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Application of Olivine Phenocrysts

to Assess Basalt Flow Correlations from the Materials and Fuels Complex in the Idaho National

Laboratory

By

Rebecca Lindsey Sutherland

A thesis

submitted in partial fulfillment

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Dedication

To my sister, Nathalie. Life is a journey never defined by any individual moment. During difficult moments, remember they are not permanent. During moments of happiness, remember to pause, truly feel each moment, and be grateful for them. Life goes on and so will you!

Your sasso,

Lindsey

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Table of Contents

List of Figures
List of Tablesx
Thesis Abstract – Idaho State University (2022) xi
Chapter 1: Introduction
1.1 Importance of Study Area 1
1.2 Project Objectives
1.3 Geologic Setting
1.3.1 Origin of the Eastern Snake River Plain
1.3.2 Eastern Snake River Plain Basalts
1.3.2.1 Physical Properties
1.3.2.2 Chemical Properties and Mineralogy
1.4 Thesis Organization
Chapter 2: Characterization of Olivine Phenocrysts and Constraints on the Pre-eruptive Temperature and H ₂ O Content of Eastern Snake River Plain Basaltic Melts
2.1 Introduction
2.2 Background
2.2.1 Olivine Phenocrysts as Petrologic Indicators
2.2.2 Olivine-Melt Thermometry and Hygrometry 10
2.2.3 Olivine-Melt Equilibrium to Contextualize Temperatures of Crystallization11
2.3 Methods
2.3.1 Basalt Core Sampling
2.3.2 Whole-Rock Major and Trace Element Analysis14
2.3.3 Phenocryst Characterization and Analysis15
2.3.3.1 Textural Characterization of Thin Sections
2.3.3.2 Scanning Electron Microscopy of Olivine Phenocrysts
2.3.3.3 Olivine Phenocryst Compositional Analysis
2.4 Results
2.4.1 Whole-Rock Geochemistry
2.4.2 Olivine Phenocryst Results

2.4.2.1 Optical Analysis	19
2.4.2.2 Scanning Electron Microscopy	19
2.4.2.3 Electron Microprobe Analysis	20
2.5 Assessing Olivine-Melt Equilibrium	21
2.5.1 Olivine Phenocryst Textures	21
2.5.2 Olivine Phenocryst Composition Histograms	21
2.5.3 Olivine Fo# versus Whole-Rock Mg#	22
2.5.4 Fe2+ -MgK _D (Olivine-Melt) Liquidus Test	22
2.6 Pre-eruptive Temperatures and Dissolved H ₂ O Content of ESRP Basaltic Melts	23
2.7 An Olivine Phenocryst Perspective on Eastern Snake River Plain Basalt Petrogenesis	26
2.7.1 Textural Evidence of Rapid Ascent	26
2.7.2 Temperatures and Minimum Dissolved Melt H ₂ O Content of the Melt	26
2.7.3 Variability of Olivine Phenocryst Populations Within a Lava Flow Layer	27
2.7.4 Conceptual Model Informed by Olivine Phenocryst Analyses	28
2.7.5 Contributions and Future Work	29
2.8 Conclusion	29
Chapter 3: Spatial Correlation of Basalt Flow Groups	31
3.1 Introduction	31
3.2 Established Flow-Group Correlation Methods	32
3.3 Existing Preliminary Subsurface Correlation at the Materials and Fuels Complex	35
3.4 Methods	37
3.4.1 Core and Surface Vent Sampling	37
3.4.2 Lithologic Logs	38
3.4.3 Whole-Rock Geochemistry	39
3.4.4 Olivine Phenocryst Compositional Analysis	39
3.5 Results	40
3.5.1 Whole-rock Geochemistry	40
3.5.2 Olivine Phenocryst Characterization	41
3.6 A Geochemical Perspective on Flow-Group Correlations Beneath the Materials and Fuel Complex	s 42
3.6.1 Whole-rock Geochemistry	42

3.6.2 Assessment of Olivine Phenocryst Characterization as a Correlation Tool	44
3.7 Conclusion	45
Chapter 4: Summary of Conclusions	47
Figures	50
Tables	83
References Cited	94

List of Figures

Figure 1.1 Regional map of ESRP with reference to Idaho	50
Figure 1.2 Aerial map of extent of ESRP Aquifer	51
Figure 1.3 Study area-MFC with reference to INL	52
Figure 1.4 Plains style volcanism	53
Figure 1.5 Cross-cut through a Pahoehoe lava flow layer	54
Figure 2.1 Rapid growth textures in olivine phenocryst	55
Figure 2.2 Representative examples of ESRP basalt thin sections	56
Figure 2.3 Rapid growth textures in olivine phenocrysts observed in this study	57
Figure 2.4 Analysis traverses across olivine phenocrysts	58
Figure 2.5 Ni concentration versus Mg# for the whole-rock geochemistry	59
Figure 2.6 TAS classification diagram of the 95 samples	60
Figure 2.7 Histograms of forsterite content for each sample	61
Figure 2.8 Distributions patterns of forsterite content within a single lava flow layer	62
Figure 2.9 NiO versus Fo# plots for each sample	63
Figure 2.10 Maximum Fo# of olivine versus Mg# of whole-rock composition	64
Figure 2.11 Temperature versus Mg# for the Mg-based and Ni-based thermometer	65
Figure 2.12 Comparison of temperature versus Mg# for sample in differing tectonic settings	66
Figure 3.1 Aerial map showing the drill locations of USGS 149, USGS 143, and ANL-OBS-A-	-
001	67
Figure 3.2 Cross-section through cores USGS 149, USGS 143, and ANL-OBS-A-001 (M.K.V.	•
Hodges, personal communication, October 1, 2020)	68
Figure 3.3 Correlation of lava flow groups between USGS 143 and USGS 149	69
Figure 3.4 Correlation of lava flow groups between USGS 149 and ANL-OBS-A-001	70
Figure 3.5 Photo of drilled basalt core in a core box	71
Figure 3.6 Regional map showing surface vent locations	72
Figure 3.7 Variation diagrams classifying the ESRP samples	73
Figure 3.8 Selected whole-rock compositions versus depth in the USGS 149 core	74
Figure 3.9 Selected whole-rock compositions versus depth in the ANL-OBS-A-001 core	75
Figure 3.10 Selected whole-rock compositions versus depth in the USGS 143 core	76
Figure 3.11 Spider diagram of flow groups	77
Figure 3.12 Olivine phenocryst characterization for the Cobb Mtn flow group in ANL-OBS-A-	-
001	78
Figure 3.13 Harker diagrams of the surface vent and associated samples in USGS 149 that	
display similar paleomagnetic inclination	79
Figure 3.14 Selected major element compositions versus depth of the samples analyzed in the	
two flow groups in USGS 143 and the single flow group at the top of core USGS 149	80
Figure 3.15 Select Harker diagrams for the three flow groups across core holes USGS 149 and	

Figure 3.16 Olivine phenocryst characterizat	on for the Cobb	Mtn. flow group is	s USGS 149 and
ANL-OBS-A-001	••••••		

List of Tables

Table 2.1. Beam conditions for standards
Table 2.2 Major element concentrations for whole-rock samples used for olivine phenocryst
analyses
Table 2.3 Ranking of optical analyses of samples from this study
Table 2.4 Olivine phenocryst analyses of the Most Mg-rich olivine phenocryst from each sample
Table 3.1 Major element analysis of the 95 whole-rock compositions analyzed in this study 87
Table 3.2 Trace element analysis of the 95 whole-rock compositions analyzed in this study 90
Table 3.3 Composition of the most Mg-rich olivine phenocryst from the samples analyzed in the
Cobb Mtn. Paleomagnetic Chron lava flow group identified in USGS 149 and ANL-OBS-A-001

Application of Olivine Phenocrysts

to Assess Basalt Flow Correlations from the Materials and Fuels Complex in the Idaho National

Laboratory

Thesis Abstract – Idaho State University (2022)

Whole-rock and olivine phenocryst geochemistry archives the petrologic evolution of the eastern Snake River Plain (ESRP) basaltic system. This study aims to assess olivine-melt equilibrium, apply olivine-melt thermometry and hygrometry to evaluate the pre-eruptive conditions of the melt, and evaluate basalt flow-group correlations between core holes drilled within the Materials and Fuels Complex region (MFC) of the Idaho National Laboratory (INL) to aid research efforts by the United States Geological Survey (USGS) to better understand groundwater migration and volcanic hazards in this region. This work demonstrates that olivine phenocrysts are in equilibrium with the whole-rock (i.e., melt) compositions; at the onset of olivine crystallization temperature and dissolved H₂O content of the melts was 1,117–1,195 °C and 0.4–2.6 wt%, respectively. Whole-rock data support correlations of flow groups within the MFC. This work provides information about the stratigraphy beneath the MFC and the petrologic evolution of ESRP basalts.

Key words:

Olivine Phenocryst Compositions Whole-rock Geochemistry Olivine-melt Thermometry Olivine-melt Equilibrium Flow-group Correlations

xi

Chapter 1: Introduction

1.1 Importance of Study Area

The eastern Snake River Plain (ESRP), in southeastern Idaho (Figure 1.1), is an active igneous province with thousands of monogenetic basaltic volcanoes (Greeley et al., 1982). A one- to two-kilometer-thick layer of Quaternary olivine basalts cap the ESRP and are associated with the Yellowstone-Snake River Plain volcanic system (Kuntz et al., 1992). These basaltic layers also host the ESRP aquifer (Figure 1.2), a critical source of water for irrigation and consumption.

The Idaho National Laboratory (INL) occupies 880 square miles of the northeast corner of the ESRP (Figure 1.1) and is a nuclear research laboratory established in 1949. The presence of nuclear facilities in this geologic setting requires research on the volcanic processes that could impact the INL, as well as the impacts the facilities may have on the groundwater aquifer. For decades, the United States Geological Survey (USGS) has collected lithologic, paleomagnetic, and geochemical data from basaltic strata recovered from core holes drilled across the INL to characterize these lava flows (Hughes et al., 2002) and thus better understand the hydrologic and geologic processes that occur within the ESRP.

Previous work has focused on regions of the INL where wastewater and waste burial has resulted in elevated concentrations of radiochemical and chemical constituents in the ESRP aquifer (Bartholomay et al., 2020). These locations include the Advanced Test Reactor Complex, Idaho Nuclear Technology and Engineering Center, and the Radioactive Waste Management Complex (Bartholomay et al., 2020). Wastewater contamination is not prevalent in the southeastern part of the INL near the Materials and Fuels Complex (MFC; Figure 1.3). However, the MFC currently has two active nuclear reactors, and a third research reactor is proposed.

Therefore, more information is needed to understand the geology and environmental impact in the vicinity of the MFC. For this reason, this study aims to characterize the subsurface basalts near the MFC, to aid research efforts by the USGS to better understand groundwater migration and volcanic hazards in this region.

1.2 Project Objectives

This study aims to evaluate conditions of olivine phenocryst crystallization and characterize the basaltic lava flows throughout the MFC region of the INL (Figure 1.3). The goals of this study are, 1) to assess initial correlations of basalt strata between core holes USGS 149, USGS 143, and ANL-OBS-A-001, which were drilled in the vicinity of the MFC, 2) characterize the olivine phenocryst populations at the lava flow-layer and flow-group scale, and 3) to evaluate olivine-melt equilibrium to apply olivine-melt thermometry and hygrometry and thus quantify the pre-eruptive conditions of these ESRP basalts. To achieve these goals, I conducted core sampling, whole-rock geochemical analysis, characterization of the texture and compositional variation of olivine phenocrysts, and subsequent data analyses of the olivine phenocrysts. This work will improve understanding of the subsurface stratigraphy at the MFC, assess olivine characterization as a potential subsurface correlation tool, and advance understanding of the petrologic processes of the basaltic volcanism of the ESRP.

1.3 Geologic Setting

1.3.1 Origin of the Eastern Snake River Plain

The ESRP is a broad topographic depression that makes up the north-eastern Snake River Plain in southeastern Idaho (Figure 1.1). This depression is interpreted to reflect the trace of the Yellowstone hotspot as the North American lithospheric plate migrated south-west over the hotspot (Pierce and Morgan, 1992; Anders and Sleep, 1992; Bradshaw et al., 1993; Foulger and

Natland, 2003; Humphreys and Schmandt, 2011). The ESRP is associated with the Yellowstone-Snake River Plain volcanic system, which includes basaltic lava flows, intermediate basaltic rocks, and rhyolitic caldera complexes, along with interbedded sediments (Doherty et al., 1979; Kuntz et al., 1992; Grimm-Chadwick, 2004). Basaltic lava flows dominate the stratigraphy of the ESRP. These olivine tholeiite basalts overlie rhyolitic volcanic centers (Doherty et al., 1979; Anderson and Liszewski, 1997), which young from west to east, ending at the Yellowstone Plateau. The time-transgressive pattern of the rhyolitic calderas throughout the Snake River Plain serves as the primary evidence for the association of the Snake River Plain with the Yellowstone volcanic system (Pierce and Morgan, 1992; Humphreys and Schmandt, 2011).

The ESRP is structurally subsiding (Rodgers et al., 2002). The structural down warping of the ESRP is interpreted to result from a dense mid-crustal layer which has been imaged seismically as an approximately 10 km thick and 90 km wide dense feature (Sparlin et al., 1982; McQuarrie and Rodgers, 1998; Yuan et al., 2010). The principal interpretation of this feature is that it is a layered mafic sill complex, a hypothesis supported by cyclical geochemical trends in erupted lavas (e.g., Shervais et al., 2006).

