INVESTIGATING THE MANTLE SOURCE OF THE LUNAR CRATER VOLCANIC FIELD, NEVADA

by

JACOB WILLIAM LEE

(Under the Direction of Michael F. Roden)

ABSTRACT

Incompatible element ratios in melt inclusions can provide information on mantle source components. Additionally, trace element concentrations in high-Mg olivines can be used to infer mantle source lithology. Lunar Crater Volcanic Field (LCVF) in central Nevada contains basalts compositionally similar to ocean island basalts (OIB), and several crustal and mantle features suggest an underlying mantle plume. Consequently, I used olivine-hosted melt inclusions, and olivine compositions to investigate source lithology and petrogenesis. Melt inclusions from Easy Chair Crater (ECC) in the LCVF are relatively Cl-rich and have Cl/K abundances similar to OIB. Ni and Mn concentrations in forsteritic olivines from ECC (including some extremely forsteritic olivines) indicate a significant amount of pyroxenite may have been present in the melt source. This evidence, combined with high equilibration temperatures in mantle-derived xenoliths from LCVF and gravitational and topographic anomalies in the region, may indicate the presence of a mantle plume beneath LCVF.

INDEX WORDS:melt inclusions, Lunar Crater Volcanic Field, incompatible elements,pyroxenite, ocean island basalt, mantle plume, forsteritic olivine

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1.0 INTRODUCTION

Geochemical analysis of volcanic rocks can provide key insight into mantle processes that lead to magmatism. A particularly interesting area in central Nevada is the Lunar Crater Volcanic Field (LCVF) because of the unusually high equilibrium temperatures measured in mantle-derived xenoliths collected in the area (Smith, 2000). Volcanism at LCVF was coeval with Basin and Range extension beginning in the Miocene, however, the nature of the mantle source responsible for magma generation is unclear.

Magma sources and the origin of their chemical components differ depending upon geologic setting, and are unique such that they can be correlated based on various tectonic and geochemical relationships. One way of inferring mantle source composition is to examine specific geochemical parameters that are least affected by melting or crystallization processes. This study investigates the mantle source of the LCVF utilizing the ratio of a key highly incompatible volatile element, Cl, (implicated in lithosphere recycling) to another highly incompatible element, K. Also considered are minor element compositions in olivines. Since olivines are generally the first minerals to crystallize from a basaltic melt, their compositions retain chemical signatures of the primitive melt. Because of this characteristic, olivine compositions have been used to infer the lithology of mantle source regions (Gurenko et al., 2010). When used in conjunction, these two methods, olivine composition and melt inclusion composition, can provide key information on the nature of the magmatic source of the LCVF and the evolution of volcanism throughout the western United States.

1.1 Geological Setting

Extensional tectonics began in the Basin and Range Province during the Oligocene (Allmendinger et al., 1987) and produced a series of normal fault-bounded, westward-tilting blocks constrained to the east by the Colorado Plateau, the Rio Grande rift, and the Wasatch Fault and to the west by the Sierra Nevada batholith. Crustal thinning associated with extension resulted in widespread volcanic activity including eruptions within the LCFV (Foland and Bergman, 1992). LCVF is a northeast-elongated, Miocene to Pleistocene aged volcanic field in the center of the Great Basin of south-central Nevada (Valentine et al., 2017) (Figure 1.1). The field is dominated by monogenetic, basaltic eruptions including more than 100 cinder cones, maars, and flows (Scott and Trask, 1971). Roughly 80 km long by 20 km wide, LCVF encompasses two mountain ranges: the Reveille range in the southwest and the Pancake range in the northeast with Easy Chair Crater (ECC), the focus of this study, lying in the central region of the latter range (Valentine and Cortés, 2013). Located approximately 70 miles northeast of Tonopah, NV, ECC records initial effusive eruptions punctuated by a phreatomagmatic explosion (Valentine and Cortes, 2013). The units in and around the crater consist mainly of alkali basalt lava flows, agglomerates, and pyroclastic deposits.

ECC is a maar comprising the southern portion of the monogenetic Easy Chair Volcano. The volcano has been 40 Ar/ 39 Ar dated at 140±5 ka (Heizler, 2013) and forms a northeast trending ridge 2.5 km in length (Valentine and Cortes, 2013). The crater is elliptical in shape with the long axis running northeast in line with the volcanic ridge. The elliptical rim has a 540 m diameter (short axis) and extends 70 m above the surrounding basin (Valentine and Cortes, 2013). Most of the interior crater walls are covered but two units outcrop and are shown in **Figure 1.2**. The lowermost horizon is a fluidal agglomerate unit predating maar formation while

the upper unit is a lapilli tuff that formed as a consequence of the maar eruption (Valentine and Cortés, 2013).

While eruptions of alkali basalt are not rare in the Basin and Range Province, most eruptions occur along or near the margins of the province (Valentine et al., 2017). LCVF is unusual because it lies in the center of the province. Additionally, Roden and Shimizu (1993) and Smith (2000) calculated abnormally high equilibrium temperatures (1230-1290°C) in Group 1 (ultramafic Mg-rich peridotites with metamorphic textures (Frey and Prinz, 1978)) xenoliths collected from LCVF. These temperatures are significantly higher than temperatures recorded for other Group 1 xenoliths elsewhere in the western United States (840-1080°C) (Brey and Kohler, 1990) suggesting an elevated geotherm in the area. One explanation for the apparent elevated upper mantle temperatures is the existence of a mantle plume beneath the field (Smith, 2000; McKenzie and Bickle, 1988). A plume hypothesis was also proposed by Saltus and Thompson (1995) following a geophysical study of the lithosphere in southern Nevada. Their work suggested crustal isostasy alone could account for no more than 50% of the 800 m difference in elevation between Tonopah (just west of the LCVF) and Las Vegas, NV. Instead, the authors concluded that deep-seated thermal buoyancy was required to explain the gravitational field and topographic anomalies in the area.

1.2 Focus and Objectives

Recently, Cl-rich apatites were identified in some Group II (relatively Fe-rich cumulate pyroxenite and peridotite (Frey and Prinz, 1978)) xenoliths found in deposits related to ECC (Mosely, 2015). Chlorine is incompatible in basaltic magmas, and abundant Cl can indicate the presence of subduction-related fluids in mantle sources (Patiño Douce and Roden, 2006). The anomalous abundance of Cl in apatite of mantle-derived products at East Chair Crater suggest a

potential mantle source enriched in volatiles and related to recycled oceanic crust. More specifically, volatile-enriched mantle, possibly infiltrated by fluids from the subducted Farallon Plate, could be the source for LCVF magmatism. Alternatively, the unusual topographic dome and gravitational field characteristics noted by Saltus and Thompson (1995), as well as the elevated temperatures in the upper mantle documented by Smith (2000) may indicate a mantle plume rather than a lithosphere source for the lavas of the LCVF.

In this study, I have tested these conflicting ideas using an incompatible element ratio, specifically Cl/K, in olivine-hosted melt inclusions to investigate mantle source components. These two elements are nominally incompatible in basaltic magmas, therefore the melt inclusion ratios should be representative of primitive magmas in the LCVF. Elevated Cl/K ratios are common in subduction related lavas due to the influence of slab-derived fluids in mantle sources whereas plume or Ocean Island Basalt (OIB) sources do not exhibit elevated Cl/K (see e.g., Patiño Douce and Roden, 2006). Consequently, measurement of the Cl/K ratios in melt inclusions should give insight into the role of subduction and/or plume-derived components in the mantle source for the LCVF. Ni contents in forsterite-rich olivine can reflect proportions of pyroxenite in mantle sources (Sobolev et al., 2005). For example, relatively high Ni contents in olivines of plume-related Hawaiian lavas compared to olivines of mid-ocean ridge basalts (MORB) is thought to reflect an important role for pyroxenite in the source for Hawaiian lavas (Sobolev et al., 2005). Following this approach, I combined the use of minor element abundances in olivine in conjunction with melt inclusion compositions to infer mantle source characteristics including lithology (pyroxenite versus peridotite proportions) and provenance (subductionrelated versus plume-related versus lithosphere-related) of the lavas at ECC.



Figure 1.1: (*Upper*) Location of Lunar Crater Volcanic Field in southern Nevada. (*Lower*) Satellite image of the Pancake range, specifically Easy Chair Crater, in the northeast corner of LCVF (Images modified from Google Earth).



Figure 1.2: (*Upper*) An image from Google Earth showing Easy Chair Crater on the southwestern end of the Easy Chair Volcano ridge (Google Earth). (*Lower*) Most of the interior crater is covered by talus, however, both the agglomerate and lapilli are exposed along the eastern wall.

2.0 ANALYTICAL METHODS

Most of the samples used for this study were collected at ECC by the author. However, 2 samples previously collected by Deborah Hassler were used for initial melt inclusion exploration. Quality Thin Sections ® prepared polished thin sections of selected field specimens. Olivine *megacrysts* collected within the crater were mounted in epoxy and polished to produce round mounts. All samples were coated with carbon to reduce charging effects during electron microprobe analysis (EMPA).

Samples were analyzed at both the University of Alabama and the University of Georgia using JEOL 8600 electron microprobes. Olivine compositions were determined using a 15 kV accelerating voltage and a 20 nA beam current. For melt inclusions, the beam current was reduced to 5 nA. Specific minerals were qualitatively identified using a Bruker 5010 Silicon Drift Detector energy dispersive X-ray detector controlled by a Bruker Quantax energy dispersive analysis system. Quantitative analyses were performed with wavelength dispersive spectrometers automated with Advanced Microbeam, Inc. electronics and Probe for EMPA software, using both natural and synthetic standards (**Tables 2.1** and **2.2**). For olivine compositions, 10-second on-peak counting times were used for major elements and 30-second counting times were used for all elements except Cl, for which a 30-second counting time was used. Oxide abundances were calculated using the Phi-Rho-Z matrix correction model of Armstrong (1988). Backscattered electron images were acquired using ESPRIT imaging software from the Quantax analysis system.

To determine the precision and accuracy of analyses, San Carlos olivine (NMNH 111312-44) and a tektite glass (NMNH 2231) were run as unknowns at the beginning of each EMPA session. Oxide concentrations were then compared to the known standard concentrations. **Tables 2.3** and **2.4** display the averaged concentration for each oxide analyzed, the calculated 2σ of the mean, and the percent error when compared to the published concentrations for the standard. The error percentages for CaO in the olivine analyses and MnO in the melt inclusions appear high but are simply a result of the low absolute abundance of each oxide in the phase. It is important to note that H₂O wt% cannot be directly measured using EPMA therefore the H₂O content is estimated by subtracting the total oxide wt. % from 100% in the case of melt inclusion glass analyses.

The Peter Hooper GeoAnalytical Lab at Washington State University performed bulk rock geochemical analysis. Major element compositions were determined by X-ray fluorescence (XRF) and trace element abundances by both XRF and inductively coupled plasma-mass spectrometry (ICP-MS). Information on the methods and precision of these analyses can be found on the laboratory's webpage (http://cahnrs.wsu.edu/soe/facilities/geolab/).

