the result of mixing with a less evolved magma, specifically the IM 2.

5. Model for the petrogenetic evolution of distinct silicic magmas

The petrogenetic model is based on several co-evolutionary processes that generate chemically distinct magma batches. These processes include partial melting of four chemically distinct crystalline sources that produces the chemically distinct melts, limited fractional crystallization, and extensive mixing. Figure 32 shows that both magma fractionation and mixing were important processes in the petrogenesis of the initial melts. The multiple inputs of the initial melts in mixing events also requires a protracted residence of several of these melts. It is important to note the lack of temporal and/ or physical constraints on the initiation and residence of each of the end member melts prior to any differentiation processes and eruption. The only constraint is provided in regards to the stratigraphic sequence, which only limits the sequence of evolution to just prior to eruption.

5.1 Guachipelin Caldera silicic melt generation

Stage 1 represents the inception of the Guachipelin magmatic system. This begins with dehydration melting of chemically distinct amphibole rich calc-alkaline sources producing the IM 2, IM 3, and IM 4 silicic melts (Figure 33). Also partial melting of an amphibole poor calc-alkaline source or a higher degree of partial melting relative to the other units generates the IM 1 silicic melt (Figure 33). The thermal energy needed to initiate this melting could be provided by advection from a hot-dry basaltic magma at the base of the crystalline rock or partially crystallized magma body (Tamura and Tatsumi, 2002).

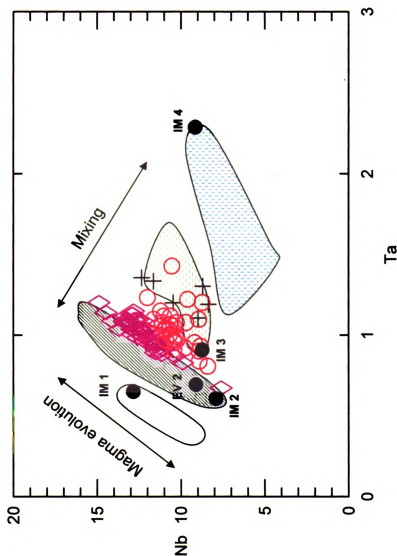


Figure 32. The general trends of magma evolution within individual units are indicated as Nb and Ta would be partitioned proportional to one another. Shifts in Ta concentration are influenced by mixing with end-member magmas with higher or lower initial Ta concentrations. Black dots represent the compositions of the four initial melts generated that would mix to produce the hybrid magmas (Salitral East: purple diamonds, Pijije: red circles, and Virginia: black crosses). Individual symbols represent pumice fragments as follows: Green Layer: purple dotted area, Santa Fe: black diagonal area, Buena Vista: green dashed vertical lines, and Liberia: blue dashed vertical lines.



STAGE 1

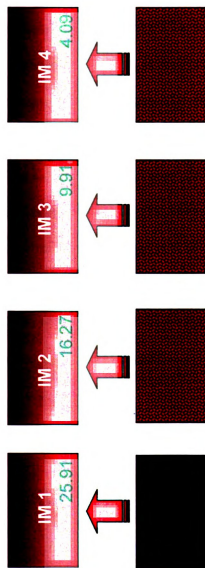


Figure 33. Dehydration melting of three distinct crystalline calc-alkaline andesites produce the IM 2, IM 3, and IM 4 magmas. Partial melting of an anhydrous calc-alkaline source generates the IM 1 magma. Nb/Ta ratios for each initial melt (IM) are provided in the lower right corner of each box.

5.2 Magma differentiation

Stage 2 includes the individual processes of magma differentiation that produce the seven chemically distinct ash-flow deposits and their sub-groups. Although there are only seven units defined, eight deposits are described due to the separate eruption of the Santa Fe-high sub-group from the Santa Fe-low. Based on the data presented above, the following individual processes are related to each unit in the series of eruptions. The Guachipelin stratigraphic sequence starts with the eruption of: 1) The Green Layer magma, volumetrically the smallest of the units erupted (Figure 34). 2) The IM 2+EV 2 undergoes extensive mixing with the IM 1 erupting the modified Santa Fe-low magma (Figure 34). 3) An intermediate melt is extracted from the evolving IM 2+ EV 2 and mixes with the IM 3 forming the Salitral East hybrid magma (Figure 34). 4a,b) The EV 2 undergoes limited mixing with the IM 1 producing the Santa Fe-high (Figure 34), a) this magma is subsequently erupted b) along with more of the Green Layer magma, which is a result of more extensive mixing between the EV 2 and IM 1 (Figure 34). These are two