1.3.2 Eastern Snake River Plain Basalts

1.3.2.1 Physical Properties

The basaltic volcanism on the ESRP is known as plains-style volcanism (Greeley et al., 1982; Figure 1.4) and it builds complex, interfingering basalt stratigraphy. This style of volcanism is characterized by single eruption events, which occur on time spans of days to decades (Kuntz et al., 1992). When an eruption concludes, the vent is abandoned and the next eruption creates an entirely new vent, resulting in many volcanoes erupted onto each other,

complicating the stratigraphy. For the purposes of this work, the products of an individual volcanic eruption will be referred to as a flow group.

ESRP flow groups are further divided into lava flow layers (Figure 1.5), which represent single pulses of lava onto the surface. Texturally, most of these lava flow layers are inflationary pahoehoe lavas (Kuntz and Dalrymple, 1979; Self et al., 1998). These lava flows erupt from a central vent, flow radially by exploiting lower elevation topography and gravity, and typically are emplaced through inflation (Hon et al., 1994; Self et al., 1998). The style of pahoehoe lava flow layer emplacement results in three, texturally distinct, facies: a glassy, vesicular base; a dense crystalline interior; and a rubbly, vesicular top (Figure 1.5; Self et al., 1998). These lava flow facies can be used to determine flow-layer breaks (e.g. Potter et al., 2019) and, therefore, delineate between individual lava flow layers.

1.3.2.2 Chemical Properties and Mineralogy

Geochemically, ESRP basalts are relatively similar in whole-rock composition, but have been subdivided into two categories: (1) Snake River olivine tholeiites (SROT), which are defined by low total alkalis and TiO₂ contents and higher MgO and CaO contents of the wholerock composition (Geist et al., 2002; Hughes et al., 2002; Christiansen and McCurry, 2008; McCurry et al., 2008); (2) more evolved basalts, sometimes referred to as hybrid basalts or high K-Fe basalts, characterized by elevated concentrations of SiO₂, and high concentrations of K₂O and FeO*, at thresholds of above 0.65 and 17.5 wt%, respectively (Leeman, 1982; Hughes et al., 2002; and Miller, 2007; McCurry et al., 2008). The olivine tholeiite basalts observed on the ESRP are further subdivided into two additional categories: (1a) slightly fractionated olivine tholeiites, with relatively higher concentrations of K₂O, P₂O₅, and TiO₂; (1b) more primitive olivine basalts with higher MgO concentrations (Leeman, 1982). Most of the basalts of the ESRP are the slightly fractionated olivine tholeiites, which typically range in SiO₂ composition from nearly 45 to 51 weight percent (wt%) and MgO from 3.5 to 12 wt% (Hughes et al., 2002; Jean et al., 2013).

The variability in the whole-rock composition of the olivine tholeiites is attributed to fractional crystallization of olivine and plagioclase phenocrysts, partial melting of heterogeneous mantle, and open-system processes such as: magma mixing or assimilation (Geist et al., 2002; Hughes et al., 2002). Although olivine and plagioclase crystallization play an important role in the petrogenesis of ESRP olivine tholeiites (Leeman, 1982), fractional crystallization alone cannot account for the observed range in incompatible trace element compositions, as evidenced by the range in La versus MgO compositions (Hughes et al., 2002). The variability in trace element and Sr-Nd isotopic compositions among the most primitive (i.e. most mantle-like) high-MgO lavas suggests that the ESRP basalts may be sourced from a compositionally heterogeneous enriched mantle (Leeman, 1982, Hughes et al., 2002; Miller, 2007). Open-system processes, such as assimilation of crustal rocks, may also contribute to the petrogenesis of the ESRP basalts (Geist et al., 2002).

The chemical differences between the olivine tholeiites and the hybrid basalts are thought to be the product of varying amounts of crustal contamination (Hughes et al, 2002; Barton, 2020). The Sr, Pb, and O isotope compositions of the hybrid basalts trends towards crustal values when compared to the olivine tholeiite compositions (Leeman, 1982; Geist et al., 2002; Hughes et al., 2002; Grimm-Chadwick, 2004; Miller, 2007). Further petrologic evidence observed in the Craters of the Moon hybrid basalts (high K-Fe) support this hypothesis because they have granulitic xenoliths (Leeman, 1982; Kuntz et al., 1992; Putirka et al., 2009).

The phenocryst assemblage of ESRP olivine tholeiites, includes varying amounts of olivine, and plagioclase phenocrysts, and the groundmass is typically made up of olivine, plagioclase, pyroxene, Fe-Ti oxides, glass, and minor accessory minerals such as apatite and sulfides (Hughes et al., 2019). One of the most abundant phenocrysts in the ESRP tholeiites is olivine. Past research has found that the olivine phenocryst forsterite content, described as Fo#, range from nearly Fo₈₇ to Fo₃₆ (Potter, 2010; Barton, 2020; Brehm, 2021).

1.4 Thesis Organization

In **Chapter 2**, I use olivine phenocrysts to constrain the pre-eruptive conditions of ESRP basaltic melts using thirteen samples collected from the USGS 149 and ANL-OBS-A-001 cores. In **Chapter 3**, I use whole-rock geochemistry to assess an initial correlation of basalt flow groups between core holes USGS 149, USGS 143, and ANL-OBS-A001. Additionally, I investigate whether olivine phenocryst characterization is an useful tool for correlating basalt flows spatially. In **Chapter 4**, the conclusions of each chapter are synthesized and summarized to connect this work to the project objectives.

Chapter 2: Characterization of Olivine Phenocrysts and Constraints on the Pre-eruptive Temperature and H₂O Content of Eastern Snake River Plain Basaltic Melts

2.1 Introduction

The phenocrysts in basaltic lavas offer a window into the evolution of mantle-derived melts. The pre-eruptive conditions of a basaltic system can be archived in olivine phenocrysts (Figure 2.1; Putirka, 2008) because they are commonly the first mineral phase to crystallize from a basaltic melt. Therefore, the textures and compositions of olivine phenocrysts in basalts can be used to better understand volcanic systems like the eastern Snake River Plain (ESRP).

The textures and compositions of olivine phenocrysts in basalts, along with melt compositions represented by melt inclusions or whole-rock compositions, have been used to determine the conditions of phenocryst crystallization, including temperature and dissolved H₂O content of the melt (e.g. Roeder and Emslie, 1970; Putirka, 2008; Bradshaw, 2012; Pu et al., 2017; Barton; 2020; Brehm and Lange, 2020; Brehm, 2021). This study uses whole-rock and olivine phenocryst compositions to determine the temperature and dissolved melt H₂O content of ESRP basaltic melts at the onset of olivine phenocryst crystallization using basaltic samples collected from drill cores USGS 149 and ANL-OBS-A-001, located in the Materials and Fuels Complex (MFC) facility of the Idaho National Laboratory (INL).

This study aims to test if the most magnesium-rich (Mg-rich) olivine phenocryst from a sample is in equilibrium with the melt, represented by the whole-rock composition (Pu et al., 2017). If equilibrium is supported, then the most Mg-rich olivine phenocryst and the corresponding whole-rock compositions can be used to calculate the temperature at which the melt began to crystallize olivine phenocrysts using two olivine-melt thermometers, a magnesium-based (Mg-based) thermometer and nickel-based (Ni-based) thermometer. The

difference between the two temperatures calculated using these thermometers can then be used to calculate the amount of dissolved H2O in the melt (Pu et al., 2017). Quantifying these preeruptive conditions can provide more information about the petrologic history of ESRP basalts. In addition, the preservation of olivine-melt equilibrium may require the rapid ascent of the basaltic melt soon after the onset of olivine crystallization, because the rapid ascent model suggests the basalt ascended soon after crystallization of olivine phenocrysts, too soon for the olivine phenocryst compositions to deviate from equilibrium with the melt composition (Brehm, 2021).

Drill cores offer a vertically complete, but one-dimensional, view through flow groups and the individual lava flow layers which make up a flow group. This perspective offers the opportunity to determine the intra-flow-group and intra-flow-layer variability of whole-rock compositions and of olivine phenocryst compositions. For this reason, this study explores these variations at separate depth intervals in the lava flow groups and within the three lava flow layer facies throughout the drilled cores.

2.2 Background

2.2.1 Olivine Phenocrysts as Petrologic Indicators

Olivine is a ubiquitous mineral in terrestrial basalts, and its textures and compositions record the igneous processes that influenced the phenocryst as it grew (Streck, 2008). Textures and zoning patterns of olivine phenocrysts record the growth history of the phenocryst. Phenocryst compositions similarly reflect igneous processes, because the phenocryst composition continually reflects the composition of the melt from which it grew from and, if preserved, archives the compositional evolution of the melt.

The concentric zonation that is commonly observed in igneous minerals, including

olivine, is traditionally interpreted to reflect the sequential growth of phenocrysts in ringed zones. In this model of phenocryst growth, each concentric zone documents how the stoichiometric partitioning of elements evolves as they are removed from the melt and incorporated into the crystal (Streck, 2008). This model for phenocryst growth suggests the oldest region of a phenocryst is in the center of the phenocryst and the phenocryst grows outward in concentric rings.

Welsch et al. (2014), however, observed phosphorus-rich zones in olivine phenocrysts concentrated in dendritic, branching patterns that suggest an alternative model for olivine growth. Phosphorus is a slow-diffusing element, and, for this reason, the dendritic branches have been interpreted to represent the initial, rapid, diffusion-limited growth pattern of olivine phenocrysts (Welsch et al., 2014). These observations of phosphorus zoning in olivine phenocrysts suggests that the oldest regions of an individual phenocryst are dendritic branches that are high in phosphorus. In this alternative model of crystal growth, euhedral crystal forms are achieved only after continued crystallization of the phenocryst fills gaps between the dendritic arms (Welsch et al., 2014). Therefore, the preservation of dendritic, or rapid growth (Figure 2.1), textures in olivine phenocrysts in basaltic lavas suggests that the lava erupted soon after the initiation of olivine crystallization. One explanation for the presence of rapid growth textures in olivine phenocrysts from samples found at the surface may be explained by rapid ascent of the basaltic magma (Brehm and Lange, 2020; Brehm, 2021).

Compositional zoning of olivine phenocrysts is also a useful indicator of whether a system experienced substantial open-system processes like assimilation or magma-mixing, or whether the system was closed during crystal growth. The normal zoning of olivine phenocrysts–that is, olivine with a Mg-rich core and a progressively more Fe-rich rim— suggests a simple

system where a single magma composition influenced the growth of the phenocryst (Pearce, 1987). This is because the partitioning of Mg^{2+} and Fe^{2+} as the olivine phenocryst grows outward matches expected patterns of compositional evolution of a magma as phenocrysts continually crystallize (Streck, 2008). In contrast, reversed or oscillatory zoning in olivine phenocrysts is commonly interpreted to reflect open-system behavior such as the influence of multiple magma batches with varying compositions, or that magma-mixing occurred through the evolution of the system (Streck, 2008).

In addition to olivine textures and zoning patterns, the compositions of olivine phenocrysts when measured quantitatively, can be used to test if the most Mg-rich olivine phenocryst in a sample arguably represents the first olivine phenocryst that grew from the basaltic melt. If that is the case, the most Mg-rich olivine phenocryst should have a composition comparable to the expected liquidus composition of the associated melt, represented by the sample's whole-rock composition (Pu et al., 2017; Brehm and Lange, 2020; Brehm, 2021). Thus, the olivine phenocryst's composition archives the pre-eruptive conditions of that melt at the onset of crystallization. Samples with such characteristics are useful for olivine-melt thermometry and hygrometry.

2.2.2 Olivine-Melt Thermometry and Hygrometry

Olivine-melt thermometers based on the partitioning of Mg²⁺ between olivine phenocrysts and associated melt composition, is long established (Roeder and Emslie, 1970; Beattie, 1993; and Putirka, 2008). However, one known limitation of the Mg-based thermometers is that they are dependent on dissolved H₂O content of the melt and, therefore, quantify crystallization temperatures for anhydrous conditions (Pu et al., 2017). As a result, in hydrous systems, these thermometers require a water correction, otherwise, the calculated

temperatures are higher than the actual (Pu et al., 2017; Brehm, 2021). Water corrections require the dissolved H₂O content of the melt to be known independently, but this is a difficult parameter to directly measure in natural systems that experience volatile exsolution during eruption. One technique used to directly measure dissolved H₂O content of the melt is to analyze volatile content in olivine-hosted melt inclusions (Stefano et al., 2011), a time consuming and tedious process.

To overcome these limitations, Pu et al. (2017) calibrated a thermometer that is based on the partitioning of Ni²⁺ between the olivine phenocryst and the melt. The relative abundance of Ni²⁺ in basaltic samples and the compatible nature of Ni²⁺ in olivine phenocrysts make this thermometer a viable tool to calculate the temperature at the onset of olivine phenocryst crystallization in basaltic samples, if olivine-melt equilibrium is established. Pu et al. (2017) also demonstrated that the partitioning of Ni²⁺ between the olivine phenocryst and melt is independent of the dissolved H₂O content of the melt and, therefore, provides the true temperature at the onset of olivine phenocryst crystallization in hydrous systems.