Element	Standard	Standard Reference
Si	San Carlos Olivine	Olivine, NMNH 111312-44
Ti	TiO ₂	Synthetic TiO ₂ C.M. Taylor
Al	Spinel	Synthetic Spinel C.M Taylor
Mg	Springwater Olivine	Olivine, USNM 2566
Fe	Fayalite	Synthetic Fayalite, U of Oregon OL-11
Mn	Spessartine	Spessartine 4b C.M. Taylor
Ca	Sphene	Sphene 1A C.M. Taylor
Ni	Ni Metal	Ni metal C.M. Taylor

 Table 2.1: Element standards used for olivine analysis

 Table 2.2:
 Element standards used for melt inclusion analysis

Element	Standard	Standard Reference
Si	Albite	Amelia Albite, (Sinkaskas, 1968)
Ti	TiO ₂	Synthetic TiO ₂ , C.M. Taylor
Al	Spinel	Synthetic Spinel, C.M Taylor
Mg	Springwater Olivine	Olivine, USNM 2566
Fe	Fayalite	Synthetic Fayalite, U of Oregon OL-11
Mn	Spessartine	Spessartine 4b, C.M. Taylor
Ca	Sphene	Sphene 1A, C.M. Taylor
Na	Albite	Amelia Albite, (Sinkaskas, 1968)
K	Orthoclase	Orthoclase 10, C.M. Taylor
Cl	Scapolite	Scapolite (Meionite), NMNH R6600

(11 10)				
Oxide	Avg. Analysis wt. %	2σ of the mean	Published values	% Error
SiO ₂	40.71	0.18	40.81	0.22
MgO	48.88	0.23	49.42	1.1
FeO	10.26	0.13	9.55	7.5
MnO	0.14	0.01	0.14	0.55
CaO	0.08	0.01	< 0.05	64.0
NiO	0.36	0.01	0.37	4.5
Mg#	89.5	0.10	90.2	0.84
Fo	88.9	0.10	89.7	0.88
Total	100.5	0.44	100.29	0.16

Table 2.3: Standard Analysis for the San Carlos olivine standard, NMNH 111312-44 (n=10)

 Table 2.4: Standard Analysis for the tektite glass standard, NMNH 2231 (n=6)

Oxide	Avg. Analysis wt. %	2σ of the mean	Published values	% Error
SiO ₂	75.78	1.26	75.75	0.05
Al ₂ O ₃	11.06	0.32	11.34	2.47
FeO	4.92	0.22	4.96	0.75
MgO	1.46	0.13	1.51	3.01
CaO	2.63	0.11	2.66	1.07
Na ₂ O	0.94	0.11	1.06	11.05
K ₂ O	1.72	0.18	1.88	8.55
TiO ₂	0.52	0.09	0.50	3.39
MnO	0.08	0.09	0.11	21.42
H ₂ O	n.d.	NA	0.10	NA
Total	99.10	1.15	99.88	0.79

3.0 RESULTS

Prior to field collection, reconnaissance was performed on samples previously collected by Deborah Hassler in order to identify lithological units most likely to contain olivine-hosted melt inclusions. From that work it was determined that the highest density of inclusions existed within clasts from a basaltic agglomerate horizon exposed along the interior crater wall (Figure **3.1**). Fourteen samples were collected from the agglomerate horizon. The agglomerate clasts are porphyritic with a glassy, vesicular groundmass often displaying flow textures. In this study, both phenocrysts (> 1 mm in diameter) and smaller groundmass crystals (< 1 mm in diameter) were analyzed so it is important to distinguish between the two. Phenocrysts include olivine, plagioclase, and clinopyroxene with olivine being the most common. The olivine is subhedral to euhedral and up to 8 mm in length. Plagioclase and clinopyroxene phenocrysts are also subhedral to euhedral and similar in size to the olivine. Groundmass crystals, while smaller, are similar in relative abundance and shape. Like many LCVF lavas, *megacrysts* are common at ECC and include olivine, amphibole, plagioclase, and pyroxene. Fourteen olivine megacrysts were collected for analysis. The megacrysts are significantly larger in size compared to the phenocrysts, ranging up to 5 cm in diameter (Figure 3.2). Additionally, a sample of a hardened lava that flowed to the west out of a cinder cone connected to the north side of ECC (referred to as "Easy Chair cinder cone basalt" in the following) was collected for both bulk rock and microprobe analysis (Figure 3.3). While melt inclusion analyses are derived entirely from samples in the agglomerate horizon, olivine analyses represent phenocrysts and groundmass

crystals from the agglomerate horizon, olivine megacrysts, and phenocrysts from the sample (16ECCC1) of the Easy Chair cinder cone basalt.

Figure 3.1 shows ECC and the location of most samples collected from the agglomerate horizon. Phenocryst assemblages in each sample are the same, however, the amount of glass contained in the matrix of each sample varies laterally. As displayed in **Table 3.1**, samples 16ECA1 through 16ECA6 and 16ECA12 through 16ECA14 contain minor amounts of glass in the matrix. Beginning with sample 16ECA7 glass content increases to the point where the matrix is nearly completely glass in sample 16ECA9. Glass content then decreases from samples 16ECA10 through 16ECA11.

Olivine textures and compositions also vary within the samples. Measured olivine oxide weight percentages were converted to cations and normalized to 4 oxygens to confirm the accuracy of mineral analyses. Samples 16ECA1 and 16ECA2 contain only heavily fractured olivine groundmass crystals with Fo contents greater than 91% and ranging up to 97.8% (**Table 3.2**). Such igneous olivines are very rare in the rock record and have recently been attributed to subsolidus oxidation occurring in stacked basalt flows (Blondes et al., 2012). Groundmass crystals in samples 16ECA6 through 16ECA14 have Fo contents of 79-88% and do not display the fractured texture. Samples 16ECA3 through 16ECA5 contains both high and low Fo olivines in the groundmass. For simplicity, olivines with Fo content over 91% will be referred to as Type 1 olivines with Fo content below 88% will be called Type 2 olivines. In this study, no olivines with Fo content of 88-91% were encountered. It is also important to note that olivine phenocrysts in all samples are Type 2 regardless of the composition of the groundmass crystals. **Fig 3.4** shows the relationship between Ni, Mn, and Ca vs. Fo content for all analyzed olivines. The most striking observation is that Ni and Ca contents are largely the same in the Type 1 and 2

olivines although Mn ranges to higher concentrations in the Fo-rich Type 1 olivines. Additionally, the cinder cone and megacryst olivines are restricted to a narrow range in Fo content (86.6 to 87.6) and plot at the high Mg end of an array defined by the Type 2 agglomerate olivines. The graphs also show that Type 1 olivines are only found in the agglomerate samples. The cinder cone and megacryst samples generally have higher Ni and lower Mn and Ca contents compared to olivines from the agglomerates. Analyses of the San Carlos olivine standard are also included in the figure to illustrate analytical precision.

Due to the distribution and preservation of melt inclusions, melt inclusion analysis was restricted to samples 16ECA5, 16ECA6, 16ECA7, 16ECA8, 16ECA9, 16ECA11, and 16ECA12. Identifying melt inclusions proved difficult due to the small size of the inclusions (1-10 microns). Using backscatterd electron (BSE) imaging inclusions could be identified by contrasts in average atomic number with the surrounding olivines: moreover, the inclusions were generally rimmed by relatively Fe-rich olivine which is recognizable on BSE images (Figure 3.5). Any inclusions breached by fractures or that otherwise appeared to be contaminated were discarded. Since the microprobe beam was 1 micron in diameter and many inclusions were not much larger, contamination of the analyses by the olivine host was a constant concern. To address this issue multiple analyses were taken on each inclusion and any results with Fe or Mg spikes were discarded. Another concern was the thickness of the inclusions and the possibility that the microprobe beam was penetrating through the inclusion and into the olivine host. This issue was addressed in the same manner as described above by excluding results with Fe and/or Mg anomalies. Matrix glass in sample 16ECA9 was also analyzed to provide context for the melt inclusion compositions.

Significant compositional variation is observed throughout the melt inclusion samples with K₂O, FeO, and CaO accounting for the most variation. The melt inclusions are tephritic to basaltic with typical concentrations of SiO₂, 47.2%, MgO, 2.7%, FeO, 7.3%, CaO, 10.4%, Na₂O, 4.7%, K₂O, 1.1% and Cl, 0.10%. Most melt inclusions are nepheline-normative (except one that is quartz normative) and have Mg numbers ranging from 24.8 to 59.4 (**Table 3.3**). Cl/K values range from 0.06 to 0.27. Relationships between various oxides and Cl/K vs. MgO are plotted in **Figure 3.6** along with glass matrix compositions from 16ECA9 and bulk rock composition. It is important to note that melt inclusions were not homogenized prior to analysis. Changes in melt inclusion composition resulting from crystallization along the inclusion wall or through elemental diffusion with the host mineral can been accounted for using reheating processes. However, because the focus of this study is ratios of incompatible elements in melt inclusions, homogenization was not necessary.

There are intriguing contrasts between the matrix glass and the melt inclusions. For example, the matrix glass has lower Al₂O₃ and higher FeO than the melt inclusions. This difference can plausibly be attributed to plagioclase saturation lowering Al₂O₃ in the matrix glass (unlike the more primitive melt inclusions) and Fe-rich haloes around the melt inclusions depleting them in Fe. The variability of the composition of the melt inclusions is clearly greater than that of the matrix glass – and such melt inclusion variability has been noted elsewhere (Sobolev, 1996; Kent et al., 2008; Danushesky et al., 2004). The high variability of the melt inclusion, reaction, and assimilation with melt occurring in boundary layers where hot basaltic melts come into contact with cooler wallrocks or crystal mushes and undergo rapid compositional change and crystallization.

In **Figure 3.7** the Cl and K abundances for Easy Chair melt inclusions are compared with Cl and K concentrations from melt inclusions in other volcanic environments including MORB, OIB, and volcanic arcs. The wide variation in K content of the melt inclusions is obvious in this plot and similar variation been reported in other melt inclusion studies (Kent et al., 2008). With respect to these two elements, the Easy Chair melt inclusions are most like melt inclusions from OIB and basalts from the Rio Grande rift. However, Cl shows limited variation in the Easy Chair inclusions – this is also true for melt inclusions from OIB for those inclusions with relatively high Cl contents. In contrast, Cl and K exhibit positive correlations in melt inclusions from volcanic arcs and the Rio Grande rift. In **Figure 3.8** the Cl/K ratio is plotted against melt inclusion Mg numbers; there is no correlation between the two variables suggesting the Cl/K ratio is not affected by magma fractionation.

Bulk rock analysis (**Table 3.4**) indicates the basalt lava flow from the Easy Chair cinder cone is an alkali basalt, specifically a basanite following the classification scheme of Le Maitre et al. (2002) (**Figure 3.9**). The basalt is silica undersaturated and nepheline-normative. X-ray fluorescence and ICP-MS analyses reveal a relative enrichment in light rare-earth elements (LREE) when normalized to chondrite concentrations similar to that observed in typical OIB (**Figure 3.10**) – a characteristic also noted by Lum et al. (1989) and Yogodzinski et al. (1996). **Figure 3.11** is a spidergram that displays normalized abundances of trace elements that behave incompatibly in basaltic magmas. Elements are ordered from left to right along the x-axis based on their relative incompatibilities with the left-most element being the most incompatible. Easy Chair cinder cone basalt is rich in the most incompatible trace elements, lacks significant trace element anomalies (e.g., no high field strength element depletions) and is similar to typical OIB.



Figure 3.1: Photo of Easy Chair Crater looking north-northeast with agglomerate horizon marked in yellow along with sample locations.



Figure 3.2: Example of olivine megacryst in the Easy Chair Crater agglomerate clasts.



Figure 3.3: Locations from which 16ECCC1, a sample of the Easy Chair cinder cone basalt, and 16ECA1 through 16ECA14 were collected. Figure modified from Valentine and Cortés (2013).



Figure 3.4: Ni, Mn, and Ca plotted against Fo content for all olivine analyses. STND are analyses of the San Carlos olivine standard.



