PETROLOGY AND GEOCHEMISTRY OF THE LAZUFRE VOLCANIC COMPLEX:
EVIDENCE FOR DIVERSE PETROGENETIC PROCESSES AND
SOURCES IN THE ANDEAN CENTRAL VOLCANIC ZONE

by

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ABSTRACT

The Lazufre volcanic complex is an area of active surface uplift ($\sim 25^{\circ}14'S$) situated between two potentially active Quaternary volcanic centers, Lastarria and Cordon del Azufre, in the Andean Central Volcanic Zone. Studies incorporated geologic field relationships, mineral compositions, textures, and whole rock geochemical and isotopic data to develop a petrogenetic model to identify the source area and petrogenetic processes for the Lazufre magmatic system. Whole rock K-Ar dates of lavas from Cordon del Azufre place the most recent eruptions at $0.6\text{-}0.3\text{ Ma} \pm 0.3\text{ Ma}$. The most recent eruptive activity at Lastarria has been dated at $\sim 0.5\text{-}0.1\text{ Ma}$. Volcanic rocks erupted from Lazufre are andesites to dacites and conform to a medium- to high-K calc-alkaline suite. Typical phenocryst assemblage is plagioclase-orthopyroxene-clinopyroxene-amphibole. Magmatic inclusions and mafic glomerocryst are present in most lava flow samples. Plagioclase and pyroxene phenocrysts in all rocks exhibit textures consistent with thermal disequilibrium. Important geochemical characteristics of these rocks include negative correlations for Mg, Fe, Ca and increased K and Na with increasing SiO_2 suggesting limited crystal fractionation. High Cr and Ni in some of the more mafic samples indicate mingling of a more mafic magma with a large volume of more silicic magma. Large ion lithophile elements are elevated at higher SiO_2 content, suggesting assimilation of more felsic rocks. A low range in $^{206}\text{Pb}/^{204}\text{Pb}$, $^{87}\text{Sr}/^{86}\text{Sr}$, and $^{143}\text{Nd}/^{144}\text{Nd}$ suggest partial melting of lower mafic crust as the dominant process in the generation of Lazufre extrusive rocks and indicate that there was relatively little involvement of ancient or felsic continental crust in magmagenesis of the area. The original magma was modified by homogenization and small degrees of mixing and assimilation and fractional crystallization during differentiation through ascent of the mid and upper crust. The results from this study are significant in that a multitude of differentiation processes and magma sources, specifically, a considerable mafic lower crustal component were involved in the generation of Lazufre Volcanic Complex magmas in the Andean Central Volcanic Zone.

CHAPTER 1: INTRODUCTION

Processes involved in magmagenesis along subduction zones and the interactions between the crust and mantle at volcanic arcs continue to be a large focus of research (Tatsumi and Eggins, 1995; Trumbull et al., 1999; McLeod et al., 2013). Previously, geology and petrology of individual volcanic centers have not been studied in detail and studies of subduction zones have focused on across-arc and along-arc variations in composition and crustal and mantle contributions to magmatism (Hildreth and Moorbath, 1988). The central Andes present an ideal location in which to study both the evolution of individual eruptive centers and the interactions between the crust and the mantle.

The Andean mountain belt represents an ideal site to study orogenic processes because it formed by long term subduction of oceanic lithosphere into the mantle below a continental plate (Schellart, 2008). The Andean orogenic belt is segmented into three major zones of volcanic activity: the Northern (NVZ), Central (CVZ), and Southern (SVZ) volcanic zones. The Central Andes Volcanic Zone is located between 16° and 28° S latitude along the South American convergent plate margin. The central Andes form a mountain belt up to 700 km wide and reach elevations greater than 6500m (Lamb and Hoke, 1997). The CVZ is anomalous in that it constitutes an area of extremely thick continental crust, up to 70-80 km thick (Beck et al., 1996). The region makes up one of the youngest and largest active silicic volcanic provinces on Earth with recent caldera formation. Magmatic processes within the CVZ are not well understood due to a lack of comprehensive studies of individual volcanic centers. The purpose of this study is to geochemically and petrologically characterize the Lazufre volcanic system. The Lazufre

region ($\sim 25^{\circ}14'S$) is an area of active uplift situated between two potentially active Quaternary volcanic centers, Lastarria and Cordon del Azufre, in the CVZ (Figure 1) (Pritchard and Simons, 2002). This volcanic area has recently become a scientific area of interest because it is one of the largest deforming volcanic systems on Earth. InSAR observations show signs of active deformation with an elliptical deformation area reaching 50 km NNE-SSW and the minor axis 40 km with a maximum inflation rate of ~ 3 cm/yr (Remy et al., 2014; Pearse and Lundgren, 2013). The inferred depth of the magma chamber(s) is centered at a depth of about 10 km (15 km below local relief; Pritchard and Simons, 2004). The inflation is thought to be related to a large steadily inflating sill-like magma body intruding into elastic crust (Pearse and Lundgren, 2013).

This study is a part of a larger collaborative effort through the National Science Foundation Continental Dynamics Program, known as The PLUTONS Project (Probing Lazufre and Uturuncu Together: Nsf, Nerc, Nserc, Sergeotecmin, Sernageomin). The PLUTONS team integrates geophysical, geochemical, and geomorphological techniques to investigate preliminary evidence for active mid-crustal intrusion and crustal formation at Lazufre and another central Andes volcanic system, Uturuncu (NSF project proposal, 2008). The program will produce an interpretation of the magmatic systems of the two areas and constrain how magma accumulates and erupts in areas of active intrusion and volcanism.

Because of the remoteness of the study site, Lazufre has not been previously been studied in detail, especially Cordon del Azufre. This study contributes to previous work of active well known arc- and caldera-related magmatic systems. Geophysical signals of

magma movement often yield non-unique solutions, therefore petrology and geochemistry can constrain and inform geophysical models. They provide insight into the origin, movement, and storage depths of magmas, their physical properties, and their evolutionary paths. The data can provide vital inputs into models of mass and thermal balance that are the framework within which the formation of plutons and volcanic systems must be understood. The source of inflation for Lazufre is especially perplexing. It could be related to one of the nearby potentially active volcanoes, a randomly located intrusion into a newly forming pluton, or even the birth of a new volcano. Without assessing important information about the eruptive history of the volcano, the subsurface magma plumbing, or current unrest, the significance or hazard associated with Lazufre would be difficult to determine.

This study targets specific research questions: (1) Do melt production and differentiation occur in a single long-lived reservoir or do they occur in discrete, independently evolving magma bodies? (2) What are the petrological and geochemical characteristics of the volcanic rocks? (3) What is the source(s) of the magmas, and what processes controlled their formation? In order to assess the research questions, multiple analytical approaches were applied: field observations and mapping; petrology and geochemistry. Studies at Lazufre focus on basic petrological and geochemical characterization of erupted products and petrologic modeling using field relationships, textural information, major and trace element, and mineral composition data.

Figure 1. Shaded relief map of a portion of NE Chile and NW Argentina and the location of the inflation at the Lazufre volcanic area. Inflation was detected using InSAR data. Older caldera systems are shaded in light blue, with faults marked by black lines. Box in inset shows location of map area; red triangle shows location of Lazufre (modified from Ruch et al., 2008).

CHAPTER 2: GEOLOGIC SETTING

2.1 Introduction

The Andes are a classic example of a modern Cordilleran type orogen formed by long term subduction of oceanic lithosphere beneath continental lithosphere. Subduction of the Nazca Plate beneath the South American Plate since the Jurassic has resulted in the formation of the Andean volcanic arc 250-300 km inland from the Peru-Chile trench (Wörner et al., 1992). The Andean orogenic belt continues along the South American west coast for over 7000 km and is divided into eight distinct tectonic segments, coinciding with variations in geometry of the subducted Nazca Plate (Dorbath, 1997). The Andean mountains are segmented into zones of shallow ($0-10^{\circ}$) and moderate dip ($25-30^{\circ}$) along strike as evidenced in distribution of the Wadati -Benioff zone seismicity (Isacks, 1988).

The shallow zones of subduction mark the boundaries between the Northern (NVZ, $5^{\circ}\text{N} - 2^{\circ}\text{S}$), Central (CVZ, $16-28^{\circ}\text{S}$), and Southern (SVZ, $33-46^{\circ}\text{S}$) volcanic zones (Figure 2.1, Stern 2004) and are associated with the absence of active volcanism (Thorpe and Francis, 1979). The volcanic zones are associated with the segments of moderately dipping subduction (Thorpe and Francis, 1979). In the NVZ and SVZ, Paleozoic to Mesozoic crust attains an average thickness of 35-40 km, whereas in the CVZ Precambrian to Paleozoic crust exceeds thicknesses of 70 km (James, 1971; Rogers and Hawkesworth, 1989; Zandt et al., 1994). There is a large compositional diversity of volcanic rocks along strike of the arc within and between the volcanic zones. The NVZ

and SVZ are characterized by basalt, basaltic andesites, and andesites while the CVZ is dominated by andesites, dacites, and large-volume dacite-rhyolite ignimbrite sheets (Harmon et al., 1984). The study site, the Lazufre Volcanic Zone, lies in the CVZ. This study's focus will be on the CVZ, unique in that convergence and crustal thickening have created the world's second thickest continental plateau and volcanic compositions that are dominated by crustal contamination (Allmendinger et al., 1997; Beck et al., 1996; Michelfelder et al., 2013).

2.2 Evolution of the CVZ

The Central Volcanic Zone occupies southern Peru, western Bolivia, northern Chile, and northwestern Argentina. The CVZ is associated with active ENE subduction of the oceanic Nazca plate beneath the South American plate and represents an end member in subduction zone systems on Earth because the continental crust is thicker (70-80 km) than any other convergent margin setting and volcanic rocks exhibit a strong "crustal signature" (Allmendinger et al., 1997; Beck et al., 1996; Michelfelder et al., 2013). The convergence rate along the South American margin is 8.7 cm/year (Scheuber et al., 1999) and the age of the subducting Nazca plate is between 45 and 55 Ma (de Silva et al., 1993). Plate convergence angles change from the northern CVZ to the southern CVZ (75° to 90° respectively), caused by the concave geometry of the South American plate in the Arica Elbow (18°S), where the strike of the Andean chain changes and no deep seismicity has ever been recorded (Wörner et al., 1992). CVZ volcanoes are ~135 to 180 m above the Wadati-Benioff zone (Feeley, 1993).

In the CVZ, the Peru-Chile trench is around 7000 m deep and starved of sediments (Thornburg and Kulm, 1987). The central Andes are known for high elevations (~4-6 km above sea level; Allmendinger et al., 1997). Eight north-trending trench-parallel structure belts from west to east across the orogeny define changes in structure, distribution of magmatism, and geomorphology. The forearc consists of the Coastal Cordillera, Longitudinal Valley, and the PreCordillera while the arc and back arc include the Western Cordillera, the Altiplano-Puna Plateau, the Eastern Cordillera, SubAndean Zone, and the Chaco Plain structural belts (Figure 2.2; Wörner et al., 1992).

The forearc contains Mesozoic to Paleogene volcanic rocks that decrease in age eastward. This marks the migration of the Andean arc since the Jurassic to its location in the Western Cordillera from the Late Miocene to Recent. Upper Miocene to Recent stratovolcanoes in the Western Cordillera comprise a nearly continuous volcanic zone aligned N-S containing almost 1100 active volcanoes (de Silva and Francis, 1991). The backarc is made up of four structural belts: the Altiplano-Puna, Eastern Cordillera, InterAndean Zone, and the Chaco Plain. The Altiplano-Puna is a high plateau sitting at a mean elevation of 4 km. The Eastern Cordillera mountain belt is dominated by folding and thrusting of Paleozoic to Cenozoic rocks. Since the late Oligocene, Paleozoic to Cenozoic sediments accumulated in the backarc have undergone compressional deformation. A doubling of the continental crust in the backarc is a result of contraction and compression, leading to thrusting of the Andean orogen over the foreland (Isacks, 1988; Lamb and Hoke, 1997) (Figure 2.2).

In the central Andes, convergence of the oceanic Nazca and continental South American plates generated the Altiplano-Puna high plateau. Uplift in this region began around 25 Ma, which coincides with an increased convergence rate (from 5 to 10 cm/year), inferred shallowing of subduction and a major decrease in the angle of obliquity to the margin (Lamb and Hoke, 1997). For these reasons, central Andean topography is often considered to be a primary tectonic signal of late Cenozoic mountain building.

Under the Altiplano-Puna and Western Cordillera, Andean crust obtains a thickness between 60-70 km, nearly twice as thick as crust in the forearc and foreland regions of the CVZ. Multiple mechanisms have been suggested to explain the thickening of the Andean crust including magmatic addition (Thorpe et al., 1981), crustal shortening (Ruetter et al., 1988), and thermally softened lithosphere combined with horizontal shortening (Isacks, 1988). In order to explain crustal thickness by magmatic addition alone, unrealistically large amounts of igneous rocks would be necessary. Aerial geology of specific regions of the Altiplano show that extrusive volcanic material simply sits on top of the plateau rather than comprising the volume of the plateau itself, with the extrusive rocks forming a thin surface cover on top of older structures (Isacks, 1988). Many recent models suggest that compressional deformation and accommodation through crustal shortening along the active plate margin during the most previous mountain building stage resulted in a thickened crust and uplifted the Altiplano (Isacks, 1988; Gubbels et al., 1993; Okaya et al., 1997). Magnitude of horizontal shortening decreases continuously from the center of the Altiplano towards the southern Puna.

There have been suggestions that erosion and replacement of cold lithospheric mantle by asthenospheric mantle could have contributed to the elevated Altiplano Plateau and Western Cordillera (Okaya et al., 1997). There is a widespread agreement through geophysical studies that there is little or no lithospheric mantle beneath the active volcanic arc (Gilbert et al., 2005; Schurr et al., 2006). It has been argued that the timing of the uplift of the plateau and deformation is synchronous with an increased convergence rate between the Nazca and South American plates throughout the late Oligocene, coinciding with ignimbrite and stratovolcanic activity. Beginning in the middle Miocene, volcanic activity has overlapped in time and space and has become progressively more and more focused in the Western Cordillera (Baker and Francis, 1978).

Recently, geophysical work has revealed a zone of low seismic velocities (the Low Velocity Zone) in the CVZ beneath the volcanic arc at depths from 20 km to the base of the crust at 70 km (Wigger et al., 1994). Coinciding with the Low Velocity Zone is a body characterized by a zone of partial melt with low density, high heat flow (>100 mW/m²), high electrical conductivities, and negative gravimetric anomalies (Schmitz et al., 1997; Schilling et al., 1997; Chmielowski et al., 1999; Zandt et al., 2003). This zone, interpreted as a large sill-like magma body known as the Altiplano-Puna magma body (APMB) underlies and is related to the Altiplano-Puna Volcanic Complex (APVC) of de Silva (1989) in southern Bolivia, northern Chile, and northwest Argentina which contains over 20 calderas and numerous ignimbrites less than 10 Ma (de Silva, 1989; de Silva and

Francis, 1991; de Silva et al., 2006). This study's site area, the Lazufre Volcanic Complex, is positioned on the southern end of the APVC.

2.3 Geology of the CVZ

Central Volcanic Zone volcanoes belong to a north-northwest trending belt of late Cenozoic calc-alkalic and alkali volcanic rocks. A consistent chain of evenly spaced volcanoes from 16° to 22°S make up the northern segment of the CVZ, while the southern segment between 22° and 28° S moves farther east and becomes wider and more irregular (Wörner et al., 1992). The crust beneath the Western Cordillera exceeds thicknesses of 70 km and decreases towards the eastern-most margin to ~60 km (James, 1971).

At 25°S, the late Cenozoic chain is roughly 100-150 km wide and sits on top of a 150,000km² Tertiary rhyolitic to dacitic ignimbrite plateau. The upper crust beneath the volcanic front consists of Paleozoic and Mesozoic rocks, with early Cenozoic volcanic rocks to the west. West of the Andean Cordillera are exposed Paleozoic granitoids and siliceous volcanic rocks. Jurassic and Cretaceous marine and continental sedimentary and volcanic rocks lie on each side of the Paleozoic rocks (Naranjo, 1992). Geophysical studies suggest that the upper 20 km of crust is composed of granitic and intermediate composition plutonic rocks comagmatic with the late Cenozoic rocks. The lower 40-50 km are likely composed of amphibolite or more siliceous anhydrous metamorphic rocks, pyroxene gneisses, and gabbros (Feeley and Hacker, 1995; Schmitz et al., 1999).

K-Ar dates suggest that late Cenozoic volcanic activity initiated during the Miocene and is characterized by two episodes based on composition and style (Baker and

Francis, 1978). The first episode is characterized by large scale regionally extensive rhyolite to dacite ignimbrite volcanism beginning ~23 Ma. The second episode overlaps in time and is represented by eruptions of basaltic andesite to dacite lavas ranging from 23 Ma to present, with the largest volumes erupted throughout the Pleistocene and Pliocene. This group, confined to the Western Cordillera, forms large stratovolcanoes and is not as regionally extensive. CVZ volcanic stratigraphy indicates that volcanic activity was dominated by early eruptions of silicic material but that a greater proportion of mafic material has been erupted over time (Baker and Francis, 1978).

2.4 Geology of the Lazufre Volcanic Complex

Pritchard and Simons (2002; 2004) identified a few large concentric and persistent deformation areas in the Altiplano-Puna region by InSAR. Among these is an area of uplift along the border of Chile and Argentina between two Quaternary volcanoes, Lastarria (25° 10'S, 68° 31' W; Naranjo, 1991) and Cordon del Azufre (25° 18'S, 68° 33'W; de Silva and Francis, 1991), hereafter called 'Lazufre'.

Lastarria (5697 m) lies at the northern end of the complex. The surrounding area is composed of Tertiary-Quaternary volcanic rocks and salars, including intermediate to acidic composition ignimbrites and lavas ranging in age from 24 Ma to recent (Naranjo, 1992). Lastarria is an active composite volcano that shows permanent passive degassing on its summit and southern upper flank (Naranjo, 1985). A series of sulfur flows have been generated from a high geothermal flux along with high SO₂ flux from the fumaroles (Naranjo, 1985). Lastarria is predominately composed of high-K andesite to dacite (57-

68% SiO₂) lava flows (Naranjo, 1986). It is accompanied by a series of young pyroclastic flow deposits on its southern flank and a debris avalanche deposit on its lower eastern flank (Naranjo and Francis, 1987). Naranjo (1992) identified three main structures that form the Lastarria volcanic complex. The Southern Spur, which has a north-south orientation, is the oldest component. Joining the Southern Spur at ~5500 m is the main edifice, Lastarria *sensu strictu*. It is conical in shape, has a north-westward-shifting vent area that has formed a series of five nested craters. The youngest volcanic structure, the Negriales, is an exogenous dome overlapping the northernmost crater rim. It is geographically associated with an andesitic-dacitic lava field that is located to the southwest and formed by several massive lava flows erupted from a single vent. The most recent activity from Lastarria has been dated at 500-100 ka (Naranjo, 1992) (Figure 2.3).

Located south of Lastarria is Cordón del Azufre, which until recently, had not been studied in detail. Previous studies have been limited to satellite image interpretation and distinguishing components on morphological grounds. Three main components were identified by de Silva and Francis (1991). The first is a lava flow cluster lying east of the main ridge in Argentina. The cluster reaches an elevation of 5100m and contains several small vents. The whole complex covers an area of roughly 45 km², containing many small flows less than 1 km long. The second component identified is an older part of Cordón del Azufre, consisting of four craters and associated flows which form a 5 km north-south trending chain. Lava flows in this complex extend for up to 5 km on the northern and western flanks. The third component contains the most recently active

center, Volcan La Moyra (de Silva and Francis, 1991). The 300-m-high cone has dark, blocky lava flows that extend for more than 6 km on the western flank and 3 km on the eastern flank. A pyroclastic eruption which has buried the proximal parts of some eruptive units is the most recent event from Cordon del Azufre. From satellite image interpretation, young evolved lava flows on the western flank could be similar in age to Lastarria's young flows (Holocene; de Silva and Francis, 1991). There is currently no activity known at Cordon del Azufre.