Additionally, Pu et al. (2017) calibrated a second thermometer (a Mg-based thermometer) on the same set of experiments as the Ni-based thermometer. When experimentally tested, both calibrations reproduced the experimental temperatures equally well for 1-bar experiments. Moreover, in hydrous samples, the difference between the temperatures calculated using the Mg-based and Ni-based thermometers ($\Delta T = T_{Mg}$ - T_{Ni}) resolved the minimum dissolved H₂O content of the melt (wt%) of the system, as the difference between the two calculated temperatures is a result of the dissolved H₂O content of the melt (Pu et al., 2017).

2.2.3 Olivine-Melt Equilibrium to Contextualize Temperatures of Crystallization

Thermometers, such as the olivine-melt thermometer, rely on mineral-melt equilibrium,

and in natural rock samples this equilibrium must be established before these tools can be correctly applied (Putirka, 2008). Olivine-melt equilibrium suggests that the olivine phenocryst composition closely approximates the expected liquidus composition of the melt. However, due to the possibility of open-system behavior during phenocryst growth, equilibrium between a sample's measured whole-rock composition (representative of the melt) and olivine phenocryst compositions cannot be assumed and always needs to be tested. To do this, the compositional patterns of the forsterite content (reported as the Fo#) for all the olivine analyses from a sample can be assessed, the relationship between the Fo# of the olivine versus the Mg# of the wholerock composition can be evaluated, and the $^{Fe2+}-MgK_D$ (olivine-melt) liquidus test can be applied (See 2.5, this study). These tests together can establish olivine-melt equilibrium between the olivine and the melt compositions.

If olivine-melt equilibrium is established, then the temperatures quantified using a thermometer will have contextual meaning to the growth history of the olivine. For instance, if the olivine phenocryst and melt compositions are found to be in equilibrium, then the temperatures calculated from this equilibrium pair represent the temperature of the system at the onset of phenocryst crystallization. If an olivine phenocryst composition is not in equilibrium with the associated melt composition, the olivine phenocryst may not have crystallized from the observed whole-rock material and, therefore, the temperature calculated using olivine-melt thermometers will not be meaningful.

For these reasons, olivine-melt equilibrium must be established to apply olivine-melt thermometers to natural rock samples. To do this, the olivine phenocryst textures and compositions are assessed. If there is strong evidence for equilibrium, then the composition of the most Mg-rich olivine phenocryst and the melt can be used to determine the temperature at the

onset of olivine phenocryst crystallization. Additionally, using the Ni-based and Mg-based olivine-melt thermometers calibrated by Pu et al. (2017) simultaneously is useful because the difference between the calculated temperatures can be used to calculate the minimum dissolved H₂O content of the melt at the time of olivine phenocryst crystallization.

2.3 Methods

2.3.1 Basalt Core Sampling

Three suites of basaltic samples were collected from the USGS 149 and ANL-OBS-A-001 cores. The USGS 149 core was initially sampled at several different spatial scales to assess whole-rock compositional variability (see also Chapter 3). To do this, the surface, interior, and bottom facies (Figure 1.5) were used to identify 33 individual lava flow layers throughout the core, using the schema outlined by Self et al. (1998). I collected samples in the dense, crystalline interior facies of each layer to reduce the possibility of *in situ* chemical fractionation of the lava flow layers (Bates, 1999). I then prepared these 33 samples for whole-rock analysis (see Section 2.3.3) and thin sections.

To collect the second suite of samples, I used observations in thin section to identify five of the initial 33 lava flow layers that were most suitable for olivine phenocryst analysis (see Section 2.3.4.1). I then returned to the core library to collect three additional subsamples of each of these five layers, in the surface, interior, and bottom facies, to assess the intra-flow-layer variability of olivine phenocrysts. This second suite of 15 additional samples were then prepared for whole-rock analysis and thin sections.

I collected the third and final sample suite from the ANL-OBS-A-001 core. The purpose of this sampling was to assess correlations of flow groups between the USGS 149 and ANL-OBS-A-001 core holes using whole-rock geochemistry and olivine phenocryst characterization

(see Chapter 3). These two cores were used because they were drilled in close proximity (1.4 kilometers apart) and, therefore, likely archive similar stratigraphy. I identified three flow groups in both USGS 149 and ANL-OBS-A-001 based on average paleomagnetic inclination including: a 47° paleomagnetic inclination flow group, a 59° paleomagnetic inclination flow group, and a - 48° paleomagnetic inclination flow group (D. Champion, personal communication, October 1, 2020; Chapter 3.3.1, this study). I sampled these flow groups in the ANL-OBS-A-001 core three times in dense interior facies of the lava layers that make up the flow group to reduce contamination of *in situ* fractionation (Bates, 1999). Sampling was conducted in this way to assess correlations of the flow groups between the two core holes using whole-rock geochemistry and olivine phenocryst characterization. Only the samples collected from the 59° paleomagnetic inclination flow group, here referred to as the Cobb Mtn. flow group, were analyzed for olivine phenocryst compositions.

Sample names correspond to the depth in the core the sample was collected from, i.e., sample U149_700_LS was collected 700 feet below land surface from the USGS 149 core. The names of the subsamples reflect the lava flow layer they were collected from and the depth at which they were collected, i.e. subsample U149_700_LS-697 was collected from the lava flow layer initially sampled at 700 feet and was subsampled at a depth of 697 feet below land surface.

2.3.2 Whole-Rock Major and Trace Element Analysis

To quantify the elemental composition of the identified flow groups in the USGS 149 and ANL-OBS-A-001 cores, each whole-rock sample was powdered and analyzed using X-Ray Fluorescence (XRF). At Idaho State University, I crushed the basalt samples to pieces on a steel anvil. To reduce contamination from calcite precipitation and aeolian sediments, I only selected the cleanest pieces for powdering; the cleanest were those that lacked obvious sediment or calcite

contamination. I then powdered the cleanest pieces using a tungsten-carbide puck and mill grinder.

At Brigham Young University's Geoscience Laboratory, under the supervision of Dr. Eric Christiansen, the whole-rock powders were analyzed for major and trace element composition using an XRF spectrometer. To analyze the major element composition of the bulk rock samples, the powdered samples were fused into individual lithium metaborate fused glass disks using a Katanax K1 Prime fluxer; the homogenous disks were then analyzed using a Rigaku ZSX Primus II XRF spectrometer operating at 50 kV and 50 mA. The composition of major oxides was determined. Estimated uncertainties for the major oxides are less than +/- 0.1% wt%, absolute (E. Christiansen, personal communication, February 2, 2022). Trace elements Sc, V, Cr, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Nd, Sm, Pb, Cl, F, S, Th, and U, were analyzed using pressed powder pellets produced in a hydraulic press at 20 tons using a combination of sample powder and briquetting additive. Analytical uncertainties, reported as 1sigma RSD (%), is reported in Table 3.2 (E. Christiansen, personal communication, February 2, 2022).

2.3.3 Phenocryst Characterization and Analysis

2.3.3.1 Textural Characterization of Thin Sections

I conducted petrographic analyses of thin sections to describe the phenocryst assemblage, modal abundance, extent of alteration, and textures of olivine phenocrysts. The goal of these analyses was to identify textural evidence for rapid growth of the olivine phenocrysts, indicated by dendritic and skeletal growth textures (Welsch et al., 2014), and to identify samples with abundant, unaltered olivine phenocrysts. These samples were suitable for further geochemical analysis to determine the composition of olivine phenocrysts using a scanning electron

microscope (SEM) and an electron probe microanalyzer (EPMA) at the Center for Advanced Energy Studies facility in Idaho Falls, ID and Boise State University, respectively.

Large olivine phenocrysts that have not experienced secondary alteration are thought to be most suitable for the application of olivine-melt thermometry, because the largest olivine phenocrysts are thought to be the first to crystallize (Pu et al., 2017). To determine which of the initial 33 USGS 149 basalt samples were most suitable for olivine-melt thermometry, I ranked each thin section on a scale of A to C to characterize the size and modal abundance of olivine phenocrysts (Table 2.3). Thin sections with large (500 to 1,000µm), abundant olivine phenocrysts were given a rank of A; those with small or sparse olivine phenocrysts were ranked with a C; and thin sections with a mixture of the two was ranked as B (Figure 2.2). To characterize the extent of alteration or oxidation of the thin section, I ranked samples from 1 to 3. Minimally altered, or clean, thin sections were ranked with a 1; highly altered thin sections ranked 3; and those with intermediate alteration were ranked with a 2 (Figure 2.2).

I chose thin sections with large, abundant olivine phenocrysts (ranking of A) and little alteration (ranking of 1) for olivine phenocryst compositional analysis. Based on these ranking, I identified five of the initial 33 basalt samples as being suitable for olivine analysis: U149_197_LS; U149_218_LS; U149_263_LS; U149_700_LS; and U149_945_LS. In each of these thin sections I identified 20 to 27 olivine phenocrysts for additional analysis.

2.3.3.2 Scanning Electron Microscopy of Olivine Phenocrysts

Using a JEOL JSM-6610LV Scanning Electron Microscope (SEM) at the Center for Advanced Energy Studies (CAES) I imaged the minimally altered thin sections (ranking of A) with large, abundant olivine phenocrysts (ranking of 1). I imaged the selected olivine phenocrysts with a Backscattered Electron (BSE) detector, which highlights intracrystalline

compositional variation within each olivine phenocryst. I used these BSE images to identify zoning patterns and rapid growth textures (Figure 2.3).

2.3.3.3 Olivine Phenocryst Compositional Analysis

I analyzed the olivine phenocryst compositions at the Micron Engineering Center at Boise State University using a Cameca SX-Five FE Electron Probe Microanalyzer (EPMA). The natural and synthetic standards used to calibrate these analyses, beam conditions and peak counting times used to analyze these standards are reported in Table 2.1.

I analyzed the olivine phenocrysts from the ten USGS 149 samples and the three ANL-OBS-A-001 samples for Al₂O₃, MgO, SiO₂, CaO, MnO, Cr₂O₃, FeO, and NiO wt%. All error associated with the analytical technique is reported as 2-sigma for each element. For Al, Cr, Ca, and Ni were below +/- 0.02 wt%. For Mg, uncertainties were below +/-0.14 wt%. For Fe, average uncertainty was around +/- 0.18 wt%; for Si, average uncertainty was +/- 0.08 wt%; for Mn, average uncertainties were below +/- 0.04 wt%.

I collected compositional analyses of olivine phenocrysts in traverses along each phenocryst; individual points were analyzed at 50 μm intervals (Figure 2.4). The electron beam was set to a voltage of 15 kV, an electron current of 20 nA, and the beam size was focused. Background and peak counting times were set to 20 seconds per elemental analysis for Al₂O₃, MgO, SiO₂, CaO, MnO, Cr₂O₃, FeO, and 40 seconds for NiO. Initially, I completed analyses of 20 olivine phenocrysts per thin section. I then used this initial batch of analyses to guide the second batch, which was aimed at analyzing the most Mg-rich olivine phenocryst per sample. To do this, I calculated the forsterite content (Fo#) for each point analysis from the first batch. Using the calculated Fo#, I identified the regions within each individual olivine phenocryst that had high Fo#'s in relation to the rest of the phenocryst. I then conducted the second batch of analyses

within these regions of the phenocrysts. Finally, I filtered all olivine phenocryst analyses to exclude those with totals outside of 98-101.5%, $Al_2O_3 > 0.1$ wt%, and CaO > 0.4 wt%. I filtered the data in this way to remove poor olivine analyses or analyses of other mineral phases. I completed a third round of analyses to ensure each thin section was analyzed across multiple olivine phenocrysts with 300 to 350 data points to obtain a representative dataset of olivine compositional variation in each sample and increase the likelihood of capturing the most Mg-rich olivine phenocryst composition. These steps were performed to ensure the quality of the temperature result obtained from the olivine-melt thermometer (Pu et al., 2017).

2.4 Results

2.4.1 Whole-Rock Geochemistry

Whole-rock major element (wt%) and Ni (ppm) concentrations for the 13 samples analyzed for olivine phenocryst compositions are reported in Table 2.2; the full suite of wholerock analyses (n=95) in this study are reported in Chapter 3 (Table 3.1). For these 13 samples, the SiO₂ concentrations range from 43.5 to 47.2 wt%, TiO₂ concentrations range from 2.0 to 3.4 wt%, Al₂O₃ concentrations range from 13.6 to 15.3 wt%, Fe₂O₃ concentrations range from 12.8 to 16.5 wt%, MnO concentrations are nearly consistent at 0.2 wt%, MgO concentrations range from 9.4 to 6.3 wt%, CaO concentrations range from 9.2 to 11.2 wt%, Na₂O concentrations range from 2.4 to 2.9 wt%, K₂O concentrations range from 0.5 to 1.0 wt%, and P₂O₅ concentrations range from 0.4 to 1.1 wt%. Ni concentrations range from 53 to 134 ppm and have a positive linear relationship with Mg# (Figure 2.5). The Mg# ($Mg\# = \frac{MgO}{(MgO + FeOT)} \times 100$) ranges from 43.4 to 59.1, and the most primitive sample is U149_945_LS-928. All the samples I used for olivine phenocryst characterization are relatively depleted in total alkalis and SiO₂ and are classified as olivine tholeiite basalts (Figure 2.6).

2.4.2 Olivine Phenocryst Results

2.4.2.1 Optical Analysis

All 50 samples from the USGS 149 core and nine samples from the ANL-OBS-A-001 core contain olivine, plagioclase, clinopyroxene, ilmenite, and magnetite. Textures range from diktytaxitic, with large plagioclase phenocrysts, to porphyritic, with large olivine phenocrysts and microcrystalline groundmass. These rocks range from highly altered to almost unaltered, as determined by the presence or absence of alteration rims around olivine phenocrysts. Olivine phenocryst abundance range from less than 1% to almost 10%, and olivine phenocrysts are 50 μ m to nearly 2,000 μ m in size. Samples with large, abundant, minimally altered olivine phenocrysts were considered ideal for the application of the olivine-melt thermometer (Table 2.3).