Figure 3.5: BSE images of an Fe-rimmed melt inclusions in an olivine groundmass crystals from the agglomerate horizon. Top image shows a Type 2 olivine and the bottom is a Type 1 olivine.



Figure 3.6: Various oxide compositions vs. MgO for melt inclusions, matrix glass, and bulk rock.



Figure 3.7: Melt inclusion Cl and K abundances from Easy Chair Crater (ECC) melt inclusions compared to compositions from other volcanic environments. Includes data from Stroncik & Haase (2004), Michael & Cornell (1998), Sun et al. (2007), Straub & Layne (2003), and Rowe & Lassiter (2009).



Figure 3.8: Cl/K plotted against Mg# for olivine-hosted melt inclusions at Easy Chair Crater.



Figure 3.9: Bulk rock composition of the Easy Chair cinder cone basalt (red dot) plotted on the total alkali-silica (TAS) diagram. Diagram is based upon coordinates from Le Maitre et al. (2002).



study. Average ocean island basalts (red) and average E-MORB (brown) values from Sun and McDonough (1989). Average LCVF (black) values from Lum et al. (1989). All values normalized to chondritic values from Sun and McDonough (1989).



Figure 3.11: MORB-normalized incompatible trace element abundances in Easy Chair cinder cone basalt. Elements ordered by degree of incompatibility, most incompatible to the left. Color scheme and data sources are the same as **Figure 3.10**. MORB-normalizing values from Sun and McDonough (1989).

		Groundmass Olivine	
Sample Name	Rock/Mineral Type	Composition	Glass Content
16ECA1 16ECA2		Fractured olivines with Fo	
IOECA2		content > 9176	
IOECAJ		Both olivine populations	Little to no glass
I6ECA4		present	in the matrix
I6ECA5		1	_
16ECA6			
16ECA7			Some glass in the
16ECA8	Basaltic agglomerate		matrix
16ECA9	Dasante aggiomerate		Glass dominated
EC121*			matrix
16ECA10			Some glass in the
16ECA11		Clivines with Fo content	matrix
16ECA12		~88%	
16ECA13			Little te me elege
16ECA14			Little to no glass
EC103*			In the matrix
16ECCC1	Cinder cone basalt		
16ECMC1 to 15	Olivine megacrysts		NA
* EC121 and EC1	03 collected by D. Hass	ler	

 Table 3.1: Description of samples collected at Easy Chair Crater
$\frac{1}{16FCA10L11} = 16FCA20L11 = 16FCA20L11 = 16FCA20L12$									
<u>Wl /o</u>	IOECAIOLII	IDECAIULIZ	IUECAZULII	10ECA20L12					
S1O ₂	42.25	42.6/	42.64	42.80					
MgO	55.82	55.98	56.03	54.62					
FeO	1.51	1.56	2.21	2.42					
MnO	0.34	0.34	0.52	0.45					
CaO	0.14	0.27	0.23	0.27					
NiO	0.21	0.18	0.19	0.19					
Total	100.29	101.00	101.80	100.78					
Si	0.997	0.999	0.995	1.008					
Number oj	1000000000000000000000000000000000000	0.000	0.005	1 009					
Mg	1.962	1.954	1.948	1.917					
Fe	0.030	0.031	0.043	0.048					
Mn	0.007	0.007	0.010						
IVIII	0.007	0.007	0.010	0.009					
Ca	0.007	0.007	0.010	0.009 0.007					
Ca Ni	0.007 0.004 0.004	0.007 0.007 0.003	0.006 0.004	0.009 0.007 0.004					
Ca Ni Total	0.007 0.004 0.004 3.003	0.007 0.007 0.003 3.001	0.006 0.004 3.005	0.009 0.007 0.004 2.992					
Ca Ni Total Fo%	0.007 0.004 0.004 3.003 97.8	0.007 0.007 0.003 3.001 97.6	0.006 0.004 3.005 96.9	0.009 0.007 0.004 2.992 96.6					

 Table 3.2: Representative analyses for olivine compositions from ECC

Type 2 Olivines								
wt%	16ECA110L30	16ECA110L41	16ECA12OL40	16ECA13OL52				
SiO ₂	39.66	39.82	39.81	40.77				
MgO	44.33	45.22	45.62	42.56				
FeO	15.26	14.61	12.80	14.92				
MnO	0.25	0.16	0.23	0.21				
CaO	0.26	0.27	0.29	0.34				
NiO	0.19	0.14	0.25	0.18				
Total	99.97	100.33	99.04	99.25				
Number of	ions on the basis of 40	0.007	1 001	1 021				
SI Ma	0.999	0.997	1.001	1.031				
Fo	1.003	0.306	1.710	0.216				
Mn	0.021	0.003	0.209	0.010				
Ca	0.007	0.007	0.008	0.009				
Ni	0.004	0.003	0.005	0.004				
Total	3.001	3.003	2.999	2.969				
Fo%	83.1	84.1	85.6	82.8				
Mø#	83.8	84 7	86.4	83.6				

Table 3.2 (cont.)

Megacrysts							
wt%	16ECMC2.12	16ECMC3.14	16ECMC5.13	16ECMC9.12			
SiO ₂	40.17	40.73	40.36	40.02			
MgO	47.68	48.00	47.83	48.38			
FeO	11.68	11.75	11.77	11.56			
MnO	0.20	0.16	0.14	0.18			
CaO	0.23	0.21	0.23	0.24			
NiO	0.31	0.31	0.24	0.26			
Total	100.43	101.30	100.62	100.73			
Number of io	ns on the basis of 40						
Si	0.993	0.997	0.994	0.985			
Mg	1.757	1.751	1.756	1.776			
Fe	0.241	0.240	0.242	0.238			
Mn	0.004	0.003	0.003	0.004			
Ca	0.006	0.005	0.006	0.006			
Ni	0.006	0.006	0.005	0.005			
Total	3.007	3.003	3.006	3.015			
Fo%	87.2	87.3	87.3	87.5			
Mg#	87.9	87.9	87.9	88.2			

Table 3.2 (cont.)

wt %	16ECA7MI5	16ECA8MI2	16ECA8MI5	16ECA8MI6
SiO ₂	47.89	46.06	44.66	45.12
TiO ₂	1.66	3.29	3.46	3.52
Al_2O_3	21.50	20.15	21.36	18.26
MgO	2.60	1.56	1.52	2.06
FeO	5 17	9 70	6.65	9 1 4
MnO	0.23	0.00	0.02	0.30
$C_{2}O$	7.68	11.22	10.26	12.30
Na ₂ O	7.00	6.08	5.88	6.45
Na ₂ O	7.50	0.08	J.00 1.05	0.43
K_2O	1.12	0.70	1.03	0.43
	0.14	0.14	0.10	0.10
lotal	95.89	98.97	94.95	97.67
Normalized to 100%				
SiO_2	49.91	46.49	46.99	46.14
TiO ₂	1.73	3.32	3.64	3.60
Al_2O_2	22.41	20.34	22.48	18 67
MgO	2 71	1 57	1.60	2 11
FeaOa	0.60	1.09	0.78	1.04
FeO	1.85	8.81	6.70	8.41
MnO	4.05	0.01	0.00	0.41
CaO	0.24	0.00	10.02	12.59
CaO N O	8.00	11.33	10.80	12.38
Na ₂ O	8.23	0.14	0.19	0.00
K_2O	1.1/	0.//	1.10	0.44
CI	0.15	0.14	0.11	0.10
Normative Minerals	(CIPW)			
Quartz				
Plagioclase	46.73	43.51	49.05	35.50
Orthoclase	6.91	4.54	6.54	2.60
Nepheline	23.17	17.99	17.84	21.52
Dionside	14 71	25.09	17.92	28.67
Olivine	4 04	0.70		20.07
Ilmenite	3 29	6.32	6.92	6 84
Magnetite	0.87	1.58	1 13	1 51
Wallastanita	0.87	1.36	1.13	1.31
			0.40	3.17
Hypersthene				
PPM				
Κ	9296	6345	8693	3544
Cl	1417	1438	967	962
Cl/K	0.152	0.227	0.11	0.272
	0.102	··	V.1 1	0.272
Mg#	17.8	32.1	47.24	28.9

Table 3.3: Representative analyses for olivine-hosted melt inclusions from ECC

wt %	16FCA11MI5	16FCA11MI2	16FCA11MI0	16FCA11MI11
wi /0	10ECAIIIVII3 15 52			
SIU ₂	45.55	48.04	45.98	4/.83
110_2	2.77	3.24	2.68	1./2
AI_2O_3	17.80	19.79	19.45	19.13
MgO	2.49	1.66	1.35	1.88
FeO	7.95	7.52	7.29	7.56
MnO	0.12	0.17	0.19	0.13
CaO	11.80	11.20	11.19	10.61
Na ₂ O	6.27	2.89	6.14	4.04
K_2O	0.60	0.73	0.57	1.87
Cl	0.09	0.08	0.08	0.12
Total	95.43	95.33	94.92	94.89
Normalized to 1	00%			
SiO ₂	47.56	50.35	48.40	50.36
TiO2	2.91	3.40	2.82	1.81
Al_2O_3	18.68	20.74	20.47	20.14
MgO	2.61	1.74	1.42	1.98
Fe ₂ O ₂	0.93	0.88	0.85	0.88
FeO	7 51	7 09	6.91	7.16
MnO	0.13	0.18	0.20	0.14
CaO	12 38	11 74	11.78	11 17
Na ₂ O	6 58	3 03	6.46	4 25
K ₂ O	0.58	0.77	0.40	1.25
Cl	0.09	0.08	0.08	0.13
Normatina Min	mals (CIDW)			
Normalive Mine	erais (CIF W)	2 55		
Quartz	27.14	5.55	10 12	51.90
Plagloclase	3/.14	03.83	48.15	54.89
Orthoclase	3./1	4.52	5.55	11.52
Nepheline	20.22	1414	10.84	5.25
Diopside	29.03	14.14	21.31	20.41
Olivine	C C 1	6 45	5.26	2.78
Ilmenite	5.51	6.45	5.36	3.41
Magnetite	1.61	1.52	1.48	1.52
Wallastonite	2.59		3.16	
Hypersthene		3.83		
PPM				
Κ	5015	6042	4699	15491
Cl	852	827	842	1158
Cl/K	0.17	0.14	0.18	0.07
Mg#	35.9	28.2	24.8	30.7

Table 3.3 (cont.)

wt %	16ECCC1		
SiO ₂	44.60		
TiO ₂	2.59		
Al_2O_3	15.05		
MgO	8.00		
FeO	11.96		
MnO	0.21		
CaO	9.95		
Na ₂ O	4.02		
K ₂ O	1.78		
P_2O_5	0.79		
Total	98.94		
PPM			
Cs*	0.51	Gd*	7.98
Rb*	49.30	Tb*	1.21
Ba*	629	Dy*	6.59
Th*	5.19	Y*	30.97
U*	1.56	Ho*	1.23
Nb*	74.74	Er*	3.10
Ta*	4.38	Tm*	0.41
La*	46.95	Yb*	2.52
Ce*	94.08	Lu*	0.38
Pb*	2.52	Sc*	22.40
Pr*	11.53	Ni*	146.20
Sr*	1003	Cr	246.30
Nd*	46.08	V	215
Zr*	243	Ga	17.13
Hf*	5.33	Cu	47.48
Sm*	9.41	Zn	89.10
Eu*	2.97		

 Table 3.4: Bulk rock analyses of Easy Chair cinder cone basalt

* Denotes values from ICP-MS analysis. All other values from XRF.