STAGE 2

1 Green Layer

2 Santa Fe-low

3 Saltillo East

4a Santa Fe-high

4b Green Layer

5 Pijjie

6 Liberia

7 Virginia

8 Buena Vista-high and low

IM 1 25.91

IM 2 16.27

IM 3 9.91

IM 4 4.09

EV 2 15.39

Figure 34. Summary diagram of the petrogenetic evolution of each individual pyroclastic deposit from the Guachipelin eruptive sequence. Solid double sided arrows represent mixing, dashed single sided arrows represent fractional crystallization, and dotted single sided arrows represent eruption event.

separate magma batches that are produced, the Green Layer deposit being the volumetrically subordinate unit. 5) The EV 2 mixes with the IM 4 forming the hybrid Pijje (Figure 34). 6) Immediately following this eruption the Liberia magma erupts (Figure 34). 7) Next, the IM 2+ EV 2 mixes with the IM 3 forming the hybrid Virginia (Figure 34). 8) The final eruption is the product of additional mixing between the IM 2+ EV 2 and IM 3 to produce the modified Buena Vista –low and -high; differences in these two magmas are a result of variability in the mixing proportions of the two initial melts (Figure 31).

VII. CONCLUSION

The Guachipelin ignimbrites can be characterized as having seven chemically distinct, silicic ash-flow sheets. A review of several studies regarding silicic magma generation in subduction zone environments - absent of continental crust - suggest partial melting of an intermediate calc-alkaline source could produce dacitic-rhyolitic melts. The results of this study are consistent with these models.

After the initial silicic melt was generated, differentiation processes are required to produce the chemical heterogeneity of the seven discrete ash-flows. Several possible methods of differentiation were tested in this study. The processes of fractional crystallization, partial melting of different intermediate sources, and mixing/ mingling were each evaluated and each played a role in the evolution of the Guachipelin magmatic system.

It was concluded that extensive mixing and protracted magma residence are required to generate this series of co-genetic magmas. Polytopic Vector Analysis (PVA) was used to evaluate mixing among four initial magma (IM) batches. The seven chemically distinct ash-flow sheets are the result of different proportions of mixing between these IM producing hybrid or modified magmas. Due to the extended residence of the IM 2 magma, it underwent limited crystal fractionation as it contributed melt, which would periodically mix with each of the other three initial melts as it evolved.

In conclusion, the numerous explosive eruptions associated with the formation of the Guachipelin Caldera require a complex network of magma pathways to elicit the extensive magma mixing displayed in this volcanic suite. Contributions from each of the

four initial magmas occurred as discontinuous pulses that required protracted residence of several of these end-members.

APPENDIX A

Polytopic Vector Analysis

The following explanation is taken directly from Tefend (2005): “*Polytopic Vector Analysis (PVA) is explicitly designed to analyze samples that are mixtures; basically, each sample in a dataset is described in terms of some proportion of each end member generated by the program. Therefore, three parameters are needed to define a mixing system: 1) the number of end members, 2) the composition of each end member, and 3) the relative proportion of each end member in each sample within the dataset. Given knowledge of 1) and 2) the mixing proportions can be derived using many procedures. PVA is designed to estimate all three parameters from ambient data (e.g. chemical analyses of rock samples). The only assumptions are that every end member be present in low proportions in at least one sample and that the proportions of each end member within each sample sums to a constant (such as 1.00).*

All mixing systems require plotting the data onto a geometric figure termed a simplex. A simplex may occur as a line with end members defined at the two ends (two end member, like the plagioclase series), an equilateral triangle (3 end members), a symmetric tetrahedron (4 end members) or a higher dimensional equivalent. For instance a five end member system requires a four dimensional simplex. Unfortunately the term “simplex” has been used as a label for the Simplex Method of Linear programming. To avoid confusion, the PVA procedure was named Polytopic Vector Analysis. All simplexes are polytopes but not all polytopes are simplexes; only “equilateral” polytopes are simplexes.

