

**COMPARATIVE GEOCHEMICAL ANALYSIS OF RECENT VOLCANIC FLOWS ON
BARVA VOLCANO, COSTA RICA**

A Thesis Presented for the
Master of Science
Degree
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Julie Marie Coulombe

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An old friend used to say to me, “life is not a dress rehearsal, there are no do-overs.” This project is a direct result of my attempts to live by that philosophy and many people have supported me in being able to accomplish this. Dr. Molly McCanta has been instrumental in keeping me centered, focused, and breathing as she advised me through this project. Her mantra, “it is what it is” was a calming balm during the last two years of unrest and I thank her for believing in me and giving me the chance to pursue this project. My committee members, Dr. Nick Dygert and Dr. Warner Cribb, have also offered invaluable aid and direction in the shaping of this research, and I thank both of them for their expertise and time.

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ABSTRACT

Barva Volcano is a dormant stratovolcano in the Cordillera Central region of Costa Rica, rising above the capital city of San Jose with a population of 347,000. Barva's recent inactivity and extensive forestation have resulted in more limited investigations of its composition, petrogenesis, and eruptive history. The objective of this research is to analyze the geochemical data from several of the most recent lava flows, evaluate variability between eruptive units, and ascertain physical conditions within the Barva magma storage region. The data collected in this study help constrain the geochemistry of flow units, providing information regarding past and future eruptive behavior.

A complete petrographic and geochemical analysis of nine samples from young lava flows obtained from the Tajo La Florida quarry on the flank of Barva has been completed. Scanning electron microscope (SEM) images and electron microprobe (EMPA) data were collected for major/minor element analysis at the University of Tennessee and XRF data were collected from Middle Tennessee State University. All lava flow samples are basaltic-andesites, with observed phenocryst phase assemblages (averaging ~15 %) of plagioclase, orthopyroxene, clinopyroxene, and iron titanium oxides within a groundmass of plagioclase and pyroxene microlites, with some glass. Groundmass glass compositions range from andesite to rhyolite, with large among samples. While the mineral modes and the matrix glass composition in the samples vary, mass balance calculations of groundmass composition (glass plus microlites) indicate slight variation from rock bulk composition. The collected trace element data also reinforces the homogenous nature of the described units. Two-pyroxene temperatures were calculated providing crystallization temperatures for both core and rims of phenocrysts. Transects from core to rim of a limited number of zoned pyroxenes provide relative cooling rates and indicate rapid cooling. The collected data all provide evidence of a stable magma system that exhibits evidence of a minor reheating event, which resulted in a cleansing of the magma chamber in multiple pulses over an unknown period of time.

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SECTION 1. INTRODUCTION

Barva Volcano is a stratovolcano nestled in the Cordillera Central area of Costa Rica. It is classified a dormant, or “resting” volcano, having not erupted since 6050 BCE (Mora et al., 2004; Quesada-Román and Mata-Cambronero, 2020). However, its proximity to the capital city of San Jose (with a population of 347,000) makes constraining its eruptive interval of great importance for hazard assessment purposes (Mora et al., 2004; Quesada-Román and Mata-Cambronero, 2020). Reactivation of this volcano would have deleterious effects on this populated metropolitan area that contains multiple water systems and large areas of agriculture (Quesada-Román and Mata-Cambronero, 2020). While the nearby active volcanoes (i.e., Poas, Irazu, Turrialba) have garnered much interest and are heavily studied in the literature (e.g., Alvarado et al., 2006; Prosser and Carr, 1987; Ruiz et al., 2019), Barva’s recent inactivity and extensive forestation have resulted in fewer investigations of its composition, petrogenesis and eruptive history (Salazar et al., 2019). In one of the few studies of Barva, Rojas et al., (2017) detail two primary historical lava flows from the most recent eruption history and provide a petrographic and morphologic description of its eruptive products. Several recent flows are exposed in Tajo La Florida, a quarry just northwest of San Jose (Figure 1) and are described by Rojas (2017). Rojas’ study focuses primarily on the morphological aspects of Barva’s SE flank. The petrological descriptions of the units identified in that study generally match up well with findings in this study. Some limited data from samples can be found in an extensive database from Carr 1990, and the dataset for Barva is used for comparison in this work.

This study builds on past knowledge to distinguish the young lava flows in more detail and investigate possible evolution of the magma storage region beneath Barva. This is done by comparing petrographic and major and trace element geochemical analyses of nine rock samples obtained from Tajo La Florida quarry. The various mechanisms used for analyzing the data (geochemistry, geothermometry, mass balancing, etc.) are all useful in being able to draw a consistent picture of Barva’s recent activity.



Figure 1. Modified map of Angeles wash (Rojas, Barahona et al. 2017) - dark gray refers to lower Angeles flow while the light gray shows the extent of the upper Angeles flow. Tajo La Florida circled in red, San Jose is ~ 15km to the south and suburbs San Rafael and Heredia are shown.

An enhanced understanding of Barva's recent output aids in our understanding of magma chamber conditions below Barva Volcano and provides more information for future hazard assessment.

SECTION 2. BACKGROUND

Costa Rica is situated in southern Central America and is considered to be among the most seismically active areas in the world (Alvarado et al., 2017; Stine and Banks, 1991). Five tectonic plates converge in the Central American region. The subduction of the Cocos plate beneath the Caribbean plate creates a convergent margin which produces Costa Rican volcanism (Figure 2). Central America's tectonic history extends to at least Jurassic emplacement of the Caribbean Large Igneous Province (CLIP, Vogel et al., 2004). The CLIP is made up of sheet flows and pillow lavas and forms the basis for the Chortega block. The Chortega block is the southernmost of the two tectonic blocks making up Central America (Hauff et al., 2000; Vogel et al., 2004). North of the Chortega is the Chortis block, composed mainly of continental basement from the Paleozoic (Vogel et al., 2004). The thickness of the pillow and sheet lavas making up the CLIP is ~40 km (Hannah et al., 2002; Hayes et al., 2013; Vogel et al., 2004). Tholeiitic basalts that were generated about 65 Ma overlie the pillow and sheet lavas, and were a result of subduction of the Farallon plate (e.g., Hayes et al., 2013; Vogel et al., 2004). During the Eocene—Oligocene periods the Central American Volcanic Arc (CAVA; Figure 2) formed over these two tectonic blocks as they converged, and a mature island arc was formed at the edge of the CLIP (Pérez et al., 2006; Vogel et al., 2004).

The subduction of the Cocos plate resulted in the Central American volcanic front (CAVF), which runs ~1100 km parallel to the Middle American Trench (Figure 2), from the Mexican border in Guatemala south to central Costa Rica (i.e., Gazel et al., 2009; Ruiz et al., 2019; Saginor et al., 2013). Ten Quaternary volcanoes in Costa Rica make up this volcanic front, and from North to South. These are: Orosi, Rincón de la Vieja, Miravalles, Tenorio, Arenal, Platanar, Poás, Barva, Irazú, and Turrialba (Alvarado et al., 2006).

The Cordillera Central (Figure 3) is a massif composed of flows from multiple volcanoes including Barva, Platanar, Irazú, and Turrialba (Prosser and Carr, 1987). It is the largest volcanic massif in Central America (Quesada-Román and Mata-Cambronero, 2020). This area of the Cordillera Central also contains about fifty percent of Costa Rica's population (Stine and Banks, 1991). Barva Volcano has an elevation of 2894 m, a base diameter of 16.6 km, and a volume of ~255 km³ (Carr, 1984; Stine and Banks, 1991).

A period of volcanic activity in the Cordillera Central region began in the Quaternary and was driven by three major constructive episodes, separated by periods of erosion (Alvarado et al., 2006; Pérez et al., 2006). Around 325 ka a large pyroclastic ash flow sheet created the Tiribi Formation. The youngest and most widespread flow of that formation is referred to as the Tiribi Tuff (Hannah et al., 2002; Pérez et al., 2006). This ignimbrite formation is thought to have been generated from the Barva caldera in multiple pulse eruptions, which flowed over the southwest flanks of Barva into the Valle Central plateau (Hannah et al., 2002; Pérez et al., 2006; Vogel et al., 2004).



Figure 2. Tectonic image of Central America. The Central American Volcanic Front (CAVF) are represented as a line of volcanoes and are the result of the Cocos plate subducting beneath the Caribbean Plate (Kaiser 2022).

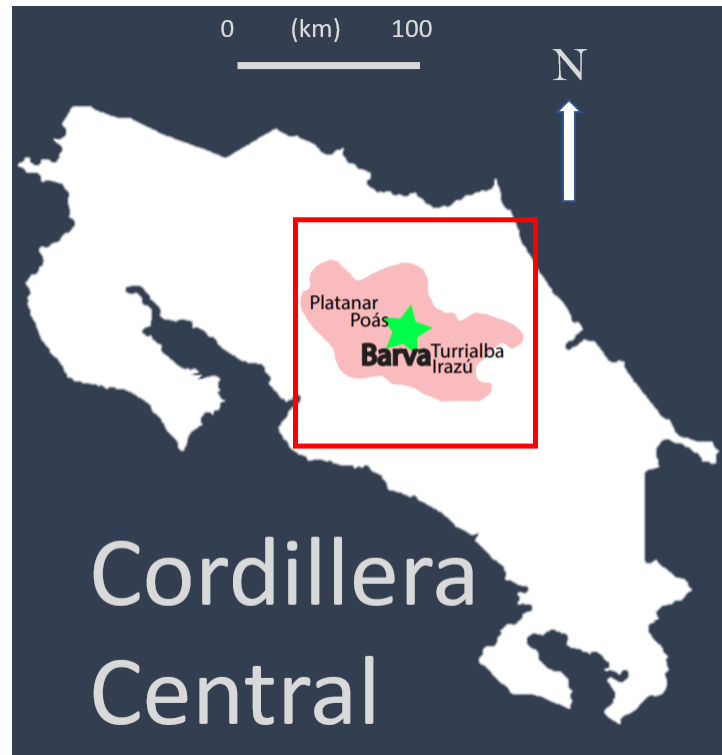


Figure 3. Outline of Costa Rica with the Cordillera Central featured. Barva is marked as green star, surrounding volcanoes are also indicated.

The Tiribi Tuff is overlain by the Barva Formation, dated by $^{40}\text{Ar}/^{39}\text{Ar}$ at ~258-270 ka (Pérez et al., 2006). Overlying the Barva Formation are more recent flows, possibly from the last confirmed eruption of Barva, that occurred ~6050 BCE and had a volcanic explosive index (VEI) of 4 (GlobalVolcanismProgram, 2013a; Quesada-Román and Mata-Cambronero, 2020). Alternatively, the last volcanic activity was about 1770–1776 and consisted of explosions and mud flows (Stine and Banks, 1991).

The more recent flows from Barva that are accessible through the Tajo La Florida quarry are of an unknown age, in part due to difficulties with age dating. They are too young for Ar-Ar dating ($\tau_{1/2} = 1.28 \times 10^9$ years), and they lack organics suitable for ^{14}C dating. An estimate of 4-15 ka has been postulated, and that timeline fits with the last eruption being 6050 BCE (Arredondo Li and Soto, 2006; Rojas et al., 2017). Also difficult to constrain is the eruptive cycle; are these volcanic flows multiple pulses from one eruption, or separate and geochemically distinct eruptive cycles? With much unknown about this volcano and considering the high population that resides within its shadow, a better petrologic understanding of these recent lava flows is required.