Figure 2.1A. Schematic map of South America and the Pacific oceanic plates showing the three volcanically active segments in the Andes, subduction geometry (indicated by depth in km to the Benioff zone), plate tectonic framework, and convergence rates and directions along the length of the Andes. Box indicates area of B. Modified from Stern (2004). 2.1B. Volcanoes of the central Andes (minor centers not shown). Modified from Stern (2004).

Figure 2.2. Cross section through Andean fold-thrust belt of the central Andes. Lightly shaded area above modern topography represents material removed via erosion. Modified from McQuarrie et al. (2008).

CHAPTER 3: ANALYTICAL METHODS

Eighty-three rock samples of one to two kg were collected from distinct lava flows distributed across the entire field area. Sample locations are shown on Figure 5.1 and UTM coordinates are listed in Appendix A. The investigated suite consists of 58 samples from Volcán Lastarria and 25 samples from Cordon del Azufre. Major and trace element, isotopic, and modal analyses were conducted on select, fresh samples, cleaned of their weathered surfaces, and broken into smaller pieces.

Major element oxide and trace element (Sc, V, Cr, Ni, Zn, Rb, Sr, Y, Zr, Nb, Ba, Pb, and Th) analyses were obtained by standard X-ray fluorescence (XRF) spectrometry. Samples were analyzed at Washington State University's GeoAnalytical Laboratory, Pullman, Washington, using a ThermoARL Advant'XP + sequential X-ray fluorescence spectrometer. The samples were ground into a fine powder in a swing mill with tungsten carbide surfaces then mixed with a di-lithium tetraborate flux in a 1:2 ratio respectively and fused. Samples were then analyzed following the technique described by Johnson et al. (1999). Estimated precision is better than 1% for most elements except Y, Nb, and Cr (better than 5%). 30 distinct samples were selected for further analysis of trace elements, including the rare earth elements, through inductively coupled plasma-mass spectrometry (ICP-MS) at Washington State University's GeoAnalytical Laboratory. The samples were analyzed by an Agilent Technologies 7700 ICP-MS following the protocol of Jarvis (1988).

Whole rock powders from 15 select, fresh samples were analyzed for Pb, Nd, and Sr isotopic compositions at New Mexico State University, Las Cruces, by thermal

ionization mass spectrometry (TIMS) on a VG Sector 54 using five Faraday collectors in dynamic mode. Calibration of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios was calculated using the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio analyzed at 3.0 V aiming intensity and normalized to 0.11940 using NBS 987 standard (0.71026 ± 0.00001) to monitor the precision of the analyses. Sr was isolated using Sr-spec resin column chromatography following the method in Ramos and Reid (2005). Elution of Nd was carried out using REE resin column chromatography in a second set of columns using the REE rich fraction gained from the above Sr separation. Nd isotopes were corrected for mass fractionation to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ and results for standard JNDi-1 were $^{146}\text{Nd}/^{144}\text{Nd} = 0.51214 \pm 0.00001$ for five analyses using TIMS. Pb was separated using the same digested samples used for Sr and Nd isotopic analyses. Pb separations used ~2 mL of anion exchange resin in a high-aspect ratio glass column with an eluent of 1N HBr and 7N HNO_3 . Purified Pb samples were dried and re-dissolved in 1 mL of 2% HNO_3 containing 0.01 ppm Tl. Elutriated Pb samples were analyzed on a ThermoFinnigan Neptune multi-collector ICP-MS with nine Faraday collectors and an ion counter. Six measurements of NBS 981 gave means of $^{208}\text{Pb}/^{204}\text{Pb} = 36.689 \pm 0.002$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.489 \pm 0.001$, and $^{206}\text{Pb}/^{204}\text{Pb} = 16.937 \pm 0.001$ to correct for accuracy and monitor precision of the analyses. The values measured for NBS 981 were within error of published ratios for NBS-981 (Todt et al., 1996).

Eight representative samples spanning the compositional range of all samples were selected for chemical analyses of plagioclase, pyroxene, olivine, and biotite. The analyses were performed at the Stanford University Microprobe Laboratory using the JEOL JXA-8230 “Superprobe” electron microprobe. Analyses for all phases were

conducted using a 20 nA beam current and a 2 micrometer beam diameter. Diopside, olivine, albite, orthoclase, kyanite, wollastonite, rutile, hematite, spessartine, and chromite standards were run twice daily.

Modal data were determined by point counting following the method described by Chayes (1956) and Hutchison (1974). Between 400-600 points per thin section were counted for the samples, with phenocrysts defined as > 0.25 mm in the longest dimension. Only primary mineral phases were identified and counted if secondary alteration products were observed.

CHAPTER 4: MORPHOLOGY OF THE LAZUFRE VOLCANIC COMPLEX

Until recently, Lazufre has not been the focus of intense study. Trumbull et al. (1999) and de Silva and Francis (1991) included Lazufre in regional studies investigating evidence of contamination of arc andesites by crustal melts but did not investigate the volcanic history. Previous geologic mapping at Lastarria performed by Naranjo (1991) identified three structures comprising the volcanic complex as well as permanent passive degassing on its summit and southern upper flank. Sulfur flows have been generated through melting of extensive sulfur deposits in the summit area and northwest flank. Stratigraphy of the complex includes lava flows, tephra, and pyroclastic units. A high velocity debris avalanche is present on the southeast flank of Lastarria (Naranjo and Francis, 1987). Recent pyroclastic flow deposits form a large apron on the northern flanks of the volcano. Bombs and blocks of banded pumice are common on the surfaces of Lastarria's lava flows indicating intermittent explosive and eruptive activity (Figure 1). Considered dormant, Cordon del Azufre has not been studied in detail, and no geologic maps exist. The volcanic complex of Cordon del Azufre covers about 60 km². Stratigraphy of Cordon del Azufre includes lava flows and domes.

Flow fronts of lava flows range in thickness from <5 m to over 200 m thick. Widths of flows vary with slope and are wider than thick for gentler slopes (Figure 4.1). Some lava flows extend for over 10 km and can be traced back to the main vents of Lastarria and Cordon del Azufre (Figure 4.2), while several smaller volume flows rarely extend for more than 2 – 3 km from the main volcanic edifices. Several lava flows have

internal flow folds and are autobrecciated at the terminus showing several meters of oxidation (Figure 4.1).

Craters occur throughout the Lazufre volcanic complex with several lava flows that can be traced back to the craters and associated vents. Craters along Cordon del Azufre are aligned N-S, and comprise a 5 km ridge. The youngest crater at Cordon del Azufre is located along the main complex and is associated with a 6 km blocky lava flow to the west dated at 0.3 ± 0.3 Ma (Figure 4.1 and Figure 4.2). Several domes occur throughout the complex and are associated with lava flows, suggesting the activity was not restricted to a central vent (Figure 4.2). A young dome rests on the crater rim of the main volcano of Lastarria. Piles of glassy, prismatic jointed blocks are interpreted as the exterior walls of domes and were used in the identification of the domes. Few, rare exposures of the dome interiors are vesiculated ranging from 5%-21% of the total volume (Figure 4.1).

Figure 4.1. Representative views of Lazufre (A) View northeast towards the edifice of Lastarria; (B) View northeast towards the edifice of Cordon del Azufre; (C) Typical flow folding in lava flows; (D) Active sulfur outgassing and fumaroles on Lastarria; (E) Typical block flow front on the southwest flank of Cordon del Azufre; (F) Typical effusive flows on Lastarria overlain by hydrothermally altered debris flows and sulfur fumaroles; (G) Massive bomb on the northwest flank of Lastarria; (H) Typical prismatically jointed block from exterior wall of a collapsed dome on Cordon del Azufre; (I) Magmatic inclusion in a Cordon del Azufre lava flow; (J) Debris avalanche on the northwest flank of Lastarria.

Figure 4.2. Aerial image of the Lazufre Volcanic Complex illustrating lava flows, vents, and craters. Annotations are as follows: (a) pyroclastic flow deposit, (b) debris avalanche, (c) active sulfur outgassing and fumaroles, (d) most recent eruptive unit Modified from Google Earth aerial image.

CHAPTER 5: PETROGRAPHY AND MINERALOGY

5.1 General Petrographic Overview of Lazufre

Lava flows from Lastarria and Cordon del Azufre were sampled (Figure 5.1) for petrographic and geochemical analyses and Lastarria tephra deposits were sampled for petrographic analysis. The predominant lava flows at both volcanic centers are medium-grey to black, blocky to platy, two-pyroxene andesites and minor dacites within a continuous range of SiO₂ wt% (see Chapter 6 for chemical classification). Based on field and aerial interpretation, tephra deposits make up less than 10% of total study area.

The andesitic flow rocks are porphyritic to seriate and variably hiatal in contrast to pyroclastic rocks which are porphyritic with an aphyric groundmass. Lava flow matrices are generally vitric with varying abundances of plagioclase microlites with trachytic to sub-trachytic texture. Modal compositions of Lazufre flow rocks vary in crystal content but are similar in mineral assemblage (Figure 5.2). Total phenocryst contents (sum of plagioclase, pyroxenes, hornblende, biotite) range from 19% - 60% total volume for all lava flows. There is little variance in the phenocryst assemblages observed between volcanic centers as well as between andesites and dacites. Modal point counting data for all Lazufre rocks are presented in Appendix B.

Lazufre flow rocks contain 11-31% plagioclase phenocrysts ranging in size from 0.5 mm to 6.5 mm, with an average length of 3 mm. Flow rock samples also contain phenocryst abundances of 0-9% orthopyroxene (OPX), 0-5% clinopyroxene (CPX), and small amounts of biotite and amphibole (0-2%) (Figure 5.2). Amphibole phenocrysts

have developed a strong oxidized reaction rim (Figure 5.3). Quartz rarely occurs in Lazufre flow rocks as a phenocryst or in the groundmass. The groundmass contains plagioclase, OPX, and CPX as well as varying amounts of brown glass and rare olivine. Opaque minerals occur as ilmenite and ulvöspinel in the groundmass, disseminated in the matrix, and in glomerocrysts. Apatite and zircon occur as accessory minerals.

Volcanic bombs ranging from centimeter to meter scale, blocks of pumice and dark scoria are common in Lastarria tephra deposits. Narrow (0.1 mm to 15 cm) subparallel flow bands, distinguishable by differences in texture and color are exhibited in the groundmass of pyroclastic flow deposit pumiceous rocks (Figure 5.4).

Glomerocrysts occur frequently in all flow rock samples and contain unique mineral assemblages compared to host rocks (plagioclase, pyroxenes, olivine, ulvöspinel, biotite, amphibole, and minor quartz) (Figure 5.5). Glomerocrysts vary from host rock in texture and mineral assemblage. Glomerocrysts are medium to coarse grained, void of vesiculation and contain more abundant ulvöspinel, biotite, and olivine than surrounding host rock. They range in size from 2 mm to 20 mm with grains from 1 mm to 7 mm.

While magmatic inclusions are sparse, they appear in most lava flow samples. They are commonly rounded to sub-rounded ellipsoidal shape and range in size from 1 mm to 16 mm. Magmatic inclusions are porphyritic with unique phenocryst assemblages of euhedral to subhedral plagioclase, olivine, and pyroxenes and typically lack quartz and biotite. Magmatic inclusions are more mafic than the host rock with an average color index of 70-75% (color index is defined as the percent of dark or “mafic” minerals). They exhibit greater degrees of vesiculation and more abundant ulvöspinel and ilmenite

than the surrounding host rock. They possess abundant acicular groundmass plagioclase grains with a trachytic texture. Chilled margins surround most magmatic inclusions (Figure 5.6).

5.2 Mineral Descriptions

5.2.1 Plagioclase

All LVC samples contain abundant plagioclase laths of various sizes and textural types. Within the same eruptive unit plagioclase phenocryst textures include a combination of sieving, dissolution surfaces, growth zones, and unzoned crystals (Figure 5.7). Often, rocks contain plagioclase with sieved or resorbed textures with weakly zoned cores surrounded by dusty zones, glass inclusions, and skeletal plagioclase. The glass inclusions are usually isolated into a narrow band very near the crystal margin. These zones are then surrounded by a clear overgrowth. Euhedral plagioclase phenocrysts from .5 mm to 6.5 mm in all rocks are common. There are several different variations of zoning in plagioclase phenocrysts including normal and reverse zoning, oscillatory zoning, as well as a combination of normal and oscillatory zoning with dusty areas in the intermediate zones. Groundmass crystals do not exhibit sieving seen in phenocrysts.

Representative plagioclase core, rim, and microlite compositions are presented in Table 5.1. Figure 5.8 shows frequency histograms of plagioclase compositions, determined by electron microprobe analysis (EMPA), in selected samples. Compositions are separated into phenocryst cores, phenocryst rims, and groundmass microlites. Plagioclase phenocrysts in the andesitic and dacitic samples most commonly have cores

that range in composition from An₄₀₋₈₀, although some core compositions range up to An₉₀. Rims are either An₄₀₋₅₅ or An₆₅₋₈₀, imparting a crudely bimodal compositional distribution. The majority of groundmass grains range in composition from An₄₅₋₇₀.

5.2.2 Orthopyroxene

Orthopyroxene occurs as phenocrysts and in the groundmass as hypersthene (En₆₃₋₇₁; Figure 5.9). The majority of OPX phenocrysts are euhedral with most ranging in size from about 0.5 mm to 3 mm and few samples contain phenocrysts up to 6 mm. Normal and reverse zoning are present in phenocrysts. In addition to the main samples, OPX commonly occurs in glomerocrysts (Figure 5.5) possessing the same composition as phenocrysts and groundmass. On rare occasion, OPX forms reaction rims on clinopyroxene.

Orthopyroxene phenocrysts have a restricted compositional range, containing ~1% Al₂O₃ and 22 to 24% MgO content, and Mg# of about 50 to 56 (FeO is total Fe present). OPX microlites have slightly higher Al₂O₃ contents ranging from 1-2%, and MgO ranging from 22-27%, and Mg# of about 51 to 56 (Figure 5.10 and Figure 5.11).

5.2.3 Clinopyroxene

In all samples, clinopyroxene is present as euhedral to subhedral phenocrysts and as groundmass microlites. CPX compositions are dominantly augites (En₃₉₋₄₇, Wo₄₀₋₄₆) (Figure 5.9). Most CPX phenocrysts range in size from about 0.5 mm to 3 mm, however locally Cordon del Azufre dacite rocks exhibit euhedral megacrysts up to 7 mm. Both normal and reverse zoning of En and Wo composition occur in the phenocrysts in most of

the samples analyzed. Usually normal zoning begins abruptly and is limited to the rim of crystals. Augite microlites have the same composition as the augite rims occurring on hypersthene.

Lazufre clinopyroxenes can be characterized by their Al and Mg content (Figure 5.10). CPX phenocrysts and microlites are poorly aluminous (0-5% Al_2O_3) and have MgO content ranging from 12-17%. Clinopyroxenes have low Al (Al/6 p.f.u. < 0.18) (Figure 5.10, Figure 5.11, Table 5.2). This suggests crystallization occurred under low-pressure, shallow-crustal conditions (Feeley et al., 2002). Figure 5.11 demonstrates that the MgO content of clinopyroxene is lower than coexisting orthopyroxene. In addition, CPX microlites and rims are the same composition while OPX microlites have varying compositions.

5.2.4 Amphibole

Amphibole is rare or absent in both volcanic centers, in both andesites and dacites. Amphibole exists in the rocks as hornblende and possesses strong oxidation reaction rims. Most hornblende phenocrysts in the lava flows have rims that are converted either partially or wholly to fine-grained opaque aggregates. In pumiceous rocks from Lastarria, amphiboles lack a reaction rim against the surrounding groundmass. Hornblende phenocrysts range in size from 0.5 mm to 2 mm.

5.2.5 Biotite

Biotite is rare to absent in Lazufre flow rocks. Where biotite does occur, phenocrysts range in size from 0.5 mm up to 1.5 mm. Most biotite phenocrysts observed

exhibit a dark reaction (oxidation) rim or conversion to opaque minerals. Locally, biotite occurs as skeletal grains with partial replacement in the cores by pyroxenes, plagioclase, and oxides. Biotite occurs within glomerocrysts (Figure 5.5) and individually in lava flows.

5.2.6 Olivine

Olivine is restricted to glomerocrysts and magmatic inclusions and is found in the groundmass of some andesites (Figure 5.5). Where observed, olivine grains are up to 1 mm, slightly rounded and have a fairly uniform composition of about Fo₈₀. Olivine microlites have compositions of about Fo₇₈. Subhedral olivine crystals are often surrounded by a rim of small grains and microlites of plagioclase, orthopyroxene, and amphibole. Rarely olivine is found in direct contact with lava groundmass. Most of the samples analyzed that contain olivine also contain hornblende and biotite, most often in glomerocrysts.

5.2.7 Quartz

Quartz is rare, but when it is observed it is rounded, fractured, and between 0.5 mm and 1 mm in size. Occurrence of quartz is restricted to dacites and pumiceous rocks.

5.2.8 Opaque Minerals

Most Lazufre rocks contain a small amount of ilmenite and ulvöspinel occurring in glomerocrysts, magmatic inclusions and groundmass microlites. Ilmenite and ulvöspinel in the lava flows occur as an amphibole breakdown product, and as inclusions

in all other phenocryst phases, especially pyroxenes and rarely in plagioclase. Fe-Ti oxides typically comprise less than 2% of the rock mode.

5.3 Summary

Magmatic inclusions that are ellipsoidal, highly vesiculated, possess chilled margins and unique mineral assemblages and glomerocrysts with unique mineral assemblages are present in most lava flow samples. Occurrence of olivine is restricted to magmatic inclusions and glomerocrysts. This suggests magma mixing of at least two different magmas. Phenocryst assemblages with disequilibrium textures are present in numerous rocks. Plagioclase phenocrysts exhibit complex and strong zoning patterns, reflecting the complicated history of the magmas.

Figure 5.1. Locations of sampled lava flows, domes, and pyroclastic flows.

Figure 5.2. Modal percent phenocrysts versus SiO_2 for representative Lazufre rocks. Vertical dashed line represents change from andesite to dacite fields.

Figure 5.3. Amphibole (hornblende) in lava flow exhibiting a strong reaction rim. Top photo is in ppl. Bottom photo is in xpl. Both photomicrographs are in 2.5x magnification.

Figure 5.4. Pumice sample exhibiting banding. Green line depicts banding in pumice matrix. Top photo is in ppl. Bottom photo is in xpl. Both photomicrographs are in 2.5x magnification.

Figure 5.5. Photomicrographs depicting two different populations of glomerocrysts. Top photos demonstrate a glomerocryst containing plagioclase, OPX, CPX, olivine, and Fe-Ti oxides. Bottom photos demonstrate a glomerocryst containing plagioclase, biotite, hornblende, and Fe-Ti oxides. Left photos are in ppl. Right photos are in xpl. All photomicrographs are in 2.5x magnification.

Figure 5.6. Photomicrograph demonstrating a magmatic inclusion within a lava flow. Top photo is in ppl. Bottom photo is in xpl. Both photomicrographs are in 2.5x magnification.

Figure 5.7. Photomicrographs demonstrating varying textures of plagioclase within lava flows. Left photos are in ppl. Right photos are in xpl. All photomicrographs are in 2.5x magnification.

Figure 5.8. Frequency histograms of plagioclase rim, core, and groundmass compositions for Lazufre rocks.

Figure 5.9. Pyroxene compositions for Lazufre volcanic rocks.

Figure 5.10. Pyroxene populations of Lazufre samples discriminated by Al and Mg contents.

Figure 5.11. Pyroxene populations of Lazufre samples discriminated by MgO contents and Mg#.

Table 5.1. Representative plagioclase compositions.