4.0 DISCUSSION

4.1 Olivine Compositions

For the purpose of clarity Type 1 and Type 2 olivines will be discussed separately. The focus of this study was on the geochemical characteristics of olivines at ECC, and Type 1 olivines represent an unexpected and unusual population that have been affected by post-eruptive processes as discussed below.

Type 2 Olivines

Elemental abundances and ratios in olivine crystals from basaltic magmas can be used to infer the petrology of the source rock for particular silicate melts. In the upper mantle, many basalts form from partial melting of peridotite. In contrast, some melts are derived from pyroxenite-rich source rocks which are thought to be transported from the lower mantle via convection (Sobolev, 2005). Ni, Mn, and Ca partition differently between peridotite-melt and pyroxenite-melt, and the abundance of these elements in relatively primitive olivine phenocrysts can be used to link primitive melts with source lithology.

Previous studies have attempted to use olivine compositions to infer magma source lithologies. Sobolev et al. (2005) postulated the existence of a hybrid, olivine-free pyroxenite source resulting from the high pressure (>3.0 GPa) reaction of silica-rich eclogite-derived melt and peridotite. This idea was predicated on the experimental and theoretical evidence for melting of eclogite at higher pressures than peridotite in upwelling mantle diapirs; thus eclogitederived melts would be expected to form in rising mantle plumes and would react with peridotite surroundings. This hybrid pyroxenite-peridotite source was used to explain high Ni and Si

concentrations observed in Hawaiian parental magmas that cannot be explained simply by melting of peridotite alone. The melting of such a hybrid source would produce a melt enriched in Ni, depleted in Ca, and having a lower Mn/Fe ratio compared to pure peridotite-derived melts (Sobolev et al., 2007). These characteristics reflect the decrease of the bulk distribution coefficient for Ni and the increase of the ratio of bulk distribution coefficients of Mn to Fe driven by the lack of olivine in the pyroxenite portion of the hybrid source (Sobolev et al., 2005; Keleman et al, 1998; Humayun et al., 2004). Additionally, the concentration of Ca, a trace element in olivine, is often lower in pyroxenite-derived melts than in peridotite-derived melts with the same Fo content. The lower Ca has been attributed to the presence of residual clinopyroxene (Herzberg, 2006) in pyroxenite-derived melts. Contribution of a hybridpyroxenite source during ocean island basalt genesis has also been suggested based on Os-He isotope studies of picrites from Iceland (Brandon et al., 2007).

As the hybrid pyroxenite-derived melt ascends into the crust the decrease in pressure will cause the melt to become olivine saturated and olivine will crystallize. These primitive olivines should retain the chemical signature of the source (Sobolev et al., 2008). Gurenko et al. (2010) quantified the geochemical parameters and developed an equation to calculate the weight percent of pyroxenite in the source rock using major and trace elemental analyses of olivine phenocrysts:

Equation 4.1

$$Xpx = 6.705E^{-4} * Ni\left(\frac{FeO}{MgO}\right) - 1.332E^{-2} * \left(\frac{Mn}{FeO}\right) + 1.5215$$

Ni = Ni ppm, FeO = FeO wt. %, MgO = MgO wt. %, Mn = Mn ppm (Sobolev et al., 2008); Gurenko et al., 2010) In the equation, Ni is normalized to (FeO/MgO) to eliminate the effects of magma fractionation while Mn is normalized to FeO to reduce the effects of olivine fractionation (Gurenko et al., 2010). Xpx (weight fraction of pyroxenite source) values will range from 0 to 1 with 1 indicating 100% contribution from a pyroxenite source and 0 indicating 0% contribution. Since pyroxenite-derived melts are interpreted as products of the melting of a source rock with a pyroxenite component derived from the lower mantle and peridotite-derived melts represent melts of upper mantle peridotite (Sobolev, 2005), this equation can be used to constrain contributions from a lower mantle component found in OIB or hotspot magmatism. One of my aims was to determine if the LCVF magmas had such a pyroxenite (OIB-type) component given the geophysical evidence suggestive of a plume beneath the LCVF as well as elevated upper mantle temperatures determined from xenoliths at LCVF. If calculations using the above equation indicate a significant pyroxenite component in the LCVF source, then that would suggest an OIB-type source (Garcia et al, 2010).

Figure 4.1 compares olivine trace element contents in olivines from various environments and those from ECC while **Figure 4.2** shows the distribution of Xpx values calculated for olivines from ECC. Following the procedure for Sobolev et al. (2008) and Gurenko et al. (2010) the Xpx calculations include only the most primitive Type 2 olivines with Mg# > 84. The large range within each population is a likely a product of instrumental precision, therefore, the average of each population is more meaningful than individual analyses. Olivine phenocrysts from the Easy Chair have calculated Xpx values from 0.13 to 0.77 and average 0.47. Xpx values for agglomerate groundmass crystals range from 0.03 to 0.85 and average 0.36. These values suggest that a substantial amount of pyroxenite was present in the source of the East Chair Crater agglomerate olivines. Megacryst values span a greater range

(0.14 to 0.84) but have a higher average Xpx of 0.49 suggesting pyroxenite may have been abundant in the source that melted to produce the Easy Chair megacrysts as well. In comparison, Sobolev et al. (2007) calculated average Xpx values of 0.17 for MORB and 0.30 to 0.61 for OIB and large igneous provinces globally. It is also important to note that Sobolev et al. (2005) encountered a wide spread of Xpx values (at least 20%) within samples derived from a single Hawaiian volcano concluding that mantle heterogeneity, to some degree, is present in most mantle-derived melts.

Individual Ni, Mn, and Ca analyses versus Fo content from this study are plotted with data for olivines from OIB and MORB compiled by Sobolev (2007) in **Figure 4.1**. Olivine phenocrysts from the agglomerate unit have Ni abundances that predominantly plot near the OIB/MORB boundary but some analyses plot in the OIB region. Groundmass crystals plot near the OIB/MORB boundary and within the MORB region while megacryst olivine and olivines from the cinder cone basalt flow have Ni concentrations that plot on the OIB/MORB boundary. Manganese concentrations for all olivine categories are concentrated in the OIB field but groundmass crystals and megacrysts range across the OIB/MORB boundary into the MORB field. Calcium concentrations for olivines from the agglomerate trend from the OIB/MORB boundary into the OIB field. It is obvious in the range of OIB Ca data points that Ca results are not as definitive regarding the amount of proxenite because OIB Ca concentrations range both above and below MORB concentrations.

It is interesting that the olivine megacryst and cinder cone concentrations for the three trace elements are similar while the concentrations from the agglomerate olivines vary. The rough trend displayed by all olivines for Ni and Mn suggests those element concentrations are very sensitive to fractionation and that the megacryst and cinder cone olivines represent the least

evolved olivines from ECC. Temporally this makes sense as the groundmass crystals were likely among the last olivines to crystalize in the system. Ultimately the data indicate that the source for the megacrysts, cinder cone, and agglomerate olivines has similarities to both OIB and MORB.

Other Work

Recent studies have questioned the viability of the hybrid-pyroxenite model. Matzen et al. (2017) suggest that an olivine-free pyroxenite source is not necessary to explain Ni enrichments observed in some OIB. Instead, the authors posit that the temperature dependence of Ni partitioning alone is enough to explain the behavior of Ni in areas of thick lithosphere (>70 km). Referring to **Figure 4.1**, the elevated Ni abundances for OIB are viewed as the product of melting a peridotite source at a depth (and temperature) greater than that for MORB generation.

Others, including Lambart et al. (2016) question the accuracy of **Equation 4.1** citing the effects of bulk composition, temperature, and melt fraction on the solidus temperature of pyroxenite and peridotite. Using a combination of experimentally-derived data and compositional modeling, the authors determined pyroxenite does not always have lower solidus temperatures than peridotite as is suggested in the "hybrid-pyroxenite" model. Instead, mantle conditions were identified that could result in as much as 50% of pyroxenite melting at shallower depths than coexisting peridotite in plume environments. Furthermore, it was suggested that shallow melting of pyroxenite in non-plume environments, like at mid-ocean ridges (MOR), could produce significant pyroxenite signatures in primitive magmas. Although not disagreeing with the general concept behind the hybrid-pyroxenite model, Lambart et al. (2016) ultimately suggest that quantifying the amount of pyroxenite contribution to primitive magmas requires more factors than are included in **Equation 4.1**.

In conclusion, olivine trace element analysis indicates the lavas from ECC are similar to both OIB and MORB. However, Ni and Mn abundances suggest a significant amount of pyroxenite was present in the mantle source that contributed to melting. This analysis supports the existence of a mantle plume beneath ECC, as previously suggested by Smith (2000) based on the study of equilibrium temperatures in xenoliths and by Saltus and Thompson (1995) stemming from their study of the gravitational field of the Tonopah area.

Type 1 Olivines

Globally, the most Mg-rich, clearly magmatic olivine phenocrysts are found in basalt or komatiite flows and have Fo contents between 85% and 94% (Deer et al., 1992). At ECC, Type 1 olivines are agglomerate groundmass crystals with Fo content from 93.9% to 97.8% and thus are compositionally unusual. The Mg-rich olivines are found in samples 16ECA1 through 16ECA5 collected from the southernmost portion of the agglomerate layer along the southeastern wall of the crater (**Figure 3.3**). Using backscatter electron imaging (BSE), the olivines can be identified by an extensive network of fractures that appear light grey in a BSE (**Figure 4.3**). The light grey material in the fracture is combination of iron-oxide minerals including hematite.

Very forsterite-rich olivines are known from several locations and a variety of geologic processes have been proposed to explain their genesis including oxidation (Blondes et al., 2012), exsolution (Petaev and Brearley, 1994), assimilation of xenoliths (Boyd and Nixon, 1978 ; Johnston and Stout, 1984), and metamorphism of carbonate-rich lithologies (Owens, 2000 ; Wenzel et al., 2002). Recently, Blondes et al. (2012) analyzed the most Mg-rich olivines to date (Fo 99.8%) collected from stacked basalt flows in the Big Pine Volcanic Field in east-central California. δ^{18} O values from the forsteritic olivines indicate a mantle-derived origin (5.4± 0.3‰), making metamorphism of crustal carbonate or xenolith assimilation unlikely. Instead,

the authors argue for high-temperature subsolidus oxidation as the driving force behind Mg enrichment. The stacked basalt flows analyzed in the Big Pine field contain both forsteritc olivines and normal (Fo < 94%) olivines, however, the two never coexist in a single flow. Additionally, forsteritic olivines often display embayed textures and have symplectite laminae of orthopyroxene and hematite or whispy Fe-rich internal bands. A key oxidation signature in the flows containing forsteritic olivine is the presence of hematite as the only iron oxide phase whereas flows containing normal olivines contain magnetite. Considering the isotopic, textural, and compositional evidence, the authors posit that the oxidation was driven by the reaction of thin, hot, and slowly cooling stacked lava flows with atmospheric oxygen resulting in Mg-rich olivine and hematite.

Type 1 olivines from ECC were likely created by a process similar to that described by Blondes et al. (2012). In the absence of isotopic data or symplectite textures, the most compelling line of evidence arises from the wispy texture observed in the Fo-rich olivines in both studies (**Figure 4.4**). Furthermore, at ECC, the Type 1 olivines were found in samples collected at the top of the agglomerate unit, Type 2 olivines came from samples lower in the unit, and samples containing both olivines types came from the middle (**Figure 4.5**). Similarly, Blondes et al. (2012) found high Fo olivines only in the uppermost, thin flows in the stacked section at Big Pine. This stratigraphic position allowed the lava to cool slowly while reacting with atmospheric oxygen. Hematite is also present in the Easy Chair samples with Type 1 olivines while only magnetite occurs in samples containing Type 2 olivines (**Figure 4.6**). Given that most magmas crystallize at low oxygen fugacities near the fayalite-quartz-magnetite oxygen buffer, crystallization of primary igneous hematite at ECC is unlikely and instead it is more likely the agglomerate unit experienced oxidizing conditions after eruption.