PVA was developed by and for geologists, and has evolved over a period of about 40 years; the procedure is now used in many other fields. The initial impetus came from

John Imbrie who at the time was interested in grain size distributions and micropaleontological data sets (Imbrie, 1963; Imbrie and Kipp, 1971). Imbrie, and his graduate student Ed Klovan, coded up a version of "Qmode" factor analysis where the data is placed in a covariance matrix that defines relationships between samples. This program was ultimately named "CABFAC" (Klovan, 1968; Klovan and Imbrie, 1971) and is now widely used to analyze faunal assemblages associated with climate analysis.

The next major development was made at the suggestion of Al Miesch, an igneous petrologist / geochemist at the USGS. Miesch and Klovan converted CABFAC into EXTENDED QMODEL and added the QMODEL procedure (Miesch, 1976a; Miesch, 1976b; Klovan and Miesch, 1976). Miesch wanted an analytical tool to test hypotheses. His concept was that petrologists had developed models of end member systems for a variety of igneous rock types and that a better way to evaluate sample data must exist in order to determine whether one or another model was feasible. Most petrologic data sets contain many more variables than the number of expected end members. If the variables (or analytes) were truly independent, then the data must be plotted using one reference axis for each analyte, in which case the data would plot as a multi-dimensional hypersphere. However, there are many correlations that exist between analytes such that fewer than k dimensions (where " k " is the number of variables) are necessary to enclose the data. Miesch and Klovan developed a superior way to determine the number of dimensions necessary for each variable: the now widely used "Coefficients of Determination" table. Once the dimensionality of the data is known, then the number of end members required is simple: one more than the true dimensionality. So, if this analysis determined that the system required 5 end members, for instance, and theory

predicted three end members, then the theoretical system was incapable of defining the variability among samples. QMODEL permits the analyst to input compositions of theoretical end members to define a simplex, and if all sample data fits within the simplex, then the imposed end member system is feasible. If some samples fall outside the simplex, negative mixing proportions occur and either the model end members are incorrect, or there are problems with data accuracy.

Finally, in 1982 the version that has evolved into the present version of PVA was developed in the context of a particular problem. The research group under Robert Ehrlich had developed a way to quantify grain shape, and it soon became clear that grain shape frequency distributions were polymodal: the sand samples were mixtures of grains of various provenance or transport history. With the help of Klován, PVA was developed; the principle developer was William Full (Full, et al., 1981, 1982; Ehrlich and Full, 1987). Full's hyper-dimensional insight resulted in the creation of the DENEG procedure (Full, et al., 1981); when a simplex based on extreme samples in the dataset proved to be insufficient or was mis-oriented, the DENEG procedure allowed an iterative systematic enlargement and rotation of the simplex such that, at convergence, a simplex is defined where the compositions of each end member (located at the vertices) had non-negative components and all of the samples could contain non negative mixing proportions. At this stage the procedure was named EXTENDED QMODEL, which was then refined over the next 20 years, and the procedure was renamed PVA. The evolution in PVA continued with major improvements by Glenn Johnson, including the idea of the CD plot as well as the art and practice of PVA implementation with different data set (Johnson, 1997; Johnson, et al., 2000; Johnson, et al., 2002).

The VSPACE Module

PVA consists of 2 modules; the first module (VSPACE) is a variant of Q mode factor analysis that decomposes the covariance matrix into eigenvectors. Eigenvectors represent a rotation of the reference axes that were previously defined by the analytes. As with the original axes, the eigenvectors are mutually orthogonal. The orientation of each eigenvector is controlled by the orientation of the cloud of multivariate variance. By design, the first eigenvector is oriented in the direction of highest variance; the second is oriented in the direction of the highest variance residual to the first, and so on. The amount of variance each eigenvector absorbs is measured by the eigenvalue associated with each eigenvector. Because eigenvectors represent progressively less variance, a common assumption is that at some level variance is so low that it mostly consists of random noise, so that if the higher numbered eigenvectors are disregarded, only noise rather than information is lost. This is the equivalent of projecting the data from the original number of dimensions defined by the number of analytes to a lower dimension defined by the reduced set of eigenvectors.