SECTION 3. METHODS

3.1 Fieldwork

Nine samples were retrieved from the Tajo La Florida quarry in 2018 (Figure 4). The samples of volcanic flows were acquired from seven potentially different flow units. Unit CR1 was sampled twice (CR1A & CR1B), once near the edge of the exposure and again from ~1.5 meters horizontally inward (Figure 5). Unit CR2 was also sampled twice (CR2A & CR2B), but in this case was sampled vertically from both the top and bottom of the flow. Sample CR3 was obtained directly beneath sample CR2B. These five samples were all collected from the same site in what appeared to be multiple emplaced units from an east-facing exposure and were all stratigraphically vertical. The next three samples were obtained from site 2 (Figure 6a) and these were approximately the same layer, with CR6 collected from the deepest lateral depth. These rocks were collected from a roadside outcrop within the quarry, whether the samples were sampled in place is uncertain. CR7 (Figure 6b) was collected from site 3 and came from a massive unit that appears to surround the quarry.

3.2 Sample Preparation

3.2a Thin Sections

Three thin sections were created from each unit sample. The thin sections were prepared generally following the method outlined by (Reed and Mergner, 1953) in the University of Tennessee, Knoxville (UTK) rock preparation lab. A billet from each sample was taken with care to avoid weathering products, with some samples requiring impregnation by epoxy due to friability. Thin sections were then ground down to a thickness of approximately 30 μm in preparation for petrography and back scatter electron (BSE) imaging.

3.2b Bulk Samples

Bulk samples were prepared by first crushing approximately one-inch cubes of the sample rock in an agate mortar. The pulverized samples were formed into homogenous glass beads in a strip furnace by placing the powder onto a molybdenum strip, which fused the sample material into a glass bead at between 1300–1600° C in a nitrogen atmosphere.

3.2c Trace Samples

Trace element samples were prepared at Middle Tennessee State University (MTSU). Approximately 25g of each sample were mechanically pulverized in a zirconium shatter box using a Rocklabs rock crusher. Pressurized disk pellets were then created using a hydraulic press at 24,000 psi for ~20 minutes (Figure 7).

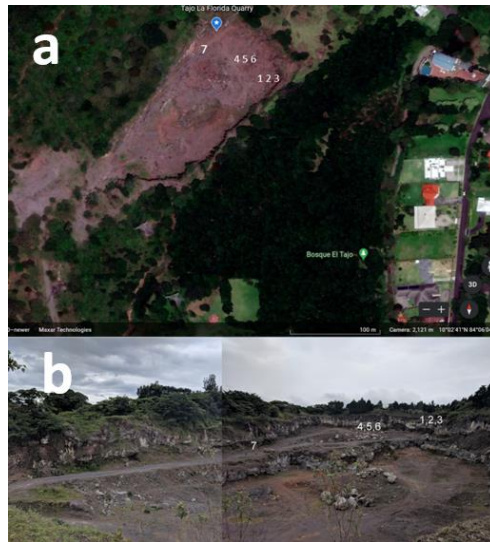


Figure 4. Top: Google Earth image of Tajo La Florida Quarry. Approximate sample locations marked. Bottom: Stitched image of field photos with approximate sample locations marked.

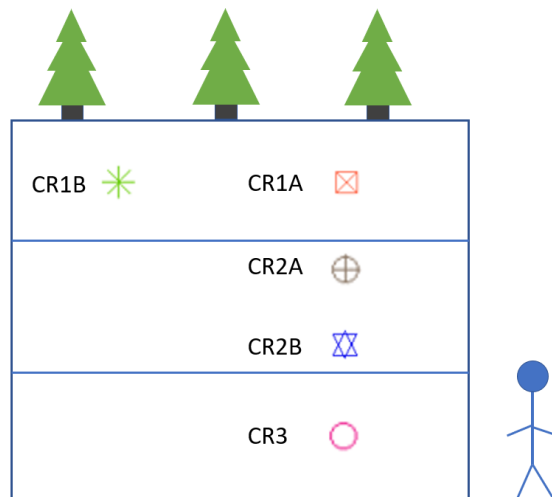


Figure 5. Cartoon illustrating approximate location of samples CR1A, CR1B, CR2A, CR2B and CR3



Figure 6. Photographs from fieldwork sites 2 and 3. Site 2 (5a) is CR4, CR5, CR6 and CR7 was collected from site 3 (b)



Figure 7. Photograph of Hydraulic Press from MTSU

3.3 SEM Imaging

The University of Tennessee Phenom Pro SEM was used for textural analysis and mass balance imaging. Thin sections from each sample were imaged and used for point counting (Figure 8).

3.4 Geochemical Data

Major element data for glass, bulk, and phenocryst composition were obtained via EMPA on the University of Tennessee Cameca SX100 electron microprobe using a mixture of natural and synthetic standards. Standards included diopside, albite, olivine (Fo₉₃), synthetic spinel, apatite, orthoclase, rutile, and hematite. Backscattered-electron images of thin sections from each sample were taken for purposes of distinguishing phases and identifying glass pockets. Glass analyses were completed at 15 kV accelerating voltage and analyzed using a 1 µm spot size and a 10 nA focused beam current, with a Na counting routine to minimize sample destruction.

Bulk rock analyses were performed using a 20 nA unfocused beam current and a 15 µm spot size. All phenocryst analyses were run at 15 kV accelerating voltage and a count time of 20 seconds.

Quantitative analysis for trace elements on the pellets was conducted on an MDX¹⁰⁸⁰ multi-dispersive x-ray fluorescence (MDXRF) spectrometer at Middle Tennessee State University. Data for elements Rb, Y, Nb, Ba, Cr, Sr and Zr were collected. Standards used for calibration were USGS samples DTS-1, BHVO-2, G-2, W-2, DNC-1, AGV-2, GSP-2, and RGM-1. USGS sample GSP-2 was used as an unknown for secondary standard purposes.

3.5 Modal Abundance and Mass Balance

BSE images from thin sections of each rock were used for point counting analysis by placing a grid over each image and tallying the area of phenocrysts (crystals greater than 0.5 mm). These abundances were then entered into a mass balance calculation spreadsheet to determine a calculated melt prior to eruption and ascent. The average phenocryst compositions used in the mass balance equation were obtained by collecting multiple spot analyses of phenocryst rims of plagioclase and pyroxenes.

Iron-Titanium oxides represent <1% of phenocrysts but are more greatly represented in the groundmass. The Strabo Tools app for iOS (<https://strabospot.org>) was used on BSE images to calculate the percentage of oxides based on the Color Index feature. Images taken included the scale bar and that was used as a metric for determining saturation. Images used were all at a scale of 1 mm and the percentages of each were averaged.

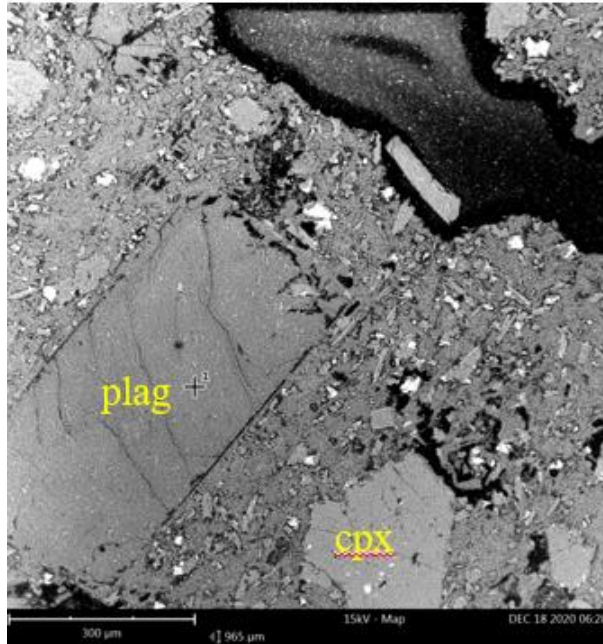


Figure 8. SEM image from CR1A used in point counting and to calculate mass balance totals.

3.6 Two-Pyroxene Geothermometry

Using BSE images to locate orthopyroxene and clinopyroxenes that are either in direct contact with each other or in close proximity with each other, major element data were gathered from both core and rim points. Multiple phenocrysts were chosen for thermometry calculations, via Putirka (2008) equations 36 & 37 using cation fractions, and are based on methods for two-pyroxene geothermometry calculations from (Brey and Kohler, 1990). One crystal from each sample was chosen for graph. Error bars are $\pm 45^{\circ}\text{C}$ (Putirka, 2008).

3.7 Zoning Analyses

Profiles were created by conducting transects in pyroxene grains that crossed a boundary between CPX and OPX, based on probe data and images. Transects were set to either 5 μm or 10 μm steps, covering distances of 40 – 100 μm (bigger steps for larger distances). Concentrations of TiO_2 and Al_2O_3 were then plotted for both CPX and OPX.

SECTION 4. RESULTS

4.1 Petrography

Petrography for the Costa Rica samples was difficult to characterize for several reasons. Inexperience in creating petrographic thin sections caused many of the sections to be too thick in areas, whilst almost completely polishing away other areas. This led to inconsistent birefringence in almost all samples, making accurate identification of minerals difficult. Despite these challenges, much information was still able to be gleaned from careful petrographic study of the thin sections.

The petrography of the rock units is homogenous overall. The samples are all porphyritic, with plagioclase and pyroxene (both CPX and OPX) phenocrysts amongst an aphanitic groundmass. The groundmass consists predominantly of plagioclase microlites, with minor amounts of pyroxenes and oxides present. The phenocrysts (defined in this paper as grain sizes > 0.5 mm), include plagioclase, orthopyroxene, clinopyroxene and iron- titanium oxides. Plagioclase grains are numerous and most easily identifiable, although generally missing the normal gray birefringence. Figure 9 illustrates a plagioclase grain with multiple twins. This plagioclase also exhibits some sieve texture, and some other crystals exhibit significant sieving at the core (Figure 10a) and rims (Figure 10b & c). Plagioclase phenocrysts in all samples are euhedral to subhedral (Figure 9 & 10) and pyroxenes range from euhedral to anhedral.

Pyroxene grains are euhedral to subhedral, and phenocrysts consist of both orthopyroxene and clinopyroxene. Orthopyroxenes all classify as enstatite. Clinopyroxenes grade from diopside cores to augite rims. In some crystals, there is evidence of zoning from OPX to CPX. Pyroxenes exhibited less sieve texture than seen in the plagioclase grains but were seen in most glomerocrysts found in the samples. In CR7, some pyroxenes have distinct reaction rims of CPX on OPX grains.

All samples have minor disequilibrium textures, such as sieve texture (Figure 10a), glomerocrysts (Figure 10b), and one sample, CR3, having both. Samples exhibit some level of weathering that can be seen in thin sections and hand samples, particularly CR4 and CR5.