SAMPLE	LAS 15	LAS 15	LAS 15	ACA 06	ACA 06	ACA 06	ALA 10	ALA 10	ACA 01	LAS 31	LAS 31	LAS 31
Remarks	Core	Rim	Microlite	Rim	Core	Microlite	Rim	Core	Microlite	Rim	Core	Microlite
SiO₂	55.47	48.02	49.30	49.81	57.16	49.86	59.76	55.96	55.36	48.02	52.09	53.13
Al₂O₃	26.05	31.08	30.25	30.25	25.62	30.28	24.42	27.09	27.62	31.02	28.78	27.62
FeO*	0.29	0.57	0.55	0.57	0.26	0.62	0.23	0.32	0.59	0.54	0.68	0.54
MnO	0.02	0.08	-0.01	-0.01	0.01	-0.01	0.03	0.00	0.02	-0.02	0.00	-0.03
MgO	0.01	0.06	0.07	0.09	0.03	0.06	0.01	0.01	0.05	0.07	0.05	0.06
CaO	9.35	15.37	13.97	14.00	8.54	13.97	6.65	9.59	10.09	15.54	13.04	11.49
Na₂O	5.78	2.91	3.59	3.72	6.44	3.53	7.09	5.83	5.54	2.67	4.03	4.70
K₂O	0.69	0.18	0.16	0.24	0.87	0.19	1.17	0.52	0.75	0.14	0.46	0.42
Total	97.71	98.28	97.95	98.72	98.97	98.53	99.39	99.34	100.05	98.02	99.19	97.97
An	46.2	77	69.9	41.6	69.6	69.5	46.6	48.4	68.3	72.1	64.2	57

Note: All Fe as FeO*.

Table 5.2. Representative clinopyroxene compositions.

SAMPLE	CA 06	CA 06	LAS 15	LAS 15	LAS 15	ACA 06	ACA 06	LAS 13	LAS 13	LAS 13	ALA 10	ALA 10	ALA 10
Remarks	Rim	Core	Rim	Core	Microlite	Rim	Core	Rim	Core	Microlite	Rim	Core	Microlite
SiO₂	49.62	50.23	49.89	52.26	52.16	52.61	51.67	52.51	52.66	49.83	52.18	52.18	52.22
Al₂O₃	3.24	3.29	2.91	0.78	0.77	0.74	0.77	0.90	0.73	4.08	1.61	1.41	1.56
TiO₂	0.67	0.56	0.80	0.17	0.16	0.17	0.17	0.19	0.15	0.98	0.42	0.37	0.46
Cr₂O₃	0.01	0.34	0.01	0.00	-0.01	0.01	0.00	0.00	0.01	0.05	0.07	0.02	0.03
FeO	9.68	7.09	8.35	8.84	8.63	8.15	8.93	8.84	8.92	8.41	8.27	10.04	8.83
MnO	0.20	0.18	0.21	0.42	0.40	0.37	0.52	0.33	0.40	0.16	0.23	0.36	0.22
MgO	15.57	16.51	14.93	14.22	14.27	14.78	14.47	14.44	14.36	14.82	15.15	14.12	15.37
CaO	19.51	20.70	21.01	22.07	22.19	22.13	21.95	21.75	22.04	20.22	21.41	21.12	21.23
Na₂O	0.39	0.37	0.31	0.31	0.29	0.30	0.34	0.33	0.35	0.30	0.25	0.36	0.27
Total	98.85	99.25	98.37	99.04	98.85	99.21	98.80	99.27	99.59	98.82	99.58	99.96	100.17
Wo	38.46	40.69	42.26	45.26	45.57	45.08	45.65	44.47	45.02	40.02	42.97	42.89	42.31
En	51.69	54.19	48.14	42.59	42.79	43.74	44.15	42.92	42.74	47.92	45.35	42.68	46.17
Fs	9.85	5.12	9.60	12.15	11.64	11.18	10.20	12.61	12.24	12.06	11.68	14.43	11.51

Note: Wo*, En*, Fs* are calculated using PyroxeneNormalization-Henry-beta3.0. All Fe as FeO*.

CHAPTER 6: WHOLE ROCK GEOCHEMISTRY

Major and trace element analyses of flow rocks were obtained for 69 total samples (48 from Volcan Lastarria and 21 from Cordon del Azufre) by X-ray fluorescence spectrometry. Based on these analyses, a representative set of 31 rocks was selected for additional determination of rare earth element (REE) and other trace element analysis by ICP-MS. A further subset of 15 samples was selected for Sr, Nd, and Pb isotopic analysis by thermal ionization mass spectrometry (TIMS). Flow rocks were the only eruptive units analyzed for whole rock geochemistry. Major and trace element whole rock and isotopic data are presented in Appendix F.

6.1 Major Element Compositions

Lazufre andesites and dacites comprise a high-K calc-alkaline suite (Figure 6.1 and 6.2; Le Bas et al., 1986; Irvine and Baragar, 1971; Gill, 1981). SiO_2 ranges continuously from 58-65 wt% with the majority of lava flows occurring as andesites between 58 and 62 wt%. Flow rocks are separated according to individual eruptive centers (Lastarria and Cordon del Azufre) and relative age (recent and older). Older flow rocks are defined as the most distal rocks from the eruptive centers while recent flow rocks are those closest to the eruptive centers. The majority of Lastarria and Cordon del Azufre volcanic rocks are inseparable in terms of major and trace elements and possess a similar range of SiO_2 .

Figure 6.3 illustrates variations in major element composition on Harker Diagrams for Lazufre rocks. A negative correlation with SiO_2 is observed for major

elements: MgO (4.0-1.5 wt.%), CaO (6.4-3.5 wt.%), TiO₂ (1.03-0.61 wt.%), and FeO (6.8-3.9 wt.%); there is positive correlation observed in K₂O (2.3-4.1 wt.%), and little variation in Na₂O (2.9-3.6 wt.%) with increasing SiO₂ contents. Compared to Cordon del Azufre lavas at similar SiO₂ (60-63 wt%) concentrations, Lastarria lavas show slightly elevated concentrations of MgO and TiO₂ (Figure 6.3).

6.2 Trace Element Compositions

Figure 6.4 illustrates variations in selected trace element compositions with respect to SiO₂ for Lazufre rocks. Large ion lithophile trace elements (LILE) show enrichment trends beyond those that can be produced by crystallization-differentiation alone including Rb = 103 - 291 ppm and Th = 18 - 66 ppm (Cole et al., 1983; Graham and Hackett, 1987); while negative correlation is observed in compatible trace elements Sr (578 - 294 ppm), Cr (61 - 10ppm), Ni (33 - 14 ppm) versus SiO₂.

There is a more significant difference in trace element concentrations than in major element concentrations between Lastarria and Cordon del Azufre. Given a similar andesitic range of SiO₂ concentrations (59-62 wt%), Lastarria samples are more enriched in Ni and Cr and depleted in Y (mantle compatible trace elements; compatible trace elements are defined as those concentrated in the solid phase more than the melt) (Winter, 2010). Cordon del Azufre lavas are more enriched in Ba, Zr, and Rb (incompatible trace elements; defined as elements concentrated in the melt more than the solid) (Winter, 2010) for similar dacitic SiO₂ concentrations (62-66 wt%)(Figure 6.4). Compatible trace element concentrations in mantle minerals (Ni and Cr) are highly

variable in the most mafic andesitic magmas, especially several lava flows from Lazufre. Ni and Cr concentrations at Lastarria are negatively correlated with SiO₂, with lesser degrees of variation with increased SiO₂ wt% while Cordon del Azufre flow rocks have constant and lower concentrations. Few Lastarria samples have anomalously high Cr and Ni concentrations at 59-62 wt% SiO₂ compared to other Lazufre samples. These flow rocks are associated with higher occurrences of magmatic inclusions. Few recent Cordon del Azufre flow rocks at ~63 wt% SiO₂ have anomalously high Rb, Zr, and Th values compared to other Lazufre samples.

Chondrite normalized REE patterns for both volcanoes are similar for all analyzed samples (Figure 6.5). These rocks are LREE enriched with La_(n) = 136-209. The middle to heavy REE patterns exhibit a shallow slope with a steeper slope for the light REE. A MORB normalized (Sun and McDonough, 1989) trace element spider diagram for Lazufre flow rocks is illustrated in Figure 6.6. All rocks exhibit similar shaped patterns with strong relative depletions in some high field strength elements (HFSE; Nb, Ta, Zr, Hf) relative to the LILE (Ba, Sr, Rb). Figure 6.5 illustrates pronounced negative Eu anomalies ($Eu^*/Eu = 0.78-0.54$; ratios close to one are considered small), low (La/Yb)_n ratios (9.3-26.3; where “n” refers to chondrite normalized values), and (Dy/Yb)_n ratios of 1.4-1.8.

Figure 6.7 illustrates abundance ratios for selected trace elements. LILE to HFSE ratios (Ba/Zr) in Lastarria and Cordon del Azufre rocks show a general trend of increasing ratios with increasing SiO₂, however at higher SiO₂ concentrations, Cordon del Azufre ratios are more elevated and possess a larger range. Sr/Y ratios are low (37-

10) in comparison to MORB slab-melts (Defant and Drummond, 1990). Lazufre flow rocks display a decrease in Sr/Y with increasing Y, consistent with other CVZ lava flows outlined in Figure 6.7.

6.3. Radiogenic Isotopes

Figure 6.8 illustrates $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic values of Lazufre lavas and other CVZ fields. The range in $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios for Lazufre rocks is small in comparison to the range observed across the CVZ. There is no large difference in isotopic ratios between Lastarria and Cordon del Azufre, as well as no systematic changes with increasing SiO_2 (Figure 6.9). Mamani et al. (2009) outline domains within the central Andean orocline (13-28°S) based on radiogenic Pb (Figure 6.10). The central Andean orocline is characterized by thick continental crust (~70 km) and coincides with the CVZ. The Arequipa domain (15.5-21.5°S) is a dominantly mafic Proterozoic accreted terrane characterized by less radiogenic Pb isotopes and low (between 16.083 and 18.453) $^{206}\text{Pb}/^{204}\text{Pb}$ isotopic ratios. The Cordillera domain is divided in northern and southern domains, the Paracas (13-15.5°S) and Antofalla (22-28°S), respectively. Both Cordillera domains are dominantly felsic terranes that were amalgamated to the western Gondwana margin (Ramos, 2008) with more radiogenic Pb values ($^{206}\text{Pb}/^{204}\text{Pb} > 18.551$). Compared to similar rocks from the “southern Cordillera domain” discussed by Mamani et al. (2008, 2009), Lazufre rocks have higher $^{206}\text{Pb}/^{204}\text{Pb}$ (18.83 - 18.88) with Cordon del Azufre exhibiting a larger range in $^{206}\text{Pb}/^{204}\text{Pb}$ ratios than Lastarria lavas, and ϵNd values

of -2.9 to -2.8 (Figure 6.10). $^{207}\text{Pb}/^{206}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$, and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios show no distinct arrays with varying SiO_2 concentrations (Figure 6.11).

6.4 Summary

The limited and continuous compositional range of SiO_2 wt% (no substantial gaps in SiO_2 wt%), limited variation in radiogenic isotopes ($^{206}\text{Pb}/^{204}\text{Pb} = 18.83\text{-}18.88$; $^{87}\text{Sr}/^{86}\text{Sr} = 0.70621\text{-}0.70719$; $^{143}\text{Nd}/^{144}\text{Nd} = 0.51221\text{-}0.51249$) along with the low $^{87}\text{Sr}/^{86}\text{Sr}$ and high $^{206}\text{Pb}/^{204}\text{Pb}$ (Figure 6.8 and 6.10) suggest partial melting of lower mafic crust as the dominant process in the generation of Lazufre extrusive rocks.

Compositionally and isotopically Lazufre rocks are similar to rocks from the "southern Cordillera domain" discussed by Mamani et al. (2008, 2010). In these regards Lazufre rocks have high Pb isotopic ratios ($^{206}\text{Pb}/^{204}\text{Pb} = 18.88 - 18.83$) and low Sr/Y ratios (37 - 10) and ϵNd values (Figure 6.7, 6.8, and 6.10). These features have been ascribed to small degrees of melting felsic bulk composition crustal rocks either at high pressures where garnet is not a stable mineral phase in the residue or melting in the upper crust in the presence of residual feldspar (Mamani et al., 2008, 2010). Due to the limited compositional range in SiO_2 (58-65 wt%) and low $^{87}\text{Sr}/^{86}\text{Sr}$ values, only small degrees of felsic crust could be assimilated into andesitic/dacitic magma.

Differences in average concentrations of MgO and TiO_2 between the two volcanic centers, as well as differences in Ni and Cr concentrations and the negative slopes of Ni and Cr in Lastarria flow rocks can be explained by limited fractionation during crystallization of olivine and clinopyroxene, with early olivine and Fe-Ti oxide

fractionation in Cordon del Azufre lavas. Linear trends in compatible major element concentrations (CaO, MgO, TiO₂, and FeO) suggest fractional crystallization occurred over a restricted compositional range.

Enrichment trends in large ion lithophile elements (Th and Rb) suggest that closed system melting and crystallization-differentiation processes alone cannot be the only factors influencing magma composition as the contents are significantly higher than those predicted by crystal fractionation processes alone (Cole et al., 1983; Graham and Hackett, 1987). The patterns illustrated in Figure 6.6 are characterized to some degree by features considered diagnostic of subduction related magmas (e.g., Nb-Ta depletion, Ba/Ta > 450; Gill, 1981; Winter, 2010). Variable Ni and Cr concentrations in the most mafic andesitic rocks, especially from Lastarria, indicate mingling of small volumes of mafic magma with more silicic magma. The variable incompatible trace element concentrations in dacitic rocks (Rb, Zr, Th) suggest mixing of variable fractionated mafic magmas with more silicic magmas.

Figure 6.1. Total alkali concentrations versus SiO₂ for LVC lavas. Fields from Le Bas et al. (1986)

Figure 6.2. A) AFM diagram for Lazufre flow rocks. Fields from Irvine and Baragar (1971). B) Lazufre flow rocks in andesite fields. Fields from Gill (1981).

Figure 6.3. Major element oxide concentrations versus SiO_2 for Lazufre lava flows.

Figure 6.4. Trace element concentrations versus SiO_2 for Lazufre rocks.

Figure 6.5. Rare earth element fields for whole rock samples from each volcanic center. Chondrite normalization values from Sun and McDonough (1989).

Figure 6.6. MORB normalized incompatible element spider diagram for Lazufre flow rocks. MORB normalization values from Sun and McDonough (1989).

Figure 6.7. Plots of selected trace element abundance ratios for Lazufre lava flows. Fields from Mamani et al. (2008, 2010).

Figure 6.8. $^{143}\text{Nd}/^{144}\text{Nd}$ ratios versus $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for Lazufre rocks and relative to selected CVZ fields; the Altiplano-Puna Volcanic Complex (APVC), northern Chile gneisses, Puna lower-crustal felsic granulites, CVZ domes, and Cerro Galan. Black arrows outline the results of AFC (assimilation fractional crystallization) calculation. Fields from de Silva et al., 2006.

Figure 6.9. Sr and Nd isotope ratios versus SiO_2 for Lazufre lava flows.

Figure 6.10. A. Location of Pb domains (from Mamani et al., 2010). B. $^{87}\text{Sr}/^{86}\text{Sr}$ and ϵNd values plotted versus $^{206}\text{Pb}/^{204}\text{Pb}$. Lazufre symbols are same as previous diagrams. Domain values from Mamani et al. (2010).

Figure 6.11. Pb isotopic ratios versus SiO_2 for Lazufre lava flows.

CHAPTER 7: PETEROGENESIS

7.1 Introduction

This chapter presents a simple working model to explain the compositional diversity observed in Lazufre rocks and constrain processes taking place within the magmatic system. By incorporating interpretations of field relationships, mineral compositions, textures, and whole rock geochemical and isotopic data for rocks at Lazufre, a petrogenetic model can be developed to a) determine the source area, and b) identify the petrogenetic processes of the Lazufre Volcanic Complex. The Lazufre Volcanic Complex provides additional insights into the petrogenesis of continental arc rocks built on thick continental crust. The following section provides an overview of characteristics of the CVZ in comparison with the NVZ and SVZ and outlines prior work conducted on Andean volcanism, specifically the CVZ. This introductory framework will then be used to interpret the magmatic history of Lazufre flow rocks.

The unique nature of magmatism in the central Andes has attracted attention due to the compositional diversity resulting from magma ascending through thick continental crust (Davidson and de Silva, 1992; Feeley, 1993; Feeley et al, 1993; Lucassen et al., 2001; Davidson et al., 2004). Most workers agree that there is a strong correlation between isotope and trace element composition and variations in crustal thickness (de Silva, 1989; Davidson et al., 1991; Wörner et al., 1992; Reiners et al., 1995; Trumbull et al., 1999). Central Andes volcanic rocks are highly differentiated and major element-oxide chemical variations in the volcanic rocks are consistent with an overall decrease in

FeO*, MgO, TiO₂ and an increase in alkalis with increasing silica (Davidson et al., 1991; Trumbull et al., 1999). CVZ volcanic rocks also conform to subduction zone related trace element trends, demonstrating a depletion in some of the high-field strength elements (Nb and Ta), and enrichment in the large ion lithophile elements such as Ba, K, Sr, and Rb (Figure 7.1)(Davidson et al., 1991). Volcanic rocks in the CVZ have elevated initial Sr ratios ($^{87}\text{Sr}/^{86}\text{Sr} = 0.705\text{-}0.715$ in the CVZ compared to $^{87}\text{Sr}/^{86}\text{Sr} < 0.705$ in the NVZ and SVZ; Harmon et al., 1984) and lower Nd isotope ratios ($^{143}\text{Nd}/^{144}\text{Nd} < 0.5123$ in the CVZ vs. $^{143}\text{Nd}/^{144}\text{Nd} = 0.5125\text{-}0.5130$ in the NVZ and CVZ; Davidson and de Silva, 1992) than volcanic rocks in the NVZ and SVZ (Davidson and de Silva, 1995)(Figure 7.2). The unique geochemical characters of the CVZ have led to three extant petrogenetic models: (1) large scale crustal contamination of mantle-wedge-derived magmas during ascent through the crust (de Silva, 1989; Davidson et al., 1991); (2) contamination of the mantle wedge by subducted crustal or sedimentary material; or (3) derivation from ancient subcontinental mantle lithosphere (Rogers and Hawkesworth, 1989).

It is difficult to support a model of derivation from subcontinental mantle lithosphere because there are no primitive volcanic rocks in the CVZ and the CVZ lithospheric mantle is considered to be highly depleted, cold and infertile (Davidson et al., 1990). In addition, geophysical data suggest that lithospheric mantle has not been present beneath the Western Cordillera since the Miocene and volcanism correlates to places where there is a substantial asthenospheric wedge (Thorpe et al., 1980; Gilbert et

al., 2005; Schurr et al., 2006). Finally, it is unlikely that a mantle melt could ascend through up to 70 km of crust unaffected (Reiners et al., 1995).

The CVZ exhibits a wide variation of isotopic composition (Sr, Nd, Pb; Figure 6.9 and 7.1) which suggests that it is controlled by compositional differences in the source area and supports a crustal contamination hypothesis (Wörner et al., 1992). Wörner et al. (1992) present two isotopic provinces that are defined by variations in crustal Sr- and Pb- isotopic compositions in a north-south traverse of the CVZ between 17.5° and 22°S latitude. In northern Chile, crustal thickness, distance to the trench, height above the Benioff zone, and sediment supply to the trench are constant. The only varying subduction zone parameter in this segment of the arc is the age (Paleozoic in the south, Proterozoic in the north) and composition of continental crust ($^{206}\text{Pb}/^{204}\text{Pb} = 17.89\text{-}18.28$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.7077$ in the north vs. $^{206}\text{Pb}/^{204}\text{Pb} = 18.59\text{-}18.79$ and $^{87}\text{Sr}/^{86}\text{Sr}$ in the south) (Wörner et al., 1992). Similarly, other studies correlate changes in isotopic composition with crustal thickness in the SVZ. Hildreth and Moorbath (1988) show that isotopic variations in the northern part of the SVZ are independent of subduction angle, convergence rate, composition of the subducting slab, and mantle composition, which all remain constant along strike between 33°-36°S. Crustal thickness is the only varying parameter in this study area. In this segment of the SVZ, the crust nearly doubles in thickness from north to south. The conclusion of Hildreth and Moorbath (1988) is that isotopic variation in the SVZ must be controlled by differences in crustal thickness, by assimilation of crust during ascent and concurrent fractional crystallization and MASH zone-type processes (Melting Assimilation Storage and Homogenization).