Within single flow groups, textures are quite varied, but I observed no systematic pattern in textures from the bottom to the top of each lava flow group. Within a flow group I observed, diktytaxitic, porphyritic and aphanitic textures. Within a single lava flow layer (Figure 1.5) surface and bottom facies are typically more porphyritic and more altered than interior facies. Interior lava flow layer facies are dominated by larger olivine phenocrysts (roughly >500 μ m) and are considerably more diktytaxitic than the surface and bottom facies.

2.4.2.2 Scanning Electron Microscopy

Using SEM, compositional patterns in olivine phenocrysts were imaged using the BSE detector. All olivine phenocrysts examined in this study appear to be normally zoned with a Mg-rich core and progressively more Fe-rich rims, represented by darker colored rims and lighter colored cores, respectively (Figure 2.3). The SEM images also revealed rapid growth textures, as evidenced by the skeletal, or branching patterns in the olivine phenocrysts (Figure 2.3). Of the

20-27 olivine phenocrysts analyzed per sample, 1-7 olivine phenocrysts displayed rapid growth textures.

2.4.2.3 Electron Microprobe Analysis

Point analyses of olivine phenocrysts were conducted along traverse lines at 50µm intervals (Figure 2.4). Analysis of the major oxides of the most Mg-rich olivine phenocryst from each of the 13 samples is presented in Table 2.4. MgO concentrations range from 34.7 to 45.2 wt%, FeO ranges from 14.5 to 27.8 wt%, NiO ranges from 0.1 to 0.2 wt%, SiO₂ ranges from 39.5 to 37.1 wt%, Al₂O₃ ranges up to 0.1 wt%, MnO ranges from 0.2 to 0.4 wt%, CaO ranges from 0.2 to 0.3 wt%, and Cr₂O₃ ranges up to 0.1 wt%.

Using the compositions of the MgO (wt%) and FeO (wt%) of the olivine phenocryst, the Fo# $\left(Fo# = \left(\frac{MgO}{40.304}\right) / \left(\left(\frac{MgO}{40.304}\right) + \left(\frac{FeO}{71.844}\right)\right)\right)$ was calculated for each point analysis of each

sample, ranging from 69.0 to 84.6. The forsterite content of each point analysis per sample is presented in the histograms of Fo# in Figure 2.7. These histograms show a continuous range in composition from the most Mg-rich analysis to the least. All samples display unimodal distribution patterns, which is defined here as continuous Fo# with no gaps between peaks in the histograms. When comparing the patterns of Fo# throughout the three lava flow layer facies for a single lava flow layer (Figure 2.8), the interior facies sample displays a wider range of Fo# (difference between the minimum and maximum Fo#'s differ by nearly 40), while the surface and bottom facies have more narrow ranges of Fo# (difference between the minimum and maximum Fo#'s differ by about 20).

Plots of NiO (ppm) as a function of Fo# for the highest 3 % Fo# analyses per sample are shown in Figure 2.9. For each plot, the data are fit to a linear relationship. For the purpose of assessing olivine-melt equilibrium, the equation for this linear fit is used to calculate the NiO for

the most Mg-rich olivine phenocryst to reduce the effect of analytical uncertainty of the temperature calculations (Pu et al., 2017; Brehm, 2021).

2.5 Assessing Olivine-Melt Equilibrium

To determine if the most Mg-rich olivine phenocryst in each sample represents the liquidus composition of the corresponding melt, represented by the whole-rock geochemistry, olivine-melt equilibrium must be established. To do this, I analyzed four characteristics of the olivine phenocrysts as described below: (1) olivine phenocryst textures, (2) olivine phenocryst compositional histograms, (3) olivine phenocryst Fo# versus whole-rock Mg#, and (4) KD liquidus test.

2.5.1 Olivine Phenocryst Textures

The preservation of rapid growth textures, or dendritic branching, of olivine phenocrysts in the samples from this study (Figure 2.3) suggests that olivine phenocrysts crystallized rapidly in diffusion-limited conditions (Welsch et al., 2014) and then, shortly after the onset of olivine crystallization, the basalt cooled rapidly. The preservation of these textures in emplaced lavas have been interpreted to reflect the rapid ascent of the melt shortly after the onset of olivine crystallization (Brehm, 2021). For this reason, these textures observed in the ESRP basalts from this study are significant because the preservation of these textures in cooled lavas support that the olivine phenocrysts grew rapidly during melt ascent, and therefore, the most Mg-rich olivine phenocryst may be in equilibrium with the whole-rock composition of the samples (Pu et al., 2017; Brehm, 2021).

2.5.2 Olivine Phenocryst Composition Histograms

To further test olivine-melt equilibrium for each of the 13 ESRP samples, I used EMPA to measure the compositional variation of olivine phenocrysts. Distribution of compositions of

individual olivine phenocryst point analyses, represented by the Fo# were displayed in histograms for each basaltic sample. All the samples analyzed in this study display unimodal distribution patterns, which is defined by no gaps between the data in the histogram (Figure 2.7 and Figure 2.8). Unimodal distribution patterns support the influence of a single melt composition, an expected prerequisite for olivine-melt equilibrium (Pu et al., 2017).

2.5.3 Olivine Fo# versus Whole-Rock Mg#

The relationship between the Fo# of the most Mg-rich olivine phenocryst in each sample and the Mg# of the sample's whole-rock composition provides another test for olivine-melt equilibrium. While, the Fo# represents the MgO composition of the olivine phenocryst and the Mg# represents the MgO composition of the whole-rock. It is expected that a basaltic melt (represented by the whole-rock composition) with a high composition of MgO should crystallize high MgO olivine. For this reason, a positive relationship (Figure 2.10) represents the expected partitioning of Fe²⁺ and Mg²⁺ between the olivine phenocrysts and the melt (Pu et al., 2017; Brehm, 2021). This provides a third piece of evidence supporting olivine-melt equilibrium in the ESRP basalts in this study.

2.5.4 Fe2+ -MgKD (Olivine-Melt) Liquidus Test

The final test of olivine-melt equilibrium is the $^{Fe2+-Mg}K_D$ (olivine-melt) liquidus test. To calculate this Fe-Mg exchange coefficient, I use the composition of the most Mg-rich olivine phenocryst from each sample and the sample's whole-rock composition. The $^{Fe2+-Mg}K_D$ (olivine-melt) is defined as:

$$Fe^{2^{+}-M} K_{D}(olivine - melt) = \left(\frac{X_{Fe^{2^{+}}O}}{X_{MgO}}\right)^{olivine} \left(\frac{X_{MgO}}{X_{Fe^{2^{+}}O}}\right)^{melt}$$
(1)

To pass the K_D liquidus test, the calculated K_D for the sample should be within the acceptable ranges defined in the literature (Roeder and Emslie, 1970; Putirka, 2088; Brehm, 2021, references therein). When applied to the ESRP basalts from this study, the calculations range from 0.27 to 0.39 (Table 2.4). All the samples, except for ANL-1-644, which had a $^{Fe2+-Mg}KD$ (olivine-melt) of 0.39, passed the liquidus test (Brehm, 2021; Pu et al., 2017). In this sample, the most Mg-rich olivine analyzed had a maximum Fo# = 69.0 which was too low to be in equilibrium with the whole-rock composition (6.3 wt%). Although more work is needed to confidently explain this observation, one possible explanation could be that the higher MgO olivine phenocrysts from this sample were lost by some mechanism such as gravitational sinking. Because ANL-1-644 did not pass the K_D liquidus test, this sample was not used to calculate a crystallization temperature.

The 12 samples that were determined to be in olivine-melt equilibrium and were used to calculate temperatures at the onset of olivine phenocryst crystallization using the Mg-based and Ni-based olivine-melt thermometers developed by Pu et al. (2017).

2.6 Pre-eruptive Temperatures and Dissolved H₂O Content of ESRP Basaltic Melts

Based on the tests described above, the most Mg-rich olivine phenocryst analyzed in 12 ESRP samples closely represents the liquidus phase of the associated whole-rock, or melt, composition. Therefore, I use the two olivine-melt thermometers to calculate the temperature at which the melt initially cooled and began to crystallize olivine phenocrysts and use the difference between the Ni-based and Mg-based temperatures to quantify the minimum dissolved H₂O content of the pre-eruptive melts (Pu et al., 2017; Brehm, 2021).

To do this, a series of calculations, published in Pu et al. (2017), using the whole-rock and EPMA data are required to use the olivine-melt thermometers. To apply the Ni-based
thermometer, I first calculated the NiO (wt%) for the highest-Mg olivine phenocryst using the equation of the slope of the trend line ($NiO = (slope \times Max Fo#) + y - intercept$) reported in the NiO versus Fo mol% (Figure 2.9) for each sample and the maximum Fo# for each sample to decrease analytical uncertainty of the Ni-based thermometer. I then converted the highest-Mg olivine phenocryst and whole-rock compositional data to mole fraction.

Using the mole fraction components of the melt and olivine phenocryst, I calculated the D_{NiO} , or the partition coefficient for NiO between the olivine phenocryst and the melt, using the equation:

$$D_{NiO} = \frac{X_{NiO}^{Ol}}{X_{NiO}^{Melt}} \quad (2)$$

where X_{Ni0}^{Ol} and X_{Ni0}^{melt} are the mole fraction components of NiO in the olivine and melt, respectively (Pu et al., 2017).

I then calculated the sum of mole fraction components of FeO, MgO, CaO, CoO, and NiO of the melt composition using the equation:

$$BX_{NM} = X_{Fe0}^{melt} + X_{Ma0}^{melt} + X_{Mn0}^{melt} + X_{Ca0}^{melt} + X_{Co0}^{melt} + X_{Ni0}^{melt}$$
(3)

where X_x^{melt} corresponds to the mole fraction of the major oxides of the melt composition.

I calculated the final parameter to plug into the Ni-based olivine-melt thermometer using the equation below:

$$BNF = (3.5 \times \ln(1 - X_{Al_2O_3}^{melt})) + (7 \times \ln(1 - X_{TiO_2}^{melt}))$$
(4)

where $X_{Al_2O_3}^{melt}$ and $X_{TiO_2}^{melt}$ correspond to the mole fraction components of Al₂O₃ and TiO₂ of the melt, respectively.

Once the above series of calculations was defined, I calculated the final crystallization temperature at the liquidus for a basalt sample using the parameters defined in equations (2-4) and the Ni-thermometer calculation (Pu et al., 2017):

$$T_{Ni}(\mathcal{C}^{\circ}) = \frac{9,416}{\left(\ln(D_{NiO}) + 0.71 \times \ln(BX_{NM}) - 0.349 \times BNF - 0.532 \times \ln(X_{SiO_2}^{melt}) + 4.319\right)} - 273.15$$
(5)
where T_{Ni} is temperature in Celsius with an uncertainty of ± 29° Celsius.

For the Mg-based thermometer, the same compositions were used and converted to mole fraction. The same parameters calculated from equation (3) and (4) were used to calculate the temperature of olivine phenocryst crystallization using the Mg-based thermometer. I used the following equation to calculate the partition coefficient for MgO:

$$D_{Mg0} = \frac{X_{Mg0}^{0l}}{X_{Mg0}^{Melt}} \quad (6)$$

where X_{Mg0}^{Ol} and X_{Mg0}^{melt} are the mole fraction components of NiO in the olivine and melt, respectively (Pu et al., 2017).

Using the Mg-based thermometer equation below, I calculated the temperature at the onset of olivine phenocryst crystallization:

$$T_{Mg}(C^{\circ}) = \frac{6,701}{\left(\ln(D_{Mg0}) + 1.12 \times \ln(BX_{NM}) - 0.640 \times BNF + 1.08 \times \ln(X_{SiO_2}^{melt}) + 4.74\right)} - 273.15 (7)$$

Where T_{Mg} is temperature in Celsius with an uncertainty of $\pm 26^{\circ}$ Celsius.

The calculated T_{Ni} values for these samples range from 1,117 to 1,195 °C. Calculated T_{Mg} values range from 1,145 to 1,217 °C (Table 2.4). The T_{Mg} range is systematically higher than those calculated with the Ni-based thermometer, (Figure 2.11). This is the expected relationship between the two temperatures calculated using these thermometers because the Mg-based

thermometer is dependent on the dissolved H_2O content of the melt and reports the temperature if the system was anhydrous. Given the dependence on dissolved H_2O content of the melt of the Mg-based thermometer, the Ni-based thermometer determines more accurate temperatures for hydrous systems.

The difference between the T_{Mg} and T_{Ni} values (ΔT) for each sample can be used to calculate the minimum dissolved melt H₂O content at the time the olivine phenocrysts began crystallizing (Pu et al., 2017; Brehm, 2021). For these 12 samples, the ΔT ranges from 2.9 to 82.9 °C and the minimum dissolved H₂O content of the melt ranges from 0.4 to 2.6 (\pm 0.5) wt% (Table 2.4).