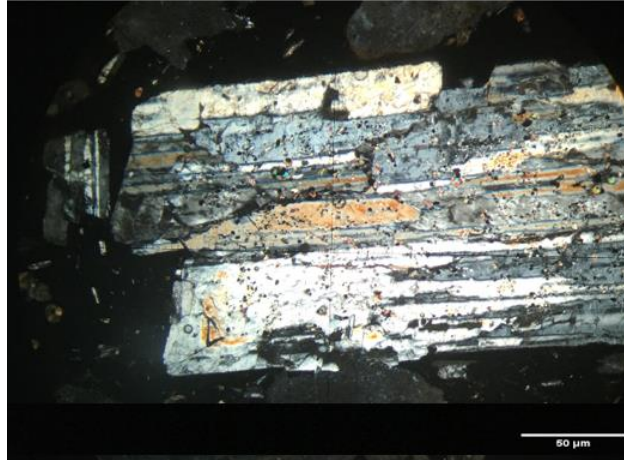


Figure 9. Microphotograph of plagioclase grain showing multiple twinning with abrupt termination of lamellae and mild sieve texture. Sample is CR1B and photo is xpl, 4x

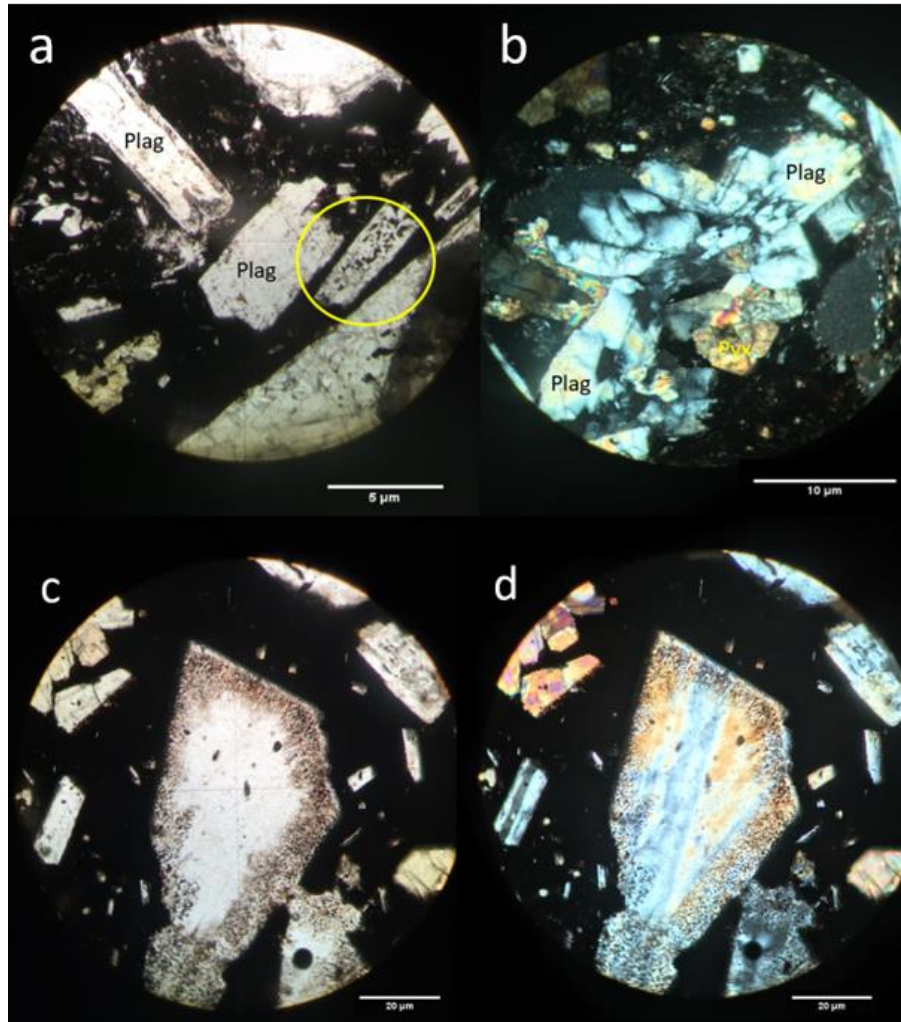


Figure 10. Photographs of thin sections. a) shows euhedral plagioclase grains from CR1B, with sieve texture present, 10x PPL. b) a glomerocryst from sample CR1A, 4x XPL. c) ppl microphotograph of plagioclase from CR2B with significant sieve texture at the rim 10x. d) xpl view of c. Plag = plagioclase, Pyx = pyroxene

4.2 Bulk Composition

The bulk compositions of samples were analyzed on the basis of 24 oxides (using the same analysis as the matrix glass for consistency). Each fused bead was run with 25–50 data points and the average for each rock were plotted on a total alkali versus silica (TAS) diagram (Figure 11). The samples from this study plot consistently within the basaltic-andesite composition (Figure 11). This agrees with the limited literature regarding Barva's geochemistry (Eiler et al., 2005; Feigenson et al., 2004) and generally with the literature regarding the CAVF, with SiO₂ abundances between 52 and 58 wt % (Vogel et al., 2004). CR1A plots slightly lower (3.22%) than the rest in this group (Table 1).

Figure 12 shows all the samples' bulk compositions plotted on Harker diagrams. Samples exhibit a variety of differences in their major element chemistry. For example, CR1 contains higher levels of Ti and Al. CR3 has higher Fe and lower Ca values and CR6 contains a high Mg# ($\text{Mg wt \%} / \text{Mg wt \%} + \text{Fe wt \%}$) and lower Al.

4.3 Glass Composition

Matrix glass analyses from the thin sections are difficult to characterize due to the small amount of interstitial glass. Much of the matrix glass has been altered or absorbed, limiting microprobe analyses to the micron scale. Samples CR1A and CR1B have matrix glass pockets that are ~2-4 μm in diameter. CR2A and CR2B (Figure 13a) contain glass pockets that are larger and easier to distinguish, on the scale of 5-10 μm . CR3 is one of the most difficult to discern glass pockets, at 300 μm magnification the pockets that were found are small ($< 2 \mu\text{m}$) and difficult to distinguish from the surrounding matrix. CR4 also has matrix glass pockets $< 2 \mu\text{m}$. CR5 and CR6 glass pockets are smaller than 10 μm . CR7 (Figure 13b) was most similar to samples CR3 with pockets $< 2 \mu\text{m}$. The difficulty of precisely resolving matrix glass inclusion in analysis of samples CR3 and CR7 may contribute to the overall error in calculations of the residual melt. After acquiring data on the matrix glass from the EMPA, results of the glass points were then filtered for; total values not to exceed 101% or fall below 98%, SiO₂ between 40-90%, Al₂O₃ values between 9-22% and only K₂O values above 1% were considered. All data not meeting these constraints were considered other than the target of matrix glass and were excluded from the data set. All individual matrix glass points are plotted in Figure 11 and plot higher in silica

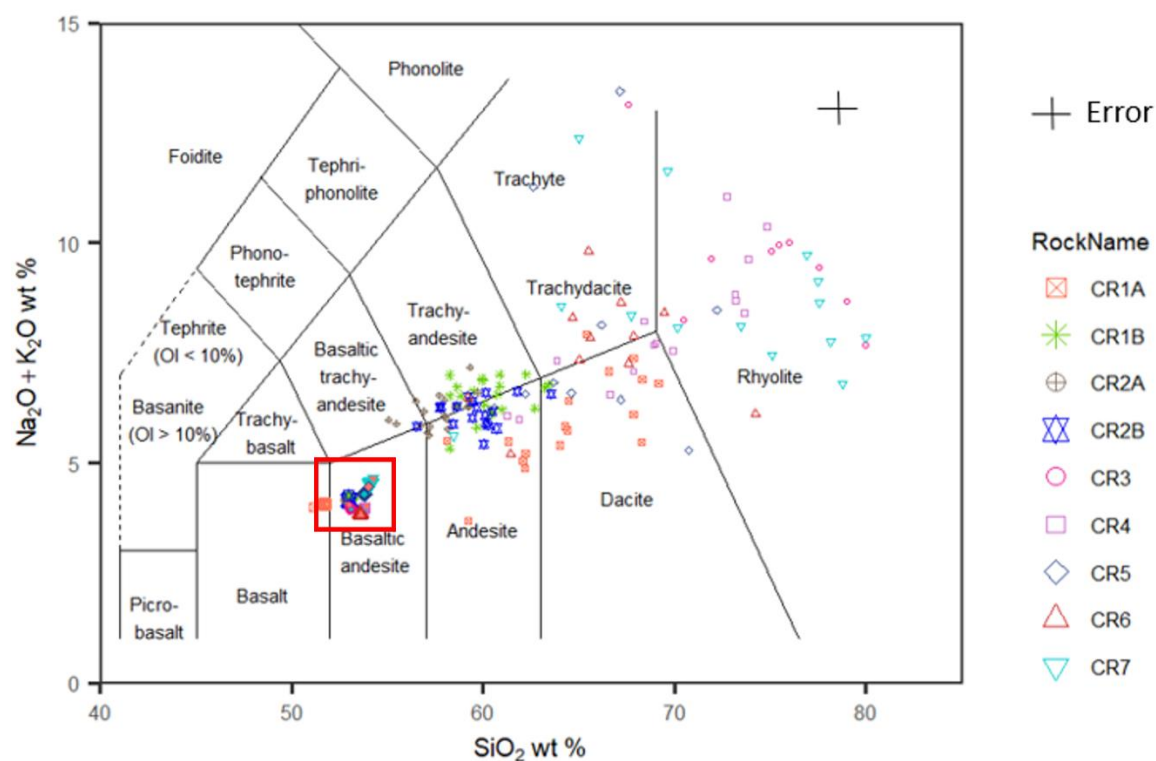


Figure 11. Total alkali vs. silica (TAS) diagram comparing average bulk composition for each rock (bold symbols inside red box), with individual matrix glass compositions (thin outline, small size) representing melt values, and calculated glass compositions (thin outline). Error based on standard deviation of data.

Table 1. Numerical comparison of major element data for all samples on the basis of bulk, matrix glass, and calculated glass compositions. Error based on standard deviation of data.

		SiO ₂	TiO ₂	Al ₂ O ₃	Cr ₂ O ₃	MgO	CaO	MnO	FeO	Na ₂ O	K ₂ O	Total	GM	Plag	Pyx
CR1A	Bulk	51.70	2.14	18.06	0.02	4.76	7.82	0.15	9.48	3.13	0.93	98.18	78.35	17.38	4.27
	Glass	64.45	2.91	12.17	0.01	0.80	3.01	0.13	7.67	2.63	3.30	97.08			
	Calculated	51.10	2.68	16.68	0.03	5.02	6.83	0.17	11.24	2.91	1.08	97.74			
CR1B	Bulk	53.06	1.91	16.83	0.02	5.16	7.69	0.15	8.99	2.99	1.17	97.97	84.02	12.32	3.66
	Glass	60.27	3.14	13.12	0.01	1.10	4.12	0.12	9.50	3.52	2.97	97.88			
	Calculated	52.98	2.23	15.74	0.02	5.30	6.90	0.16	10.02	2.91	1.34	97.61			
CR2A	Bulk	52.89	1.97	16.79	0.03	4.63	8.02	0.13	8.98	3.06	1.10	97.61	88.53	9.55	1.92
	Glass	57.85	2.99	13.44	0.01	1.85	4.95	0.14	10.12	3.58	2.60	97.54			
	Calculated	52.78	2.21	15.87	0.03	4.80	7.62	0.15	9.77	2.93	1.19	97.35			
CR2B	Bulk	53.00	1.83	17.00	0.04	5.15	7.77	0.14	8.75	3.02	1.13	97.82	87.18	9.09	3.73
	Glass	59.66	3.05	13.04	0.01	1.53	4.52	0.14	10.20	3.44	2.71	98.29			
	Calculated	52.96	2.07	16.44	0.04	5.00	7.24	0.15	9.37	3.00	1.26	97.53			
CR3	Bulk	53.08	1.91	15.24	0.02	5.84	7.34	0.17	10.19	2.83	1.12	97.75	85.05	11.20	3.75
	Glass	74.78	0.23	13.51	0.01	0.04	0.92	0.01	0.74	2.86	6.76	99.88			
	Calculated	53.01	2.21	14.10	0.03	5.94	6.69	0.18	11.21	2.75	1.28	97.41			
CR4	Bulk	53.81	1.99	17.22	0.02	4.22	7.94	0.13	8.54	2.94	1.01	97.83	88.19	8.06	3.75
	Glass	69.28	0.73	15.27	0.01	0.24	3.29	0.03	1.78	3.08	4.99	98.71			
	Calculated	53.91	2.22	16.79	0.02	3.96	7.39	0.14	9.08	2.90	1.12	97.54			
CR5	Bulk	53.84	1.99	15.87	0.03	4.71	7.96	0.15	8.96	3.12	1.18	97.81	82.35	13.28	4.37
	Glass	65.71	1.39	15.83	0.00	0.23	3.83	0.03	3.00	3.42	4.51	97.96			
	Calculated	54.00	2.36	14.27	0.03	4.55	7.22	0.16	10.00	3.07	1.39	97.05			
CR6	Bulk	53.56	1.92	14.40	0.04	6.34	7.99	0.16	9.48	2.72	1.11	97.72	88.05	8.98	2.97
	Glass	66.16	1.21	14.71	0.01	0.32	3.46	0.05	4.43	3.21	4.36	97.92			
	Calculated	53.62	2.15	13.29	0.05	6.59	7.52	0.17	10.26	2.62	1.21	97.46			
CR7	Bulk	54.11	1.95	15.59	0.02	4.97	7.22	0.15	9.07	3.14	1.39	97.62	87.93	9.42	2.65
	Glass	72.33	0.35	14.96	0.01	0.22	2.10	0.02	1.07	4.15	4.43	99.63			
	Calculated	54.25	2.20	14.60	0.02	5.00	6.70	0.15	9.75	3.10	1.56	97.33			