Figure 4.7 is an image of an olivine groundmass crystal from sample 16ECA3. As stated previously the sample contains both Type 1 and Type 2 olivines. The core of the crystal is compositionally similar to a Type 2 olivine while the rim is Mg-rich and fractured similar to Type 1 olivines. This crystal likely represents a quenched intermediate stage of the oxidizing process. In a response to external conditions, the reaction starts along the crystal rim removing Fe from the olivine in order to form iron-oxide minerals while at the same time increasing the Fo content of the rim simply through subtraction of Fe.

4.2 Melt Inclusions

Melt inclusions are small pockets of melt that become trapped within crystals during growth. Once trapped, the inclusion is isolated from the rest of the melt and is thus not affected by subsequent fractionation, assimilation, and/or degassing (Sobolev, 1996), although, inclusion composition can be affected by crystal growth along the wall of the host mineral or diffusion. In basalt flows, olivine-hosted melt inclusions are particularly useful because olivine is early forming and more likely to entrap a primitive melt. Since Cl is both volatile and incompatible in a basaltic melt, melt inclusions provide a unique opportunity to measure Cl amounts that likely represent the initial melt composition when normalized to an involatile, incompatible element such as K (Rowe and Lassiter, 2009).

Following the work of Aoki et al. (1981) and Jambon et al. (1995), Cl content can be normalized to the highly incompatible K in order to produce a ratio that is insensitive to crystallization within or along the walls of the inclusion. The Cl/K ratio can be used to differentiate magmatic source components. As displayed in **Figure 3.7**, melt inclusions in basalts from subduction-related environments typically display increased amounts of Cl (400 to 10000 ppm) when compared to other magmatic settings as well as a positive correlation of Cl

with K. The elevated levels reflect the tendency of Cl to partition into hydrous fluids and thus be recycled during subduction-related melting (Carroll and Webster, 1994). Alternatively, melt inclusions in ocean island basalts display comparatively lower Cl levels (80 to 1000 ppm) and the Cl/K correlation flattens at relatively high Cl contents. Given the complex tectonics of the western U.S. including subduction of the Farrallon plate during the early Tertiary and continental extension during the latter part of the Tertiary (Humphreys et al., 2003), Cl contents may help to determine the relative influences of continental mantle lithosphere, subduction-modified lithosphere, and OIB type plume sources in the magma sources for the LCVF.

In **Figure 3.7** ECC melt inclusions plot between the volcanic arc and OIB fields. However, the slope of the Easy Chair trend is flatter than that of the volcanic arc trend. The flattening reflects relatively constant Cl concentrations over a range of K concentrations, i.e., Cl was not incompatible during the melting process. This behavior could indicate that Cl in the melt was buffered by a Cl-bearing residual phase – possibly apatite. Intriguingly, Moseley (2015) identified Cl- and H₂O-rich apatites in Type II xenoliths from basalt flows just north of ECC, strengthening the argument for Cl-rich apatite playing a role in melt generation at LCVF. The melt inclusions have higher Cl/K than the matrix glass and generally have higher Cl concentrations (**Fig. 3.6**). The higher Cl/K and Cl abundance in melt inclusions combined with the lack of correlation between Cl/K and MgO (**Figure 3.8**) suggests that the melt inclusions are relatively undegassed and unmodified by crystal fractionation. Therefore the Cl/K ratios of the melt inclusions are probably indicative of the Cl/K ratios of the primary magma for ECC.

The abundance of Cl in ECC glasses tends to be higher than what is typical of OIB (**Fig. 3.7**). Lassiter et al. (2002) previously suggested that the deep mantle Cl budget is relatively unaffected by subduction because most Cl is removed from oceanic crust prior to entering the

asthenospheric mantle. If this is true, ECC melt inclusions, similar to Rio Grande rift melt inclusions, are too Cl-rich to be purely derived from lower mantle sources. However, volcanic arc lavas exhibit a strong, positive correlation between Cl and K as well as relatively high Cl abundances (e.g., Patiño Douce and Roden, 2005). The correlation is a product of the incompatible nature of Cl and K, in conjunction with the mobility of Cl in subduction-related aqueous fluids. The melt inclusions from ECC do not show a positive correlation between Cl and K suggesting if there was a subduction component added to the mantle source, its signature is obscured by the apparent buffering of Cl as noted above.

Rowe and Lassiter (2009) identified the shallow subduction of the Farallon plate beneath the western U.S. as the source for Cl-enrichment in melt inclusions from the Rio Grande rift – in these inclusions Cl and K are positively correlated (Fig. 3.7). Using a suite of trace element data from melt inclusions, these authors were able to discount crustal contamination/assimilation and melt fractionation as influences on the Cl/K ratio observed in the Rio Grande rift samples. The most K-rich melt inclusions from ECC have similar Cl, K and Cl/K concentrations to the most K-rich melt inclusions from the Rio Grande rift (Fig. 3.7), however, the positive correlation between K and Cl in the melt inclusions from the Rio Grande rift contrasts with the nearly constant Cl in the melt inclusions from ECC. One difference between Rio Grande rift analyses and ECC is the apparent mantle input. Rowe and Lassiter (2009) suggested that the Rio Grande rift lavas had variable mantle sources ranging from depleted, MORB-like sources to subductionmodified lithospheric mantle sources. In contrast, the similarity between the Cl/K ratios of melt inclusions from ECC to some OIB lavas, as well as the high absolute Cl contents suggests that both OIB- and subduction-related mantle sources contributed to the LCVF lavas. The OIB-like mantle input is further supported by the olivine trace element analysis discussed above. The Rio

Grande rift and ECC are separated by 800 miles (including the Colorado Plateau) so it is likely that different mantle sources contributed to magma generation, however, the Cl-enrichment observed in both data sets is very interesting. If melt generated from a depleted mantle source was enriched through interaction with a Cl-rich lithospheric mantle to produce Rio Grade rift lavas, then it is feasible that ECC lavas were enriched in a similar fashion, but at least some of the melt could instead have been generated from an upwelling, pyroxenite-rich mantle source. This explanation explains the OIB-like trend in Cl/K values and the elevated Cl abundance in samples from Easy Chair.

Major element trends in Melt Inclusions

While melt inclusions are isolated from processes in the larger melt system, fractionation still occurs within the inclusions. Inclusion/host rock reaction is common and often results in "plating" or mineral crystallization along the walls of the inclusion (Lowenstern, 1995). Elemental diffusion between host and melt inclusion can also occur as inclusions and host minerals attempt to equilibrate post-entrainment. Melt inclusion studies attempting to estimate the composition of parental magmas re-homogenize melt inclusions prior to analysis to mitigate changes caused by inclusion differentiation including crystallization of multiple phases within the inclusion. However at ECC, rapid quenching appears to have prevented the latter complexity but bright haloes around inclusions in BSE imagery clearly show that there was growth of olivine at the expense of the melt inclusion (Fig. 3.5) Since this study focuses on ratios of incompatible elements in inclusions, re-homogenization was not necessary. In **Figure 3.1** melt inclusion compositions are plotted along with matrix glass compositions and bulk rock data. Melt inclusions with compositions significantly different from the host lava are not uncommon but are most often observed in primitive lavas with high-Fo olivines (Danyushevsky et al., 2004).

The low abundance of MgO and FeO in the melt inclusions compared to the bulk rock and matrix glass data is likely in part a result of olivine plating along the inclusion wall. Since the melt in the inclusion was saturated in olivine at the time of entrapment, olivine is the first mineral to crystallize along the wall of the inclusion. Crystallization occurs on the inclusion wall because nucleation energy is relatively low along the pre-existing phase boundary (Roedder, 1979). Initially, forsteritic olivine in equilibrium with the host olivine crystallized on the interior walls of the inclusion. Gradually the olivine became more Fe-rich olivine as Mg became depleted in the melt; this change was likely responsible for the Fe-rich rim that surrounds most melt inclusions at ECC. Throughout this process the concentration of olivine-incompatible elements increased in the melt inclusion (Kent, 2008).

The melt inclusions from ECC exhibit significant major element heterogeneity, especially compared to the relatively homogeneous matrix glass from sample 16ECA9 (Fig. 3.6). For example, TiO₂ concentrations range from 1 to 3.5 wt.% with about half of the concentrations being similar to the matrix glass and bulk rock data (2.5 to 3.5 wt%). The TiO₂ variation is significant and it is possible that some melt inclusions with relatively high TiO₂ concentrations may reflect post-entrapment contamination by the groundmass, however, other oxide relationships clearly identify the two populations of glasses as different and the melt inclusions to be compositionally heterogeneous. Al₂O₃ and SiO₂ wt.% are much higher in the inclusions than in the matrix glass or bulk rock and exhibit no correlation with MgO which would be expected if the major element heterogeneity was due to the crystallization of olivine along the inclusion walls. Commonly these oxides are correlated with MgO and can be used as indicators of crystal fractionation (e.g., Wright and Okamura, 1977), yet in the ECC melt inclusions there is no correlation suggesting that fractionation is not the cause of the major element heterogeneity.

 K_2O abundances also show significant variation (0.43 to 2.53 wt.%) a characteristic also noticed by Kent et al. (2008) in olivine-hosted melt inclusions from the Juan de Fuca Ridge and attributed to localized compositional variation within the melt.

What Melt Inclusions Represent

It is not uncommon for melt inclusions to display significant compositional variation even among samples from the same locality (Sobolev, 1996; Kent et al., 2008; Danushesky et al., 2004). This observation has caused researchers to question what melt inclusions represent. Compatible element variation likely represents sampling from small-volume, heterogeneous, possibly short-lived volumes of melt that are later homogenized, prior to or during eruption (Kent et al., 2008). Incompatible element concentrations are less variable in most systems, including ECC, and are likely controlled by larger scale processes such as melt source lithology (Kent et al., 2008). The effect of small-volume, heterogeneous melts on final melt composition is unclear, however, melt inclusions offer the unique opportunity to study the variability of parental melts before their signatures are muted in larger volume melts. At LCVF further study is warranted of melt inclusions from other lavas with the aim of understanding the extent of the compositional heterogeneity of the melt inclusions.



Figure 4.1: Olivine compositions for Type 2 olivines plotted against values for OIB and MORB from Sobolev (2007).

Phenocrysts



Figure 4.2: Xpx calculated using **Equation 4.1** for Type 2 olivines with Fo content greater than 84 following Sobolev (2007).



Figure 4.3: BSE images of a Type 1 olivine (*top*) from sample 16ECA5 and a Type 2 olivine (*bottom*) from 16ECA10.



Figure 4.4: Left image shows an olivine from Blondes et al. (2012) and right image shows a Type 1 olivine from this study. Both display a network of wispy, Fe-rich regions indicative of high temperature oxidation during cooling



Figure 4.5: View of Easy Chair Crater facing NNW. White lines are contacts between stacked agglomerate units. All Type 1 olivines were collected from the overlying unit while only Type 2 olivines were collected in the underlying unit. Samples containing both olivine types were collected along the contact between the two the two.



Figure 4.6: Groundmass Type 1 olivine crystal with hematite from the agglomerate unit.



Figure 4.7: Groundmass olivine crystal with an Fe-rich core and a Mg-rich rim. Rim also displays the wispy Fe-oxide strands indicative of Type 1 olivines.