2.7 An Olivine Phenocryst Perspective on Eastern Snake River Plain Basalt Petrogenesis 2.7.1 Textural Evidence of Rapid Ascent

The preservation of rapid growth textures, or diffusion limited textures (Figure 2.3), in ESRP basalts suggests that the phenocrysts grew rapidly under diffusion-limited conditions. Soon after crystallization of olivine began, the magma must have erupted to the surface and cooled (Pu et al., 2017; Welsch et al., 2014). The onset of phenocryst crystallization and the eruption of the basalt must have occurred too quickly for the olivine phenocrysts to grow into euhedral textures, suggesting the onset of crystallization occurred during rapid ascent of the basalt (Pu et al., 2017; Brehm, 2021).

2.7.2 Temperatures and Minimum Dissolved Melt H₂O Content of the Melt

For the twelve olivine-melt pairs that were found to be in equilibrium temperatures calculated using the olivine-melt thermometers reflect the temperatures experienced when the basaltic melt first begins to crystallize olivine phenocrysts. The temperatures calculated, using the Ni-based thermometer, range from 1,117 to 1,195 °C, are consistent with past research on

other ESRP basalt samples (Figure 2.12; Brehm, 2021). The temperatures calculated using the Mg-based thermometer were consistently higher, with a range from 1,145 to 1,217 °C, probably reflecting the dissolved melt H₂O content. Using the difference between the temperatures calculated using the Ni-based and Mg-based thermometers for each sample, the minimum dissolved water content of the melt was calculated was found to range from 0.4 to 2.6 wt%, consistent with water content calculated in other studies on ESRP basalts (Table 2.4; Stefano et al., 2011; Barton, 2020; Brehm, 2021).

2.7.3 Variability of Olivine Phenocryst Populations Within a Lava Flow Layer

When compared to each other, the analyses of the olivine phenocryst populations from the three flow layer facies shows variation in olivine phenocryst compositional range with narrow ranges of Fo# in the top and bottom facies (a difference of 20 between the minimum and maximum Fo#) and much wider ranges in the interior facies (a difference of 40 between the minimum and maximum Fo#) (Figure 2.8). I hypothesize this may be due to an insulation mechanism associated with the cooling of the lava flow layer.

The variation in textures and alteration probably reflect the emplacement process of the inflated pahoehoe (Kuntz, 1979). When the layer is initially erupted onto the surface, the outer facies cool rapidly when in contact with the cooler ground and ambient air, this results in smaller phenocrysts and the preservation of vesicles. The interaction with the ground and air also increases the likelihood of interaction with surface H₂O, which can oxidize the outer facies, resulting in more altered phenocrysts. I hypothesize that the interior facies is insulated by the cooled outer facies and, therefore, has more time to grow phenocrysts, resulting in larger grained, more euhedral phenocrysts.

Between the three flow layer facies, the whole-rock compositions, and the highest Fo#

for each sample are similar. When histograms of Fo# are compared between the three flow facies within a single lava flow layer, I observe narrow ranges of Fo# in the top and bottom facies and much wider ranges in the interior facies (Figure 2.8). One possible explanation for this observation is the presence of an insulation mechanism as the lava flow layer cooled. When the lava flow layer erupted to the surface, the surface and bottom facies cooled quickly. I hypothesize that the cooled, outer facies insulated the interior facies and allowed for a prolonged crystallization of olivine phenocrysts in the interior, resulting in progressively more Fe²⁺ rich olivine phenocrysts. Further investigations of the olivine phenocryst compositions in individual lava flow layers would help to understand the observed trends more fully.

2.7.4 Conceptual Model Informed by Olivine Phenocryst Analyses

Our model of ESRP petrogenesis begins with the on-set of olivine phenocryst crystallization. Using the Ni-based olivine-melt thermometer and the Mg-based olivine-melt thermometer, the temperature at the onset of olivine phenocryst crystallization and the dissolved melt H₂O content was determined to range from 1,117 to 1,195 °C and 0.4 to 2.6 ± 0.5 wt%, respectively. These values fall within what has been reported for Snake River Plain basalts in the literature (Stephano et al., 2011; Bradshaw, 2012; Barton, 2020; Brehm, 2021). The onset of olivine phenocryst crystallization occurs as the melt begins to rise rapidly to the surface, a hypothesis supported by rapid growth textures in olivine phenocrysts and olivine-melt equilibrium. Once erupted to the surface, the magma batch does so as individual pulses of lava, which appear in basaltic drill core as lava flow layers. The surface and bottom facies of the lava flow layers interact with the much cooler ground and the ambient air, resulting in rapid cooling of the outer facies. I hypothesize that the outer facies then insulate the interior magma in the lava flow layer and enable prolonged crystallization of olivine phenocrysts, supported by observations

of phenocryst textures and forsterite content. This prolonged crystallization in the interior facies is also one possible explanation for the presence of both euhedral and rapid growth textures of olivine phenocrysts in the samples.

2.7.5 Contributions and Future Work

The workflow discussed in this Chapter provides an outline for future studies to further investigate olivine phenocrysts in ESRP basalts. To minimize alteration of olivine phenocrysts and determine full range of olivine phenocryst compositions in a lava flow layer, this work shows that sampling should be conducted in the dense interior facies of lava layers.

To build on this study, more ESRP basalt samples could be analyzed using the workflow described here to provide additional information on the variability of crystallization temperatures and minimum dissolved H₂O content of the melts of basalts in this volcanic system. Similarly, continued analyses through cross-sections of lava flow groups could assess variability of these pre-eruptive conditions throughout a single flow group, which could provide additional insight to the processes occurring during a single volcanic eruption.

2.8 Conclusion

In this study, I used the composition of olivine phenocrysts and the associated whole-rock composition, representative of the melt, to inform the pre-eruptive conditions and the petrologic history of these ESRP basalts. The preservation of olivine rapid growth textures supports the hypothesis that olivine phenocrysts grew rapidly under diffusion-limited conditions. All but one of the olivine-melt pairs appear to be in equilibrium. The olivine textures, unimodal distribution patterns of the histograms of the forsterite content for each sample, and the calculated K_D values using the ^{Fe2+-Mg}K_D (olivine-melt) liquidus test supports olivine-melt equilibrium. One possible process that could preserve olivine rapid growth textures and olivine-melt equilibrium could be

rapid ascent of the magma soon after the onset of olivine phenocryst crystallization. Using the Ni-based olivine-melt thermometer and the Mg-based olivine-melt thermometer, the temperature at the onset of olivine phenocryst crystallization and the dissolved melt H₂O content was determined to range from 1,117 to 1,195 °C and 0.4 to 2.6 wt%, respectively. The distribution patterns of the forsterite content of samples collected from the three flow layer facies point to a possible insulation mechanism after the inflated pahoehoe flow layers are erupted onto the surface. The textures and compositions of olivine phenocrysts observed in the ESRP basalts provide additional insight to the pre-eruptive conditions and petrologic history of the basaltic system.

Chapter 3: Spatial Correlation of Basalt Flow Groups

3.1 Introduction

To predict the migration of radioactive and chemical contaminants throughout the eastern Snake River Plain (ESRP) aquifer and understand the magmatic evolution of the ESRP volcanism to assess the risks associated with the volcanic hazards of the ESRP volcanic system, the subsurface basaltic stratigraphy beneath the Idaho National Laboratory (INL) must be investigated (Bartholomay et al., 2020). To do this, the United States Geological Survey (USGS) has collected lithologic, paleomagnetic, and geochemical data from basalt strata in drilled cores within the INL to characterize lava flow groups and correlate them spatially (Hodges et al., 2016). Along with the lithologic and paleomagnetic data, the time-space variations in the wholerock compositions of individual flow groups have been used to delineate separate flow groups and correlate the flow groups spatially (Geist et al., 2002; Hughes et al., 2002). These correlations have been used to constrain the subsurface stratigraphy and thus better understand the hydrologic and geologic processes that occur within the ESRP. (Reed et al., 1997; Geist et al., 2002; Hughes et al., 2002; Miller, 2007; Potter, 2010).

To aid the USGS efforts to reconstruct the subsurface stratigraphy beneath the INL, this study aims to characterize the basalt flow groups that make up the stratigraphic rock cores USGS 149, USGS 143, and ANL-OBS-A-001, which were drilled in the Materials and Fuels Complex (MFC) region of the INL (Figure 3.1). Prior to this study, the USGS began an investigation into the lithologic and paleomagnetic characteristics of basalt drill cores from the MFC region. This initial investigation produced a preliminary stratigraphic cross-section through drill cores USGS 149, USGS 143, and ANL-OBS-A-001 (Figure 3.2; M. K. V. Hodges, personal communication, March 24, 2022). This work will assess these initial correlations using whole-rock geochemistry.

Additionally, I assess the correlations of surface vents Vent 5350, Microwave Butte, Radiofacility Butte, and Topper Butte to flow groups observed at depth in the USGS 149 core using whole-rock geochemistry. This assessment will aid the USGS correlate flow groups from the surface to the subsurface in the MFC region of the INL. Finally, I evaluate if olivine phenocryst characterizations presented in Chapter 2—including the textures, olivine-melt equilibrium, and calculated crystallization temperatures and minimum dissolved H₂O content of the basaltic melt—are useful as an additional tool to correlate basalts flows. This evaluation of olivine phenocryst characterization as a correlation tool is applied to the Cobb Mtn. Paleomagnetic Chron flow group (i.e., the Cobb Mtn. flow group). This work builds on the previous work of the subsurface stratigraphy beneath the INL to help characterize the subsurface beneath the MFC, a prerequisite for understanding the migration of chemical contaminants throughout the ESRP aquifer and the volcanic hazards associated with the ESRP volcanic system (Bartholomay et al., 2020).

3.2 Established Flow-Group Correlation Methods

The lithology of the cores, including the presence of rhyolitic and sedimentary interbeds, are used to identify and correlate basaltic lava flow groups. Sedimentary interbeds can be useful markers of flow-group boundaries, as the deposition of sediment marks an eruption hiatus (Hughes et al., 2002). When sedimentary beds are not present, the textures and morphologies of the lava flow groups, and the many lava flow layers which make up the flow groups (see section 1.2.2.1), can be used to determine flow-group breaks (Self et al., 1998; Potter et al., 2019). Welhan et al. (2002) showed that flow groups can be defined when a molding texture is observed in the rock core. This texture is produced when a flow group migrates over a pre-existing flow group, filling in gaps on the surface of the pre-existing flow group as it does so (Welhan et al.,

2002). Flow-layer breaks can be determined by the repetition of the three flow layer facies, described by Self et al. (1998) as a vesicular top, dense interior, and glassy, vesicular base (Figure 1.5). The complex stratigraphy of the ESRP can be partially reconstructed by the lithology of rock cores, however, lithology is not usually sufficient to delineate between flow groups (Hughes et al., 2002). This is because basaltic stratigraphy does not produce perfectly horizontal beds and, therefore, the same flow group observed across multiple core holes can have heterogenous textures and thicknesses. To delineate flow groups more comprehensively, further analyses are required.

To further delineate between lava flow groups, paleomagnetic inclination is used as a tool to identify and correlate lava flow groups (Champion et al., 1997; Champion et al., 2011; Champion et al., 2013). This is because paleomagnetic inclination can determine if two batches of erupted material erupted to the surface at the same time in Earth's history. As a flow group cools, the declination and inclination of the Earth's dipole at the time of cooling is archived in the rock, as the magnetic moment of the Fe-rich minerals that make up the rock align with the Earth's dipole. The eruption of ESRP basalts occurs on short timescales (days to decades) relative to the migration of Earth's dipole (nearly four degrees per century) therefore the inclination archived in the rock can be used to distinguish between flow groups when the average paleomagnetic inclination varies by more than approximately two degrees (Champion and Shoemaker, 1977). Along with clear lithologic breaks, these paleomagnetic data can identify lava flow groups separated by eruption hiatuses in individual cores. If lava flow groups observed in separate cores have similar paleomagnetic inclination, then this suggests they erupted at the same time. Thus, paleomagnetic evidence supporting similar timing of eruption, together with similar lithology and relative stratigraphic positions, suggests the flow groups are correlative. Lithology

and paleomagnetic inclination alone, however, aren't always sufficient to distinguish between flow groups.

In principle, geochemistry of lava flows can be used to support subsurface correlations because each flow group represents a single eruption event originating from separate magma batches and, therefore, the geochemistry of a flow group may be distinctive (Kuntz et al., 1992). Chemically distinct flow groups, like the evolved basalts of the ESRP (see section 1.3.2.2), can be correlated based on their geochemical composition. Most ESRP basalts, however, are compositionally very similar (Kuntz and Dalrymple, 1979; Hughes et al., 2002; Geist et al., 2002), making subsurface correlations based on geochemistry alone difficult.

Despite the relatively homogeneous nature of ESRP basalt flow groups, the trends in geochemistry have been used to delineate flow-group breaks and in turn the position these flow breaks has been used to assess correlations inferred from lithology and paleomagnetic inclination. Using whole-rock major and trace element data, Hughes et al. (2002) demonstrated that geochemical variations within a single flow group follow characteristic patterns. The bottoms of flow groups are characterized as more primitive, with higher concentrations of MgO and lower concentrations of TiO₂ and SiO₂. Flow groups commonly become progressively more evolved towards the top of the flow group with decreases in MgO, this trend is interpreted to reflect fractional crystallization (Geist et al., 2002; Hughes et al., 2002). A decrease in Cr, from the bottom to the top of a flow group, has also been observed and has been interpreted to reflect olivine crystallization (Reed et al., 1997; Geist et al., 2002; Hughes et al. 2002). These studies also noted concentrations of La increasing from bottom to tops of flow groups, an observation that corresponds with a decrease in MgO, possibly reflecting open-system assimilation of the mid-crustal sill or heterogeneity in partial melt source (Geist et al., 2002; Hughes et al., 2002).