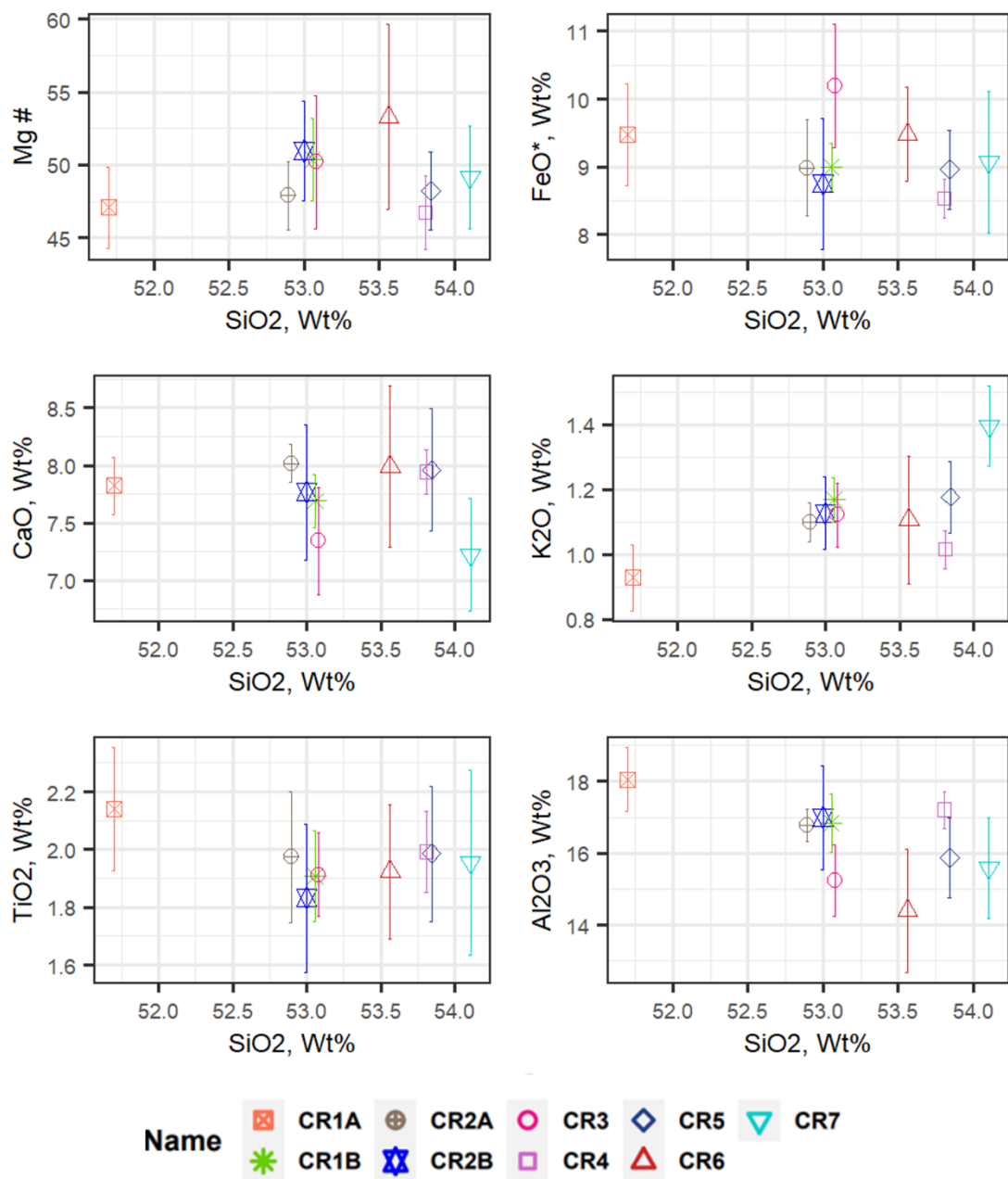


Figure 12. Harker diagrams of major element comparison for averaged bulk compositions of all samples. Mg number (Mg#) calculated as (Mg wt % / Mg wt % + Fe wt %). The low levels of SiO₂ in CR1A and high levels in CR7 are apparent but the rocks display an overall homogeneity

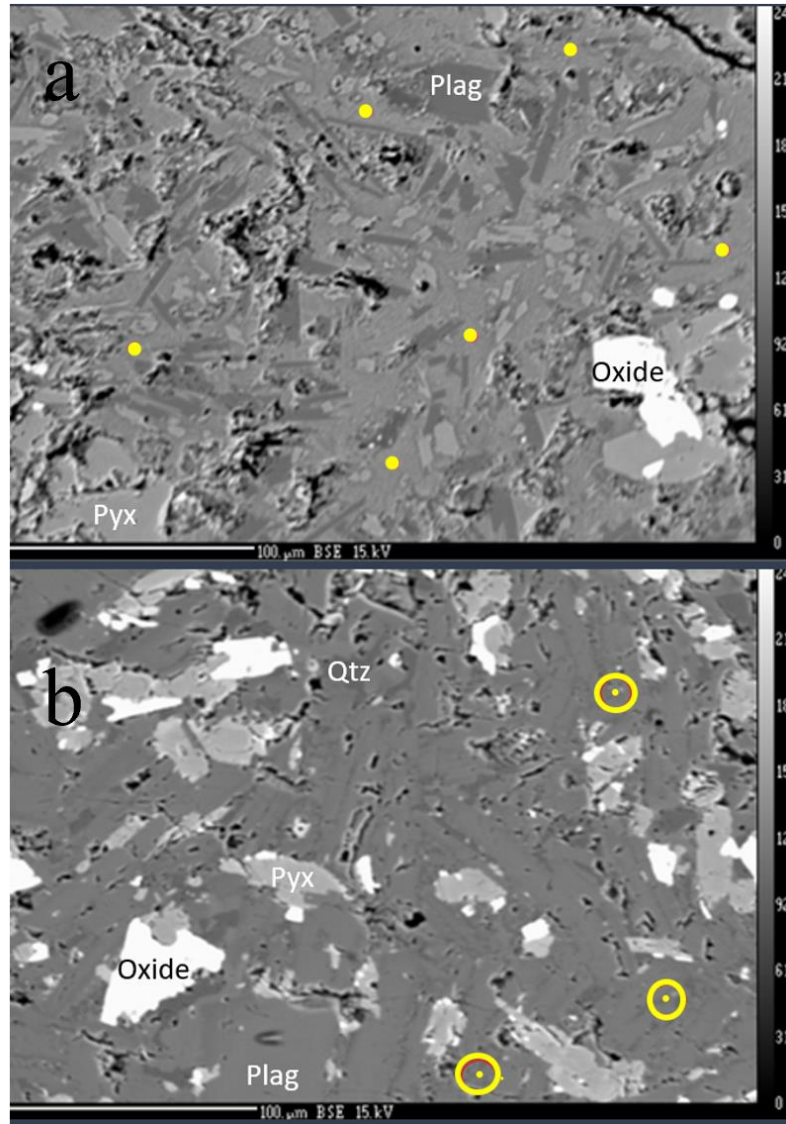


Figure 13. Backscatter electron micrographs of glass pockets in CR2A (a) and CR72 (b). Dots are not scaled but rather to indicate areas where matrix glass was found. CR7 matrix pockets were so small they have a red circle surrounding them for clarity.

than their bulk counterparts. CR3, CR4 and CR7 plot higher than other samples.

Mass balance compositions (Table 1) were used to constrain the melt composition of the magma chamber. That melt composition can then be used in a further mass balance calculation to determine the amount of crystallization that was required to attain the glass compositions obtained from the microprobe data and those results are presented in Table 2 and in Figure 14.

4.4 Trace Element Composition

Trace element concentrations (Table 3) are chondrite normalized and plotted on a log scale (Figure 15). Standard deviation and analytical error are included in Table 3. Ba, Nb and Zr standard deviations are outside the analytical error, all other elements are within error. Figure 15 shows that on a log scale, Rb, Sr and Nb plot within narrow margins, with slightly wider spread seen in Ba, Cr and Zr as a result of the larger deviation. Trace element data collected from Barva in other studies are averaged and included as a black line with squares (Carr, 1987).

Figure 16 shows a spider diagram comparing various locations based on source components. The OIB and mid ocean ridge basalt (MORB) values were taken from Sun and McDonough (1989), while the Hawaii, Galapagos, Caribbean large igneous province (CLIP) and Mt. St. Helens data were pulled from the GEOROC database (<https://georoc.eu>). The CLIP forms the basement of the Cordillera Central, Mt. St. Helens provides an example of a typical volcanic arc composition, and Hawaii and Galapagos provide examples of mantle plume sources. The Galapagos are thought to be the source of the OIB signature in Costa Rican volcanics. In the more incompatible elements (Rb, Ba, Nb & Sr), the MORB is significantly depleted while the plume sources all show comparative enrichments. The Barva samples are most enriched in the LILEs Rb and Ba, and while depleted in Nb, they are not as significantly depleted as the other OIB's. The differences in enrichment become smaller and all sources become more depleted as we move toward more compatible elements.