Data from well-studied central Andean eruptive centers can be used to construct a hypothesis about petrogenetic processes and sources. Many centers possess high-K₂O andesitic to rhyodacitic compositions, complex phenocryst zoning patterns, a diverse assemblage of silicic andesitic inclusions, cognate norite nodules, and crustal xenoliths. These features all attest to a multitude of potential differentiation processes, contaminants, and magma sources (Feeley and Davidson, 1994; Klemetti et al., 2007; Sparks et al., 2008; Grunder et al., 2008).

Petrogenetic models for volcanic rocks of intermediate to silicic composition usually invoke a variety of differentiation processes and sources. These are (1) fractional crystallization from more mafic magmas, (2) partial melting of a mafic (lower crust) or ultramafic (mantle) source, (3) mixing of coeval magmas from different sources and of varying compositions, and (4) melting and assimilation of older crustal rocks and/or mixing of magmas derived from partial melting of plutonic rocks related to the same magmatic system (de Silva, 1989; Davidson et al., 1991; Trumbull et al., 1999). These will be addressed in this study in regard to Lazufre.

7.2 Key Observations

Several important observations can be made to assist in identifying petrogenetic processes and sources. First, there is little difference in field observations, trace and major element, and isotopic compositions between the two volcanic centers, Lastarria and Cordon del Azufre therefore the centers can be combined to one study site. No areal or temporal patterns exist between the two centers or within each individual center at the

current level of temporal resolution. Magmatic inclusions and mafic glomerocrysts are present in most lava flow samples. There is very little alteration present in Lazufre flow rocks as well as little to no hydration, and only minor late oxidation in amphibole and biotite. Occurrence of olivine is restricted to magmatic inclusions, glomerocrysts, and rarely in the groundmass.

Lazufre flow rocks possess a restricted continuous compositional range (58-65 wt% SiO₂) of high-K, calc-alkaline andesites to dacites. Major elements show negative correlations for Mg, Fe, Ca and increased K and Na with increasing SiO₂. These patterns follow trends for limited crystal fractionation over a relatively restricted SiO₂ range. Anomalously high Cr and Ni in some, but not all, of the more mafic samples may indicate local mingling with a more mafic magma. This is supported by the presence of mafic magmatic inclusions in the flow rocks. Rb, Zr, and Th concentrations at higher SiO₂ content suggest assimilation of more felsic rocks.

7.3 Magmatic Processes

7.3.1 Partial Crustal Melting

Pb isotopes are a sensitive indicator of mixing and/or contamination processes as they are easily affected by crustal contamination. The ratio of Pb isotopic concentrations in typical crustal rocks is very high compared to those of mantle-derived mafic rocks (Davidson and de Silva, 1995). The limited and continuous compositional range SiO₂ wt%, low range in radiogenic isotopes ($^{206}\text{Pb}/^{204}\text{Pb} = 18.83\text{-}18.88$; $^{87}\text{Sr}/^{86}\text{Sr} = 0.70621\text{-}0.70719$; $^{143}\text{Nd}/^{144}\text{Nd} = 0.51221\text{-}0.51249$), low $^{87}\text{Sr}/^{86}\text{Sr}$ and high $^{206}\text{Pb}/^{204}\text{Pb}$ relative to

southern CVZ crustal ignimbrites, eastern Altiplano crustal ignimbrites, and upper crustal contamination trends (Figure 7.3) suggest partial melting of lower mafic crust as the dominant process in the generation of Lazufre extrusive rock. These data indicate that there is relatively little involvement of ancient or felsic continental crust in magmagenesis in this area. Davidson and de Silva (1995) suggest that fixed Pb isotope ratios are dictated by deep crustal contamination, followed by modification of major and trace element components with further differentiation at shallower depths. This is consistent with trends observed in Lazufre flow rocks and with the composition of the continental crust at $\sim 25^{\circ}\text{S}$ explained by Feeley and Hacker (1995) and Schmitz et al. (1999). The lower crust ($\sim 50\text{-}70$ km depth) is composed of Paleozoic amphibolites and gabbros while the upper crust (from ~ 50 km deep to surface) is composed of late Cenozoic granitic and intermediate composition plutonic rocks (see Chapter 2). Vigneresse et al. (1996) determined that a 20-25% melt threshold must be generated in order for a melt to segregate from the lower crust and ascend towards the upper crust. Rapp and Watson (1995) experimentally determined the composition of magma generated from partial melting of amphibolites. They report that silicic to intermediate composition liquids result from 20-40% melting of and higher degrees of melting ($\sim 40\text{-}60\%$) of amphibolite result in basalt to basaltic andesite compositions. Their results require that between $\sim 30\text{-}50\%$ partial melt must be generated from the lower crust to create a basaltic andesite to andesite composition melt proposed for the generation of Lazufre magmas.

7.3.2 Magma Mixing and Mingling

Numerous rocks demonstrate phenocryst assemblages with disequilibrium textures and there is common evidence for mixed plagioclase populations. Plagioclase phenocrysts show complex and strong zoning patterns which reflect the complicated history of the magmas. Lazufre flow rocks contain plagioclase phenocrysts with sieved zones as well as phenocrysts with dusty margins around the crystal edges occurring in the same samples and groundmass as normal, clear plagioclase grains (Figure 5.7). Some plagioclase grains have unusually Ca-rich cores ($\sim\text{An}_{90}$ compared with An_{50-60} for the majority of phenocryst cores). Typically, the composition of plagioclase rims are similar to the groundmass plagioclase in the same samples (Figure 5.8). Tsuchiyama (1985) experimentally determined that grains with sieved textures come from a more felsic magma which was subsequently mixed into andesite during ascent. In addition, Feeley and Dungan (1996) suggest that sieved zones in plagioclase are due to alternating stages of normal crystallization and melting of zones with different compositions.

Numerous phenocryst assemblages observed in Lazufre rocks present further evidence of temperature disequilibrium (Anderson, 1976; Eichelberger, 1978, 1980; Sakuyama, 1979). Amphibole phenocrysts in Lazufre lava flows possess strong Fe-Ti oxidation rims while amphibole in pumiceous rocks from Lastarria lack a reaction rim with the surrounding groundmass, with no resorption textures. Normally zoned pyroxene phenocrysts are found in the same samples as reversely zoned pyroxenes (Figure 5.9). Normally zoned pyroxenes are an indication of decreasing temperatures, while the latter indicate increasing temperatures (O'Callaghan and Francis, 1986).

Some dacites from Lazufre contain coexisting olivine and quartz without reaction rims. O’Callaghan and Francis (1986) suggest that it is unlikely for olivine to reside in magmas of dacitic composition for extended periods of time. These disequilibrium textures provide evidence suggesting that at least two magmas were mixed before eruption.

The presence of undercooled mafic magmatic inclusions in Lazufre flow rocks indicates interaction between two or more magmas. This is supported by observed textures in the inclusions which include the following: the abundant trachytic acicular plagioclase groundmass grains are indicative of crystallization in an undercooled state (Lofgren, 1974; Corrigan, 1982) and the vesiculated nature, ellipsoidal shape, and chilled margins all suggest the inclusions formed by chilling of hot, mafic magma in a cooler, more silicic host magma (Feeley and Dungan, 1996).

Compatible trace elements are strongly depleted in most lava flows and display non-linear trends on variation diagrams: Sr (578 - 294 ppm), Cr (61 - 10ppm), Ni (33 - 14 ppm) (Figure 6.4). This reflects mixing of variably fractionated magmas. In addition, anomalously high Cr and Ni in more mafic samples may indicate mingling of a more mafic magma.

7.3.3. Assimilation and Fractional Crystallization

Clinopyroxenes have low Al and Ti content suggesting crystallization occurred under low-pressure, shallow-crustal conditions (Appendix D) (Feeley et al., 2002). Trends in major and trace element concentrations suggest that crystallization-differentiation over a restricted range of SiO₂ compositions were important in the

evolution of the magmas. These trends include consistent decreases with MgO (4.0 - 1.5 wt.%), CaO (6.4 - 3.5 wt.%), TiO₂ (1.03 - 0.61 wt.%), and FeO (6.8 - 3.9 wt.%); variable increases in K₂O (2.3 - 4.1 wt.%), and little variation in Na₂O (2.9 - 3.6 wt.%) with increasing SiO₂ contents (Figure 6.3). Lazufre rocks have slightly higher Pb isotopic ratios compared to similar rocks from the “southern Cordillera domain” discussed by Mamani et al. (2008) (Figure 6.10). These features have been ascribed to melting of felsic bulk composition crustal rocks either at high pressures where garnet is not a stable mineral phase in the residue or melting in the upper crust in the presence of residual feldspar. All Lazufre rocks have pronounced negative Eu anomalies (0.78 - 0.54), low (La/Yb)_n ratios (9.3 - 26.3; where "n" refers to chondrite normalized values), and shallow sloping middle to heavy REE patterns ([Dy/Yb]_n = 1.4 - 1.8). In addition Lazufre flow rocks do not exhibit a garnet trace element signature of strongly depleted HREEs, which is expected from subduction erosion in the high pressure of the mantle wedge (Goss and Kay, 2009; Godoy et al., 2014). For these reasons, the latter hypothesis is favored for Lazufre. Decreasing Sr/Y ratios with increasing Y is consistent with other CVZ centers (Figure 6.7) and attests to participation of large amounts of plagioclase during low pressure fractional crystallization (Defant and Drummond, 1993; Feeley and Hacker, 1995). Anomalously high Rb, Zr, and Th concentrations at higher SiO₂ content suggests partial assimilation of more felsic rocks as the LILE contents are much higher than those predicted by crystal fractionation of plagioclase and pyroxenes (Cole et al., 1983; Graham and Hackett, 1987). Depletion in Nb and Ta (Figure 7.2) are diagnostic of

subduction zone magmatism and most likely were derived from assimilation of mid to upper crustal rocks (Mamani et al., 2010; Godoy et al., 2014).

7.4 Petrogenetic Model

The textural and geochemical evidence described above suggest the following petrogenetic processes took place. Figure 7.4 presents a schematic diagram illustrating a possible scenario for generation of the andesites and dacites observed at Lazufre. The production of Lazufre flow rocks involved a multi-stage crustal modification process. (1) Dehydration of the subducting Nazca Plate results in partial melting of the mantle wedge and possibly the slab, generating a high MgO primary basalt (Tatsumi et al., 1983). (2) Feeley and Davidson (1994) and Feeley and Hacker (1995) suggest that primary basalts reside at the boundary of the upper mantle and lower continental crust, generating partial melt of lower, mafic crust with low $^{143}\text{Nd}/^{144}\text{Nd}$ values ($^{143}\text{Nd}/^{144}\text{Nd} < 0.5122$) and enrichment in incompatible trace elements. At deep crustal levels, $^{87}\text{Sr}/^{86}\text{Sr}$ values are low ($^{87}\text{Sr}/^{86}\text{Sr} = 0.755\text{-}0.706$) (Davidson and de Silva, 1995). In contrast, Lazufre $^{87}\text{Sr}/^{86}\text{Sr}$ values are slightly higher ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70621\text{-}0.70719$) than that of the lower crust. Davidson and de Silva (1995) suggest that a diverse range of parental magmas is generated in the process of primary basalt generation (see “Range of magmas from deeper crustal levels” field in Figure 7.3). (3) The basaltic andesite/andesite ascends through the lower crust to shallower crustal levels until it is slowed or stopped due to the reduced density of the Low Velocity Zone (zone of partial melt at depths >20 km; refer to Chapter 2) in the mid crust under the Western Cordillera (Schmitz et al., 1997; Schilling

et al., 1997; de Silva, 1989; Trumbull et al., 1999). On ascent to upper crustal levels, magmas collect in magma chambers and homogenize much of the diversity that may have been generated at lower crustal levels (Davidson and de Silva, 1995). Trumbull et al. (1999) suggest that the hot magma could pond in the low density partial melt, thus increasing crustal melting and assimilation. Assimilation at mid crustal levels explains the elevated $^{87}\text{Sr}/^{86}\text{Sr}$ values observed in Lazufre flow rocks relative to lower crust as $^{87}\text{Sr}/^{86}\text{Sr}$ values are high in the upper crust of the Altiplano-Puna ($^{87}\text{Sr}/^{86}\text{Sr} > 0.71$; Davidson and de Silva, 1995). Contamination is also reflected in elevated contents of some highly mantle incompatible elements (Rb, Th, K). This is consistent with the shallow MASH-type (Melting Assimilation Storage and Homogenization) process proposed by Hildreth and Moorbath (1988) for magma generation in the CVZ volcanic chain. MASH processes are also demonstrated in Figure 7.5 in the limited range of and low values $^{87}\text{Sr}/^{86}\text{Sr}$ relative to upper crustal values. Due to the limited compositional range in SiO_2 (58-65 wt%) and low $^{87}\text{Sr}/^{86}\text{Sr}$ values, only small degrees of felsic crust could be assimilated, slightly modifying the andesitic/dacitic magma. (4) Once the density of the magma is decreased through minor degrees of assimilation and fractional crystallization, the andesitic magma migrates to the upper crust and accumulates in a shallow crustal andesitic magma chamber (Feeley and Hacker, 1995). As the magma cools, fractionation of a plagioclase and pyroxene mineral assemblage occurs, resulting in an andesite to dacite assemblage. Injections of less-fractionated, more mafic magmas occur, causing mingling and mixing of small volumes of a more

mafic melt with large volumes of cooler, more silicic magma. (5) Finally, fractional crystallization of andesitic and dacitic magmas takes place at shallow crustal levels.

7.5 Summary

The petrogenetic model for Lazufre can be compared to models proposed for other CVZ volcanic systems. The San Pedro-Linzor volcanic chain lies to the north of Lazufre (~22°S). Godoy et al. (2014) propose that there is not a significant role of lower continental crust during magmatic differentiation and primary magma ascent to upper crustal levels. The Lazufre model proposes the primary magmatic source to be andesitic magma generated by partial melting of mafic lower crust, followed by ascent through upper crust with little influence on the compositional diversity of the magma. Both models propose a MASH zone occurring in the zone of partial melt in the mid to upper crust, impacting incompatible trace elements and isotopic signatures followed by shallow level fractional crystallization.

Davidson and de Silva (1995) present a petrogenetic model for volcanic centers in the Bolivian Altiplano (~18-21°S). $^{87}\text{Sr}/^{86}\text{Sr}$ values in this area are more variable and higher on average ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7058\text{-}0.7137$). Their model suggests crustal contamination and assimilation as a major process in the generation of the magmas. In addition, they suggest that magmas are not stored or differentiated in the upper crust, as is proposed for Lazufre. The model does, however, suggest that magmas are generated in the lower crust and then undergo processing at several levels in the crust which is consistent with the proposed petrogenetic model for Lazufre.

Figure 7.1. MORB normalized incompatible element spider diagram for Lazufre flow rocks (black lines) and central Altiplano-Puna samples (shaded grey). MORB normalization values from Sun and McDonough (1989). Altiplano fields from Davidson and de Silva (1995).

Figure 7.2. A: Nd and Sr isotope compositions of Lazufre flow rocks relative to island-arc volcanic rocks (IAV) and volcanic rocks of northern, central, and southern Andean volcanic zones (NVZ, CVZ, and SVZ, respectively). B: Pb isotope compositions of Lazufre flow rocks relative to volcanic rocks from the Andean arc and basalts and sediments of subducted Nazca plate. Fields from Davidson and de Silva (1992).

Figure 7.3. Lazufre isotopic compositions in comparison with crustal isotopic signatures. Shaded fields from Davidson and de Silva (1995).

Figure 7.4. Schematic diagram of a petrogenetic model for Lazufre. 1) Generation of a high MgO primary basalt; 2) partial melting of lower crust generated basaltic andesite/andesite; 3) magma ascends to mid crustal levels, is slowed and undergoes MASH-type processes; 4) magma migrates to upper crust where fractionation and mixing occur; 5) fractional crystallization occurs, generating andesites and dacites of final composition.

Figure 7.5. $^{87}\text{Sr}/^{86}\text{Sr}$ vs. SiO_2 diagram for Lazufre flow rocks. $^{87}\text{Sr}/^{86}\text{Sr}$ show trends consistent with MASH processes and minor AFC processes. Fields from Godoy et al. (2014).

CHAPTER 8: DISCUSSION

8.1 Volcanic Hazards

Aside from one recent lava flow at Cordon del Azufre appearing to postdate glaciation, glacial erosion at Lazufre suggests that both Lastarria and Cordon del Azufre are in periods of dormancy. However, new geophysical data has shown a large active elliptical deformation area positioned between the two volcanic centers (Pritchard and Simons, 2002; Remy et al., 2014; Pearse and Lundgren, 2013) which could be related to future eruptions. The observation of the spatial distribution of lava flows that have previously been erupted suggests that it would be difficult to predict where a lava flow would be likely to occur in a future potential eruption. The active deformation at Lazufre suggests that the inflation is due to the injection of new magma beneath the volcanic centers (Pearse and Lundgren, 2013). This uplift could cause instability of altered rocks around the flanks of the centers, especially Lastarria, causing partial collapse of a vent and debris avalanches. This is further evidenced by the debris avalanche deposits on Lastarria's lower eastern flank (Naranjo and Francis, 1987). In addition, this event has occurred in other CVZ composite cones (Grunder et al., 2008; Feeley et al., 1993; de Silva et al., 1993). Pyroclastic flows and volcanic blasts have been associated with debris avalanches at other intermediate centers (Clavero et al., 2004; Voight et al., 2002; Sparks and Young, 2002). Nearby zones could potentially be affected with ash fall in a more explosive eruption; however there are no populated areas in the nearby vicinity, therefore consequences of such an eruption would be minimal.

CHAPTER 9: CONCLUSIONS

This study combines field, petrographic, and geochemical data to characterize and identify processes occurring at the Lazufre Volcanic Complex, at $\sim 25^{\circ}14'S$, in the CVZ. The results obtained are permissive of the following conclusions.

- (1) Volcanic rocks erupted from Lazufre are andesites to dacites within a limited compositional range (59-67 wt% SiO_2) and conform to a medium- to high-K calc-alkaline suite. Typical phenocryst assemblage is plagioclase-orthopyroxene-clinopyroxene-amphibole. Micro-inclusions and glomerocrysts contain trace olivine.
- (2) Plagioclase and pyroxene phenocrysts in all rocks exhibit textures consistent with thermal disequilibrium. Magmatic inclusions indicate ‘comingling’ of more than one magma during eruption and injections of a hotter, more mafic magma into a larger volume of cooler, less evolved magma.
- (3) Observed geochemical trend differences from Lastarria and Cordon del Azufre cannot be explained by fractional crystallization alone. Their magmas were most likely derived from partial melt of mafic lower crust. Further processes followed, including fractional crystallization, assimilation, and mixing to explain the differences. At Lazufre, fractionation was dominated by plagioclase, CPX, and OPX with minor fractionation of amphibole and biotite.
- (4) Sr, Nd, and Pb isotopic geochemistry of the volcanic rocks cannot be explained through a closed-system, fractionation-dominated origin. The variation in isotopic composition suggests a parental magma was generated in the lower crust which was later modified by homogenization and small degrees of mixing and assimilation (MASH-type

processes) and fractional crystallization during differentiation through ascent of the mid and upper crust.

(5) The origin of Lazufre Volcanic Complex rocks involved a multitude of differentiation processes and magma sources. These include partial melting of mafic lower crust, crystallization-differentiation from more mafic magmas, melting and assimilation of older crustal rocks, and magma mixing and mingling.