Regardless of the geologic processes that produce these trends, the predictable variability of the whole-rock geochemistry throughout a flow group can be used to delineate flow-group breaks. For example, in a rock core a return to a more primitive, magnesium-rich (Mg-rich) composition, following a trend towards more evolved compositions, can be used to suggest a flow-group break. This is because the return to primitive composition is inferred to represent the base of a flow group.

In this study, I evaluate a preliminary interpretation of the MFC subsurface stratigraphy (Figure 3.2) that was produced using lithologic and paleomagnetic data using additional evidence that has previously been used to aid in correlation efforts: whole-rock geochemistry. I quantified the whole-rock major and trace element compositions and the major oxide compositions of olivine phenocrysts in order to characterize the basaltic strata and evaluate if the geochemical trends support the initial correlations (Figure 3.2). Additionally, I develop and evaluate a new geochemical correlation tool, termed olivine phenocryst characterization. This work will improve understanding of the subsurface stratigraphy beneath the MFC region of the INL and thus add additional information about the hydrogeologic processes that occur within the ESRP.

3.3 Existing Preliminary Subsurface Correlation at the Materials and Fuels Complex

Prior to this study, the USGS began investigating the stratigraphy beneath the MFC region of the INL and produced a preliminary correlation among core holes USGS 149, USGS 143, and ANL-OBS-A001 (Figure 3.2). The depth below land surface and the sequence of inclination values of the basaltic strata in these cores were used to evaluate possible flow-group correlations between these three core holes (Champion et al., 2011; Hodges et al., 2016; M. K. V. Hodges, personal communication, March 24, 2022). Flow-group breaks were inferred when

average paleomagnetic inclination between two sample locations deviated by two degrees or more (Champion et al., 2011).

In this initial investigation, two flow groups are inferred to correlate between core holes USGS 143 and USGS 149: a flow group defined by an average paleomagnetic inclination of 65°, and a flow group with a 63° average paleomagnetic inclination. In USGS 143, the 65° average paleomagnetic inclination flow group spans the rock core from 154 feet to 374 feet below Earth's surface. In USGS 149, this same flow group spans the core from 167 to 239 feet below Earth's surface (Figure 3.3). At deeper stratigraphic levels, the 63° average paleomagnetic inclination flow group spans the cores from 437 to 502 and from 261 to 401 in USGS 143 and USGS 149, respectively. In contrast, at the top of each core there are flow groups with similar 63-64° average paleomagnetic inclinations that are not correlated due to their stratigraphic context (M.K.V. Hodges, personal communication). These three initial interpretations of USGS 143 and USGS 149—the correlation of the 65° flow group, the correlation of the 63°, and the non-correlation of the near-surface flow groups with similar paleomagnetic inclinations of 63° to 64°—are assessed in this study using whole-rock geochemistry.

The preliminary correlation between core holes USGS 149 and ANL-OBS-A-001 suggests that five flow groups correlate (Figure 3.2). Whole-rock geochemical data only exists for three of these flow groups from the ANL-OBS-A-001 core, so these are the focus of this study. In both the USGS 149 and ANL-OBS-A-001 cores those three flow groups have been defined based on average paleomagnetic inclinations of 47°, 59° (Cobb Mtn.), and - 48°. In the USGS 149 core, the flow groups span the core from 401 to 527, 581 to 957, and 957 and to 975 feet below Earth's surface, respectively (Figure 3.4). In the ANL-OBS-A-001 core, the flow groups span the core from 402 to 1045, respectively (Figure 3.4).

Here, I use whole-rock geochemistry to assess the correlations made in the initial investigation and then I evaluate olivine phenocryst characterization of samples collected from the Cobb Mtn. flow group as an additional correlation tool.

3.4 Methods

3.4.1 Core and Surface Vent Sampling

To better constrain the subsurface stratigraphy in the MFC region of the INL, I used geochemistry to assess correlations of lava flow groups, inferred by lithology and paleomagnetic inclination, among volcanic vents at the surface and core holes USGS 149, USGS 143, ANL-OBS-A-001 (Figure 3.2; M. K. V. Hodges, personal communication, March 24, 2022). To do this, I sampled basaltic surface vents and basalt at depth in each core for petrography and whole-rock geochemistry (Figure 3.5).

Surface vents Vent 5350, Microwave Butte, Radiofacility Butte, and Topper Butte were sampled to correlate lava flow groups from surface to depth in the USGS 149 core, an addition to the reconstruction of the stratigraphy of the ESRP (Figure 3.6). These vents were chosen for analysis based on existing paleomagnetic inclination data (D. Champion, personal communication, October 1, 2020), which suggests possible correlations to flow groups in the USGS 149 core. Each vent was sampled for whole-rock geochemistry once using a sledge hammer. To avoid chemical contamination from soils, lichen crust, and caliche, the outer rim of each sample was removed in the field. I collected 1 to 2 kg of basalt from each outcrop to ensure enough sample material for whole-rock geochemical analysis and the production of thin sections.

The 50 samples collected from the USGS 149 core, as described in Chapter 2.3 of this study, were used to assess correlations of lava flow groups among the USGS 149 core hole and

surface vents, the USGS 143 core hole, and the ANL-OBS-A-001 core hole. Sampling was conducted to determine compositional variability at the intra-flow-group and intra-flow-layer scale. To do this, lava flow groups were sampled at multiple depth intervals, and lava flow layers were subsampled in the three flow layer facies.

USGS 143 was sampled by M. Sjoblom, Geology Faculty at Brigham Young University -Idaho, in 2019 for whole-rock geochemistry. Thirty-two basalt samples were collected from the USGS 143 core. These samples were collected in the dense interior of the lava flow layers with the motivation of identifying flow groups based on geochemical variation (M. Sjoblom, personal communication, January 21, 2022).

To further assess the utility of olivine phenocryst geochemistry to inform flow-group correlations in the MFC region, I sampled the ANL-OBS-A-001 core within the Cobb Mtn. flow group three times. Each of the three samples was collected in dense, crystalline sections of the flow groups, to reduce the impact of *in situ* alteration on the measured whole-rock composition (Bates, 1999). These samples were prepared for whole-rock geochemistry and thin sections.

3.4.2 Lithologic Logs

Using the RockWare Software, LogPlotTM, I described and analyzed rock core USGS 143. The basalt characteristics, including- abundance of vesicles, amount of fractionation, and color- were noted with depth and sediment intervals were logged. The USGS 149 core was described and logged by USGS staff in 2019 using the same procedure. These LogPlotTM core logs describe the petrologic characterization down core, the vesicular composition of the core, and the degree of fracture within the core. Emphasis was placed on minimizing interpretation of each core. The lithology of the ANL-OBS-A-001 core was described and analyzed in the mid-

1990s using televiewer log methods by the USGS and an independent contractor (Paillet and Boyce, 1996).

3.4.3 Whole-Rock Geochemistry

Using the same methods outlined in Chapter 2.3.2 of this study, powders of the basalt samples collected from the four surface vents and the USGS 149 and ANL-OBS-A001 core were prepared at Idaho State University. Preparation and powdering of the 32 USGS 143 basalt samples were conducted by M. Sjoblom in 2019. Whole-rock compositional analyses were performed at Brigham Young University under the supervision of Dr. Eric Christiansen. Major and trace element compositions were analyzed using a Rigaku ZSX Primus II XRF spectrometer (E. Christiansen, personal communication, February 2, 2022). Estimated uncertainties for the major oxides are less than +/- 0.1% wt% (E. Christiansen, personal communication, February 2, 2022). Trace elements Sc, V, Cr, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Nd, Sm, Pb, Cl, F, S, Th, and U, were analyzed.

3.4.4 Olivine Phenocryst Compositional Analysis

To evaluate if olivine phenocryst characterizations are useful as an additional correlation tool, olivine phenocrysts in thin sections of samples collected from the Cobb Mtn. flow group in both the USGS 149 and ANL-OBS-A-001 cores were analyzed for major oxide composition using an EPMA. Seven samples from the USGS 149 core were collected from two lava flow layers within the flow group. Three samples were collected from the flow group in the ANL-OBS-A-001 core, each from dense, crystalline sections of the flow group. Twenty to twentyseven olivine phenocrysts from each of the five thin sections sampled from this flow group were analyzed using the Cameca SX-Five EPMA at Boise State University. Analysis of olivine phenocrysts from the samples were conducted as described in Chapter 2.3.6.1.

3.5 Results

3.5.1 Whole-rock Geochemistry

The 95 basalt samples analyzed for major and trace elements from the USGS 149, USGS 143, ANL-OBS-A-001 cores, and surface vents are reported in Table 3.1 and Table 3.2. For these samples, SiO₂ ranges from 42.5 to 47.3 wt%, MgO ranges from 4.2 to 10.0 wt%, TiO₂ ranges from 1.9 to 4.0 wt%, and Ni ranges from 10 to 143 ppm. Based on the total alkalis and range in SiO₂, these samples are classified as basalts (Figure 2.6). Following the compositional classifications developed for ESRP basalts from the Kimama core (Potter et al., 2018), 84 samples were classified as Snake River Plain olivine tholeiites (SROT), ten samples were classified as high Fe-Ti basalts, and one sample is classified as a high K-Fe basalt (Figure 3.7). None of the samples in this study have $K_2O/TiO_2 < 0.11$ wt% and thus none fall within the low-K SROT compositional group. This observation is expected as the low-K lavas have been associated with hydrothermal alteration, which is dominant at depths in the subsurface below 1050 meters, and the samples from this study were collected above this depth (lowest samples collected in the ANL-OBS-A-001 core at 1,039 feet from land's surface).

In each core, the whole-rock composition varies from the bottom of a paleomagneticinclination-defined flow group to the top (Figure 3.8; Figure 3.9; Figure 3.10). From the bottom to the top of a lava flow group, or from the oldest erupted material to the youngest erupted material, the whole-rock composition gradually gets more evolved: more enriched in SiO₂ and TiO₂ and more depleted in MgO and Ni (Figure 3.8; Figure 3.9; Figure 3.10). When normalized to primitive mantle values (Sun and McDonough, 1989), trace element values of the whole-rock composition of individual samples collected from the same flow group follow similar patterns (Figure 3.11).

3.5.2 Olivine Phenocryst Characterization

The composition of the most Mg-rich olivine phenocrysts that I analyzed from the ten samples collected from the Cobb Mtn. flow group in the USGS 149 and ANL-OBS-A-001 cores are reported in Table 3.3. The forsterite content (Fo#) of the most Mg-rich olivine phenocrysts range from Fo₈₅ to Fo₆₉. The distribution patterns of the olivine phenocryst compositions per sample are unimodal, i.e., have a range of Fo# that produces a single dominant peak with no gaps (Figure 2.7). There is a positive linear relationship between the Fo# of the most Mg-rich olivine phenocryst in each sample and the Mg# of the whole-rock composition (Figure 2.10). All but one of the samples passed the ^{Fe2+-Mg}KD (olivine-melt) liquidus test (see section 2.5.4, Table 2.4) with a calculated KD value of 0.32 ± 0.05 (Brehm, 2021, references therein). Sample ANL-1-644 has a calculated KD of 0.39 and therefore did not pass this test (Table 2.4).

The four olivine-melt pairs from the Cobb Mtn. flow group that passed the KD-liquidus test were used to calculate crystallization temperatures and minimum dissolved H₂O contents of the melt. The temperatures calculated using the Ni-based olivine-melt thermometer ranges from 1,117 to 1,195 °C, and the temperatures calculated using the Mg-based olivine-melt thermometer ranges from 1,145 to 1,217 °C. The Δ T, therefore, range from 2.9 to 82.9 °C and the minimum H₂O content of the melt ranges from 0.4 to 2.6 (± 0.5) wt% (Table 2.4).

Throughout the Cobb Mtn. flow group and within individual flow layers there are trends in the olivine phenocryst compositions. From the bottom to the top of the flow group, the maximum olivine Fo# decreases, reflecting more Fe-rich olivine phenocrysts towards the top of the flow group. This trend in olivine phenocryst composition corresponds with the decreasing trend in MgO (wt%) of the whole-rock composition, an observation that reflects olivine-melt equilibrium (Figure 3.12). Within the two flow layers analyzed, the olivine phenocryst

compositions are much more variable in the interior facies than in the surface and bottom facies; the largest difference between the maximum and minimum Fo# reported in interior facies is 40, whereas the largest difference reported in a surface or bottom facies is < 20. (Figure 2.8).

3.6 A Geochemical Perspective on Flow-Group Correlations Beneath the Materials and Fuels Complex

3.6.1 Whole-rock Geochemistry

To assess if the surface vents—Vent 5350, Microwave Butte, Radiofacility Butte, or Topper Butte (Figure 3.6)—correlate with the flow groups at depth in the USGS 149 core using whole-rock geochemistry, I use Harker diagrams to compare the similarity of the whole-rock compositions of the vents and the flow groups that may correlate to them based upon paleomagnetic inclination (Figure 3.13). When compared to the 95 ESRP basalt samples analyzed in this study, the vents and the correlative flow groups are not definitively distinguishable because the geochemistry of all the ESRP samples is too similar. For instance, consider the whole-rock compositional variations throughout the Cobb Mtn flow group, which varies in SiO₂, TiO₂, and MgO by 4.63, 1.85 and 3.27 wt%, respectively. When these ranges are plotted with the whole-rock compositions of all the 95 ESRP samples, the range in this single flow group almost defines the total range between all 95 samples (Figure 3.13). The correlations of each vent and the associated flow group at depth in core USGS 149 can neither be supported or refuted based on the samples presented in this study because the samples are too geochemically similar to clearly assess a correlation.