Figure 17 is a multi-element spider diagram comparing Barva to other volcanoes (Table 3). While all these samples are similar overall, there are some differences reflected. Barium in

Table 2. Phase modes required to reach microprobe glass compositions from each unit.
Calculated from a melt composed of the calculated glass compositions from Table 1

	Phase Modes				
Sample	Plag	Pyx	Oxide	Glass	Total
CR1A	39.78	17.68	8.88	32.49	98.83
CR1B	30.34	17.06	3.77	47.6	98.77
CR2A	34.09	21.98	4.49	38.76	99.32
CR2B	35.81	18.29	3.61	40.74	98.45
CR3	34.3	28.88	9.79	26.4	99.37
CR4	39.75	16.78	8.02	34.04	98.59
CR5	37.22	16.49	7.99	36.58	98.28
CR6	37.7	18.14	7.91	35.05	98.8
CR7	37.84	25.13	6.77	27.21	96.95

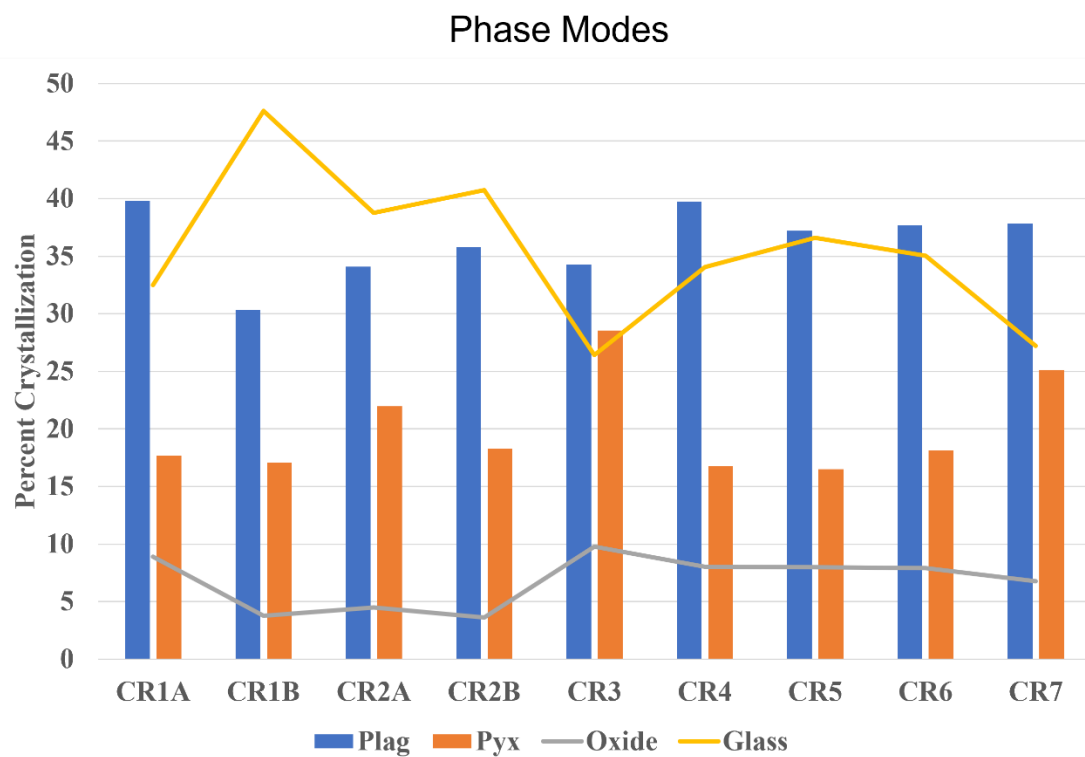


Figure 14. Bar chart of phase modes required to reproduce matrix glass compositions as analyzed by electron microprobe

Table 3. Table with XRF trace element data collected from MTSU. Concentrations in ppm

Sample	CR1A	CR1B	CR2A	CR2B	CR3	CR4	CR5	CR6	CR7	StdDev	Error
Rb	35	42	42	44	38	34	34	38	38	3.7	12.5
Ba	480	501	505	564	628	564	560	557	629	52.5	43.5
Cr	130	141	136	136	127	144	138	129	125	6.6	51.5
Nb	20	19	23	20	15	19	21	20	19	2.1	2.2
Sr	507	480	484	488	546	501	497	498	520	20.4	10.2
Zr	352	367	500	379	278	309	327	271	282	71.7	6
Y	27	28	28	28	25	26	25	25	23	1.8	2.5

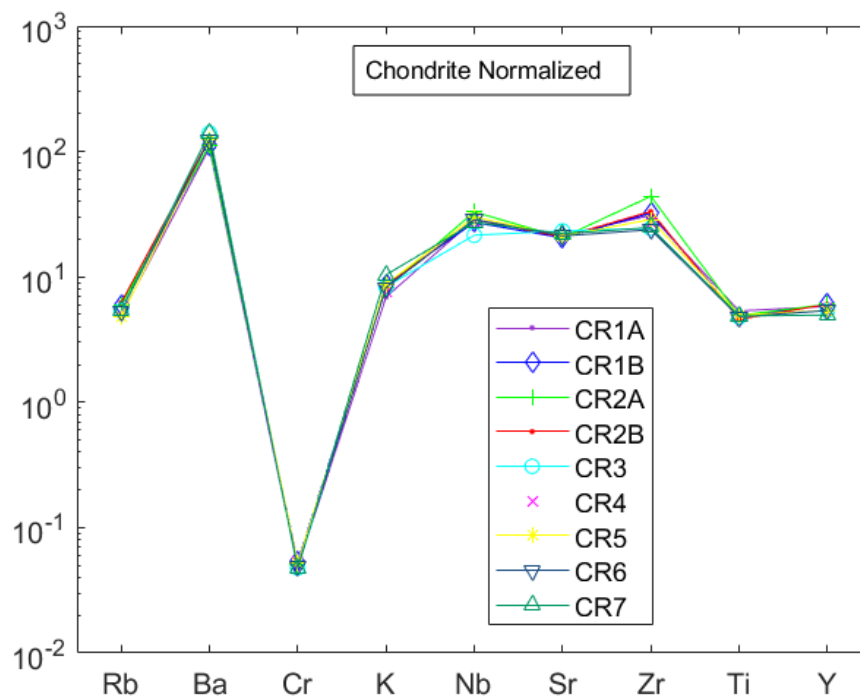


Figure 15. Spider diagram showing trace elements plotted on a log y axis. Plot is chondrite normalized

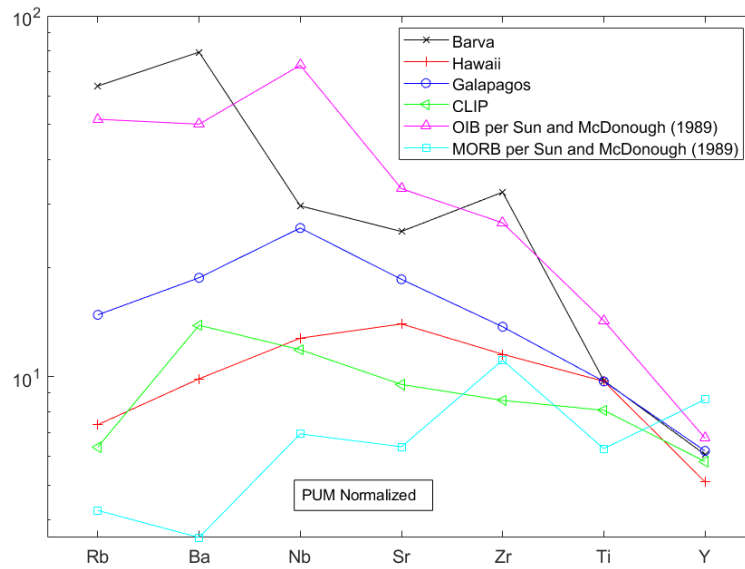


Figure 16. Spider diagram showing various source locations normalized to primitive upper mantle. Values for PUM, OIB and MORB from Sun and McDonough, 1989. Datasets for Hawaii, Galapagos and CLIP pulled from GEOROC.

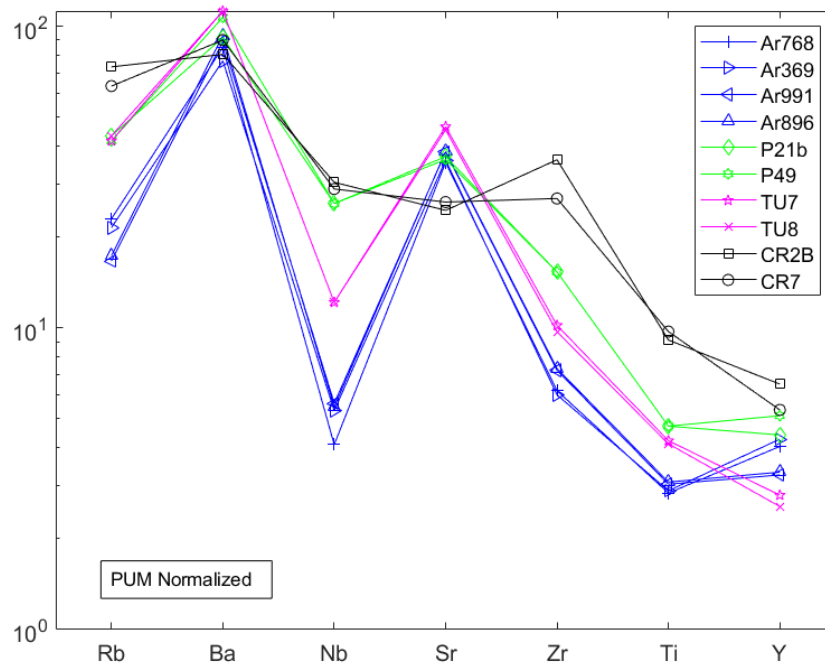


Figure 17. Spider diagram showing samples from Table 3. Arenal samples are blue, Poas samples are green, Turrialba samples are pink and samples from this study are in black.

Barva is about equal to Arenal, but lower than Poás and Turrialba, while Sr in this study is lower than all the other volcanoes. The HFSE are all significantly more enriched at Barva than the other locations. Poás and Barva have similar Nb concentrations, while the other three volcanoes Nb concentrations are significantly lower.

Plotting Y/Nb ratios as a function of the Zr/Nb concentrations (Figure 18), is useful in looking at partitioning of HFSE. The Nb depletion is substantial in arc magmas. Nb, Zr, and Ti are all HFSE, which means they are immobile and therefore not sensitive to fluids. Data from Table 4 are plotted in Figure 18 comparing Y/Nb ratios to Zr/Nb. Generally, OIB sources such as Galapagos and Hawaii are expected to have a Zr/Nb ratio of ~ 10 (Bolge et al., 2006; Winter, 2010). Different from the strong Nb depletions seen in typical arc magmas, these OIB magmas are less depleted compared to the mantle. The Barva samples from this study plot with higher Zr/Nb ratios than 10, but less than that of MORBs and typical IABs, which indicates a more enriched source is contributing to Barva's magma system. Arenal's higher Zr/Nb ratios are most likely the result of the significantly lower Zr concentrations, along with the lower Nb concentrations.

4.5 Geothermometry

The results of temperature calculations are presented in Figure 19. Cores range from a low of 907°C in CR2B to a high of 1043°C in CR4. Rims range from a low of 993°C in CR2A to a high of 1076°C in CR1B. Calculated rim temperatures are higher than core temperatures. Error bars represent an uncertainty of $\pm 45^\circ \text{C}$ per Putirka (2008).