A chronic problem has been to decide how many eigenvectors to discard. VSPACE utilizes criteria first described by Klován and Miesch (1976) and later, extended by Johnson et al. (2002). In general these criteria are based on the agreement, variable by variable, between the values in the original data and the values of each variable obtained by back calculation using progressively fewer retained eigenvectors. If, for instance, all of the variables are well approximated by two eigenvectors, then all of the relationships between samples can be displayed on a two dimensional graph. As

discussed above, the number of end members is one higher than the number of necessary dimensions.

Often it is unclear whether there are k or $(k+1)$ dimensions; commonly both solutions are run. The difference between the two solutions often hangs on the “importance” of the agreement between raw data and the back-calculated values for one or two variables.

The PVA Module

The second module is PVA proper. The task of the PVA module is to fit a simplex that encloses the data cloud once the number of end members is determined in the first module, VSPACE. Two criteria are needed to run PVA: 1) an initial guess for the initial simplex and 2) the DENE procedure (Full et al., 1982).

PVA is an iterative procedure; that is, it starts with an initial simplex and then enlarges and reorients it so as to leave no samples outside the final simplex such that all of the vertices (end member compositions) have elements in the negative orthant. There are several ways to define the location of the initial simplex; the preferred procedure is to choose the most mutually distant samples. The EXRAWC procedure attempts this by initializing on the k samples (where k is the number of end members), each having maximum varimax loadings on an eigenvector; next, a simplex defined by those points is constructed, and then tested, to determine whether any sample is located outside of the simplex (e.g. has negative mixing proportions). The Achilles heel of this option is its' sensitivity to outliers that actually represent data analytical error or entry errors. However, proper use of information from VSPACE can largely mitigate this problem; hence, this is the default option in PVA.

It is a simple matter to determine which samples fall outside the polytope, as well as determine the composition of any vertex (the candidate end member); the DENEG procedure is an iterative procedure aimed at defining a simplex that encloses all samples and determines the compositions of the vertices. The procedure is designed to operate incrementally by moving any "side" of the simplex outwards a given distance (the DNEG value) parallel to itself or until the DENEG distance contains no samples; at this point, the procedure signals convergence. Thus, each iteration has two parts: 1) the movement of the simplex edges outwards, thus defining new vertices, and 2) changing any negative elements in the end member compositions to zero, thus rotating the simplex.

Sometimes PVA does not converge, or it converges so slowly that the number of iterations is very large. If so, this can be ameliorated by either changing the DENEG value or accepting an iteration that has low negative values in either mixing proportions or end member compositions. Sometimes a lack of convergence reflects the fact that the data cloud is hyper-spherical and thus unmixing is not applicable."

APPENDIX B

Buena Vista-low

The Buena Vista pumice fragments are light gray to tan in color, hypocrySTALLINE with a degree of crystallinity ~21%. The matrix is dominated by a light and dark glass intermingled, with few microlites.

Mineralogy:

Most plagioclase are subhedral to euhedral, 0.05-2.875mm, albite twinning and oscillatory zoning are common. Amphibole are anhedral to euhedral, 0.125-1.5mm, with some twinning and zircon inclusions. Fe-Ti oxides are anhedral to euhedral, 0.025-0.75mm.

Textures:

Phenocrysts are found not only isolated, but in glomeroporphyritic clots of the smaller plagioclase, amphibole, and Fe-Ti oxides. A bi-modal distribution could be inferred based on the relative size difference between the plagioclase in the small clots and those that are isolated. Some plagioclase are anhedral and have sieve textures suggesting disequilibrium between mineral and melt. Amphibole have a brush-like texture along the rim, which could reflect disequilibrium between mineral and melt or be the result of eruptive fragmentation.

ESTIMATED MODAL PERCENTAGE**Primary:**

Plagioclase	15%
Amphibole	3%
Fe-Ti oxides	3%

Accessory:

Zircon	<<1%
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Buena Vista-high

The Buena Vista pumice fragments are light gray to tan in color, hypocrystalline with a degree of crystallinity 8-21%. The matrix is dominated by a light glass with few microlites.