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APPENDICES

APPENDIX A

SAMPLE LOCATIONS

Sample Location	Sample Number	Longitude (S)	Latitude (W)	Elevation (ft)
Lastarria	LAS 02	25.274	68.613	14186
	LAS 03	25.274	68.612	14274
	LAS 04	25.271	68.611	14481
	LAS 05	25.267	68.608	14584
	LAS 06	25.266	68.609	14163
	LAS 07	25.275	68.609	14358
	LAS 08	25.277	68.605	14433
	LAS 09	25.251	68.610	14573
	LAS 10	25.216	68.630	14321
	LAS 11	25.256	68.608	14540
	LAS 12	25.252	68.598	14919
	LAS 13	25.253	68.594	15153
	LAS 14	25.250	68.588	15573
	LAS 15	25.250	68.593	15558
	LAS 16	25.243	68.599	15268
	LAS 17	25.152	68.546	14943
	LAS 18	25.146	68.549	14757
	LAS 19	25.145	68.556	14492
	LAS 20	25.133	68.557	14356
	LAS 21	25.151	68.537	15327
	LAS 22	25.151	68.522	16217
	LAS 23	25.182	68.523	16296
	LAS 24	25.184	68.524	16317
	LAS 25	25.184	68.525	16314
	LAS 26	25.140	68.539	14922
	LAS 27	25.129	68.542	14485
	LAS 29	25.139	68.510	15648
	LAS 30	25.146	68.511	16304
	LAS 31	25.145	68.513	16225
	LAS 32	25.136	68.517	15424
	LAS 33	25.155	68.512	17508
Cordon del Azufre	CA 01	25.330	68.603	13923
	CA 02	25.330	68.602	13992
	CA 04	25.325	68.590	14448
	CA 05	25.326	68.588	14452
	CA 06	25.329	68.593	14272
	CA 07	25.335	68.580	14839

	CA 08	25.344	68.581	14328
	CA 09	25.349	68.574	14871
	CA 10	25.281	68.601	14303
	CA 11	25.289	68.561	15525
	CA 12	25.285	68.565	15320
	CA 15	25.357	68.552	15737
Ancestral				
Lastarria				
	ALA 01	25.263	68.613	14301
	ALA 04	25.186	68.629	14041
	ALA 06	25.152	68.475	16348
	ALA 07	25.156	68.479	16576
	ALA 08	25.161	68.470	15842
	ALA 09	25.136	68.473	15087
	ALA 10	25.180	68.611	13962
Ancestral Cordon				
del Azufre				
	ACA 01	25.342	68.610	13736
	ACA 02	25.344	68.607	
	ACA 03	25.284	68.610	14119
	ACA 04	25.281	68.614	14080
	ACA 06	25.279	68.577	15130
	ACA 07	25.295	68.630	13680
	ACA 08	25.278	68.628	13932

APPENDIX B

MODAL POINT COUNTING DATA

Sample	Groundmass	Plagioclase	Opaque	CPX	OPX	Hornblende	Biotite	Quartz	Olivine	Sphene	TOTAL Phenocrysts
LAS 01	76.4	12.0	3.4	0.3	4.6	1.1	0.0	0.3	1.7	0.3	23.6
LAS 02	81.7	7.2	7.8	0.0	0.0	2.5	0.0	0.0	0.6	0.3	18.3
LAS 03	80.6	11.3	5.2	0.3	0.3	1.2	0.0	0.0	0.9	0.3	19.4
LAS04	40.0	25.3	3.3	17.0	1.0	10.0	0.8	0.0	0.0	2.8	60.0
LAS05	50.0	21.8	1.5	15.3	0.8	7.5	0.5	0.0	0.0	2.8	50.0
LAS06	60.0	22.3	1.0	9.5	3.0	4.0	0.0	0.3	0.0	0.0	40.0
LAS07	40.0	32.0	1.5	17.8	1.0	6.0	1.0	0.0	0.0	0.8	60.0
LAS08	35.0	31.8	1.3	17.0	1.3	6.8	6.5	0.0	0.0	0.5	65.0
LAS09	60.0	22.8	0.3	11.8	0.5	4.5	0.0	0.0	0.0	0.3	40.0
LAS10	55.0	24.5	1.0	11.8	2.0	0.3	2.0	1.5	0.0	2.0	45.0
LAS11	60.0	20.0	1.3	11.3	1.0	3.0	1.5	1.0	0.0	1.0	40.0
LAS12	65.3	19.3	0.5	8.3	1.3	5.0	0.0	0.0	0.0	0.3	34.7
LAS13	60.0	16.0	1.3	10.0	2.5	9.5	0.8	0.0	0.0	0.0	40.0
LAS14	60.0	15.5	0.8	15.0	1.8	3.3	2.8	0.8	0.0	0.3	40.0
LAS15	65.0	17.3	0.5	13.3	1.3	1.3	0.0	0.3	0.0	0.0	35.0
LAS16	60.0	18.8	0.0	11.8	3.5	4.8	1.0	0.3	0.0	0.0	40.0
LAS17	75.0	12.3	0.5	8.8	1.0	2.5	0.0	0.0	0.0	0.0	25.0
LAS18	70.0	16.5	0.8	7.0	4.0	1.8	0.0	0.0	0.0	0.0	30.0
LAS19	65.0	13.5	0.0	10.5	5.3	5.8	0.0	0.0	0.0	0.0	35.0
LAS20	70.0	16.3	0.3	9.3	1.3	1.8	1.3	0.0	0.0	0.0	30.0
LAS21	75.0	11.5	0.8	7.8	2.0	2.5	0.5	0.0	0.0	0.0	25.0
LAS22	70.0	17.0	0.3	10.8	0.5	1.5	0.0	0.0	0.0	0.0	30.0
LAS23	60.0	18.5	1.0	13.3	2.3	2.8	1.0	1.0	0.0	0.0	40.0
LAS24	70.0	12.0	0.0	10.5	1.0	2.8	1.3	1.3	0.0	1.3	30.0
LAS25	75.0	12.5	0.5	8.5	2.0	0.8	0.8	0.0	0.0	0.0	25.0
LAS26	70.0	11.8	1.8	8.3	3.5	4.0	0.8	0.0	0.0	0.0	30.0
LAS27	65.0	16.8	0.3	10.0	3.3	4.3	0.5	0.0	0.0	0.0	35.0
LAS28	75.0	12.5	0.3	8.5	0.8	2.0	1.0	0.0	0.0	0.0	25.0
LAS29	75.0	10.0	0.3	6.8	3.0	3.0	1.3	0.0	0.0	0.8	25.0
LAS30	70.0	14.0	0.8	9.8	1.8	2.8	0.5	0.0	0.0	0.5	30.0
LAS31	60.0	17.5	1.0	9.8	4.3	0.0	0.0	0.8	5.3	1.3	40.0

Sample	Groundmass	Plagioclase	Opaque	CPX	OPX	Hornblende	Biotite	Quartz	Olivine	Sphene	TOTAL Phenocrysts
LAS32	80.0	8.5	0.5	6.3	1.3	2.5	0.8	0.0	0.0	0.3	20.0
LAS33	70.0	14.5	1.0	9.3	1.8	3.0	0.5	0.0	0.0	0.0	30.0
CA 01	76.8	13.4	6.0	0.3	0.5	1.4	0.0	0.0	1.6	0.0	23.2
CA 02	74.7	16.5	4.8	0.0	0.4	1.2	0.0	0.4	2.0	0.0	25.3
CA 03	76.8	12.3	5.7	0.0	2.3	1.7	0.0	0.0	0.9	0.3	23.2
CA 04	76.0	11.2	6.1	0.4	0.9	2.9	0.0	0.0	2.0	0.4	24.0
CA 05	58.2	21.4	11.0	0.0	1.2	4.2	0.0	0.6	3.6	0.0	41.8
CA 06	68.1	15.8	9.3	0.3	1.4	3.7	0.0	0.0	1.4	0.0	31.9
CA 06E	34.8	16.0	39.0	0.6	2.2	4.2	0.0	0.0	2.2	1.0	65.2
CA 07	64.2	16.0	6.2	0.5	4.3	6.5	0.0	0.0	1.4	0.8	35.8
CA 08	73.2	13.8	6.6	0.3	0.9	2.0	1.2	0.0	1.7	0.3	26.8
CA 09	79.4	13.9	3.1	0.6	1.4	1.7	0.0	0.0	0.0	0.0	20.6
CA 10	82.6	10.5	3.9	0.6	0.6	0.8	0.0	0.0	1.1	0.0	17.4
CA 11	66.9	17.8	8.5	0.0	0.6	2.5	0.6	0.0	2.0	1.1	33.1
CA 12	82.4	13.3	2.5	0.6	0.0	0.0	0.0	0.0	1.2	0.0	17.6
CA 13	58.3	24.3	8.3	0.0	0.3	2.6	1.4	0.0	3.7	1.1	41.7
CA 14	83.1	10.3	4.2	0.0	0.3	0.3	0.0	0.3	1.5	0.0	16.9
CA 15	71.4	11.1	10.6	0.9	1.4	2.3	0.0	0.6	1.7	0.0	28.6
CA 16	56.2	22.7	10.0	0.3	0.8	5.7	0.0	0.0	4.1	0.3	43.8
CA 17	78.4	10.2	5.8	0.8	1.4	2.5	0.0	0.0	0.8	0.0	21.6
CA 20	67.2	15.4	8.6	0.6	1.8	3.6	0.0	1.2	1.5	0.3	32.8
CA 21	66.2	16.0	13.1	0.3	0.3	2.7	0.0	0.0	1.2	0.3	33.8
CA 23	62.7	17.0	12.2	0.5	1.4	4.6	0.0	0.0	1.4	0.3	37.3
ALA01	75.1	9.4	10.2	0.3	0.6	2.2	0.0	0.3	1.9	0.0	24.9
ALA02	70.6	14.7	6.5	0.6	0.8	1.7	2.0	0.3	2.8	0.0	29.4
ALA08	60.5	18.4	0.3	13.6	1.5	2.0	1.0	0.8	0.0	2.0	39.5
ALA09	45.1	23.1	1.3	15.5	1.0	5.5	0.3	5.5	0.0	2.8	54.9
ALA10	50.0	22.0	5.0	10.8	1.3	6.5	1.0	0.8	0.0	2.0	50.0
ACA01	68.6	17.6	5.5	0.7	2.6	2.9	0.0	0.0	2.1	0.0	31.4

Sample	Groundmass	Plagioclase	Opaque	CPX	OPX	Hornblende	Biotite	Quartz	Olivine	Sphene	TOTAL Phenocrysts
ACA02	79.9	13.4	2.5	0.0	1.0	1.6	0.0	0.0	1.6	0.0	20.1
ACA03	83.3	10.0	3.2	0.5	1.0	0.2	0.0	0.0	1.7	0.0	16.7
ACA04	75.2	17.2	0.6	2.3	2.6	0.0	0.0	0.0	2.0	0.0	24.8
ACA05	71.4	18.5	4.4	0.3	0.5	0.3	0.0	2.1	2.6	0.0	28.6
ACA06	71.9	13.4	7.8	0.0	0.6	1.4	0.0	1.1	2.5	1.4	28.1
ACA07	64.6	17.1	9.1	0.8	1.7	3.3	0.0	0.0	3.0	0.3	35.4
ACA08	68.2	18.0	7.9	0.0	2.0	2.3	0.0	0.0	1.7	0.0	31.8

Note: All modal point counting data are reported in %.

APPENDIX C

FELDSPAR COMPOSITIONS

Appendix C. Feldspar Compositions

PHENOCRYST	SAMPLE	REMARK	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	SUM
Plag 1- normal	CA 06	Rim	55.64	25.95	0.30	0.01	8.38	6.27	0.96	97.55
Plag 1- normal	CA 06	Intermediate	56.60	25.65	0.36	0.04	8.14	6.40	0.97	98.16
Plag 1- normal	CA 06	Core	55.83	25.80	0.34	0.03	8.14	6.31	0.97	97.46
Plag 2- normal	CA 06	Rim	55.73	26.39	0.36	0.04	8.89	5.88	0.86	98.13
Plag 2- normal	CA 06	Intermediate	56.58	25.87	0.35	0.03	8.33	6.22	0.88	98.30
Plag 2- normal	CA 06	Core	54.93	26.75	0.43	0.04	9.44	5.78	0.79	98.18
Plag 3- sieved	CA 06	Rim	50.37	30.17	0.42	0.02	13.10	3.90	0.32	98.32
Plag 3- sieved	CA 06	Core	73.65	11.46	1.11	0.06	0.43	1.55	6.18	95.59
Plag 3- sieved	CA 06	Intermediate	58.53	22.45	0.95	0.09	7.50	4.43	1.61	95.92
Plag 3- sieved	CA 06	Core	50.64	30.11	0.31	0.01	12.98	4.05	0.33	98.47
Plag 3- sieved	CA 06	Core	51.85	29.01	0.52	0.07	12.01	4.56	0.41	98.42
Plag 4- normal	CA 06	Rim	56.81	25.78	0.34	0.03	8.15	6.41	1.01	98.56
Plag 4- normal	CA 06	Core	56.80	25.56	0.35	0.01	8.15	6.36	1.02	98.23
Plag 4- normal	CA 06	Rim	56.40	25.94	0.38	0.02	8.39	6.17	0.99	98.33
Plag 5- normal	CA 06	Rim	56.23	25.85	0.36	0.03	8.45	6.29	0.96	98.19
Plag 5- normal	CA 06	Core	55.34	26.59	0.36	0.02	9.14	5.87	0.78	98.15
Plag 5- normal	CA 06	Rim	54.63	26.75	0.46	0.03	9.15	5.98	0.82	97.77
Plag 6- sieved	CA 06	Rim	50.65	29.12	0.57	0.06	12.21	4.44	0.42	97.53
Plag 6- sieved	CA 06	Core	48.06	31.29	0.51	0.04	14.59	3.36	0.27	98.15
Plag 6- sieved	CA 06	Intermediate	48.57	30.51	0.54	0.06	13.76	3.77	0.19	97.37
Plag 7- glomerocryst	CA 06	Rim	56.42	25.55	-0.17	0.02	8.07	6.33	1.02	97.27
Plag 7- glomerocryst	CA 06	Core	54.06	27.37	0.37	0.04	9.98	5.57	0.63	98.03
Plag 7- glomerocryst	CA 06	Rim	53.73	27.68	0.42	0.01	10.36	5.35	0.62	98.22
Plag microlite 2	CA 06	Microlite	49.76	29.77	0.69	0.05	12.68	3.89	0.39	97.26
Plag microlite 3	CA 06	Microlite	51.56	28.53	0.63	0.07	11.55	4.71	0.46	97.52

PHENOCRYST	SAMPLE	REMARK	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	SUM
Plag microlite 4	CA 06	Microlite	52.41	28.38	0.69	0.04	10.98	5.06	0.52	98.12
Plag microlite 5	CA 06	Microlite	52.20	27.96	0.58	0.03	10.60	5.28	0.63	97.32
Plag microlite 6	CA 06	Microlite	51.16	29.14	0.61	0.04	11.90	4.57	0.50	97.97
Plag microlite 7	CA 06	Microlite	51.61	28.29	0.66	0.06	11.18	4.94	0.51	97.32
Plag 1- sieved	LAS 15	Core	55.47	26.05	0.29	0.01	9.35	5.78	0.69	97.71
Plag 1- sieved	LAS 15	Rim	48.02	31.08	0.57	0.06	15.37	2.91	0.18	98.28
Plag 2- normal	LAS 15	Rim	56.77	25.26	0.39	0.01	8.41	6.37	0.87	98.13
Plag 2- normal	LAS 15	Core	52.95	27.72	0.30	0.03	11.09	4.83	0.47	97.43
Plag 2- normal	LAS 15	Rim	57.51	24.75	0.37	0.02	7.81	6.49	0.90	97.88
Plag 3- sieved	LAS 15	Rim	49.70	30.09	0.58	0.08	14.14	3.42	0.15	98.22
Plag 3- sieved	LAS 15	Core	47.29	31.74	0.60	0.04	15.99	2.35	0.12	98.16
Plag 4- sieved	LAS 15	Rim	48.42	30.75	0.58	0.09	14.79	2.97	0.14	97.75
Plag 4- sieved	LAS 15	Intermediate	54.80	26.41	0.34	0.03	9.79	5.58	0.72	97.66
Plag 4- sieved	LAS 15	Core	55.18	25.95	0.31	0.02	9.09	5.70	0.82	97.15
Plag 5- sieved	LAS 15	Rim	49.52	30.09	0.51	0.07	14.20	3.45	0.22	98.09
Plag 5- sieved	LAS 15	Intermediate	55.81	25.76	0.30	0.00	8.51	6.38	0.74	97.55
Plag 5- sieved	LAS 15	Core	56.21	25.66	0.27	0.00	8.61	6.27	0.71	97.71
Plag 6- sieved	LAS 15	Rim	48.40	30.69	0.62	0.06	15.09	2.87	0.17	97.94
Plag 6- sieved	LAS 15	Intermediate	49.27	29.77	0.58	0.06	14.06	3.43	0.18	97.38
Plag 6- sieved	LAS 15	Core	46.96	31.61	0.62	0.05	16.03	2.40	0.09	97.85
Plag 7- sieved	LAS 15	Rim	50.15	29.44	0.63	0.08	13.45	3.88	0.21	97.85
Plag 7- sieved	LAS 15	Core	47.44	31.53	0.64	0.03	15.59	2.59	0.14	97.97
Plag 7- sieved	LAS 15	Rim	49.12	30.50	0.62	0.07	14.33	3.36	0.15	98.18
Plag 8- normal	LAS 15	Rim	67.56	13.92	2.18	0.21	2.51	3.02	3.66	93.98
Plag 8- normal	LAS 15	Core	56.91	25.02	0.34	0.03	7.88	6.45	1.00	97.69
Plag 9- sieved	LAS 15	Rim	50.02	29.63	0.61	0.08	13.46	3.80	0.20	97.81

PHENOCRYST	SAMPLE	REMARK	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	SUM
Plag 9- sieved	LAS 15	Core	51.13	28.09	0.93	0.06	12.75	3.16	0.80	97.17
Plag 9- sieved	LAS 15	Rim	48.48	30.64	0.59	0.08	14.62	3.30	0.17	97.91
Plag microlite 1	LAS 15	Microlite	49.30	30.25	0.55	0.07	13.97	3.59	0.16	97.95
Plag microlite 2	LAS 15	Microlite	46.04	31.87	0.62	0.08	16.55	2.09	0.09	97.43
Plag microlite 3	LAS 15	Microlite	50.26	29.51	0.64	0.09	13.45	3.72	0.15	97.88
Plag microlite 4	LAS 15	Microlite	50.43	29.39	0.69	0.10	13.14	3.97	0.23	97.98
Plag microlite 5	LAS 15	Microlite	48.92	30.38	0.61	0.08	14.19	3.43	0.15	97.80
Plag microlite 6	LAS 15	Microlite	48.07	30.29	0.67	0.09	13.67	3.83	0.17	96.82
Plag microlite 7	LAS 15	Microlite	49.35	30.06	0.59	0.09	14.03	3.56	0.17	97.83
Plag microlite 8	LAS 15	Microlite	45.76	32.63	0.62	0.05	16.63	2.06	0.06	97.84
Plag microlite 9	LAS 15	Microlite	50.05	29.61	0.74	0.07	13.71	3.76	0.17	98.18
Plag microlite 10	LAS 15	Microlite	49.13	30.30	0.56	0.07	13.97	3.64	0.14	97.83
Plag 1- sieved	ACA 06	Rim	49.81	30.25	0.57	0.09	14.00	3.72	0.24	98.72
Plag 1- sieved	ACA 06	Intermediate	57.77	25.15	0.30	0.03	7.65	6.72	1.03	98.63
Plag 1- sieved	ACA 06	Core	57.16	25.62	0.26	0.03	8.54	6.44	0.87	98.97
Plag 1- sieved	ACA 06	Rim	53.12	27.80	0.73	0.04	12.03	3.97	0.80	98.64
Plag 2- normal	ACA 06	Rim	49.83	30.15	0.60	0.08	14.34	3.53	0.21	98.82
Plag 2- normal	ACA 06	Intermediate	56.16	26.52	0.31	0.02	9.16	6.17	0.77	99.15
Plag 2- normal	ACA 06	Intermediate	57.25	25.86	0.28	0.02	8.29	6.50	0.90	99.16
Plag 2- normal	ACA 06	Core	55.88	26.56	0.31	0.00	9.33	6.09	0.69	98.89
Plag 3- sieved	ACA 06	Rim	47.00	32.23	0.67	0.04	16.11	2.37	0.18	98.61
Plag 3- sieved	ACA 06	Intermediate	57.08	25.57	0.29	0.02	7.94	6.76	1.00	98.68
Plag 3- sieved	ACA 06	Core	56.43	26.04	0.25	0.02	8.61	6.43	0.87	98.68
Plag 3- sieved	ACA 06	Rim	59.85	22.85	1.11	0.08	9.06	3.10	2.31	98.89
Plag 4- normal	ACA 06	Rim	56.30	25.58	0.17	0.02	7.87	6.90	0.93	97.74
Plag 4- normal	ACA 06	Core	56.02	26.06	0.02	0.02	8.25	6.60	0.86	97.86