5.0 CONCLUSIONS

Trace element compositions in primitive, high-Fo olivines can provide information about source lithologies in mantle-derived volcanic systems (e.g., Sobolev et al., 2005). At ECC, electron microprobe analysis has identified two distinct olivine populations in the pre-eruptive agglomerate unit exposed along the interior crater wall. Type 1 olivines have anomalously high Fo content (up to 97.8%) resulting from sub-solidus oxidation reactions driven by the interaction of atmospheric oxygen with hot, stacked basalt flows. Type 2 olivines are primitive (Fo. > 85%) and contain Ni, Mn, and Ca concentrations that show similarities to both OIB and MORB. Incompatible element abundances of the LCVF lavas and specifically the lava flow at ECC (Lum et al., 1989; Yogodzinski et al., 1996; this work) have OIB-like compositions. Furthermore, estimates of the fraction of pyroxenite, Xpx, in the mantle source for ECC suggest significant amounts of pyroxenite-dervied melt where involved which could indicate the presence of an OIB-type source such as a mantle plume.

The incompatible element ratio Cl/K in olivine-hosted melt inclusions is similar to high K melt inclusions from OIB and the Rio Grande rift. Specifically, the melt inclusions from ECC are quite similar to K-rich melt inclusions from the Rio Grande rift, which also show Clenrichment. However, the strong correlation between Cl and K evident in the Rio Grande rift samples is not observed at ECC. Instead, ECC inclusions show relatively constant Cl concentrations over a range of K concentrations. This behavior could reflect buffering of Cl by a phase such as apatite in the mantle source for LCVF. This phase could have been stabilized by metasomatism of the mantle lithosphere by a Cl-rich fluid derived from the Farallon plate. If so, the difference in Cl/K trends between the melt inclusions at ECC and those of the Rio Grand rift could represent a subduction-related, Cl-bearing phase that was absent in the mantle source for the lavas of the Rio Grande rift. Additionally, input from a mantle plume at ECC is suggested by olivine trace element analysis, the high equilibrium temperatures from mantle-derived xenoliths near the crater (Smith, 2000), and by the gravitational and topographic anomaly described by Saltus and Thompson (1995).

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APPENDIX A: Complete list of microprobe analyses

Olivine

Type 1 g	groundmass crystals							
wt%	16ECA10L11	16ECA10L12	16ECA10L20	16ECA10L21	16ECA10L22	16ECA10L34	16ECA2OL10	16ECA2OL11
SiO2	42.26	42.67	41.02	41.21	40.97	41.59	41.90	42.64
MgO	55.82	55.98	51.92	52.25	52.01	52.91	53.69	56.03
FeO	1.51	1.56	5.14	4.80	4.86	5.05	3.11	2.21
MnO	0.34	0.34	0.40	0.39	0.39	0.20	0.42	0.52
CaO	0.14	0.27	0.26	0.30	0.19	0.19	0.23	0.23
NiO	0.21	0.18	0.19	0.18	0.15	0.12	0.15	0.19
Total	100.29	101.00	98.94	99.19	98.62	100.11	99.54	101.80
Number	of ions on the basi	is of 40						
Si	0.997	0.999	0.997	0.998	0.998	0.998	1.003	0.995
Mg	1.962	1.954	1.882	1.887	1.889	1.892	1.915	1.948
Fe	0.030	0.031	0.104	0.097	0.099	0.101	0.062	0.043
Mn	0.007	0.007	0.008	0.008	0.008	0.004	0.009	0.010
Ca	0.004	0.007	0.007	0.008	0.005	0.005	0.006	0.006
Ni	0.004	0.003	0.004	0.004	0.003	0.002	0.003	0.004
Total	3.003	3.001	3.003	3.002	3.002	3.002	2.997	3.005
Fo %	97.8	97.6	93.9	94.2	94.3	94.4	96.0	96.9
Mg#	98.5	98.5	94.7	95.1	95.0	94.9	96.9	97.8

Olivine								
Type 1	groundmass crystals		Type 2 groundmas	s crystals				
wt%	16ECA2OL12	16ECA2OL20	16ECA3OL10	16ECA3OL11	16ECA3OL12	16ECA3OL30	16ECA3OL32	16ECA110L10
SiO2	42.80	43.02	39.24	39.71	39.23	39.65	39.18	39.76
MgO	54.62	53.45	45.20	45.81	45.38	45.67	45.71	43.92
FeO	2.42	2.89	13.31	12.81	12.76	13.42	12.92	13.94
MnO	0.45	0.44	0.19	0.21	0.18	0.20	0.19	0.25
CaO	0.27	0.53	0.26	0.31	0.28	0.26	0.30	0.27
NiO	0.19	0.11	0.17	0.24	0.21	0.19	0.19	0.12
Total	100.78	100.71	98.48	99.22	98.13	99.43	98.59	98.34
Numbe	r of ions on the basi	is of 40						
Si	1.008	1.017	0.996	0.998	0.997	0.996	0.992	1.011
Mg	1.917	1.884	1.710	1.717	1.719	1.711	1.726	1.665
Fe	0.048	0.057	0.283	0.269	0.271	0.282	0.274	0.297
Mn	0.009	0.009	0.004	0.005	0.004	0.004	0.004	0.005
Ca	0.007	0.013	0.007	0.008	0.008	0.007	0.008	0.007
Ni	0.004	0.002	0.003	0.005	0.004	0.004	0.004	0.002
Total	2.992	2.983	3.004	3.002	3.003	3.004	3.008	2.989
Fo %	96.6	95.9	85.2	85.7	85.7	85.2	85.6	84.2
Mg#	97.6	97.1	85.8	86.4	86.4	85.8	86.3	84.9

Olivine								
Type 2	groundmass crystal	S						
wt%	16ECA110L11	16ECA110L12	16ECA110L21	16ECA110L30	16ECA110L31	16ECA11OL40	16ECA110L41	16ECA12OL10
SiO2	39.79	39.73	39.42	39.66	39.84	39.64	39.82	39.35
MgO	44.15	44.23	44.76	44.33	44.12	44.77	45.22	45.14
FeO	13.95	13.60	13.18	15.26	15.10	14.40	14.61	12.43
MnO	0.19	0.26	0.20	0.25	0.24	0.20	0.16	0.22
CaO	0.27	0.29	0.26	0.26	0.28	0.30	0.27	0.41
NiO	0.14	0.10	0.18	0.19	0.12	0.15	0.14	0.21
Total	98.59	98.27	98.06	99.97	99.76	99.50	100.33	98.24
Numbe	r of ions on the bas	sis of 40						
Si	1.010	1.010	1.003	0.999	1.004	0.999	0.997	1.001
Mg	1.670	1.676	1.698	1.665	1.658	1.683	1.687	1.712
Fe	0.296	0.289	0.280	0.321	0.318	0.304	0.306	0.265
Mn	0.004	0.006	0.004	0.005	0.005	0.004	0.003	0.005
Ca	0.007	0.008	0.007	0.007	0.008	0.008	0.007	0.011
Ni	0.003	0.002	0.004	0.004	0.002	0.003	0.003	0.004
Total	2.990	2.990	2.997	3.001	2.996	3.001	3.003	2.999
Fo %	84.3	84.6	85.2	83.1	83.3	84.1	84.1	85.7
Mg#	84.9	85.3	85.8	83.8	83.9	84.7	84.7	86.6
Olivine	2							
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Type 2	groundmass crystal	S						
wt%	16ECA12OL11	16ECA12OL30	16ECA12OL32	16ECA12OL40	16ECA12OL41	16ECA13OL20	16ECA13OL21	16ECA13OL22
SiO2	39.67	38.44	39.84	39.81	39.87	39.01	39.22	39.00
MgO	45.32	47.27	46.83	45.62	46.33	43.95	43.76	42.95
FeO	12.62	12.06	11.07	12.80	12.56	15.29	15.76	15.72
MnO	0.24	0.17	0.14	0.23	0.18	0.18	0.24	0.24
CaO	0.41	0.29	0.26	0.29	0.29	0.25	0.29	0.27
NiO	0.22	0.29	0.31	0.25	0.27	0.11	0.18	0.09
Total	98.84	98.57	98.57	99.04	99.59	98.87	99.53	98.36
Numbe	r of ions on the bas	sis of 40						
Si	1.003	0.972	1.000	1.001	0.997	0.995	0.996	1.002
Mg	1.707	1.783	1.752	1.710	1.727	1.671	1.657	1.644
Fe	0.267	0.255	0.232	0.269	0.263	0.326	0.335	0.338
Mn	0.005	0.004	0.003	0.005	0.004	0.004	0.005	0.005
Ca	0.011	0.008	0.007	0.008	0.008	0.007	0.008	0.008
Ni	0.004	0.006	0.006	0.005	0.005	0.002	0.004	0.002
Total	2.997	3.028	3.000	2.999	3.003	3.005	3.004	2.998
Fo %	85.6	86.7	87.6	85.6	86.1	83.1	82.5	82.4
Mg#	86.5	87.5	88.3	86.4	86.8	83.7	83.2	83.0

Olivine	2							
Type 2	groundmass crystal	S						
wt%	16ECA13OL30	16ECA13OL31	16ECA13OL40	16ECA13OL41	16ECA13OL42	16ECA13OL50	16ECA13OL51	16ECA13OL52
SiO2	40.10	40.23	40.24	40.55	40.50	40.71	40.62	40.77
MgO	47.36	47.86	47.46	47.73	47.69	42.46	47.07	42.56
FeO	11.80	11.83	12.14	12.01	12.21	14.60	12.81	14.92
MnO	0.16	0.15	0.18	0.14	0.12	0.29	0.22	0.21
CaO	0.29	0.27	0.23	0.25	0.25	0.37	0.30	0.34
NiO	0.31	0.27	0.28	0.32	0.27	0.18	0.19	0.18
Total	100.07	100.67	100.60	101.02	101.07	98.87	101.33	99.25
Numbe	r of ions on the bas	sis of 40						
Si	0.994	0.991	0.994	0.995	0.994	1.033	0.998	1.031
Mg	1.750	1.758	1.747	1.747	1.746	1.605	1.724	1.605
Fe	0.245	0.244	0.251	0.247	0.251	0.310	0.263	0.316
Mn	0.003	0.003	0.004	0.003	0.003	0.006	0.005	0.004
Ca	0.008	0.007	0.006	0.007	0.006	0.010	0.008	0.009
Ni	0.006	0.005	0.006	0.006	0.005	0.004	0.004	0.004
Total	3.006	3.009	3.006	3.005	3.006	2.967	3.002	2.969
Fo %	87.0	87.1	86.8	87.0	86.8	83.0	86.1	82.8
Mg#	87.7	87.8	87.4	87.6	87.4	83.8	86.8	83.6

Olivin	e						
Phenoc	crysts						
wt%	16ECA1pheno13	16ECA1pheno14	16ECA1pheno21	16ECA2pheno11	16ECA3pheno1	16ECA9pheno12	16ECA10pheno13
SiO2	39.99	40.29	39.63	38.78	39.10	38.90	37.94
MgO	44.82	46.31	45.25	46.22	45.35	44.67	44.10
FeO	13.77	12.59	12.74	12.16	14.32	13.84	13.89
MnO	0.22	0.14	0.17	0.17	0.23	0.15	0.20
CaO	0.16	0.23	0.25	0.23	0.23	0.24	0.26
NiO	0.21	0.24	0.33	0.25	0.23	0.20	0.20
Total	99.19	99.93	98.57	97.90	99.57	98.05	96.67
Numbe	er of ions on the bas	is of 40					
Si	1.007	1.003	1.003	1.013	0.987	0.994	0.986
Mg	1.683	1.718	1.707	1.678	1.707	1.702	1.709
Fe	0.290	0.262	0.270	0.283	0.302	0.296	0.302
Mn	0.005	0.003	0.004	0.005	0.005	0.003	0.004
Ca	0.004	0.006	0.007	0.005	0.006	0.007	0.007
Ni	0.004	0.005	0.007	0.004	0.005	0.004	0.004
Total	2.993	2.997	2.997	2.987	3.013	3.006	3.014
Fo %	84.7	86.2	85.6	85.0	84.3	84.6	84.3
Mg#	85.3	86.8	86.4	85.6	84.9	85.2	85.0