Mineralogy:

Most plagioclase are subhedral to euhedral, 0.05-2.875mm, albite twinning and oscillatory zoning are common. Amphibole are anhedral to euhedral, 0.75-2.25mm, with some twinning. Some amphibole have Fe-Ti oxide, biotite, zircon, or apatite inclusions. Fe-Ti oxides are anhedral to euhedral, 0.025-0.7mm, with zircon inclusions. Biotite are anhedral, 0.125-0.625mm. Quartz are anhedral, 0.05-2.5mm.

Textures:

Phenocrysts are found not only isolated, but in glomeroporphyritic clots of the smaller plagioclase, amphibole, and Fe-Ti oxides. A bi-modal distribution exists between a population of larger isolated crystals and the clots that occur as bands. Some plagioclase are anhedral and have sieve textures, overgrowths, or embayments suggesting disequilibrium between mineral and melt. Quartz are typically resorbed. Amphibole have a brush-like texture along the rim, which could reflect disequilibrium between mineral and melt or be the result of eruptive fragmentation.

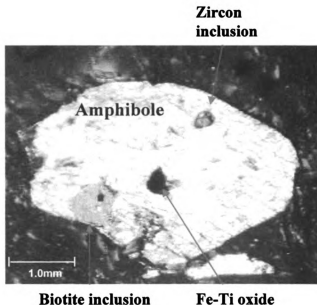
ESTIMATED MODAL PERCENTAGE

Primary:

Plagioclase	7-15%
Amphibole	<1-2%
Biotite	<1%
Quartz	<1-4%
Fe-Ti oxides	1-2%

Accessory:

Zircon	<<1%
Apatite	<<1%



Liberia

The Liberia pumice fragments are light gray to tan in color, hypocrySTALLINE with a degree of crystallinity 14-16%. The matrix is dominated by a light glass with few microlites.

Mineralogy:

Most plagioclase are anhedral to subhedral, 0.05-3.625mm, albite twinning and oscillatory zoning are common. Amphibole are subhedral to euhedral, 0.075-1.5mm, with some twinning and Fe-Ti oxide inclusions. Fe-Ti oxides are anhedral, 0.025-1.25mm. Biotite are anhedral to euhedral, 0.025-1.875mm, some have Fe-Ti oxide inclusions. Quartz are anhedral, 0.125-4.5mm.

Textures:

Phenocrysts are typically found isolated, but some plagioclase are intergrown along with the Fe-Ti oxides. Some plagioclase have sieve textures and overgrowths suggesting disequilibrium between mineral and melt. Quartz are typically resorbed. Glass displays a distinct flow texture.

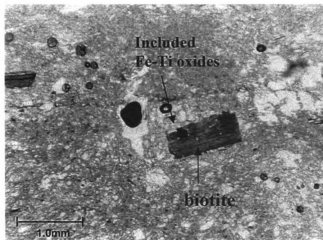
ESTIMATED MODAL PERCENTAGE

Primary:

Plagioclase	7-8%
Amphibole	<1%
Biotite	5-7%
Quartz	<1-2%
Fe-Ti oxides	<1%

Accessory:

Zircon	<<1%
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Virginia

The Virginia pumice fragments are light gray to tan in color, hypocrystalline with a degree of crystallinity ~4%. The matrix is dominated by a light glass.

Mineralogy:

Most plagioclase are anhedral to euhedral, 0.05-3.75mm, albite twinning and oscillatory zoning are common. Some plagioclase have amphibole or Fe-Ti oxide inclusions. Amphibole are anhedral to subhedral, 0.05-1.25mm, with some twinning. Fe-Ti oxides are anhedral, 0.025-0.375mm.

Textures:

Phenocrysts are found not only isolated, but in glomeroporphyritic clots of the smaller plagioclase, amphibole, and Fe-Ti oxides. Some plagioclase have sieve textures and embayments suggesting disequilibrium between mineral and melt.