PHENOCRYST	SAMPLE	REMARK	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	SUM
Plag 4- normal	ACA 06	Rim	55.90	25.92	0.26	0.02	8.10	6.71	0.89	97.79
Plag 5- sieved	ACA 06	Rim	49.82	30.15	0.57	0.08	13.72	3.74	0.22	98.33
Plag 5- sieved	ACA 06	Intermediate	54.70	27.19	0.35	0.01	9.77	5.90	0.63	98.57
Plag 5- sieved	ACA 06	Core	56.46	26.09	0.33	0.02	8.45	6.53	0.85	98.73
Plag 5- sieved	ACA 06	Rim	51.92	29.10	0.48	0.07	12.08	4.63	0.40	98.73
Plag 6- normal	ACA 06	Rim	56.74	26.00	0.29	0.00	8.47	6.61	0.76	98.90
Plag 6- normal	ACA 06	Core	55.41	26.85	0.29	0.01	9.10	6.27	0.70	98.64
Plag 6- normal	ACA 06	Intermediate	57.44	25.33	0.27	0.02	7.60	6.74	0.99	98.45
Plag 7- normal	ACA 06	Rim	56.15	26.36	0.25	0.02	8.92	6.27	0.74	98.74
Plag 7- normal	ACA 06	Intermediate	57.86	25.08	0.27	-0.13	7.35	6.92	1.05	98.40
Plag 7- normal	ACA 06	Core	55.70	26.48	0.22	0.00	9.00	6.20	0.76	98.38
Plag microlite 1	ACA 06	Microlite	50.75	29.40	0.38	0.02	12.06	4.77	0.41	97.84
Plag microlite 2	ACA 06	Microlite	55.64	26.81	0.28	0.02	9.88	5.88	0.67	99.14
Plag microlite 3	ACA 06	Microlite	51.25	29.44	0.63	0.08	12.69	4.37	0.35	98.88
Plag microlite 4	ACA 06	Microlite	56.76	25.57	0.30	0.06	8.10	6.61	0.77	98.17
Plag microlite 5	ACA 06	Microlite	49.86	30.28	0.62	0.06	13.97	3.53	0.19	98.53
Plag microlite 6	ACA 06	Microlite	50.41	30.01	0.51	0.06	13.74	3.72	0.19	98.67
Plag microlite 7	ACA 06	Microlite	50.08	30.51	0.70	0.07	13.92	3.79	0.26	99.35
Plag microlite 8	ACA 06	Microlite	51.49	29.63	0.47	0.04	12.65	4.32	0.32	98.96
Plag 1- sieved	LAS 13	Rim	50.16	29.59	0.65	0.03	13.43	3.73	0.25	97.88
Plag 1- sieved	LAS 13	Intermediate	56.92	25.26	0.26	-0.01	7.98	6.70	0.75	97.85
Plag 1- sieved	LAS 13	Core	51.40	28.82	0.27	0.02	12.37	4.45	0.29	97.61
Plag 1- sieved	LAS 13	Rim	57.08	25.20	0.20	0.01	7.81	6.64	0.92	97.82
Plag 2- normal	LAS 13	Rim	55.66	25.92	0.29	0.02	8.72	6.29	0.77	97.68
Plag 2- normal	LAS 13	Intermediate	54.05	27.20	0.35	0.02	10.15	5.61	0.61	98.01

PHENOCRYST	SAMPLE	REMARK	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	SUM
Plag 2- normal	LAS 13	Rim	56.59	25.40	0.30	0.03	8.45	6.26	0.88	97.92
Plag 2- normal	LAS 13	Core	57.09	25.24	0.29	0.01	8.06	6.44	0.95	98.09
Plag 3- normal	LAS 13	Rim	51.44	28.72	0.60	0.05	12.28	4.46	0.39	97.99
Plag 3- normal	LAS 13	Intermediate	57.07	25.36	0.32	0.03	8.27	6.38	0.87	98.28
Plag 3- normal	LAS 13	Core	56.22	25.63	0.30	0.02	8.57	6.31	0.80	97.88
Plag 3- normal	LAS 13	Rim	56.16	25.57	0.33	0.03	8.40	6.23	0.85	97.58
Plag 4- normal	LAS 13	Rim	57.65	25.23	0.31	0.01	7.73	6.76	1.00	98.72
Plag 4- normal	LAS 13	Intermediate	56.01	26.24	0.29	0.00	8.63	6.23	0.71	98.16
Plag 4- normal	LAS 13	Core	55.52	26.58	0.26	0.01	9.26	6.09	0.68	98.43
Plag 5- sieved	LAS 13	Rim	51.25	26.79	0.61	0.04	12.88	4.12	0.31	96.04
Plag 5- sieved	LAS 13	Intermediate	55.19	24.68	0.23	0.02	9.75	5.71	0.58	96.20
Plag 5- sieved	LAS 13	Core	56.11	23.78	0.29	0.03	8.88	6.18	0.72	96.03
Plag 6- sieved	LAS 13	Rim	50.62	26.93	0.64	0.09	13.50	3.83	0.23	95.90
Plag 6- sieved	LAS 13	Intermediate	48.31	28.02	0.78	0.04	14.86	2.86	0.16	95.03
Plag 6- sieved	LAS 13	Core	50.68	26.91	0.54	0.04	13.17	3.90	0.30	95.56
Plag 7- normal	LAS 13	Rim	56.20	23.39	0.37	0.03	8.86	5.92	0.72	95.51
Plag 7- normal	LAS 13	Intermediate	56.79	23.64	0.33	0.02	8.33	6.27	0.91	96.31
Plag 7- normal	LAS 13	Core	57.16	23.13	0.30	0.02	8.24	6.24	0.93	96.07
Plag microlite 1- inclusion	LAS 13	Microlite	50.90	26.73	0.99	0.08	12.71	4.00	0.35	95.91
Plag microlite 2- inclusion	LAS 13	Microlite-	50.89	26.31	0.81	0.02	12.85	3.40	0.47	94.89
Plag glomerocryst 1	LAS 13	glomerocryst	56.73	23.28	0.46	0.03	8.31	6.19	0.81	95.84
Plag microlite 3	LAS 13	microlite	50.30	27.21	0.63	0.06	13.21	3.85	0.30	95.59
Plag microlite 4	LAS 13	microlite	49.77	27.34	0.58	0.08	13.71	3.53	0.22	95.34
Plag microlite 5	LAS 13	microlite	50.01	27.22	0.61	0.06	13.48	3.59	0.25	95.22
Plag microlite 6	LAS 13	microlite	51.54	26.08	0.53	0.06	12.18	4.41	0.35	95.22
Plag microlite 7	LAS 13	microlite	50.53	26.89	0.67	0.08	13.16	3.98	0.28	95.62
Plag microlite 8	LAS 13	microlite	48.07	28.61	0.63	0.05	15.08	2.80	0.17	95.45

PHENOCRYST	SAMPLE	REMARK	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	SUM
Plag 1- normal	CA 10	Intermediate	56.13	23.88	0.38	0.02	8.83	6.01	0.94	96.23
Plag 1- normal	CA 10	Rim	49.89	28.10	0.91	0.11	13.67	3.73	0.25	96.73
Plag 1- normal	CA 10	Core	56.21	24.09	0.38	0.03	8.75	6.19	0.98	96.64
Plag 1- normal	CA 10	Intermediate	56.52	24.23	0.42	0.03	8.63	6.20	0.95	97.00
Plag 1- normal	CA 10	Rim	52.26	26.96	0.40	0.04	12.00	4.60	0.40	96.71
Plag 2- sieved	CA 10	Rim	57.58	23.36	0.32	0.02	7.92	6.79	0.64	96.67
Plag 2- sieved	CA 10	Intermediate	56.18	24.19	0.27	0.01	9.13	6.26	0.67	96.74
Plag 2- sieved	CA 10	Core	55.88	24.85	0.31	0.02	9.08	6.25	0.64	97.05
Plag 2- sieved	CA 10	Rim	56.25	24.46	0.34	0.02	8.72	6.50	0.56	96.89
Plag 3- normal	CA 10	Rim	56.01	24.46	0.29	0.02	9.18	6.25	0.56	96.79
Plag 3- normal	CA 10	Intermediate	54.68	25.14	0.22	0.01	10.05	5.78	0.30	96.20
Plag 3- normal	CA 10	Core	54.94	25.21	0.26	0.00	9.96	5.84	0.32	96.59
Plag 3- normal	CA 10	Rim	55.55	24.73	0.32	0.01	9.51	6.02	0.51	96.66
Plag 4- normal	CA 10	Rim	56.93	23.42	0.41	0.03	8.43	6.31	0.92	96.50
Plag 4- normal	CA 10	Intermediate	56.38	23.90	0.41	0.04	8.82	6.04	0.89	96.53
Plag 4- normal	CA 10	Core	56.11	24.42	0.38	0.01	8.83	6.09	0.84	96.69
Plag 4- normal	CA 10	Rim	56.33	23.84	0.53	0.03	8.77	6.00	0.92	96.46
Plag 5- sieved	CA 10	Rim	49.92	27.92	0.96	0.05	13.62	3.69	0.32	96.59
Plag 5- sieved	CA 10	Core	55.22	24.92	0.43	0.04	9.64	5.62	0.87	96.79
Plag 5- sieved	CA 10	Rim	54.51	25.27	0.48	0.03	9.68	5.66	0.81	96.47
Plag 6- normal	CA 10	Rim	54.50	24.87	0.46	0.03	10.32	5.46	0.51	96.17
Plag 6- normal	CA 10	Intermediate	56.27	24.07	0.43	0.02	8.71	6.23	0.72	96.49
Plag 6- normal	CA 10	Core	55.77	24.67	0.40	0.03	9.41	5.91	0.77	96.93
Plag 6- normal	CA 10	Rim	51.43	26.79	0.77	0.07	12.87	4.11	0.27	96.38
Plag 7- sieved	CA 10	Rim	48.61	28.35	0.79	0.06	14.81	3.05	0.22	95.92
Plag 7- sieved	CA 10	Core	56.22	24.30	0.44	0.02	8.59	6.31	0.94	96.84
Plag 7- sieved	CA 10	Intermediate	56.43	24.16	0.44	0.01	8.73	6.01	0.95	96.78

PHENOCRYST	SAMPLE	REMARK	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	SUM
Plag 8- normal	CA 10	Rim	60.22	21.35	0.69	0.06	7.23	5.76	1.48	96.95
Plag 7- sieved	CA 10	Rim	48.77	28.15	0.70	0.07	14.68	3.07	0.20	95.71
Plag 8- normal	CA 10	Core	55.06	23.75	0.45	0.04	9.48	5.89	1.04	95.75
Plag 8- normal	CA 10	Rim	56.95	23.74	0.52	0.02	7.93	6.52	1.22	96.94
Plag 9- normal- inclusion	CA 10	Rim	56.64	23.95	0.45	0.03	8.40	6.45	0.94	96.91
Plag 9- normal- inclusion	CA 10	Intermediate	56.90	23.87	0.37	0.03	8.37	6.28	0.90	96.77
Plag 9- normal- inclusion	CA 10	Core	56.58	24.13	0.38	0.02	8.72	6.25	0.84	96.91
Plag 9- normal- inclusion	CA 10	Rim	49.64	27.41	0.90	0.08	13.73	3.65	0.26	95.72
Plag 10- normal- inclusion	CA 10	Rim	56.64	24.04	0.35	0.01	8.37	6.39	0.95	96.77
Plag 10- normal- inclusion	CA 10	Core	56.87	23.75	0.32	0.02	8.23	6.33	0.94	96.48
Plag 11- sieved- inclusion	CA 10	Rim	49.59	28.16	0.89	0.07	13.97	3.51	0.26	96.53
Plag 11- sieved- inclusion	CA 10	Core	54.36	25.53	0.42	0.05	10.32	5.42	0.67	96.79
Plag 12- sieved- inclusion	CA 10	Rim	47.37	30.24	0.70	0.04	16.24	2.15	0.25	97.07
Plag 12- sieved- inclusion	CA 10	Core	53.69	25.83	0.45	0.04	10.66	5.28	0.53	96.52
Plag 13- normal- inclusion	CA 10	Rim	48.86	28.61	0.71	0.11	14.31	3.25	0.24	96.10
Plag 13- normal- inclusion	CA 10	Core	55.64	24.64	0.46	0.05	9.32	5.95	0.85	96.95
Plag microlite 1	CA 10	microlite	55.70	24.61	0.30	0.02	9.16	6.25	0.48	96.55
Plag microlite 2	CA 10	microlite	56.39	23.70	0.20	0.00	8.75	6.37	0.66	96.08
Plag microlite 3	CA 10	microlite	54.31	25.57	0.31	0.02	10.52	5.65	0.30	96.77
Plag microlite 4	CA 10	microlite	56.20	23.81	0.20	0.01	9.02	6.20	0.51	95.95
Plag microlite 5	CA 10	microlite	56.18	24.33	0.21	0.02	9.13	6.13	0.52	96.55
Plag microlite 6- inclusion	CA 10	microlite	49.75	27.07	0.96	0.08	13.72	3.64	0.28	95.50
Plag microlite 7- inclusion	CA 10	microlite	50.23	27.33	0.95	0.10	13.61	3.75	0.27	96.35
Plag microlite 8- inclusion	CA 10	microlite	50.14	26.85	1.03	0.07	13.42	3.78	0.34	95.64
Plag microlite 9- inclusion	CA 10	microlite	50.38	27.26	0.91	0.11	13.62	3.74	0.25	96.37
Plag microlite 10- inclusion	CA 10	microlite	49.73	27.64	0.84	0.10	13.99	3.51	0.26	96.17
Plag 1- normal	ALA 10	Rim	59.76	24.42	0.23	0.01	6.65	7.09	1.17	99.39

PHENOCRYST	SAMPLE	REMARK	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	SUM
Plag 1- normal	ALA 10	Core	55.96	27.09	0.32	0.01	9.59	5.83	0.52	99.34
Plag 1- normal	ALA 10	Intermediate	57.50	26.01	0.36	0.01	8.48	6.34	0.64	99.34
Plag 1- normal	ALA 10	Intermediate	55.71	27.27	0.34	0.02	9.96	5.75	0.48	99.50
Plag 1- normal	ALA 10	Rim	57.96	25.86	0.26	0.01	8.40	6.34	0.67	99.53
Plag 2- sieved	ALA 10	Rim	57.96	25.47	0.29	0.00	8.12	6.44	0.88	99.12
Plag 2- sieved	ALA 10	Intermediate	48.65	31.97	0.33	0.01	15.37	2.73	0.13	99.25
Plag 2- sieved	ALA 10	Core	54.68	27.88	0.31	0.01	10.69	5.30	0.48	99.41
Plag 2- sieved	ALA 10	Rim	58.08	25.11	0.32	0.00	7.73	6.63	0.91	98.79
Plag 3- sieved	ALA 10	Rim	50.97	30.01	0.69	0.07	13.59	3.76	0.26	99.39
Plag 3- sieved	ALA 10	Intermediate	53.63	27.89	0.77	0.05	12.10	3.57	1.08	99.17
Plag 3- sieved	ALA 10	Core	49.14	30.91	0.73	0.03	15.00	2.94	0.23	99.03
Plag 3- sieved	ALA 10	Rim	50.09	30.62	0.69	0.07	14.07	3.27	0.21	99.06
Plag 4- normal	ALA 10	Rim	59.22	24.90	0.26	0.00	7.22	6.89	1.08	99.58
Plag 4- normal	ALA 10	Intermediate	56.90	26.24	0.28	0.02	8.87	6.18	0.66	99.13
Plag 4- normal	ALA 10	Core	56.96	26.13	0.35	0.03	8.62	6.37	0.66	99.13
Plag 4- normal	ALA 10	Rim	58.62	25.23	0.33	0.00	7.67	6.70	0.88	99.46
Plag 5- sieved	ALA 10	Rim	47.94	32.13	0.66	0.04	15.67	2.51	0.10	99.08
Plag 5- sieved	ALA 10	Intermediate	46.73	33.06	0.45	0.04	16.69	1.98	0.11	99.07
Plag 5- sieved	ALA 10	Core	47.35	32.86	0.43	0.02	16.52	2.19	0.11	99.53
Plag 5- sieved	ALA 10	Rim	48.33	31.97	0.66	0.07	15.78	2.52	0.12	99.48
Plag 6- sieved	ALA 10	Rim	59.91	25.07	0.74	0.04	9.34	4.32	1.63	101.16
Plag 6- sieved	ALA 10	Intermediate	55.40	27.66	0.35	0.03	10.20	5.35	0.54	99.63
Plag 6- sieved	ALA 10	Core	56.76	26.54	0.44	0.04	9.21	5.95	0.73	99.71
Plag 7- normal	ALA 10	Rim	57.00	26.36	0.29	0.04	8.95	6.01	0.76	99.43
Plag 7- normal	ALA 10	Intermediate	57.17	26.39	0.33	0.03	8.68	6.36	0.62	99.64
Plag 7- normal	ALA 10	Core	55.97	27.04	0.37	0.02	9.65	5.86	0.49	99.41
Plag 7- normal	ALA 10	Rim	56.23	26.88	0.39	0.01	9.32	5.98	0.59	99.43