Pheno	crysts					
wt%	16ECA12pheno12	16ECA13pheno2	16ECA13pheno10	16ECA13pheno13	16ECAP13pheno22	16ECA13pheno24
SiO2	38.41	38.94	40.58	40.87	41.67	41.34
MgO	45.53	46.93	45.92	46.16	47.89	48.12
FeO	11.67	12.00	14.91	12.98	12.25	12.00
MnO	0.18	0.18	0.18	0.23	0.14	0.13
CaO	0.22	0.23	0.27	0.25	0.20	0.23
NiO	0.23	0.25	0.24	0.17	0.26	0.27
Total	96.35	98.63	102.19	101.00	102.55	102.11
Si	0.991	0.983	0.998	0.987	1.007	1.002
Si	0 991	0.983	0 998	0 987	1 007	1.002
Mg	1.751	1.766	1.683	1.753	1.725	1.739
Fe	0.252	0.253	0.306	0.259	0.248	0.243
Mn	0.004	0.004	0.004	0.004	0.003	0.003
IVIII					0.005	0.007
Ca	0.006	0.006	0.007	0.006	0.005	0.006
Ca Ni	0.006 0.005	0.006 0.005	0.007 0.005	0.006 0.005	0.005	0.006 0.005
Ca Ni Total	0.006 0.005 3.009	0.006 0.005 3.017	0.007 0.005 3.002	0.006 0.005 3.013	0.005 0.005 2.993	0.006 0.005 2.998
Ca Ni Total Fo %	0.006 0.005 3.009 86.8	0.006 0.005 3.017 86.8	0.007 0.005 3.002 83.9	0.006 0.005 3.013 86.5	0.005 0.005 2.993 86.9	0.006 0.005 2.998 87.1

Olivin	e		
Pheno	crysts		
wt%	16ECA13pheno61	16ECA3OLRim20.3	16ECA3OLCore20.1
SiO2	39.09	40.99	38.87
MgO	45.76	50.87	40.67
FeO	11.91	6.10	19.16
MnO	0.16	0.57	0.24
CaO	0.23	0.44	0.15
NiO	0.22	0.11	0.16
Total	97.44	99.16	99.31

Number of ions on the basis of 40

Si	0.996	1.000	1.004
Mg	1.739	1.850	1.566
Fe	0.254	0.124	0.414
Mn	0.003	0.012	0.005
Ca	0.006	0.011	0.004
Ni	0.004	0.002	0.003
Total	3.004	3.000	2.996
Fo %	86.6	92.5	78.6
Mg#	87.3	93.7	79.1

Olivine								
Megacry	sts							
wt%	16ECMC1.12	16ECMC2.11	16ECMC2.12	16ECMC3.12	16ECMC3.13	16ECMC3.14	16ECMC3.15	16ECMC5.12
SiO2	39.84	40.89	40.17	40.34	40.20	40.73	40.21	40.56
MgO	46.95	48.36	47.68	47.88	47.73	48.00	47.42	47.85
FeO	12.22	11.60	11.68	11.98	11.79	11.75	11.40	11.63
MnO	0.16	0.15	0.20	0.18	0.20	0.16	0.15	0.18
CaO	0.21	0.24	0.23	0.27	0.22	0.21	0.26	0.22
NiO	0.26	0.23	0.31	0.26	0.29	0.31	0.26	0.32
Total	99.72	101.59	100.43	100.99	100.60	101.30	99.80	100.85
Number	of ions on the basi	s of 40						
Si	0.993	0.996	0.993	0.992	0.992	0.997	0.997	0.996
Mg	1.745	1.757	1.757	1.754	1.756	1.751	1.754	1.753
Fe	0.255	0.236	0.241	0.246	0.243	0.240	0.236	0.239
Mn	0.003	0.003	0.004	0.004	0.004	0.003	0.003	0.004
Ca	0.005	0.006	0.006	0.007	0.006	0.005	0.007	0.006
Ni	0.005	0.005	0.006	0.005	0.006	0.006	0.005	0.006
Total	3.007	3.004	3.007	3.008	3.008	3.003	3.003	3.004
Fo %	86.7	87.5	87.2	87.0	87.1	87.3	87.5	87.3
Mg#	87.3	88.1	87.9	87.7	87.8	87.9	88.1	88.0

Olivine								
Megacry	/sts							
wt%	16ECMC5.13	16ECMC5.15	16ECMC6.12	16ECMC8.11	16ECMC8.12	16ECMC8.13	16ECMC8.15	16ECMC9.11
SiO2	40.36	40.97	39.87	39.73	39.22	39.29	39.73	39.68
MgO	47.83	48.08	46.91	47.27	47.62	47.31	47.38	47.27
FeO	11.77	11.80	11.97	11.48	11.51	11.49	11.45	11.15
MnO	0.14	0.12	0.13	0.14	0.21	0.16	0.14	0.18
CaO	0.23	0.23	0.22	0.22	0.20	0.21	0.26	0.22
NiO	0.24	0.25	0.27	0.30	0.29	0.27	0.31	0.30
Total	100.62	101.55	99.39	99.36	99.01	98.83	99.44	98.88
Number	of ions on the basi	s of 40						
Si	0.994	0.999	0.995	0.992	0.982	0.987	0.991	0.993
Mg	1.756	1.748	1.745	1.761	1.779	1.771	1.762	1.764
Fe	0.242	0.241	0.250	0.240	0.241	0.241	0.239	0.233
Mn	0.003	0.002	0.003	0.003	0.004	0.003	0.003	0.004
Ca	0.006	0.006	0.006	0.006	0.005	0.006	0.007	0.006
Ni	0.005	0.005	0.005	0.006	0.006	0.006	0.006	0.006
Total	3.006	3.001	3.005	3.008	3.018	3.013	3.009	3.007
Ec. 9/	07 2	07 2	96.0	97 /	97 /	97 /	97 /	976
го % Ма#	87.3 87.0	87.3 87.0	80.9	87.4 88.0	0/.4 QQ 1	87.4 88.0	0/.4 20 1	8/.0 80 2
ivig#	07.9	07.9	07.5	88.0	00.1	88.0	00.1	00.3

Olivine								
Megacry	vsts							
wt%	16ECMC9.12	16ECMC9.13	16ECMC9.14	16ECMC10.11	16ECMC10.12	16ECMC10.13	16ECMC10.14	16ECMC12.11
SiO2	40.02	39.77	39.94	39.64	39.58	40.11	40.22	40.27
MgO	48.38	47.76	47.60	47.66	47.63	47.97	47.79	47.56
FeO	11.56	11.67	11.82	11.85	11.37	12.22	11.71	12.20
MnO	0.18	0.17	0.16	0.14	0.14	0.15	0.17	0.16
CaO	0.24	0.21	0.23	0.21	0.20	0.23	0.21	0.22
NiO	0.26	0.29	0.27	0.27	0.26	0.27	0.29	0.27
Total	100.73	99.96	100.11	99.86	99.28	101.01	100.50	100.80
Number	of ions on the basi	s of 40						
Si	0.985	0.987	0.990	0.986	0.988	0.987	0.993	0.993
Mg	1.776	1.768	1.759	1.767	1.773	1.760	1.758	1.748
Fe	0.238	0.242	0.245	0.247	0.237	0.251	0.242	0.252
Mn	0.004	0.004	0.003	0.003	0.003	0.003	0.004	0.003
Ca	0.006	0.005	0.006	0.006	0.005	0.006	0.005	0.006
Ni	0.005	0.006	0.005	0.005	0.005	0.005	0.006	0.005
Total	3.015	3.013	3.010	3.014	3.012	3.013	3.007	3.007
F 0/	07.5	07.2	07.1	07.0	07 (0.6.0	07.2	06.0
F0 %	87.5	87.3	87.1	87.2	87.6	86.9	87.3	86.8
Mg#	88.2	87.9	87.8	87.8	88.2	87.5	87.9	87.4

wiegac	erysts				Cinder cone		
wt%	16ECMC12.12	16ECMC12.13	16ECMC12.14	16ECMC12.15	16ECCC1Pheno1	16ECCC1Pheno2	16ECCC1Pheno3
SiO2	40.25	40.39	40.30	40.42	41.13	40.92	39.93
MgO	47.73	47.51	47.31	47.84	47.47	47.77	48.26
FeO	11.97	11.46	12.01	11.96	12.18	11.65	11.37
MnO	0.20	0.17	0.16	0.17	0.19	0.14	0.13
CaO	0.22	0.23	0.21	0.21	0.20	0.24	0.26
NiO	0.30	0.25	0.26	0.27	0.24	0.23	0.33
Total	100.74	100.15	100.37	101.00	101.49	101.02	100.33
Si	0.992	0.999	0.997	0.993	1.005	1.002	0.986
Numb	er of ions on the bo	usis of 40					
Ma	0.992	0.999	0.337	0.773	1.003	1.002	0.980
Fo	1.734	1.731	1.744	1.735	1.720	1.744	1.///
FE .	0.247	0.237	0.240	0.240	0.249	0.2.39	
10	0.004	0.004	0.002	0.004	0.004	0.002	0.233
Mn	0.004	0.004	0.003	0.004	0.004	0.003	0.235
Mn Ca	0.004 0.006	0.004 0.006	0.003 0.006	0.004 0.006	0.004 0.005	0.003 0.006	0.233 0.003 0.007
Mn Ca Ni	0.004 0.006 0.006	0.004 0.006 0.005	0.003 0.006 0.005	0.004 0.006 0.005	0.004 0.005 0.005	0.003 0.006 0.005	0.233 0.003 0.007 0.006
Mn Ca Ni Total	0.004 0.006 0.006 3.008	0.004 0.006 0.005 3.001	0.003 0.006 0.005 3.003	0.004 0.006 0.005 3.007	0.004 0.005 0.005 2.995	0.003 0.006 0.005 2.998	0.233 0.003 0.007 0.006 3.014
Mn Ca Ni Total Fo %	0.004 0.006 0.006 3.008 87.0	0.004 0.006 0.005 3.001 87.4	0.003 0.006 0.005 3.003 86.9	0.004 0.006 0.005 3.007 87.1	0.004 0.005 0.005 2.995 86.8	0.003 0.006 0.005 2.998 87.4	0.233 0.003 0.007 0.006 3.014 87.6