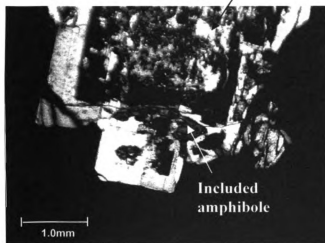
ESTIMATED MODAL PERCENTAGE

Primary:

Plagioclase	3-4%
Amphibole	<1%
Fe-Ti oxides	1%

Accessory: Not observed

**Corroded
plagioclase cores**



**Included
amphibole**

Salitral East

The Salitral East pumice fragments are light gray to tan in color, hypocrystalline with a degree of crystallinity 8-10%. The matrix is dominated by a light glass.

Mineralogy:

Most plagioclase are anhedral to subhedral, 0.075-2.5mm, albite twinning and oscillatory zoning are common. Amphibole are subhedral to euhedral, 0.075-2.0mm, with some twinning and Fe-Ti oxide, biotite, and apatite inclusions. Fe-Ti oxides are anhedral to subhedral, 0.025-0.75mm, with some zircon inclusions. Biotite are anhedral, 0.05-0.875mm. Quartz are anhedral, 0.25-3.375mm.

Textures:

Phenocrysts are typically found isolated, but some plagioclase are intergrown along with the Fe-Ti oxides. Some plagioclase have embayments suggesting disequilibrium between mineral and melt. Quartz are typically resorbed. Glass displays a distinct flow texture.

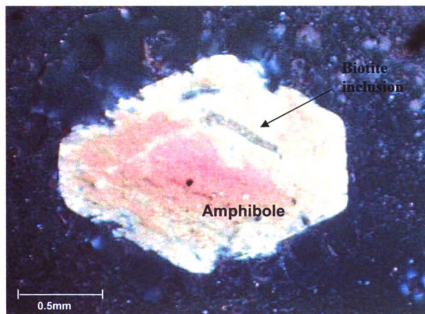
ESTIMATED MODAL PERCENTAGE

Primary:

Plagioclase	5%
Amphibole	2-4%
Biotite	<1%
Quartz	<1-1%
Fe-Ti oxides	1%

Accessory:

Zircon	<<1%
Apatite	<<1%



Pijije

The Pijije pumice fragments are light gray to tan in color, hypocrystalline with a degree of crystallinity 10-50%. The matrix is dominated by a light and dark glass intermingled, with few microlites.

Mineralogy:

Most plagioclase are anhedral to euhedral, 0.05-5.0mm, albite twinning and oscillatory zoning are common. Amphibole are anhedral to euhedral, 0.175-1.5mm, with some twinning and Fe-Ti oxide inclusions. Fe-Ti oxides are anhedral to subhedral, 0.025-0.75mm. Biotite are anhedral to euhedral, 0.05-2.5mm, some have Fe-Ti oxide inclusions. Quartz are anhedral, 0.075-3.75mm, with sparse amphibole inclusions.

Textures:

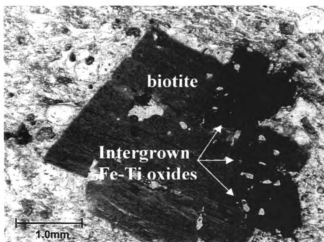
Phenocrysts are typically found isolated, but some plagioclase are intergrown along with the Fe-Ti oxides. Some plagioclase have sieve textures, overgrowths, or embayments suggesting disequilibrium between mineral and melt. Quartz are typically resorbed. Glass displays a distinct flow texture and microlites an intermediate trachytic texture. In samples that display two distinct glasses a bi-modal distribution of plagioclase and amphibole exists.

ESTIMATED MODAL PERCENTAGE

Primary:

Plagioclase	6-40%
Amphibole	<1-10%
Biotite	1-7%
Quartz	<1-10%
Fe-Ti oxides	<1%

Accessory: Not observed



Santa Fe-low

The Santa Fe-low pumice fragments are light gray to tan in color, hypocrystalline with a degree of crystallinity ~8-18%. The matrix is dominated by a light and dark glass intermingled, with few microlites.

Mineralogy:

Most plagioclase are anhedral to euhedral, 0.025-2.5mm, albite twinning and oscillatory zoning are common, with some Fe-Ti oxide inclusions. Amphibole are anhedral to subhedral, 0.125-2.5mm, with some twinning and Fe-Ti oxide inclusions. Fe-Ti oxides are anhedral, 0.025-0.5mm.