PHENOCRYST	SAMPLE	REMARK	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	SUM
Plag 8- sieved	ALA 10	Intermediate	53.64	28.66	0.49	0.06	11.51	4.87	0.41	99.69
Plag 8- sieved	ALA 10	Rim	53.97	28.10	0.98	0.08	12.85	3.23	0.91	100.29
Plag 8- sieved	ALA 10	Core	53.39	28.79	0.44	0.02	11.66	4.68	0.57	99.56
Plag 9- normal	ALA 10	Rim	56.68	26.55	0.30	0.00	9.11	6.14	0.55	99.35
Plag 9- normal	ALA 10	Core	57.53	26.08	0.31	0.03	8.40	6.43	0.66	99.46
Plag microlite 1	ALA 10	Microlite	55.97	27.24	0.26	0.01	9.69	5.93	0.52	99.60
Plag microlite 2	ALA 10	Microlite	57.09	26.17	0.37	0.03	8.86	6.27	0.63	99.44
Plag microlite 3	ALA 10	Microlite	50.98	30.10	0.57	0.04	13.45	3.79	0.28	99.29
Plag microlite 4	ALA 10	Microlite	50.68	30.22	0.67	0.08	13.83	3.69	0.17	99.35
Plag microlite 5	ALA 10	Microlite	50.33	30.29	0.75	0.06	13.80	3.55	0.28	99.33
Plag microlite 6	ALA 10	Microlite	58.45	25.45	0.31	0.02	7.84	6.59	0.92	99.63
Plag microlite 7- inclusion	ALA 10	Microlite	51.41	29.92	0.87	0.07	13.16	3.90	0.26	99.62
Plag microlite 8- inclusion	ALA 10	Microlite	52.33	29.02	0.58	0.05	12.18	4.52	0.50	99.23
Plag microlite 9- inclusion	ALA 10	Microlite	50.46	29.46	0.83	0.11	13.47	3.79	0.39	98.57
Plag microlite 10- inclusion	ALA 10	Microlite	51.16	29.85	0.71	0.11	13.36	3.88	0.27	99.41
Plag 1- sieved	ACA 01	Rim	51.05	30.24	0.61	0.10	13.69	3.71	0.29	99.70
Plag 1- sieved	ACA 01	Intermediate	45.92	34.13	0.67	0.06	17.96	1.43	0.08	100.31
Plag 1- sieved	ACA 01	Core	46.13	33.88	0.69	0.04	17.39	1.69	0.10	99.93
Plag 1- sieved	ACA 01	Rim	46.71	33.55	0.66	0.07	17.12	1.77	0.12	100.00
Plag 2- sieved	ACA 01	Rim	52.09	29.85	0.62	0.05	13.07	4.04	0.38	100.11
Plag 2- sieved	ACA 01	Core	45.36	34.46	0.46	0.01	17.90	1.45	0.06	99.67
Plag 2- sieved	ACA 01	Intermediate	47.99	32.70	0.67	0.04	16.37	2.29	0.17	100.21
Plag 3- normal	ACA 01	Rim	60.02	24.83	0.39	0.01	6.95	6.92	1.46	100.77
Plag 3- normal	ACA 01	Intermediate	49.59	31.77	0.37	0.03	14.88	3.10	0.24	100.04
Plag 3- normal	ACA 01	Core	48.84	32.51	0.38	0.02	15.70	2.76	0.14	100.45
Plag 3- normal	ACA 01	Rim	59.81	24.87	0.39	0.02	6.91	6.99	1.40	100.43
Plag 4- normal	ACA 01	Rim	57.54	26.44	0.40	0.03	8.70	6.25	0.88	100.32

PHENOCRYST	SAMPLE	REMARK	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	SUM
Plag 5- normal	ACA 01	Rim	55.90	27.69	0.32	0.02	9.99	5.76	0.64	100.34
Plag 4- normal	ACA 01	Core	49.88	31.41	0.43	0.01	14.48	3.34	0.26	99.81
Plag 5- normal	ACA 01	Intermediate	55.67	27.34	0.31	0.03	9.63	5.79	0.70	99.47
Plag 5- normal	ACA 01	Core	57.74	26.19	0.41	0.03	8.68	6.31	0.89	100.25
Plag 5- normal	ACA 01	Rim	47.85	32.73	0.45	0.01	15.91	2.39	0.14	99.54
Plag 6- normal	ACA 01	Rim	52.09	28.58	0.63	0.07	12.22	-0.11	0.44	94.00
Plag 6- normal	ACA 01	Intermediate	52.96	29.27	0.38	0.02	12.00	4.68	0.37	99.75
Plag 6- normal	ACA 01	Core	55.32	27.56	0.36	0.03	9.84	5.67	0.67	99.46
Plag 6- normal	ACA 01	Rim	56.70	27.16	0.58	0.06	9.70	5.85	0.75	100.80
Plag 7- sieved	ACA 01	Rim	52.24	29.38	0.87	0.11	12.81	4.26	0.34	100.09
Plag 7- sieved	ACA 01	Intermediate	53.72	28.92	0.53	0.04	11.45	5.04	0.48	100.23
Plag 7- sieved	ACA 01	Core	51.27	30.55	0.69	0.08	13.54	3.88	0.26	100.30
Plag 8- inclusion	ACA 01	Rim	49.71	31.64	0.69	0.06	14.72	3.16	0.16	100.13
Plag 8- inclusion	ACA 01	Core	48.13	32.73	0.49	0.04	15.94	2.62	0.12	100.11
Plag 9- glomerocryst	ACA 01	Rim	56.96	26.98	0.26	0.01	9.02	6.28	0.69	100.22
Plag 9- glomerocryst	ACA 01	Core	60.28	24.53	0.40	0.05	7.52	6.46	1.35	100.64
Plag 1- glomerocryst	ACA 01	microlite	54.54	28.49	0.38	0.02	11.17	5.16	0.47	100.30
Plag microlite 2	ACA 01	microlite	53.48	29.04	0.36	0.02	11.78	4.82	0.49	100.08
Plag microlite 3	ACA 01	microlite	57.13	26.70	0.32	0.02	9.04	6.11	0.93	100.26
Plag microlite 4	ACA 01	microlite	50.80	30.79	0.86	0.07	13.98	3.57	0.28	100.41
Plag microlite 5	ACA 01	microlite	55.36	27.62	0.59	0.05	10.09	5.54	0.75	100.05
Plag microlite 6	ACA 01	microlite	49.16	31.86	0.62	0.05	15.30	2.82	0.19	100.07
Plag microlite 7	ACA 01	microlite	52.08	29.72	0.72	0.09	12.95	4.16	0.37	100.14
Plag microlite 8	ACA 01	microlite	48.93	32.30	0.70	0.05	15.49	2.84	0.13	100.48
Plag microlite 9	ACA 01	microlite	53.51	29.21	0.44	0.05	11.87	4.77	0.33	100.21
Plag microlite 10	ACA 01	microlite	52.39	29.58	0.78	0.12	12.76	4.30	0.35	100.26
Plag 1- normal	LAS 31	Rim	55.62	27.00	0.36	0.03	9.84	5.66	0.62	99.16

PHENOCRYST	SAMPLE	REMARK	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	SUM
Plag 1- normal	LAS 31	Core	56.92	26.11	0.35	0.01	8.67	6.11	0.76	98.93
Plag 1- normal	LAS 31	Intermediate	55.86	26.49	0.40	0.03	9.07	5.96	0.72	98.58
Plag 1- normal	LAS 31	Rim	56.50	26.10	0.42	0.02	8.69	6.12	0.73	98.61
Plag 2- normal	LAS 31	Rim	55.21	27.02	0.39	0.03	9.77	5.59	0.64	98.63
Plag 2- normal	LAS 31	Intermediate	56.58	26.24	0.36	0.02	8.83	6.05	0.71	98.83
Plag 2- normal	LAS 31	Core	56.55	26.27	0.35	0.02	8.88	5.95	0.76	98.77
Plag 2- normal	LAS 31	Rim	55.93	26.80	0.45	0.02	9.30	5.90	0.63	98.99
Plag 3- normal	LAS 31	Rim	56.51	26.10	0.37	0.03	8.53	6.34	0.80	98.71
Plag 3- normal	LAS 31	Intermediate	56.86	25.72	0.34	0.00	8.24	6.30	0.81	98.28
Plag 3- normal	LAS 31	Core	56.64	26.06	0.34	0.02	8.51	6.15	0.73	98.50
Plag 4- sieved	LAS 31	Rim	48.02	31.02	0.54	0.07	15.54	2.67	0.14	98.02
Plag 4- sieved	LAS 31	Intermediate	52.09	28.78	0.68	0.05	13.04	4.03	0.46	99.19
Plag 4- sieved	LAS 31	Core	49.48	30.67	0.60	0.04	14.53	3.28	0.24	98.88
Plag 4- sieved	LAS 31	Rim	48.60	30.50	0.54	0.07	15.10	2.84	0.15	97.87
Plag 5- glomerocryst	LAS 31	Rim	58.06	25.19	0.23	0.01	7.61	6.70	0.88	98.71
Plag 5- glomerocryst	LAS 31	Intermediate	57.48	24.98	0.28	0.03	8.14	6.54	0.82	98.25
Plag 5- glomerocryst	LAS 31	Core	57.62	25.35	0.31	0.02	8.17	6.42	0.81	98.70
Plag 5- glomerocryst	LAS 31	Rim	55.47	26.54	0.32	0.02	9.91	5.73	0.56	98.56
Plag 6- sieved	LAS 31	Rim	49.96	29.66	0.52	0.06	13.93	3.48	0.24	97.89
Plag 6- sieved	LAS 31	Core	52.94	27.33	0.43	0.06	11.56	4.85	0.36	97.55
Plag 6- sieved	LAS 31	Rim	51.47	28.75	0.51	0.05	12.84	4.15	0.31	98.09
Plag 7 - sieved	LAS 31	Rim	53.30	27.72	0.51	0.03	11.62	4.73	0.45	98.38
Plag 7 - sieved	LAS 31	Intermediate	56.15	25.78	0.32	0.02	9.11	5.93	0.84	98.17
Plag 7 - sieved	LAS 31	Core	51.76	28.84	0.44	0.03	12.65	4.14	0.35	98.21
Plag 7 - sieved	LAS 31	Rim	50.50	29.96	0.51	0.03	13.69	3.70	0.27	98.68
Plag microlite 1	LAS 31	microlite	53.13	27.62	0.54	0.06	11.49	4.70	0.42	97.97
Plag microlite 2	LAS 31	microlite	52.45	28.23	0.50	0.05	12.16	4.56	0.31	98.31

PHENOCRYST	SAMPLE	REMARK	SiO₂	Al₂O₃	FeO	MgO	CaO	Na₂O	K₂O	SUM
Plag microlite 3	LAS 31	microlite	50.78	29.20	0.70	0.06	13.25	3.76	0.30	98.10
Plag microlite 4	LAS 31	microlite	55.97	25.83	0.44	0.02	9.13	6.01	0.72	98.12
Plag microlite 5	LAS 31	microlite	52.15	29.03	0.46	0.02	12.40	4.43	0.42	98.89
Plag microlite 6	LAS 31	microlite	53.55	27.22	0.72	0.04	10.99	4.84	0.52	97.96
Plag microlite 7	LAS 31	microlite	55.07	27.07	0.47	0.03	10.17	5.53	0.60	98.95
Plag microlite 8	LAS 31	microlite	52.93	28.09	0.62	0.03	11.68	4.65	0.36	98.41

Note: FeO = all Fe reported as Fe²⁺.

APPENDIX D

PYROXENE COMPOSITIONS

Appendix D. Pyroxene Compositions

SAMPLE	POINT	REMARK	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	Cr ₂ O ₃	MgO	CaO	Na ₂ O	SUM
CA 06	22	Rim	49.62	0.67	3.24	9.68	0.20	0.01	15.57	19.51	0.39	98.85
CA 06	23	Intermediate	50.23	0.56	3.29	7.09	0.18	0.34	16.51	20.70	0.37	99.25
CA 06	24	Intermediate	49.95	0.60	2.74	9.24	0.18	0.00	15.41	20.50	0.41	98.98
CA 06	25	Core	49.89	0.66	3.60	7.31	0.12	0.09	15.96	21.01	0.33	98.94
CA 06	26	Rim	49.99	0.57	3.18	6.98	0.14	0.27	16.52	20.56	0.36	98.51
CA 06	27	Rim	51.76	0.26	1.14	8.92	0.31	-0.01	15.08	21.79	0.32	99.55
CA 06	28	Intermediate	52.00	0.17	0.65	8.84	0.39	-0.01	15.32	22.13	0.26	99.73
CA 06	29	Core	51.73	0.25	1.00	9.05	0.30	0.02	15.04	21.86	0.32	99.55
CA 06	30	Rim	51.64	0.22	1.23	9.58	0.35	0.01	14.46	21.49	0.36	99.31
CA 06	31	Intermediate	51.67	0.29	1.17	9.10	0.36	0.02	14.78	21.67	0.33	99.35
CA 06	32	Core	51.46	0.19	0.76	9.13	0.45	0.00	14.84	21.96	0.30	99.09
CA 06	33	Rim	52.34	0.19	1.04	8.81	0.40	-0.01	14.66	21.99	0.35	99.68
CA 06	34	Intermediate	51.37	0.26	1.00	8.78	0.37	0.00	14.90	21.86	0.34	98.81
CA 06	35	Core	51.44	0.21	0.91	8.76	0.30	0.00	15.13	21.77	0.36	98.82
CA 06	36	Rim	51.91	0.15	0.71	9.02	0.42	0.00	15.00	22.12	0.31	99.63
CA 06	37	Intermediate	51.85	0.17	0.51	21.19	0.65	-0.02	24.22	0.94	0.02	99.46
CA 06	38	Core	52.27	0.15	0.54	20.52	0.57	0.01	24.37	0.96	0.02	99.36
CA 06	42	Rim	51.86	0.19	1.05	8.87	0.36	0.01	15.26	21.77	0.31	99.66
CA 06	43	Core	50.93	0.23	0.97	8.81	0.33	0.04	15.22	21.87	0.35	98.69
LAS 15	27	Rim	49.89	0.80	2.91	8.35	0.21	0.01	14.93	21.01	0.31	98.37
LAS 15	28	Core	52.26	0.17	0.78	8.84	0.42	0.00	14.22	22.07	0.31	99.04
LAS 15	29	Rim	49.89	0.62	2.82	8.56	0.21	0.01	14.36	21.31	0.29	98.05
LAS 15	30	Core	51.69	0.26	1.14	8.26	0.25	0.00	14.98	21.48	0.31	98.36
LAS 15	31	Rim	50.28	0.66	2.52	8.58	0.19	0.03	15.11	21.25	0.29	98.92
LAS 15	32	Intermediate	51.59	0.25	1.05	9.32	0.53	0.00	13.71	21.82	0.35	98.60

SAMPLE	POINT	REMARK	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	Cr ₂ O ₃	MgO	CaO	Na ₂ O	SUM
LAS 15	33	Core	51.93	0.17	0.78	8.75	0.34	0.01	14.24	21.83	0.30	98.32
LAS 15	34	Rim	52.32	0.14	0.44	21.44	0.70	0.00	22.68	0.88	0.02	98.59
LAS 15	35	Core	52.40	0.12	0.42	20.86	0.65	0.00	22.67	0.95	0.02	98.02
LAS 15	46	microlite	52.06	0.20	0.83	8.38	0.31	-0.02	14.41	22.06	0.30	98.49
LAS 15	47	microlite	52.16	0.16	0.77	8.63	0.40	-0.01	14.27	22.19	0.29	98.85
ACA 06	26	Rim	52.61	0.17	0.74	8.15	0.37	0.01	14.78	22.13	0.30	99.21
ACA 06	27	Core	51.67	0.17	0.77	8.93	0.52	0.00	14.47	21.95	0.34	98.80
ACA 06	28	Rim	50.38	0.64	2.50	8.91	0.17	0.00	15.19	20.97	0.30	99.04
ACA 06	29	Core	52.74	0.20	0.80	8.48	0.38	-0.01	14.65	22.15	0.29	99.65
ACA 06	32	Rim	52.64	0.16	0.83	9.13	0.42	0.00	14.44	21.97	0.31	99.87
ACA 06	33	Core	51.56	0.18	0.78	8.72	0.34	-0.02	14.87	21.91	0.32	98.63
LAS 13	32	Rim	52.51	0.19	0.90	8.84	0.33	0.00	14.44	21.75	0.33	99.27
LAS 13	33	Core	52.66	0.15	0.73	8.92	0.40	0.01	14.36	22.04	0.35	99.59
LAS 13	34	Rim	52.62	0.19	0.75	8.85	0.45	-0.01	14.42	22.02	0.30	99.58
LAS 13	35	Core	52.80	0.20	0.74	8.64	0.48	0.01	14.34	22.17	0.29	99.66
LAS 13	36	Rim	52.68	0.19	0.80	8.30	0.28	0.01	14.81	22.11	0.30	99.46
LAS 13	37	Core	52.80	0.19	0.73	8.45	0.41	0.02	14.50	21.91	0.27	99.27
LAS 13	38	Rim	52.74	0.19	0.84	8.68	0.35	0.00	14.62	21.72	0.31	99.44
LAS 13	39	Core	52.82	0.13	0.66	9.39	0.59	0.00	14.05	21.59	0.34	99.54
LAS 13	50	Microlite	52.48	0.19	0.80	8.43	0.31	0.00	14.71	21.87	0.27	99.07
LAS 13	51	Microlite	50.74	0.60	2.17	9.08	0.23	0.03	14.76	20.84	0.32	98.78
LAS 13	52	Microlite	49.83	0.98	4.08	8.41	0.16	0.05	14.82	20.22	0.30	98.82
CA 10	45	Rim	52.73	0.18	0.65	21.34	0.58	0.01	22.93	1.11	0.01	99.53
CA 10	46	Core	52.28	0.23	1.10	21.31	0.60	0.02	22.76	1.14	0.04	99.44
CA 10	47	Rim	50.81	0.63	3.39	7.28	0.15	0.37	15.26	21.02	0.34	99.29
CA 10	48	Core	52.57	0.28	1.07	9.96	0.29	0.03	14.72	20.15	0.36	99.39
CA 10	49	Rim	50.07	0.74	3.64	7.07	0.14	0.33	15.43	20.95	0.31	98.69

SAMPLE	POINT	REMARK	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	Cr ₂ O ₃	MgO	CaO	Na ₂ O	SUM
CA 10	50	Core	51.20	0.64	3.13	7.16	0.16	0.24	15.94	20.80	0.31	99.58
CA 10	51	Rim	51.12	0.56	2.75	6.91	0.13	0.25	16.17	20.96	0.28	99.12
CA 10	52	Core	50.67	0.58	2.40	11.88	0.33	0.18	13.11	19.83	0.54	99.50
CA 10	54	microlite	51.65	0.38	1.45	10.86	0.29	0.05	13.93	20.10	0.43	99.10
CA 10	56	microlite	52.58	0.19	0.64	21.47	0.60	-0.01	22.76	1.04	0.02	99.29
ALA 10	34	Rim	52.18	0.42	1.61	8.27	0.23	0.07	15.15	21.41	0.25	99.58
ALA 10	35	Core	52.18	0.37	1.41	10.04	0.36	0.02	14.12	21.12	0.36	99.96
ALA 10	36	Rim	50.53	0.77	4.12	7.64	0.13	0.30	15.65	20.75	0.34	100.21
ALA 10	37	Core	53.00	0.11	0.62	10.25	0.51	-0.01	14.12	21.53	0.33	100.43
ALA 10	38	Rim	52.64	0.21	0.87	9.50	0.35	0.00	14.40	21.66	0.33	99.98
ALA 10	39	Core	52.69	0.19	0.87	10.52	0.37	0.00	13.82	21.64	0.27	100.37
ALA 10	40	Rim	51.26	0.67	3.21	6.75	0.17	0.29	15.99	20.92	0.32	99.56
ALA 10	41	Core	52.14	0.37	1.38	10.86	0.28	0.01	14.14	20.23	0.37	99.79
ALA 10	54	Microlite	52.12	0.56	1.81	7.97	0.22	-0.01	15.47	21.28	0.26	99.75
ALA 10	55	Microlite	53.37	0.37	1.84	15.52	0.38	-0.01	26.64	1.33	0.02	99.43
ALA 10	56	Microlite	51.72	0.66	2.36	8.47	0.25	0.01	16.73	19.33	0.17	99.74
ALA 10	57	Microlite	52.22	0.46	1.56	8.83	0.22	0.03	15.37	21.23	0.27	100.17
ACA 01	29	Rim	52.63	0.27	0.92	11.15	0.44	0.00	14.03	20.87	0.27	100.58
ACA 01	30	Core	53.01	0.23	0.77	9.99	0.36	0.00	14.40	21.52	0.26	100.55
ACA 01	31	Rim	51.17	0.65	2.24	11.86	0.38	0.01	14.11	19.32	0.34	100.07
ACA 01	32	Core	50.91	0.57	2.14	11.68	0.37	0.04	13.85	19.98	0.35	99.90
ACA 01	33	Rim	51.99	0.35	1.58	10.82	0.28	0.00	14.30	20.38	0.35	100.03
ACA 01	34	Core	51.40	0.44	1.83	11.15	0.34	0.03	13.83	20.59	0.41	99.99
ACA 01	35	Rim	51.24	0.53	1.78	13.17	0.34	0.03	13.54	18.88	0.37	99.87
ACA 01	36	Core	51.34	0.57	1.74	12.25	0.29	0.03	14.18	18.77	0.35	99.52
ACA 01	37	Rim	52.35	0.33	1.04	11.61	0.39	0.00	13.69	20.65	0.31	100.36
ACA 01	38	Core	52.40	0.31	1.29	10.51	0.37	0.01	14.45	20.83	0.31	100.47