The patterns in whole-rock geochemistry with depth in the five flow groups initially correlated amongst core holes USGS 143, USGS 149, and ANL-OBS-A001 (Figure 3.3 and Figure 3.4) support the preliminary interpretation that these flow groups do indeed correlate. For

each of these flow groups, the whole-rock geochemical composition becomes more evolved from the bottom to the top of the lava flow groups, with increases in SiO₂, TiO₂, La, and Ba concentrations towards the top of the sequences. MgO, Cr, and Ni concentrations decrease towards the top of the lava flow groups (Figure 3.3, Figure 3.4). To assess the lava flow group correlations interpreted by paleomagnetic inclination, abrupt returns to less-evolved compositions were used to mark flow-group boundaries, for example, the return to a more primitive composition at the top of the 48° flow group and the bottom of the Cobb Mtn. flow group in the USGS 149 and ANL-OBS-A-001 cores (Figure 3.4). In some cases, a few additional samples could make these correlations even more robust. For example, collecting one additional sample in the USGS 143 core at a depth of 502 feet, near the bottom of the flow group defined by an average paleomagnetic inclination of 63°, would make the trend in whole-rock geochemistry more complete and thus more comparable to the correlative flow group in the USGS 149 core.

Finally, the preliminary choice to not correlate the three flow groups near the top of the USGS 143 and USGS 149 cores—which have similar paleomagnetic inclination of roughly 63° to 64° (Figure 3.2)—can neither be refuted nor supported based on the available whole-rock geochemistry. Only one sample was collected from the flow group in question in core USGS 149 because this flow group was relatively thin (only 20 feet thick) and only one flow layer was identified, so I cannot compare intra-flow-group trends (Figure 3.14). However, the concentration in MgO, K_2O , and TiO₂, of each sample collected throughout the flow groups are similar (Figure 3.14, Figure 3.15), which may suggest that the flow groups are correlative.

3.6.2 Assessment of Olivine Phenocryst Characterization as a Correlation Tool

To assess olivine phenocryst characterization as a new flow-group correlation tool, I overlaid paleomagnetic inclination and whole-rock geochemical data with olivine phenocryst analyses of the ten samples from the Cobb Mtn. flow group that is present in the USGS 149 and ANL-OBS-A-001 cores.

The olivine phenocryst compositions vary throughout lava flow layers and, therefore, lava flow groups. From the bottom to the top of a flow group, olivine phenocryst compositions progressively become less Mg-rich (Figure 3.12), as expected with the observed trends in wholerock composition which displays an increase in evolution of basalt from bottom to top of the flow group. The trends in the olivine phenocryst characteristics, i.e., the change in MgO concentration of phenocrysts from the bottom to the top of a flow group, may be useful as a tool to signify flow-group breaks, similarly to the application of trends in whole-rock geochemistry, as shown by the trends in variation of olivine phenocryst characteristics in the Cobb Mtn. flow group (Figure 3.12).

As discussed in Chapter 2, all but one of the samples analyzed in this study passed the olivine-melt equilibrium tests. This means that the olivine phenocryst compositions are in equilibrium with the whole-rock compositions. Therefore, it is not surprising that the flow-group-scale trends in whole-rock geochemistry and olivine phenocryst compositions both become more depleted in MgO from the bottom to the top of a flow group (Figure 3.16). These compositional variations throughout a flow group, in both types of data, affirm that a single sample collected from a flow group is not representative of an entire flow group. For this reason, individual whole-rock and olivine phenocryst compositions cannot be used to distinguish between flow groups. The repetition of compositional trends with depth a rock core, however,

can be used to mark flow-group breaks. The repetition of these trends, and the flow-group breaks that they suggest, serve as an effective assessment of flow-group correlations, when used in conjunction with lithologic and paleomagnetic data.

If the samples analyzed in this study are typical of ESRP basalts, and therefore olivinemelt equilibrium is common in these olivine tholeiites, then for the purposes of subsurface correlations olivine phenocryst characterizations appear to be redundant observations that reiterate the trends observable in the whole-rock data. However, if olivine-melt equilibrium is the norm across the ESRP and a flow group is found to have olivine-melt *disequilibrium*, this distinctive feature could be useful as a correlation tool.

3.7 Conclusion

In this study, the initial cross-section through core holes USGS 149, USGS 143, and ANL-OBS-A-001, informed by lithology and paleomagnetic inclination (Figure 3.2), was assessed and a new correlation tool, olivine phenocryst characterization, was evaluated. The observed trends in whole-rock composition with individual flow groups are consistent with the literature, which show evolution of geochemistry from the bottom to the top of the flow group as observed by previous workers in other parts of the ESRP (e.g. Geist et al., 2002, Potter et al., 2018). The trends are consistent throughout the flow groups across the cores and, therefore, support the initial interpretations. All but one of the olivine-melt pairs analyzed in this study were found to be in equilibrium. This relationship between the olivine phenocryst and the associated melt, represented by the whole-rock composition, suggests that the olivine phenocryst compositions are consistent with the whole-rock compositions. For this reason, for the purposes of subsurface correlation the olivine phenocryst characterization does not provide additional information that is independent of the whole-rock composition.

These assessments provide additional information about the subsurface stratigraphy of the MFC region of the INL, a necessary prerequisite to understand the migration of radioactive and chemical contaminants through the ESRP aquifer and understand the magma evolution and volcanic hazards associated with the ESRP volcanic system.

Chapter 4: Summary of Conclusions

In this study, I collected and analyzed whole-rock and olivine phenocryst geochemistry data from eastern Snake River Plain (ESRP) basalt flow groups sampled in core drilled in the vicinity of the Materials and Fuels Complex (MFC) of the Idaho National Laboratory (INL) with the goal of improving understanding of the ESRP volcanic system and the stratigraphy beneath the MFC (Figure 1.3). This work was conducted in collaboration with the United States Geological Survey (USGS) to aid the efforts of the USGS to predict the migration of radioactive contaminants through the ESRP aquifer and advance understanding of the ESRP volcanic system and the volcanic hazards associated with the system.

In **Chapter 2**, thirteen ESRP samples were analyzed for whole-rock and olivine phenocryst composition to determine the pre-eruptive conditions of the system, which improves our understanding of petrologic history of the ESRP volcanic system. Rapid growth textures were observed in olivine phenocrysts in the samples (Figure 2.3), which suggests the olivine phenocrysts grew rapidly under diffusion-limited conditions. Using a series of tests, olivine-melt equilibrium was established for twelve of the thirteen ESRP samples. One possible explanation for the preservation of olivine rapid growth textures and olivine-melt equilibrium is that soon after olivine phenocrysts began to crystallize, the basaltic magma rapidly ascended to the surface and then cooled quickly. Olivine-melt thermometry and hygrometry was applied to the twelve olivine-melt pairs that were shown to be in equilibrium and the temperature at the onset of olivine phenocryst crystallization and the dissolved H₂O content of the melt was determined to range from 1,117 to 1,195 °C and 0.4 to 2.6 wt%, respectively (Table 2.4). Observations throughout the facies of a lava flow layer show narrow ranges of forsterite content of olivine phenocrysts in the surface and bottom facies and more broad compositions in the interior facies (Figure 2.8). These observations may be explained by an insulation mechanism after flow layer emplacement.

In Chapter 3, whole-rock compositions were used to assess the initial correlations between core holes USGS 149, USGS 143, ANL-OBS-A-001, and select surface vents, and olivine phenocryst characterization was evaluated as a correlation tool (Figure 3.2 The correlations of each vent and the associated flow group at depth in the USGS 149 core can neither be supported or refuted based on the samples presented in this study because the samples are too geochemically similar to clearly assess a correlation (Figure 3.13). For the flow groups analyzed in this study, the whole-rock compositions become more evolved with higher concentrations of SiO₂ and TiO₂, and lower concentrations of MgO, Ni, and Cr (Table 2.2). These patterns have been previously observed in past research and are typically inferred to represent the fractionation of Mg-rich olivine and plagioclase (Geist et al., 2002; Hughes et al., 2002; Servais et al., 2006, Potter et al., 2018). These observation supports the initial correlations which were informed by lithology and paleomagnetic inclination. Olivine phenocryst compositions follow similar trends from the bottom to the top of flow groups and are consistent with whole-rock geochemistry (Figure 3.16). For this reason, for the purposes of subsurface correlations olivine phenocryst characterizations appear to be redundant observations that reiterate the trends observable in the whole-rock data. However, if olivine-melt equilibrium is the norm across the ESRP and a flow group is found to have olivine-melt *disequilibrium*, this distinctive feature could be useful as a correlation tool.

This work supports the efforts of the USGS to improve understanding of the subsurface stratigraphy through which the ESRP aquifer migrates to best predict the migration of radioactive and chemical contaminants and to determine volcanic hazards. In particular, the

analyses and assessments described above provide additional information to understand the geology and environmental impact of the radiological facilities around the MFC.



Figures

Figure 1.1. Regional map of Idaho showing the relative boundary of the eastern Snake River Plain (ESRP), outlined in black. Boundary of the Idaho National Laboratory (INL) shaded in gray. ID- Idaho, YS- Yellowstone (Basemap satellite imagery from Earthstar Geographics).



Figure 1.2. Aerial view of ESRP Aquifer, modified from Lindholm (1996). Boundary of aquifer outlined in gray, and south-western direction of groundwater flow is indicated by the yellow arrows.



Figure 1.3. Map of the Idaho National Laboratory (INL). Materials and Fuels Complex (MFC) indicated by the black dot. Gray lines represent state roads in and around the INL: U.S. Route 26 and U.S. Route 20.



Partial Melt Source

Figure 1.4. Generalized cross-sectional diagram showing plains style, or distributed, volcanism modified from Grimm-Chadwick (2004) and references therein. Up-arrow represents the direction of rapid ascent of the melt during the onset of olivine phenocryst crystallization.



Figure 1.5. Cross-section through an inflated pahoehoe lava flow layer, which forms when single pulses of magma are erupted. Emplacement of an inflated pahoehoe flow layer result in three, texturally distinct, facies: a glassy, vesicular base; a dense crystalline interior; and a rubbly, vesicular top. In a core, the repetition of these facies can be used to determine flow-layer breaks (modified from Potter et al., 2019 and Self et al., 1998).



Figure 2.1. Representative example of a rapid growth texture in an olivine phenocryst from sample U149_945_LS-928 collected from the USGS 149 core. Photomicrograph in plain polarized light. Pl—plagioclase; Ol—olivine.



Figure 2.2. Representative examples of basalt thin sections exemplifying ranking system used to determine which thin sections had large, unaltered olivine phenocrysts, which were ideal for further analysis. (a) Sample U149_945_LS in plain-polarized lighting (PPL), ranked A and 1 because of the large unaltered olivine phenocrysts (b) Sample U149_945_LS in cross-polarized lighting (XPL) (c) Sample U149_633_LS in PPL, ranked with a C and 3 because of the small olivine phenocryst size and alteration around exterior (d) Sample U149_633_LS in XPL.



Figure 2.3. (a-c) BSE images, captured using a SEM, of olivine phenocrysts from this study displaying representative rapid growth textures and normal zoning. The skeletal, or branching, pattern in these olivine phenocrysts are representative of rapid growth. Darker colored interiors indicate higher concentrations of Mg, lighter colored rims indicate enrichments in Fe, a pattern of normal zoning of olivine phenocrysts.



Figure 2.4. (a-f) BSE images, captured with a SEM, of olivine phenocrysts analyzed from samples collected from the USGS 149 core. Darker phenocryst interiors represent Mg-rich compositions, while lighter outer rims are more Fe-rich. The yellow annotations are the compositional analysis traverses using an EPMA and calculated Fo# at individual spots in the olivine phenocrysts.



Figure 2.5. Ni concentrations (ppm) of the whole-rock compositions versus the calculated Mg# for the whole-rock composition showing the positive linear relationship between the two compositional elements.


Figure 2.6. TAS classification diagram of the 95 samples analyzed in this study. SROT, high Fe-Ti, and high K-Fe classifications from Potter et al. (2018).



Figure 2.7. Distribution patterns of the forsterite content (Fo#) of each spot analysis for each of the nine samples collected from the interior facies of a flow layer. (a-f) samples collected in core USGS 149, (g-i) samples collected in core ANL-OBS-A-001. The samples collected from the Cobb Mtn flow group in both USGS 149 and ANI-OBS-A-001 are annotated. Plots are annotated with the whole-rock MgO wt% and maximum olivine Fo# for each sample.

Cobb Mtn flow group



Figure 2.8. Histograms of forsterite content (Fo#) for each sample collected within the three flow-layer facies sampled at 700 and 945 feet in depth in the USGS 149 core. Whole-rock MgO wt% and maximum olivine Fo# is reported for each sample. Range of Fo# is annotated by the green brackets. Samples from the interior facies consistently have a much wider range of olivine compositions than those from the bottom or surface facies.



Figure 2.9. Olivine phenocryst NiO wt% versus Fo mol % for the top 3 % Fo# per sample. Data are fit to a linear relationship and the equation of each line is reported. (a-j) samples collected in core USGS 149, (k-m) samples collected in core ANL-OBS-A-001. (d-g) and (h-j) are samples collected from core USGS 149 at 700 and 956 feet below land surface, respectively. Note, sample U149_700LS-710 scatter plot displays the top 5% Fo#. Equations of the lines were used to calculate the NiO (wt%) for the most Mg-rich olivine phenocryst to decrease analytical uncertainty of the Ni-based thermometer, where x is replaced by the maximum Fo# for each sample (Pu et al., 2017).