4.6 Diffusion

Concentration profiles were created from phenocrysts exhibiting patchy zoning (Figure 20). Examples of two concentration profiles are presented in Figure 21 and represent transects from two different samples. Concentrations in wt % of incompatible elements TiO_2 and Al_2O_3 are plotted from both CPX and OPX (left and right respectively). CR6 (Figure 21a) shows a level concentration in the CPX for both Al and Ti, with a slightly less flat concentration for these elements in the OPX, particularly within the Al. CR7 (Figure 21b) shows a flat concentration of both TiO_2 and Al_2O_3 in the CPX with a generally flat concentration in the OPX. Error bars indicate 5% analytical error. Figure 22a is a BSE micrograph of an orthopyroxene crystal with

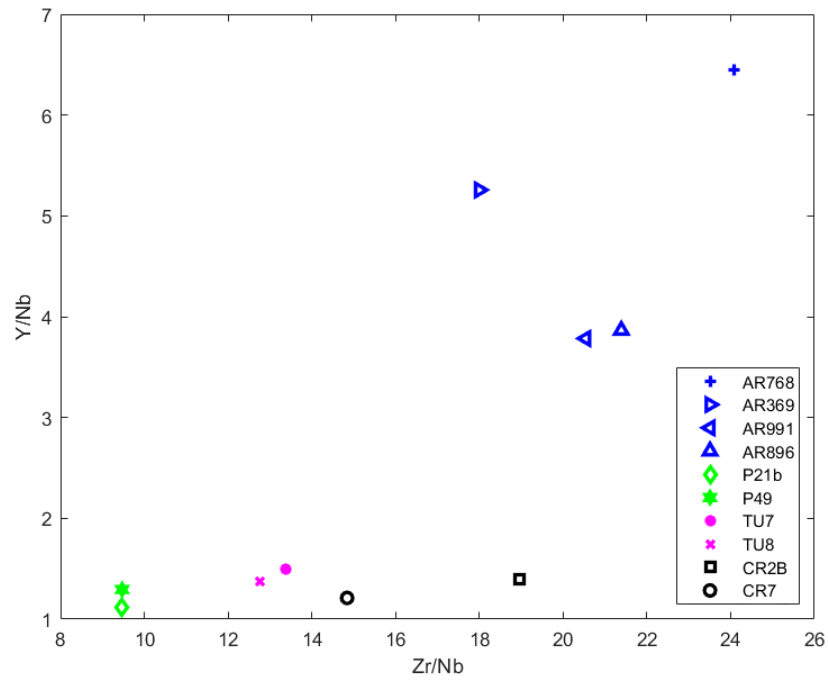


Figure 18. Y/Nb ratios plotted as a function of Zr/Nb ratios from data from Table 4. Sample from this study all plotted with symbols as Figure 17.

Table 4. Major and trace element comparison of data compiled for CVF volcanoes in geographic order from N-S. * wt % and † is ppm. Arenal data are representative samples from recent eruptions (1968-91). P21b and P49 are Poás samples from Botos Cone and P2 is from the main crater. Turrialba samples are a lava flow from SW flank.

Sample	Reagan 1987		Streck 2001		Cignoli 1991			Coulombe 2022		Di Piazza 2015	
	Ar7/68	Ar3/69	Ar9/91	Ar8/96	P21b	P49	P2	CR2B	CR7	TU7	TU8
SiO ₂ *	55.99	55.19	54.52	54.65	50.9	51.2	54.4	53.00	54.11	57.95	57.86
TiO ₂ *	0.57	0.58	0.61	0.62	0.95	0.95	0.72	1.83	1.95	0.85	0.83
Al ₂ O ₃ *	20.3	20.05	19.1	19	17.6	17.3	19.19	17.00	15.59	17.81	17.76
Fe ₂ O ₃ /FeO*	6.95	7.45	8.05	8.04	8.28	8.13	7.65	8.75	9.07	6.73	6.99
MnO*	0.15	0.16	0.14	0.14	0.14	0.14	0.12	0.14	0.15	0.1	0.1
MgO*	2.96	3.42	4.62	4.61	7.36	7.09	3.85	5.15	4.97	4.23	4.13
CaO*	8.77	8.99	8.94	8.85	9.71	9.49	9.41	7.77	7.22	7.27	6.52
Na ₂ O*	3.41	3.31	3.17	3.2	2.61	2.54	3.05	3.02	3.14	3.92	3.93
K ₂ O*	0.7	0.67	0.67	0.7	1.43	1.46	0.99	1.13	1.39	1.4	1.4
P ₂ O ₅ *	0.19	0.18	0.18	0.18	0.38	0.38	0.12	0.33	0.32	0.26	0.25
Total	99.99	100.1	99.19	99.27	100.12	99.36	99.5	98.11	97.92	101	100.5
Mg#	43.16	45.00	50.57	50.55	61.31	60.85	47.29	51.18	49.39	52.84	51.30
Rb [†]	13.8	12.9	10	10.4	26	25	21	44	38	25	26
Ba [†]	595	537	622	651	641	748	450	564	629	784	785
Sr [†]	703	716	761	765	736	719	566	488	520	925	902
Zr [†]	65	63	76	77	161	161		379	282	107	102
Nb [†]	2.7	3.5	3.7	3.6	17	17		20	19	8	8
Y [†]	17.4	18.4	14	14.3	19	22		28	23	12	11
V [†]	141	145	168	163						180	177
Ni [†]	7	12	32	32	95	84				50	40
Cr [†]	10	18	39	37	280	236		136	125	50	50
	Arenal				Poas			Barva		Turrialba	

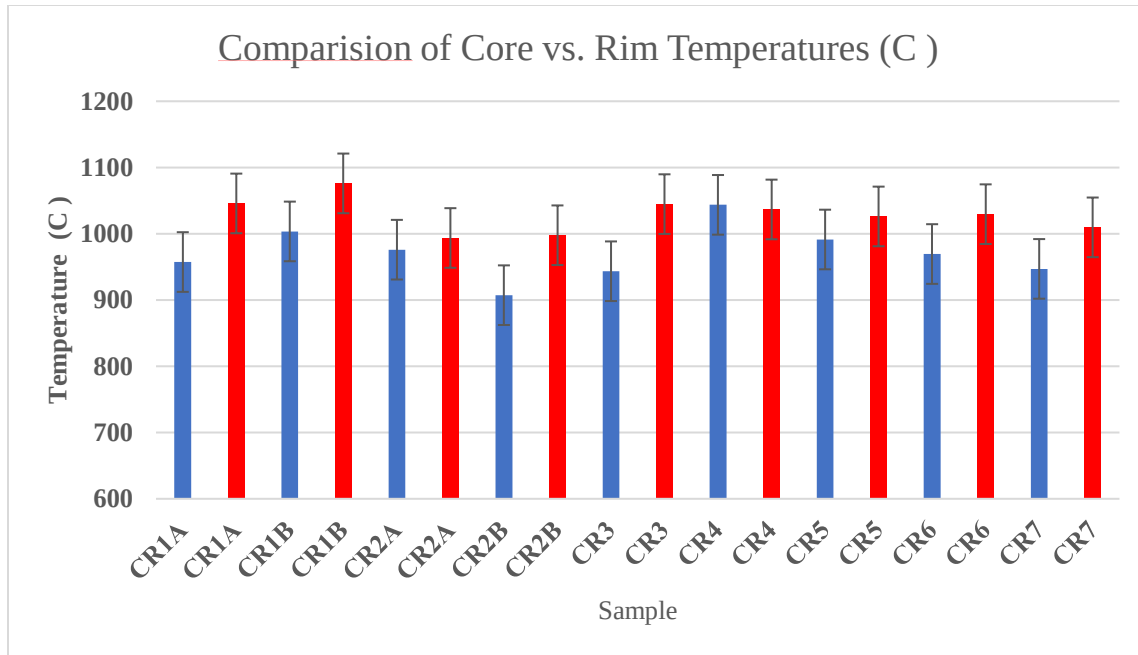


Figure 19. Comparison of calculated temperatures showing cores (blue) and rims (red). Temperatures were calculated according to Putirka (2008), using methods from Brey and Köhler (1995). Error bars indicate $\pm 45^{\circ}\text{C}$ ((Putirka, 2008).

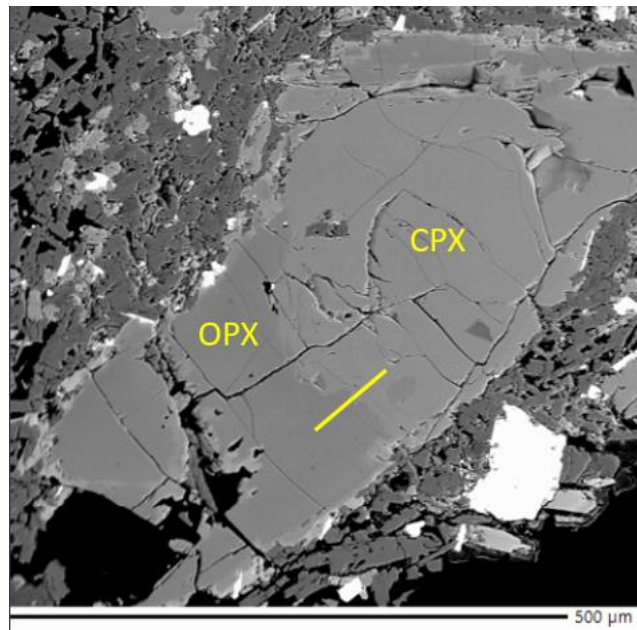


Figure 20. BSE of a pyroxene crystal from CR7 with patchy zoning. Yellow line indicates transect C run via EMPA

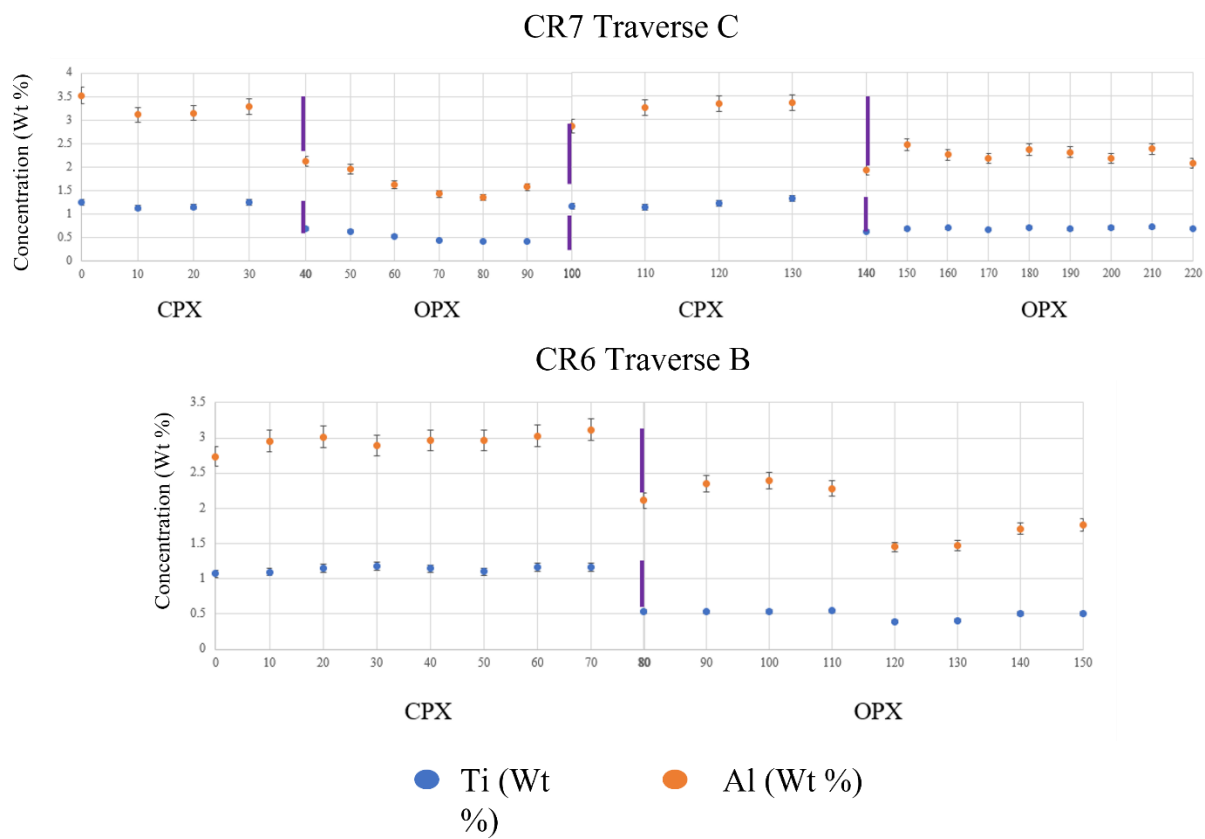


Figure 21. Grain-scale transects taken from CR7 (a) and CR6 (b)