Textures:

Phenocrysts are not only found isolated, but in glomeroporphyritic clots of intergrown plagioclase, amphibole, and Fe-Ti oxides. Some plagioclase have sieve textures or embayments suggesting disequilibrium between mineral and melt. Amphibole have a brush-like texture along the rim and some have corroded cores, which could reflect disequilibrium between mineral and melt or be the result of eruptive fragmentation.

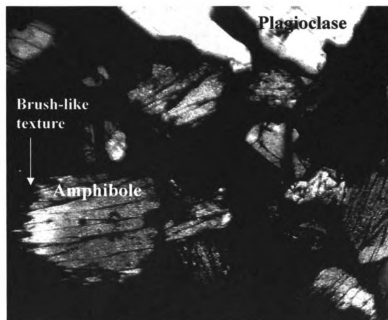
ESTIMATED MODAL PERCENTAGE

Primary:

Plagioclase	6-15%
Amphibole	1-2%
Fe-Ti oxides	1%

Accessory:

Not observed



Santa Fe-high

The Santa Fe-high pumice fragments are light gray to tan in color, hypocrySTALLINE with a degree of crystallinity 7-9%. The matrix is dominated by a light glass.

Mineralogy:

Most plagioclase are anhedral to subhedral, 0.05-3.75mm, albite twinning and oscillatory zoning are common. Amphibole are anhedral to euhedral, 0.15-1.625mm, with some twinning and Fe-Ti oxide inclusions. Fe-Ti oxides are anhedral to subhedral, 0.025-0.45mm. Biotite are anhedral to euhedral, 0.125-2.125mm, some have Fe-Ti oxide inclusions. Quartz are anhedral, 0.25-5.0mm.

Textures:

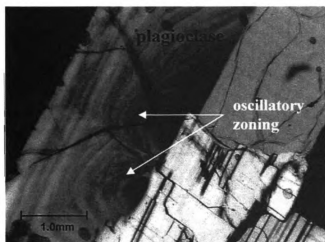
Phenocrysts are typically found isolated, but some plagioclase are intergrown along with the Fe-Ti oxides. Quartz are typically resorbed. Glass displays a distinct flow texture and microlites an intermediate trachytic texture.

ESTIMATED MODAL PERCENTAGE

Primary:

Plagioclase	3-7%
Amphibole	<1%
Biotite	1-2%
Quartz	2-3%
Fe-Ti oxides	<1%

Accessory: Not observed



Green Layer

The Green Layer pumice fragments are light gray to tan in color, hypocrystalline with a degree of crystallinity ~9-11%. The matrix is dominated by light glass, although some have a light and dark glass intermingled.

Mineralogy:

Most plagioclase are anhedral to euhedral, 0.25-4.9mm, albite twinning and oscillatory zoning are common. Amphibole are anhedral to euhedral, 0.25-2.75mm, with some twinning and Fe-Ti oxide inclusions. Fe-Ti oxides are anhedral, 0.025-0.5mm.

Textures:

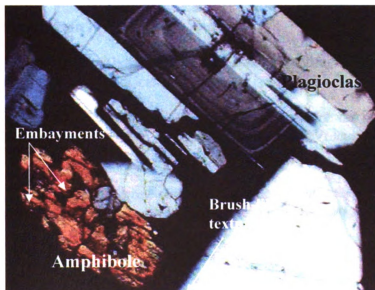
Phenocrysts are found not only isolated, but in glomeroporphyritic clots of the smaller plagioclase, amphibole, and Fe-Ti oxides. A bi-modal distribution of these minerals could be inferred based the size differences between the phenocrysts in the clots and those that are isolated. Some plagioclase have sieve textures or overgrowths suggesting disequilibrium between mineral and melt. Amphibole have a brush-like texture along the rim and/ or embayments, which could reflect disequilibrium between mineral and melt or be the result of eruptive fragmentation.

ESTIMATED MODAL PERCENTAGE

Primary:

Plagioclase	7%
Amphibole	2-4%
Fe-Ti oxides	1%

Accessory: Not observed



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