wt %	16ECA5MI7	16ECA6MI4	16ECA6MI7	16ECA6MI9	16ECA6MI12	16ECA6MI16
SiO ₂	48.84	49.90	44.52	48.90	48.87	46.93
TiO ₂	1.70	1.08	2.12	2.78	2.24	1.76
Al ₂ O ₃	21.25	18.61	18.37	19.24	21.14	18.97
MgO	2.15	1.82	4.00	4.11	4.23	3.88
FeO	7.39	7.62	7.97	6.75	5.12	7.73
MnO	0.00	0.07	0.07	0.08	0.13	0.18
CaO	11.06	8.53	11.50	11.91	5.96	9.53
Na ₂ O	4.46	6.68	5.42	1.15	4.13	5.29
K_2O	0.74	1 1 5	0.35	0.51	2.43	0.90
Cl	0.07	0.07	0.08	0.07	0.12	0.11
Total	97.66	95.54	94.39	95.53	94.36	95.28
Normalized	to 100%					
SiO ₂	49.97	52.19	47.12	51.16	51.75	49.21
TiO	1 74	1 13	2.24	2 91	2 37	1.85
Al_2O_2	21.74	19.46	19 44	20.13	22.39	19.89
MgO	2 20	1 90	4 23	4 30	4 48	4 07
FeaOa	0.84	0.89	0.94	0.78	0.60	0.90
FeO	6.80	7.17	7 59	636	4 88	7 30
MnO	0.00	0.07	0.07	0.08	0.14	0.19
CaO	11.32	8.92	12.17	12.46	631	0.19
Na-O	4.56	6.92	5 74	1 20	4.37	5 55
K ₂ O	4.30 0.76	1.20	0.37	0.53	ч.57 2 57	0.94
Cl	0.07	0.07	0.08	0.07	0.13	0.12
Normative]	Minerals (CIPW)					
Ouartz						
Plagioclase	64 69	49 49	42 31			
Orthoclase	4 48	7 11	2.19			
Nepheline	5 46	14.82	17.28			
Dionside	15.97	21.68	27.66			
Olivine	4 75	3 32	4 78			
Ilmenite	3 31	2.15	4 26			
Magnetite	1 22	1.28	1.20			
Wollastonite	a 1.22	1.20	1.50			
Hypersthene	2					
PPM						
K	6114	9519	2917	4257	20138	7500
Cl	689	689	774	736	1166	1051
Cl/K	0.113	0.07	0.27	0.18	0.06	0.14
Mg#	34.1	29.7	46.6	52.0	59.4	47.2

Melt Inclusi	ons					
wt %	16ECA7MI1	16ECA7MI3	16ECA7MI5	16ECA7MI8	16ECA7MI9	16ECA8MI2
SiO_2	48.88	46.48	47.89	49.39	46.27	46.06
TiO ₂	1.32	2.05	1.66	2.10	3.49	3.29
Al_2O_3	20.92	15.75	21.50	19.17	19.83	20.15
MgO	4.16	2.89	2.60	3.25	1.75	1.56
FeO	5.43	9.90	5.17	5.98	6.76	9.70
MnO	0.14	0.24	0.23	0.19	0.09	0.00
CaO	7.52	14.82	7.68	10.11	11.59	11.22
Na ₂ O	6.78	3.36	7.90	2.91	2.66	6.08
K_2O	1.19	1.24	1.12	0.62	1.09	0.76
Cl	0.12	0.13	0.14	0.14	0.06	0.14
Total	96.47	96.86	95.89	93.86	93.59	98.97
Normalized	to 100%					
SiO ₂	50.64	47.93	49.91	52.58	49.40	46.49
TiO ₂	1.37	2.11	1.73	2.24	3.73	3.32
Al_2O_3	21.67	16.24	22.41	20.41	21.17	20.34
MgO	4.31	2.98	2.71	3.46	1.87	1.57
Fe_2O_3	0.63	1.13	0.60	0.71	0.80	1.09
FeO	5.06	9.19	4.85	5.73	6.50	8.81
MnO	0.15	0.25	0.24	0.20	0.10	0.00
CaO	7.79	15.28	8.00	10.76	12.37	11.33
Na ₂ O	7.02	3.46	8.23	3.10	2.84	6.14
K_2O	1.23	1.28	1.17	0.66	1.16	0.77
Cl	0.12	0.13	0.15	0.15	0.06	0.14
Normative M	linerals (CIPW)					
Quartz						
Plagioclase		35.80	46.73			43.51
Orthoclase		7.57	6.91			4.54
Nepheline		9.55	23.17			17.99
Diopside		40.33	14.71			25.09
Olivine		4.02	4.04			0.70
Ilmenite		4.02	3.29			6.32
Magnetite		1.65	0.87			1.58
Wollastonite		0.83				
Hypersthene						
PPM	205-				0.05	
K	9855	10315	9296	5178	9081	6345
CI	1212	1341	1417	1360	632	1438
Cl/K	0.12	0.13	0.152	0.26	0.07	0.227
Mg#	57.7	34.2	47.2	49.2	31.5	22.3

Melt Inclusions					
wt %	16ECA8MI5	16ECA8MI6	16ECA11MI1	16ECA11MI2	16ECA11MI3
SiO ₂	44.66	45.12	44.59	48.04	49.58
TiO ₂	3.46	3.52	3.28	3.24	1.93
Al_2O_3	21.36	18.26	18.73	19.79	17.95
MgO	1.52	2.06	1.86	1.66	2.23
FeO	6.65	9.14	9.49	7.52	8.02
MnO	0.02	0.30	0.11	0.17	0.20
CaO	10.26	12.30	12.03	11.20	9.82
Na ₂ O	5.88	6.45	4.87	2.89	4.28
K ₂ O	1.05	0.43	2.53	0.73	2.18
Cl	0.10	0.10	0.14	0.08	0.15
Total	94.95	97.67	97.61	95.33	96.33
Normalized t	o 100%				
SiO_2	46.99	46.14	45.62	50.35	51.42
TiO ₂	3.64	3.60	3.36	3.40	2.00
Al_2O_3	22.48	18.67	19.16	20.74	18.61
MgO	1.60	2.11	1.90	1.74	2.31
Fe ₂ O ₃	0.78	1.04	1.08	0.88	0.92
FeO	6.30	8.41	8.74	7.09	7.49
MnO	0.02	0.31	0.11	0.18	0.21
CaO	10.80	12.58	12.31	11.74	10.18
Na ₂ O	6.19	6.60	4.98	3.03	4.44
K ₂ O	1.10	0.44	2.59	0.77	2.26
CĨ	0.11	0.10	0.14	0.08	0.16
Normative M	inerals (CIPW)				
Ouartz				3.55	
Plagioclase	49.05	35.50		65.83	50.70
Orthoclase	6.54	2.60		4.52	13.38
Nepheline	17.84	21.52			5.44
Diopside	17.92	28.67		14.14	21.20
Olivine					3.84
Ilmenite	6.92	6.84		6.45	3.61
Magnetite	1.13	1.51		1.52	1.34
Wollastonite	0.40	3.17			
Hypersthene				3.83	
PPM					
Κ	8693	3544	20966	6041	18096
Cl	967	962	1351	827	1509
Cl/K	0.111	0.272	0.06	0.14	0.083
Mg#	28.9	28.7	25.9	28.2	33.1

wt %	16ECA11MI4	16ECA11MI5	16ECA11MI9	16ECA11MI11	16ECA12MI1
SiO ₂	46.14	45.53	45.98	47.83	47.75
TiO ₂	2.94	2.77	2.68	1.72	2.88
Al_2O_3	18.47	17.80	19.45	19.13	19.91
MgO	2.53	2.49	1.35	1.88	4.81
FeO	8.09	7.95	7.29	7.56	5.87
MnO	0.14	0.12	0.19	0.13	0.07
CaO	10.95	11.80	11.19	10.61	8.86
Na ₂ O	3.41	6.27	6.14	4.04	3.03
K ₂ Õ	0.62	0.60	0.57	1.87	0.68
CĨ	0.11	0.09	0.08	0.12	0.07
Total	93.40	95.43	94.92	94.89	93.94
Normalized i	to 100%				
SiO ₂	49.35	47.56	48.40	50.36	50.80
TiO ₂	3.14	2.91	2.82	1.81	3.06
Al_2O_3	19.76	18.68	20.47	20.14	21.18
MgO	2.71	2.61	1.42	1.98	5.12
Fe ₂ O ₃	0.96	0.93	0.85	0.88	0.69
FeO	7.79	7.51	6.91	7.16	5.62
MnO	0.15	0.13	0.20	0.14	0.07
CaO	11.71	12.38	11.78	11.17	9.43
Na ₂ O	3.65	6.58	6.46	4.25	3.22
K_2O	0.66	0.63	0.60	1 97	0.72
Cl	0.12	0.09	0.08	0.13	0.07
Normative M	linerals (CIPW)				
Quartz					
Plagioclase		37.14	48.13	54.89	
Orthoclase		3.71	3.55	11.52	
Nepheline		20.22	16.84	5.23	
Diopside		29.03	21.31	20.41	
Olivine				2.78	
Ilmenite		5.51	5.36	3.41	
Magnetite		1.61	1.48	1.52	
Wollastonite		2.59	3.16		
Hypersthene					
РРМ					
K	5119	5015	4699	15491	5672
Cl	1050	852	842	1158	747
Cl/K	0.21	0.17	0.18	0.07	0.13
Mø#	35.8	35.8	24.8	30.7	59.3

wt %	16ECA9MG1	16ECA9MG2	16ECA9MG3	16ECA9MG4	16ECA9MG5
SiO ₂	43.24	43.80	44.03	44.16	43.47
TiO ₂	3.25	3.24	3.13	3.15	3.44
Al_2O_3	16.05	16.03	15.90	15.60	15.70
MgO	4.35	4.58	4.62	4.45	4.42
FeO	12.03	11.71	12.47	11.51	11.61
MnO	0.18	0.17	0.17	0.16	0.05
CaO	11.67	11.95	11.64	11.66	12.18
Na ₂ O	2.92	3.41	3.50	3.45	3.80
K ₂ O	2.00	2.12	2.19	2.12	2.12
Cl	0.07	0.08	0.10	0.06	0.08
Total	95.77	97.09	97.77	96.33	96.87
Normalized t	to 100%				
SiO ₂	45.09	45.05	44.98	45.79	44.81
TiO ₂	3.39	3.33	3.20	3.27	3.55
Al_2O_3	16.74	16.49	16.24	16.17	16.19
MgO	4.54	4.71	4.72	4.61	4.56
Fe ₂ O ₂	1 39	1 34	1 42	1 33	1 33
FeO	11 29	10.84	11 47	10.74	10.77
MnO	0.19	0.17	0.17	0.17	0.05
CaO	12.17	12.29	11.89	12.09	12.56
Na ₂ O	3.05	3 51	3 58	3 58	3.92
K ₂ O	2.09	2.18	2 24	2 20	2.19
Cl	0.07	0.08	0.10	0.06	0.08
Normative M Quartz Plagioclase Orthoclase Nepheline Diopside Olivine Ilmenite Magnetite Wollastonite Hypersthene	linerals (CIPW)				
РРМ					
K	16594	17614	18178	17601	17596
Cl	702	755	1004	642	838
Cl/K	0.04	0.04	0.06	0.04	0.05
	20.2	41.1	20.9	10.9	40.4

Matrix Glass	
wt %	16ECA9MG7
SiO ₂	44.26
TiO ₂	2.93
Al_2O_3	15.87
MgO	4.89
FeO	11.26
MnO	0.26
CaO	11.91
Na ₂ O	3.73
K ₂ O	2.15
Cl	0.09
Total	97.35

Normalized to 100%

1.00 100,000 100 100 /0	
SiO ₂	45.41
TiO ₂	3.01
Al ₂ O ₃	16.28
MgO	5.02
Fe ₂ O ₃	1.28
FeO	10.40
MnO	0.27
CaO	12.22
Na ₂ O	3.83
K ₂ O	2.21
Cl	0.09

Normative Minerals (CIPW)

Quartz Plagioclase Orthoclase Nepheline Diopside Olivine Ilmenite Magnetite Wollastonite Hypersthene

PPM

K Cl	17808 928
Cl/K	0.05
Mg#	43.6