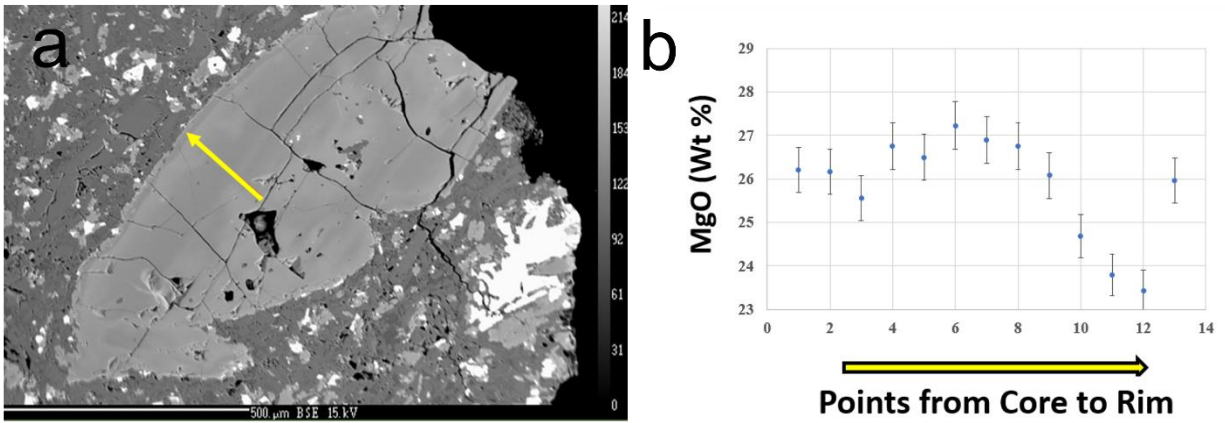


Figure 22. a) BSE micrograph of an orthopyroxene crystal. Yellow line represents transect taken from core to rim, and the arrow highlights the higher MgO rim. b) Graph representing MgO concentration in wt % compared to distance from the core of an OPX phenocryst.

patchy zoning. Figure 22b shows the MgO wt % concentration variation from the core to the rim across the patchy zoning. Error bars show 2% analytical error. The MgO increases in the center of the transect and decreases as the rim is approached. The last point at the rim shows a spike in MgO concentration.

SECTION 5. DISCUSSION

5.1 Evidence for magma mixing

Heterogeneities in a magma composition are representative of differences in mantle source composition, fractionation processes and mixing events (Herstrom et al., 1995). A magma chamber can have material sourcing from the mantle, a subducted slab, and/or sediment from the mantle wedge, wall rock from the chamber, or a transport pathway. The melt in a magma chamber provides a snapshot of the current magmatic conditions, whereas the crystals in a magma chamber record/retain evidence of past magma conditions (Streck, 2008). Geochemistry can be used to tease out these sources and indicate conditions of a magma chamber. Using a combination of both the phenocrysts in a volcanic rock as well as the matrix glass compositions (melt) we can unravel past and present magma conditions under Barva volcano.

There have been multiple attempts at describing magmatic conditions at convergent tectonic boundaries. One such model combines the processes of melting, assimilation, storage and homogenization, which help to describe the combination of factors potentially affecting a melt prior to eruption (Hildreth and Moor bath, 1988). This model has been fine-tuned by multiple authors (e.g., Putirka, 2017; Spera and Bohrs on, 2002; Streck, 2008) More silicic systems than Barva may also be described by the “MUSH” model ((Marsh, 1995), which is described as the zone with which crystallinity is between 25-55%. However, since this model is applicable only to magmas with crystallinities of >25% crystals, it does not apply to Barva. Putirka (2017) describes the “RCME” model (recharge, crystallization + mixing, and eruption), but also advises that magmatic systems are complicated and that it may be impossible to boil down such intricate processes into a simple acronym.

Magma mixing occurs when two different magmas come into contact with each other. The magmas may be exhibit compositional, temperature and/or viscosity differences (Grove, 1982; Winter, 2010). Mixing occurs most easily when differences between the magmas are lowest. Significant differences in temperature, composition, or the amount of crystallinity between melts result in large differences in viscosity, which makes mixing harder to fully accomplish. Low differences in temperature and composition result in the most fully

homogenizing the magmas (Streck, 2008; Winter, 2010). In mixing scenarios with larger differences in magma composition and viscosity, mixing rarely produces complete homogenization, and it can be easier to see due to heterogeneities. Mixing has the effect of raising the overall temperature of a magma, as well as initiating an eruption. Incoming magma recharge will be hotter than the magma that has been cooling and crystallizing in a chamber. This influx of warmer melt also could change the composition of the melt, again depending on how different recharge is from the existing magma. Some of the evidence of magma mixing may include 1) zoning of crystals, including patchy zoning 2) disequilibrium textures, such as sieve and glomerocrysts and 3) phenocryst cores that crystallized at temperatures cooler than the rims.

Magma mixing can occur as the result of several different mechanisms, such as convection or temperature increase. Self-mixing is the result of a homogenous magma mixing in a magma body due to convection currents that occur within that body (Couch et al., 2001). It produces porphyritic rocks with similar mixing and disequilibrium textures as those seen in this study. The work from Couch et al. 2001 focused on a more silicic system than Barva, but the process described has interesting implications for typical evidence of mixing. The compositional variations described by Couch et al., (2001) are the result of zones of heating and cooling within the chamber. Cooling near the surface results in textures similar to those resulting from magma ascent, such as lower temperature rims on existing crystals and the production of microlites. Near the bottom of the chamber heating processes occur, and textures within this zone include resorption features such as sieve textures (Couch et al., 2001). The anorthosite (An) composition of plagioclase phenocrysts and microlites, specifically higher Ca content in rims and microlites indicative of heating, can be evidence of self-mixing. The Barva samples in this study have rims that are slightly lower in Ca concentration (An_{55-60}) than the phenocryst cores (An_{53-71}) in all cases except CR2A (which had unusually low Ca content). Microlite composition data was limited to one sample (CR7), but here the An concentrations were also lower (An_{40-53}) than seen in plagioclase phenocryst cores. As higher An# compositions in rims and microlites are evidence of self-mixing, the lower An# phenocryst rims and microlites seen in this study point away from self-mixing as the driving mixing mechanism. Streck (2008) discusses temperature

as a mechanism for mixing and eruption. Streck (2008) builds on Ruprecht and Wörner (2007) in pointing out that if high An ratios are tied to high Fe concentrations, that can be a sign of self-mixing resulting from magma mixing with more calcic magmas. However, in the Barva samples from this study An content fluctuates independently of Fe content, which indicates the changing An concentrations are more likely the result of temperature changes than mixing of a more felsic magmas. This independent fluctuation of An indicates mixing at Barva is more likely the result of increased temperatures of the magma than convection.

Patchy zoning is a disequilibrium texture indicative of magma mixing, and this feature is found in several of the Barva samples (Figure 16). This texture can result when crystals are attempting to reequilibrate through the diffusion of cations, especially Mg and Fe but also incompatible elements such as Ti and Al. Diffusion is the process of transporting ions from one area to another by particle motion, and within minerals it is the only mechanism available (Zhang, 2010). Areas of high concentration will passively migrate to areas of low concentration. Diffusion is a critical process in the forming of rocks, as it is required to allow crystals to remain in equilibrium with a changing melt composition as magmas are cooling or heating (Philpotts and Ague, 2009). Pyroxenes work well for the investigation of diffusion rates because they easily substitute trace elements in their M1 and M2 sites in the crystal lattices (Cherniak and Liang, 2012). Clinopyroxene is especially useful as it is partial to trace elements such as titanium, aluminum, chromium and sodium (Sun and Liang, 2014; Yamamoto et al., 2017). Titanium is also favorable as it has a diffusion rate similar to REE's in OPX and similar to Al in CPX when at high temperatures and is not sensitive to pyroxene composition (Cherniak and Liang, 2012). An additional benefit is that experimental research has shown that Ti is generally insensitive to crystallographic orientation, which can be a limiting factor in some diffusion studies of other elements such as REE's (Cherniak and Liang, 2012). If concentrations the incompatible elements may build up during, that is faster the cooling rate can be estimated in kinetic models. In the Barva samples, no incompatible elements concentration gradients were observed, as evidenced by the flat profiles of the Ti and Al concentrations in the CPX (Figure 21). This provides two pieces of information for these samples; 1) the cooling rate of crystals was rapid enough to prevent buildup of the Ti and Al in the CPX, and 2) the crystals were out of

equilibrium with the surrounding melt and the low MgO pyroxene is attempting to overprint the higher MgO pyroxene.

Plagioclase phenocrysts in all Barva samples show evidence of disequilibrium, and therefore magma mixing. Many plagioclase crystals display crystal resorption by the melt (sieve texture). This occurs when the temperature of a melt rises, it dissolves the crystal, by taking in the lowest melting cations first (Streck, 2008). Zones of more sodic plagioclase will have a slightly lower melting temperature than more calcic zones and so differing areas of a crystal will be taken in by the melt, leaving the higher melting temperature sections of the crystal behind, creating a distinctive pattern that is the hallmark of this texture. Figure 9a is an example of sieve texture and shows a core that has been mostly reabsorbed. This would indicate the core was more sodic and possibly formed later in the magma chamber, in a slightly more evolved melt. When the crystal came into contact with a higher temperature slightly more mafic melt it would begin to dissolve the crystal. The rim of this crystal appears intact and is evidence of time spent in a more calcic melt, creating growth bands of higher Ca plagioclase. In contrast, Figures 9c & 9d show a plagioclase grain that has an intact core and strong reaction rim. This could be interpreted as a phenocryst that crystallized early in the chamber history, under more primitive conditions, and has since been reheated during contact with more evolved (higher Na) melts. In the reheating event, those higher Na growth sectors are now being resorbed by hotter melt.

Another indication of magma mixing is the presence of glomerocrysts. Glomerocrysts (or crystal aggregates) form as crystals move through the melt. There are two general methods for the creation of glomerocrysts. Synneusis is a term for the joining of crystals, defined as “the process of drifting-together and mutual attachment of crystals suspended in a melt” (Vance, 1969). Synneusis has been related to turbulent movement, as well favorable low-energy growth conditions (Vance, 1969). The primary twinning seen in the plagioclase crystals (Figure 9) is likely the result of synneusis, as the broad faces contain the lowest interfacial energy providing favorable energetic conditions for crystal bonding and growth (Vance, 1969; Vernon, 2004; Winter, 2010). Another method of glomerocryst formation is as a result of changes in the temperature of the melt. Increases in temperature causes crystals to begin to dissolve, and when the crystals encounter each other, the supersaturated liquid bonds the phenocrysts together

(Hogan, 1993; Vernon, 2004). As the glomerocrysts seen in the Barva samples are randomly oriented (Figure 8), it is reasonable to believe these were created via this method of increasing temperature of the melt.