SAMPLE	POINT	REMARK	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	Cr ₂ O ₃	MgO	CaO	Na ₂ O	SUM
ACA 01	39	Rim	53.05	0.10	0.65	10.09	0.60	0.00	13.89	22.11	0.30	100.77
ACA 01	40	Core	52.60	0.12	0.59	9.99	0.60	0.02	13.76	22.37	0.31	100.35
ACA 01	41	microlite	51.96	0.53	1.71	9.77	0.27	0.01	14.52	21.10	0.30	100.13
ACA 01	42	microlite	52.80	0.53	1.57	9.26	0.28	0.00	16.38	19.49	0.18	100.51
ACA 01	43	microlite	52.12	0.62	1.91	8.46	0.29	0.00	15.99	21.10	0.28	100.75
ACA 01	44	microlite	53.54	0.42	1.27	17.31	0.47	0.03	25.73	1.32	0.02	100.06
LAS 31	27	Rim	53.21	0.16	0.73	18.98	0.55	0.00	24.45	1.11	0.03	99.14
LAS 31	28	Core	53.15	0.13	0.42	21.37	0.66	-0.01	22.70	1.02	0.01	99.39
LAS 31	29	Rim	52.34	0.31	1.15	8.57	0.28	0.01	14.71	21.76	0.28	99.40
LAS 31	30	Core	52.86	0.17	0.77	8.51	0.37	0.01	14.53	22.16	0.32	99.69
LAS 31	31	Rim	53.21	0.15	0.49	20.23	0.67	0.00	23.67	0.95	0.01	99.31
LAS 31	32	Core	53.17	0.14	0.49	20.92	0.66	0.00	23.18	0.93	0.02	99.47
LAS 31	33	Rim	52.58	0.16	0.72	21.68	0.62	0.02	22.54	1.03	0.03	99.33
LAS 31	34	Core	52.14	0.17	0.53	21.56	0.70	0.02	22.05	0.97	0.01	98.09
LAS 31	35	Rim	52.51	0.28	1.04	8.30	0.30	0.00	14.71	21.97	0.28	99.37
LAS 31	36	Core	52.64	0.24	0.85	8.64	0.41	0.00	14.70	22.04	0.33	99.82
LAS 31	37	Rim	52.56	0.14	0.63	8.41	0.66	-0.01	14.18	22.43	0.31	99.30
LAS 31	38	Core	52.23	0.25	1.08	9.53	0.28	-0.01	14.25	21.60	0.31	99.52
LAS 31	39	Rim	49.24	0.87	4.58	10.49	0.19	0.03	13.33	19.98	0.56	99.28
LAS 31	40	Core	52.16	0.25	1.11	8.91	0.39	-0.01	13.89	22.20	0.34	99.24
LAS 31	41	Rim	52.70	0.18	0.77	8.30	0.40	0.01	14.63	22.00	0.35	99.29
LAS 31	42	Core	52.68	0.21	0.93	8.48	0.36	0.02	14.59	21.94	0.26	99.48
LAS 31	44	microlite	52.28	0.17	0.96	9.89	0.56	0.02	14.05	21.57	0.35	99.83
LAS 31	45	microlite	50.23	0.71	3.96	6.20	0.11	0.67	16.31	19.97	0.44	98.58
LAS 31	46	microlite	40.66	3.70	12.41	11.82	0.13	0.06	13.36	11.33	2.36	96.70

Note: FeO = all Fe reported as Fe²⁺.

APPENDIX E

OLIVINE COMPOSITIONS

Appendix E. Olivine Compositions

SAMPLE	POINT	REMARK	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	Cr ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	SUM
ACA 06	30	Rim	50.65	0.34	4.14	16.31	0.38	0.01	25.96	1.33	0.00	0.00	99.13
ACA 06	31	Core	38.80	0.02	-0.04	16.73	0.26	0.02	43.96	0.13	-0.01	-0.03	99.83
CA 10	53	microlite	38.46	0.04	-0.03	21.93	0.30	0.02	39.06	0.12	0.01	-0.02	99.88
CA 10	55	microlite	38.01	0.03	0.00	21.13	0.29	0.02	39.96	0.17	0.01	-0.02	99.58
CA 10	57	microlite	39.01	0.01	-0.02	20.56	0.25	-0.01	40.35	0.11	0.02	-0.01	100.27
ALA 10	42	Rim	39.55	0.01	0.00	18.28	0.26	0.00	42.25	0.12	0.01	-0.03	100.44
ALA 10	43	Core	39.28	0.01	-0.01	18.43	0.22	0.02	42.13	0.09	0.01	-0.02	100.17

Note: FeO = all Fe reported as Fe²⁺.

APPENDIX F

MAJOR AND TRACE ELEMENT CONCENTRATIONS

Appendix F. Major and trace element concentrations.

SAMPLE	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Sum	Ni	Cr	V	Ba	Rb	Sr	Zr	Y	Nb	Pb	Th
LAS02	60.11	0.97	16.38	5.82	0.09	3.22	5.86	3.26	2.50	0.24	98.46	25	49	143	484	106	520	189	18	12	12	21
LAS04	60.89	1.00	16.44	5.98	0.09	3.29	5.90	3.38	2.60	0.22	99.78	26	49	147	477	124	471	198	19	14	13	24
LAS05	60.40	1.00	16.24	5.93	0.09	3.28	5.82	3.26	2.65	0.22	98.88	27	47	147	469	123	461	198	20	12	12	25
LAS06	63.80	0.82	15.79	4.62	0.07	2.27	4.49	3.40	3.50	0.21	98.96	21	51	108	699	148	466	226	15	12	17	25
LAS07	61.16	0.92	16.08	5.47	0.08	2.91	5.29	3.41	2.86	0.23	98.41	24	41	130	494	131	492	198	18	13	13	25
LAS08	60.32	1.01	16.44	6.10	0.09	3.20	5.76	3.54	2.46	0.26	99.18	27	48	134	488	106	543	194	21	12	11	20
LAS09	59.24	0.99	17.42	5.75	0.09	2.85	5.78	3.20	2.63	0.22	98.16	21	22	142	525	115	501	217	21	14	14	26
LAS10	59.24	1.01	16.83	6.19	0.10	3.00	5.99	3.01	2.64	0.23	98.24	15	19	150	435	156	537	250	26	15	14	42
LAS11	61.68	0.90	15.75	5.30	0.08	2.59	5.00	3.18	3.27	0.22	97.97	20	24	123	488	195	450	249	24	14	15	42
LAS12	60.05	0.92	15.89	5.48	0.08	2.94	6.04	3.09	2.61	0.20	97.32	22	41	141	475	124	452	188	23	13	11	25
LAS13	60.26	0.98	16.27	5.73	0.09	3.15	5.75	3.23	2.56	0.21	98.23	25	45	137	467	120	464	198	20	13	11	24
LAS14	63.94	0.77	16.16	4.57	0.07	2.16	4.69	3.46	3.17	0.18	99.18	16	18	106	505	171	429	198	21	13	15	34
LAS15	58.49	1.02	17.27	6.41	0.10	3.07	6.32	3.35	2.28	0.23	98.53	15	11	162	447	103	499	192	20	12	10	18
LAS16	61.54	0.91	16.66	5.33	0.08	2.65	5.41	3.42	2.79	0.21	98.99	20	22	128	507	137	472	204	18	13	14	25
LAS17	62.05	0.86	16.27	5.21	0.08	2.68	4.99	3.40	2.86	0.21	98.61	22	36	125	503	146	454	201	21	14	14	29
LAS18	62.17	0.73	16.60	5.48	0.11	2.46	5.57	3.15	2.90	0.18	99.33	8	11	126	434	126	483	168	27	12	13	23
LAS19	61.54	0.72	16.43	5.45	0.11	2.41	5.40	3.01	2.87	0.18	98.11	9	11	126	428	125	474	169	31	13	14	23
LAS20	62.10	0.88	16.10	5.38	0.08	2.72	5.18	3.47	2.87	0.22	99.00	23	33	124	506	143	469	204	19	14	15	27
LAS21	59.64	0.95	16.31	5.81	0.09	3.05	5.35	3.37	2.61	0.22	97.39	23	38	145	473	124	487	193	17	13	13	23
LAS22	63.30	0.86	16.08	5.18	0.08	2.67	5.09	3.55	2.97	0.22	100.01	22	39	125	519	145	472	198	19	13	15	28
LAS23	61.39	0.88	16.12	5.41	0.08	2.88	5.18	3.43	2.75	0.21	98.34	23	43	130	491	136	469	194	19	13	15	25
LAS24	61.97	0.84	16.39	4.95	0.08	2.57	4.78	3.39	2.91	0.20	98.08	21	41	119	502	147	434	199	16	13	14	28
LAS25	63.01	0.68	16.01	4.87	0.10	2.13	4.93	3.18	3.10	0.17	98.18	9	10	111	442	143	455	167	30	13	15	26
LAS27	61.03	0.90	16.28	5.37	0.08	2.83	5.39	3.44	2.77	0.22	98.29	22	34	129	504	132	487	201	20	14	14	26
LAS29	60.40	1.00	16.22	5.93	0.09	3.81	5.99	3.53	2.58	0.27	99.81	40	77	149	512	119	544	194	20	14	13	22
LAS30	60.32	0.99	15.68	6.00	0.09	3.94	5.80	3.44	2.48	0.25	99.00	47	101	143	504	109	516	196	17	12	11	19
LAS31	59.73	1.02	16.18	6.07	0.09	3.86	6.00	3.50	2.54	0.27	99.27	41	79	152	508	116	542	198	18	13	12	22
LAS32	60.43	0.97	16.00	5.84	0.09	3.69	5.80	3.47	2.58	0.26	99.13	40	82	145	506	120	560	197	19	14	13	22
LAS33	61.72	1.05	16.20	5.97	0.09	3.26	5.63	3.53	2.65	0.25	100.35	23	39	153	559	116	515	215	18	12	11	21
LAS 13-01	60.96	0.74	15.65	4.45	0.07	2.25	5.21	3.25	2.98	0.20	95.76	18	30	106	488	157	522	188	18	13	14	31

SAMPLE	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Sum	Ni	Cr	V	Ba	Rb	Sr	Zr	Y	Nb	Pb	Th
LAS 13-07	61.73	0.85	15.95	5.18	0.09	2.73	5.36	3.37	2.91	0.21	98.37	24	41	125	505	146	503	196	21	13	14	27
LAS 13-06	61.37	0.82	16.93	5.01	0.08	2.10	5.33	3.38	2.93	0.20	98.15	13	12	116	496	151	440	223	21	13	13	29
LAS 13-10	62.08	0.92	16.32	5.43	0.08	2.58	5.11	3.52	2.98	0.22	99.26	17	21	128	529	154	464	224	22	14	14	30
LAS 13-11	63.59	0.75	16.34	4.46	0.07	1.88	4.36	3.49	3.31	0.19	98.44	18	15	103	525	158	434	202	20	12	17	26
LAS 13-12	62.29	0.76	16.81	4.87	0.08	2.22	4.83	3.32	3.32	0.19	98.70	21	17	107	527	146	446	201	20	12	16	25
LAS 13-13	62.06	0.90	16.60	5.54	0.09	2.63	5.28	3.53	3.07	0.21	99.92	30	21	130	504	157	436	215	23	13	16	32
LAS 13-15	61.30	1.02	15.51	6.00	0.09	3.77	5.47	3.47	2.63	0.26	99.52	41	92	147	518	117	505	209	18	13	14	21
CA01	63.13	0.78	14.95	4.78	0.07	2.10	4.18	2.92	4.00	0.16	97.08	16	30	110	509	275	293	338	29	17	18	62
CA02	62.58	0.78	14.92	4.61	0.07	2.07	4.51	2.90	3.89	0.16	96.48	16	28	110	511	270	301	328	28	17	17	62
CA04	62.89	0.77	14.85	4.70	0.07	2.07	4.17	2.85	4.10	0.16	96.64	15	29	110	485	284	295	330	29	17	18	65
CA05	62.42	0.85	16.19	5.29	0.08	2.68	5.25	3.30	3.05	0.19	99.29	21	22	128	476	177	432	219	22	13	15	38
CA06	60.65	0.91	16.17	5.44	0.08	2.84	5.47	3.37	2.77	0.21	97.92	22	38	135	503	133	467	201	18	12	13	25
CA07	61.14	0.94	16.26	5.46	0.09	2.87	5.50	3.39	2.82	0.22	98.70	23	36	137	508	133	471	206	20	14	13	25
CA08	58.61	0.93	16.73	6.76	0.11	3.50	6.46	3.18	2.44	0.21	98.94	16	30	175	459	113	522	193	24	12	10	21
CA09	61.10	0.81	15.69	5.43	0.09	3.28	5.42	2.94	3.25	0.17	98.18	33	72	130	429	185	371	203	24	14	15	40
CA10	64.14	0.69	15.58	4.44	0.08	2.25	4.52	3.27	3.26	0.17	98.38	15	32	103	566	151	432	179	19	13	15	27
CA11	63.44	0.79	16.17	5.25	0.08	2.54	5.03	3.37	3.05	0.17	99.87	21	25	107	484	183	410	221	22	14	12	42
CA12	66.53	0.60	15.24	3.91	0.07	1.84	3.90	3.52	3.31	0.15	99.06	14	23	83	606	157	395	178	19	12	17	31
CA15	59.12	0.90	16.27	6.41	0.11	3.28	6.22	2.61	2.95	0.18	98.04	19	29	167	393	165	425	204	27	13	12	35
CA 13-01	64.11	0.79	16.15	5.02	0.09	2.03	4.72	3.57	3.06	0.21	99.76	8	11	103	504	159	411	204	23	13	12	29
CA 13-02	63.10	0.85	15.59	4.83	0.07	2.56	4.58	3.43	3.37	0.21	98.59	25	63	116	625	152	437	223	18	13	16	27
ALA01	59.33	0.95	15.97	6.26	0.10	3.03	5.92	2.83	3.01	0.20	97.61	17	26	151	470	162	414	204	23	13	12	30
ALA04	63.55	0.74	15.65	4.70	0.08	2.27	4.57	3.17	3.51	0.16	98.40	17	29	109	474	235	377	255	25	15	17	58
ALA06	59.42	0.96	16.21	5.73	0.10	3.21	5.90	3.28	2.44	0.22	97.48	26	36	148	474	148	501	209	21	13	13	27
ALA07	65.07	0.69	16.23	3.56	0.04	1.44	3.40	3.32	3.18	0.07	96.99	16	22	95	565	155	390	193	17	13	15	28
ALA09	62.98	0.77	15.75	5.07	0.08	2.60	5.00	3.24	2.98	0.17	98.63	30	63	118	449	168	387	185	22	13	12	30
ALA10	62.67	0.81	15.80	5.18	0.08	2.64	5.12	3.25	3.15	0.19	98.88	18	32	121	468	190	461	226	27	15	17	45
ACA01	64.43	0.78	15.14	4.66	0.07	2.03	4.11	2.99	4.13	0.16	98.50	16	26	107	515	291	294	343	29	18	18	66
ACA02	63.80	0.80	15.98	4.38	0.07	1.82	4.32	3.47	3.37	0.28	98.30	14	13	96	795	120	612	240	17	13	16	19

SAMPLE	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Sum	Ni	Cr	V	Ba	Rb	Sr	Zr	Y	Nb	Pb	Th
ACA04	60.80	0.92	16.38	5.92	0.09	2.82	5.59	3.08	3.03	0.20	98.83	16	21	140	476	156	448	209	24	14	14	32
ACA03	62.05	0.65	14.78	4.18	0.07	2.11	5.43	3.15	3.23	0.16	95.81	15	30	99	539	150	410	172	18	12	15	26
ACA06	60.01	0.89	16.21	5.85	0.09	3.45	5.78	3.14	2.77	0.19	98.39	33	68	142	460	129	436	190	22	12	13	25
ACA07	60.23	0.95	16.12	6.20	0.10	2.80	6.19	3.21	2.76	0.20	98.76	15	22	152	438	144	463	201	24	13	12	27
ACA08	59.39	1.01	16.18	6.64	0.10	3.27	6.14	2.93	2.92	0.22	98.80	17	29	159	433	152	425	208	23	14	12	28
BA01	60.20	0.92	16.45	6.09	0.10	3.14	5.95	2.99	2.77	0.20	98.81	19	38	147	445	136	506	192	25	13	13	28
LAS03	60.83	0.92	16.03	5.53	0.08	2.94	5.34	3.35	2.74	0.23	97.99	24	43	134	496	128	492	196	19	12	12	25
LAS03R	61.42	0.93	16.21	5.50	0.08	2.97	5.40	3.38	2.77	0.23	98.88	25	44	132	492	128	495	197	18	13	14	24
LAS26	60.34	0.99	16.23	5.87	0.09	3.60	5.91	3.52	2.57	0.26	99.37	36	71	148	514	118	578	200	19	13	12	22
LAS26R	60.39	0.99	16.23	5.93	0.09	3.59	5.92	3.51	2.57	0.26	99.49	37	72	147	512	118	577	199	19	13	12	21
ALA08	62.60	0.79	16.03	4.95	0.08	2.14	4.52	3.11	3.25	0.20	97.68	16	17	112	504	202	400	250	23	15	17	43
ALA08R	63.01	0.80	16.13	4.97	0.08	2.17	4.55	3.13	3.27	0.20	98.31	17	16	111	502	203	401	253	23	15	16	42
LAS 13-02	60.09	0.90	16.24	6.16	0.11	3.48	6.08	3.26	2.59	0.20	99.12	21	52	155	468	122	495	198	24	12	12	23
LAS 13-02R	60.25	0.90	16.26	6.16	0.11	3.50	6.07	3.25	2.59	0.20	99.28	19	54	153	464	121	493	195	25	13	12	24

Note: Major element data are in wt%, trace element data are in ppm; all analyses by XRF, FeO* = all Fe reported as Fe²⁺.

APPENDIX G

ISOTOPE RATIOS

Appendix G. Isotope ratios.

SAMPLE	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{84}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{145}\text{Nd}/^{144}\text{Nd}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$
LAS12	0.707191	0.056735	0.512477	0.348328	18.849	15.623	38.769	2.05683	0.82888
LAS13	0.707232	0.056504	0.512414	0.348412	18.848	15.624	38.774	2.05720	0.82896
LAS15	0.707161	0.056554	0.512433	0.348402	18.847	15.623	38.772	2.05716	0.82895
LAS18	0.706211	0.056505	0.512383	0.348358	18.852	15.625	38.748	2.05535	0.82883
LAS31	0.706849	0.056516	0.512473	0.348400	18.850	15.622	38.766	2.05657	0.82873
CA01			0.512210	0.348411					
CA02	0.707111	0.056611	0.512422	0.348392	18.879	15.624	38.805	2.05549	0.82762
CA06	0.707110	0.056488	0.512493	0.348387	18.847	15.622	38.767	2.05690	0.82889
CA08	0.706476	0.056512	0.512459	0.348422	18.840	15.618	38.740	2.05631	0.82899
CA10	0.706892	0.056502	0.512364	0.348144	18.829	15.624	38.753	2.05810	0.82975
CA12	0.706950	0.056547	0.512422	0.348392					
ALA09	0.706821	0.056475	0.512481	0.348451	18.860	15.622	38.773	2.05586	0.82835
ALA10	0.706688	0.056501	0.512486	0.348382	18.842	15.621	38.756	2.05694	0.82908
ACA01	0.707148	0.056460	0.512447	0.348417	18.881	15.625	38.809	2.05547	0.82756
ACA06	0.706957	0.056630	0.512457	0.348430	18.845	15.621	38.760	2.05674	0.82893