As previously mentioned, some pyroxenes exhibit zoning (Figures 16, 18a). A graph comparing the MgO wt % content with the distance from core to rim of an OPX phenocryst (Figure 22b), shows the changing MgO concentrations as we move out to the rim. A higher MgO wt % concentration is associated with higher temperatures (per Bowen's Reaction series). The patchy zoning in figure 18a corresponds with the higher MgO seen in figure 18b and could be evidence of a mild heating event. About at point# 8 we see the MgO concentration begin to decrease steadily, indicating cooling magma temperatures, a typical zoning pattern. However, at point 13 there is a sudden and significant spike in MgO concentration, which is good evidence for an increase in magma temperatures in the melt shortly before eruption of the chamber. This interpretation is further supported by looking at the temperatures calculated from the pyroxenes (Figure 15). Temperatures were calculated for both cores (blue) and rims (red). The average temperature of the cores is 971°C and the average for the rims is 1029°C. These temperatures fall in the high range of intermediate magmas (andesites erupt at temperatures of 850 - 1100° C). This general trend towards higher temperatures at the rim strengthens the theory of a reheating event warming the melt and causing crystallization of more magnesium rich pyroxene.

5.2 Comparison with other Central American Volcanoes

The small concentrations found in trace elements allow them to be more sensitive to smaller variations, which can be useful in understanding magma sourcing and geochemical signatures. The concentration and fractionation of large ion lithophile elements (LILEs), rare earth elements (REEs) and high field strength elements (HFSE; elements with small radii and high electrical charges) contain information about the processes occurring within a magmatic system. HFSE (niobium (Nb), tantalum (Ta) and titanium (Ti)) depletions are characteristic of volcanic arc magmas (Gazel et al., 2009), as are LILE enrichment and other HFSE depletions ((Bolge et al., 2009; Carr et al., 2007b). Another way to learn more about Barva's magma system is to compare these various trace elements with other volcanoes in Costa Rica. Arenal, Poás and Turrialba are all active volcanoes in near proximity to Barva (Figure 3) and may

contribute to a more comprehensive picture of Barva's magmatic system. Data from studies of these volcanoes is presented in Table 4.

Arenal Volcano is located in a volcanic gap that lies between the Cordillera Guanacaste, which contains notable volcanoes such as Rincón de la Vieja and Miravalles, and the Cordillera Central (Carr et al., 2007). Arenal was not considered an active volcano until an eruption in 1968 that lasted until 2010 (Bolge et al., 2006; GlobalVolcanismProgram, 2013c). It is 1670 m and has an approximate volume of 11 km³ (Carr et al., 2007). Lava flows from Arenal are basaltic andesites, but with slightly higher silica than Barva (Table 4)(Bolge et al., 2006; Streck et al., 2002). They contain the same general phase assemblage as Barva of plagioclase, OPX and CPX, but with the addition of large (up to 10 mm) hornblende phenocrysts. Bolge et al., (2006) also reports considerably higher levels of crystallinity (50-60%) than the 12-22% seen in the Barva samples (Table 1). Two-pyroxene geothermometry estimates temperatures for basaltic andesites from Arenal to be 1064-1120° C, which is slightly above the calculated temperatures seen in this study.

Poás is an active basaltic-andesite stratovolcano that is 2697 m high, with a volume of ~97 km³ (GlobalVolcanismProgram, 2013b; Rymer et al., 2000). It has three craters, the currently active one contains Laguna Caliente, one of the most acidic lakes in the world (GlobalVolcanismProgram, 2013b). The high activity of this crater lake, as well as the close proximity to San Jose (~30 km) have made this volcano the subject of intense research since the 1980s (Rymer et al., 2000). Its most recent volcanic activity was February to September 2019 consisting of phreatic explosions with a maximum volcanic explosion index (VEI) of 2 (GlobalVolcanismProgram, 2013b).

Poás' petrography is similar to Barva. The basalts are porphyritic and dominated by plagioclase, which makes up 20-40% of the modal abundance (Prosser and Carr, 1987). This basaltic phase assemblage also contains OPX, augite and rarely olivine. The andesites are similar although the two pyroxenes are more common and what little olivine is present is rimmed by OPX. The andesites also contain glomeroporphyritic clusters in the "summit" group, which is described as representing the most recent activity from Poás (Prosser and Carr, 1987).

Temperature estimates for the samples in Table 4 are 950-1100° C, which is nearly identical to

the temperatures calculated in this study. Xenocrysts are present in the Botos crater basalts, which is not something seen in the Barva samples (Cigolini et al., 1991).

Turrialba is the southernmost stratovolcano of the CAVF and is located about 20 km southeast of San Jose. It is also an active volcano and is currently in an eruptive cycle that began in November of 2021. It is taller than the other volcanoes discussed thus far, at 3340 m high and has a volume of $\sim 112 \text{ km}^3$ (Carr et al., 2007). Rock types on Turrialba range from basaltic-andesite to dacite, and the samples included in Table 4 for comparison are andesites (Di Piazza et al., 2015). The petrography of samples TU7 and TU8 are similar to the other samples discussed, they contain plagioclase in high abundance ($>50\% \text{ vol}\%$), OPX and CPX, although OPX is present only as microphenocrysts and in the groundmass (Di Piazza et al., 2015). Unlike Barva, Turrialba samples contain olivine phenocrysts, with TU7 and TU8 containing $\sim 5\%$ volume (Di Piazza et al., 2015). Di Piazza et al., (2015) describes these particular samples as adakites. This is exhibited by the enriched strontium (Sr) and barium (Ba) concentrations present in these samples, as well as the depleted Zr, Nb and Rb (Table 4). All other geochemistry is similar, but this is a good example of how trace element data can highlight subtle differences in magma genesis due to greater sensitivity of incompatible elements.

A review of neighboring volcanoes can be useful in placing the new Barva data into the bigger overall picture. Similarities with area volcanoes point to larger scale processes, while differences may point to more regional magmatic variations. One of the interesting characteristics of the Cordillera Central volcanic rocks is an anomalous ocean island basalt (OIB) signature. This particular anomaly is distinct from all other segments in this arc, and is seen only in the volcanoes south of Arenal (Carr et al., 2007b). OIB is a type of magma that is characteristic of intraplate or hotspot magmatism. It generally represents deeper sources, arising from mantle plumes. The OIB signature seen in the Cordillera Central is reflected in LILE and REE variations. Changes in LILE and REE patterns from a typical arc system in Cordillera Central (such as less LILE enrichment) result from some OIB source (Carr et al., 2007b; Harpp and Weis, 2020).

Figure 16 shows examples of various source locations plotted on a log scale spider diagram. The OIB values from Sun and McDonough (1989) are pulled from the literature, and

so may represent many different examples of OIB. This may explain the more enriched trend when compared to Hawaii and the Galapagos. These two OIB examples also do not plot directly with each other, which could be a factor of differing source reservoirs and stage of volcanism (Harpp and Weis, 2020). Data from this study does not follow any of these trends (“OIB”, Hawaii, or Galapagos). Figure 17 shows data from Table 4 plotted on a spider diagram, and similarly data from this study does not follow the trends of nearby volcanoes.

One reason that trace elements might reflect differences from the expected trends could be the crystallization of the phenocrysts. The limited number of samples that were analyzed for this study may reflect only one small portion of what is crystallizing in the chamber. For instance, the Nb concentrations are slightly higher than those in Poás, and considerably higher than Arenal and Turrialba (Table 1). Nb is highly compatible in rutile (Kelemen et al., 2003) and in typical arc magmas Nb is highly depleted as the rutile takes it in along with tantalum. While neither rutile nor ilmenite are seen in any abundance in these samples (<1%), the samples do not necessarily represent the full suite of crystallization taking place in the chamber.

Another trace element that differs from the other Central American volcanoes is Sr. Sr substitutes easily for calcium (Ca) in plagioclase (Sun et al., 2017). While the modal abundance of plagioclase in the samples from this study were not high enough to account for such a Sr depletion, it is possibly there are layers of cumulate containing higher abundances of plagioclase that could account for the observed lower concentration. The other volcanoes discussed here all had considerably higher plagioclase abundances than Barva, so this is a likely scenario.

An alternative explanation for the trace elements not closely matching the Central American volcanoes trend could be that some other component is being assimilated into the magma. Because so many processes are occurring in this region, it is difficult to ascertain sources of variation. Changes in angle of subducting slab, metasomatizing fluids from the downgoing slab, and possible contamination from pelagic sediment or even wallrock, all could be contributing factors to variations in trace elements compared to other OIB settings and even surrounding volcanoes.

A third possibility for the variations in Barva trace elements is error in the trace element analysis. All of the HFSE appear to be quite higher than the other locations. The Zr in particular stands out, being 2-5x higher in concentration than the other volcanoes but the Nb and Ti are also higher. Interestingly, the Ti concentrations compared in Table 4 were obtained via EMPA, while the Zr and Nb concentrations were obtained via XRF. Reproduction of the trace element analysis will help to more deeply evaluate the significance of the preliminary results presented here.

SECTION 6. CONCLUSIONS

In this study, nine volcanic rock samples were obtained from Tajo La Florida quarry in Central Costa Rica and were analyzed in the lab. The samples from Barva Volcano have evidenced an overall homogeneity. They are all porphyritic, indicating two separate cooling regimes, one of phenocryst growth in the chamber and one of microlites and groundmass forming during ascent. They are all composed of the same phase assemblages of plagioclase, orthopyroxene, clinopyroxene, and iron-titanium oxides. They all exhibit some evidence of disequilibrium, most commonly sieve textures in the plagioclase, but also zoning, patchy diffusion of pyroxenes, and formation of glomerocrysts. The zoning and calculated pyroxene temperatures provide convincing evidence of rising temperature of the surrounding melt, and the narrow range in major and trace element concentrations indicate the rising temperature of the melt was not associated with a significant compositional variation. This is interpreted as an influx of compositionally homogenous magma recharge, which warmed the existing magma and caused the magma to clear the chamber resulting in the lava flows sampled for this study.

Trace element data was also analyzed in this study and the results indicate high concentrations of HFSE such as Nb and Zr. While Central Costa Rica volcanics generally more closely resemble an OIB signature than a typical volcanic arc signature, the trace element ratios in this study do not conform to the trend seen in surrounding volcanoes. This could be due to 1) crystallization of phenocrysts that are outside of the range of assemblages seen in these limited samples 2) possible assimilation of other source components that change the trace composition for this localized magma system or 3) error in concentrations from analyzed samples.

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VITA

Julie Marie Coulombe was born in Bolton, Vermont in 1970. After many years spent working in finance for multiple companies such as Keurig, they reentered academia to study geology. They received an Associate of Science degree in geology with highest honors at Pellissippi State Community College in 2016. They transferred to the University of Tennessee's department of Earth and Planetary Science in January of 2017, where they obtained a Bachelor of Science in geology with honors in 2019. As an undergraduate at the University of Tennessee they had the opportunity to work on several research projects, including Holocene fire and climate history in Georgia wetlands, cataloguing biodiversity in the gulf coast of Louisiana, identification of Paleozoic brittle stars, and analyzing glass compositions of Costa Rican volcanic rock samples. Their work on the brittle stars resulted in the honor of having a brittle star named after them, *Furcaster coulombae*. Upon acceptance to the master's program at the University of Tennessee, Knoxville they continued their research of the petrology and geochemistry of Barva Volcano in central Costa Rica under the supervision of their advisor, Dr. Molly McCanta. They presented results from that research at the Geological Society of America 2021 national conference, and as an invited speaker to the April 2022 monthly meeting of the East Tennessee Geological Society.