Figure 2.10. Fo# versus Mg# for all of the 13 samples analyzed from the USGS 149 and ANL-OBS-A-001 cores. The positive linear relationship between max Fo# and Mg# indicate the olivine-melt pairs, represented by individual dots in this plot, are in equilibrium.



Figure 2.11. T_{Mg} and T_{Ni} versus Mg# for each of the twelve olivine-melt pairs that were found to be in equilibrium from the USGS 149 and ANL-OBS-A-001 cores. The difference between the two calculated temperature values directly reflects the amount of the dissolved H₂O (wt%) of the melt for each sample. Uncertainties for the T_{Mg} and T_{Ni} are ±26 and ±29 °C, respectively (Pu et al., 2017).



Figure 2.12. Temperature (calculated using the Ni-based thermometer calibrated by Pu et al., 2017) versus whole-rock Mg# for the samples from this study (green closed circles) and samples from other work of differing tectonic settings (gray symbols).



Figure 3.1. Reference map showing the locations of the three core holes analyzed in this study relative to the location of the Materials and Fuels Complex (MFC) within the Idaho National Laboratory (INL). Cross-section through the core stratigraphy is indicated by A'-A. U.S. route 20 crosses the southern part of the study area.

Cross-section A-A'



Figure 3.2. The preliminary stratigraphic correlation between the USGS 149, USGS 143, and ANL-OBS-A-001 core holes, informed by paleomagnetic inclination of lava flow groups and lithology. Each color-coded region represents an individual flow group (M. K. V. Hodges, personal communication, March 24, 2022).



Figure 3.3. Whole-rock composition of selected major element oxides versus depth (in feet) from the 65° and 63° inclination flow groups found in the USGS 143 and USGS 149 cores, which are correlated in the preliminary subsurface cross section (Figure 3.2; colors from this cross section). SROT and high Fe-Ti classifications from Potter et al. (2018).



Figure 3.4. Whole-rock composition of selected major element oxides versus depth (in feet) from the three flow groups found in the USGS 149 and ANL-OBS-A-001 cores, which are correlated in the preliminary subsurface cross section (Figure 3.2; colors from this cross section). SROT and high Fe-Ti classifications from Potter et al. (2018).



Figure 3.5. Photo of basalt rock core from the USGS 149 core in three separate boxes. The core width is three inches wide. Depth in feet is documented on the core, written in black marker. Blue and red lines indicate the direction of up. Blue foam blocks indicate loss of core during the drilling process.



Figure 3.6. Regional map of the INL showing locations of surface vents, indicated by black, open triangles, with reference to the location of core holes USGS 149, USGS 143, and ANL-OBS-A-001 (black, closed circles). U.S. Route 26 and U.S. Route 20 cross the study area.



Figure 3.7. Three major-element variation diagrams classify the 95 samples analyzed in this study into three compositional groups, following the approach of Potter et al. (2018) for the Kimama core. Most samples (open circles) are classified as typical Snake River Olivine Tholeiites (SROT). (a) A FeO* vs. TiO₂ plot illustrates the compositional threshold (black dotted line) that defines the high Fe-Ti compositional group. This threshold is defined by 15.0 wt% for FeO* and 3.6 wt% for TiO₂. Ten of the 95 samples analyzed in this study are classified as High Fe-Ti. (b) A K₂O/TiO₂ vs. MgO plot illustrates that none of the samples in this study have K₂O/TiO2 < 0.11 wt% and thus none fall within the low-K SROT compositional group. (c) A K₂O vs. TiO₂ plot emphasizes the single sample from the USGS 143 core (filled triangle) that falls in the high K-Fe compositional group, defined by Potter et al. (2018) as lavas with FeO > 17.5 wt% and K₂O > 0.65 wt%. Compositionally, this high K-Fe lava is similar to those from the Craters of the Moon system.



USGS 149

Figure 3.8. Whole-rock compositions of MgO, TiO₂, K₂O, Ba, Cr, La, Ni versus depth (in feet) for samples from the USGS 149 core. Gray dotted lines indicate flow-group boundaries determined by paleomagnetic inclination from the initial correlation (Figure 3.2). SROT, high Fe-Ti, and high K-Fe classifications from Potter et al. (2018).



ANL-OBS-A-001

Figure 3.9. Whole-rock compositions of MgO, TiO₂, K₂O, Ba, Cr, La, Ni versus depth (in feet) for samples from theANL-OBS-A-001 core. Gray dotted lines indicate flow-group boundaries determined by paleomagnetic inclination from the initial correlation (Figure 3.2). SROT, high Fe-Ti, and high K-Fe classifications from Potter et al. (2018).



Figure 3.10. Whole-rock compositions of MgO, TiO₂, K₂O, Ba, Cr, La, Ni versus depth (in feet) for samples from the USGS 143 core. Gray dotted lines indicate flow-group boundaries determined by paleomagnetic inclination from the initial correlation (Figure 3.2). SROT, high Fe-Ti, and high K-Fe classifications from Potter et al. (2018).



Figure 3.11. Trace element concentrations normalized to primitive mantle (Sun and McDonough, 1989) for the five flow groups initially correlated between the USGS 149, USGS 143, and ANL-OBS-A-001 core holes. Colors reflect those used to organize the flow groups in the initial correlation (Figure 3.2).





Figure 3.12. Trends in the olivine population in the Cobb Mtn. flow group sampled three times_in the ANL-OBS-A-001 core. Maximum Fo# is reported in green and the MgO (wt%) of the whole-rock composition is reported below the sample name. The maximum MgO composition of the olivine phenocrysts (represented by the maximum Fo#) decreases from the bottom to the top of this flow group, which is consistent with the trends in the whole-rock data from these samples.



Figure 3.13. Selected Harker diagrams displaying the whole-rock geochemistry of the surface vents and the associated flow groups found at depth in the USGS 149 core; whole-rock composition of all the 95 samples analyzed in this study (open circles) are shown for reference. The variation in SiO₂, TiO₂, and MgO from the Cobb Mtn flow group is outlined by the solid and dotted line ovals to illustrate the whole-rock compositional variation throughout a single flow group. (a) Vent 5350 and associated flow groups from USGS 149 (b) Microwave Butte and associated flow groups from USGS 149 (c) Radiofacility Butte and associated flow groups from USGS 149.



Figure 3.14. Selected major-element compositions versus depth of the samples analyzed in the two flow groups in the USGS 143 core and the single flow group at the top of the USGS 149 core. Colors reflect those used in the initial correlation.



Figure 3.15. Select Harker diagrams for the three flow groups across core holes USGS 149 and USGS 143 at the tops of each core (Figure 3.2). Colors reflect those used in the initial correlation.



Figure 3.16. Olivine characterization and the whole-rock compositional analyses from the Cobb Mtn Flow group in the USGS 149 and ANL-OBS-A-001 cores. The whole-rock compositions become more depleted in MgO, Cr, and Ni from the bottom to the top of the core, perhaps due to fractional crystallization. The olivine phenocryst compositions are consistent with the whole-rock compositions, with similar trends of depletion in MgO from the bottom to the top of the flow group.

Tables

Table 2.1. Beam Conditions Used to	Analyze the Standard	ls to Calibrate t	he EPMA				
Reference Sample Name	Reference Sample Name Value	Count time	Reference Uncertainty Unit	Number Of Measurements	Voltage (kV)	Current (nA)	Beam Size (μm)
Anorthite (Great Sitkin Island, Alaska, USA; NMNH 137041)	15	20	wt %	7	15	20	5
Chromite (Tiebaghi Mine, New Caledonia; NMNH 117075)	15	20	wt %	7	15	20	5
Fayalite (Rockport, Massachusetts, USA; NMNH 85276)	15	20	wt %	7	15	20	5
Basaltic Glass (Juan de Fuca Ridge; NMNH 111240-52, VG-2)	15	20	wt %	7	15	20	5
Kakanui hornblende (Kakanui, New Zealand; NMNH 143965)	15	20	wt %	7	15	20	5
Ilmenite (Ilmen Mountains, Russia; NMNH 96189)	15	20	wt %	7	15	20	5
San Carlos Olivine (San Carlos, Arizona, USA; NMNH 111312-44)	15	20	wt %	7	15	20	5

Table 2.1. Beam conditions of microprobe to analyze the standard materials used to calibrate the EPMA for olivine phenocryst analyses.

Sample collection depth in core USGS 149	197	218	263	690	697	700	710	928	945	950
SiO ₂ (wt%)	45.9	45.7	47.2	46.3	46.4	45.1	47.2	46.9	43.5	46.6
TiO ₂ (wt%)	3.0	3.0	3.3	3.1	3.0	3.2	3.2	2.0	2.4	2.4
Al ₂ O ₃ (wt%)	14.2	14.0	13.5	14.3	14.3	13.8	14.2	15.2	13.9	14.7
Fe ₂ O ₃ (wt%)	15.7	15.9	16.6	16.0	15.7	16.5	15.8	12.8	15.8	14.2
MnO (wt%)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
MgO (wt%)	7.8	7.9	6.3	6.8	7.0	7.0	6.5	9.4	9.1	8.6
CaO (wt%)	9.9	9.9	9.5	9.6	9.6	10.1	9.2	10.8	11.2	10.1
Na ₂ O (wt%)	2.5	2.5	2.5	2.6	2.7	2.7	2.5	2.4	2.9	2.5
K ₂ O (wt%)	0.6	0.6	1.0	0.8	0.8	0.8	0.8	0.5	0.7	0.6
P ₂ O ₅ (wt%)	0.6	0.6	1.1	0.8	0.8	0.8	0.8	0.4	0.5	0.5
Total	100.4	100.4	101.3	100.4	100.4	100.3	100.4	100.5	100.3	100.4
Mg#	49.6	49.6	42.8	45.6	46.6	45.7	44.9	59.1	53.2	54.6
Ni (ppm)	84	79	53	79	74	69	68	134	84	78

Table 2.2. Whole-Rock Compositonal Analysis of Select Samples From Cores USGS 149 and ANL-OBS-A001

Sample collection depth in core ANL- OBS-A-001	644	825	903
SiO ₂ (wt%)	46.6	46.4	46.8
TiO ₂ (wt%)	3.3	2.6	2.0
Al ₂ O ₃ (wt%)	14.1	14.9	15.3
Fe ₂ O ₃ (wt%)	16.2	14.9	13.1
MnO (wt%)	0.2	0.2	0.2
MgO (wt%)	6.3	8.2	9.2
CaO (wt%)	9.5	9.9	10.8
Na ₂ O (wt%)	2.6	2.6	2.4
K ₂ O (wt%)	0.9	0.6	0.5
P ₂ O ₅ (wt%)	0.9	0.5	0.4
Total	100.6	100.7	100.7
Mg#	43.4	51.9	58.1
Ni (ppm)	56	95	103

Table 2.2. Whole-rock major element and Ni compositions of the thirteen samples collected from the USGS 149 and ANL-OBS-A-001 cores. Analytical uncertainty (1-sigma) on the major elements and Ni analysis is $\pm 0.1\%$ wt% and less than 1 ppm, respectively (E. Christiansen, personal communication, February 2, 2022; see also Chapter 3). Sample collection depth is reported in feet.

Table 2.3. Opt	Sample													
Sample collection depth in core USGS 149	197	218	263	690	697	700	710	928	945	950				
Extent of alteration	1	1	1	3	2	1	3	1	1	1				
Abundance of olivine	Α	А	В	С	В	В	С	А	А	А				
Size range of olivine (µm)	200-800	300-750	100-800	200- <mark>600</mark>	300-800	300-850	300-750	300-1,000	200-1,200	300-1,000				
Sample collection depth in core ANL-OBS-A-001	644	825	903											
Extent of alteration	1	2	1											
Abundance of olivine	В	A	A											
Size range of olivine (µm)	50-400	100-1,000	100-1,000											

Table 2.3. Rankings of olivine phenocryst abundance, alteration, and size range for the thirteen samples analyzed for olivine phenocryst compositions. Sample collection depth is reported in feet.

Table 2.4. C	Composit	ional Ana	lysis of th	e Most N	Ag-Rich C	livine Ph	enocryst			
Sample collection depth in core USGS 149	197	218	263	690	697	700	710	928	945	950
Al ₂ O ₃	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.0
MgO	41.5	40.9	38.0	39.2	38.4	38.7	40.2	45.2	43.9	42.7
SiO ₂	38.8	38.7	38.0	38.8	38.0	38.1	38.8	38.5	39.5	38.6
MnO	0.2	0.2	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.2
Cr ₂ O ₃	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CaO	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3
FeO	19.6	20.5	24.2	21.1	21.3	22.2	20.6	14.7	17.1	16.8
NiO	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.1	0.1
Total	100.5	100.8	101.0	99.8	98.5	99.8	100.3	99.1	101.2	98.8
Fo#	79.1	78.1	73.6	76.9	76.2	75.7	77.7	84.6	82.1	81.9
KD	0.30	0.32	0.34	0.29	0.31	0.31	0.27	0.30	0.29	0.31
TMg (°C)	1185	1190	1147	1159	1169	1169	1145	1214	1217	1203
TNi (°C)	1151	1152	1134	1156	1131	1117	1127	1195	1164	1150
ΔT (°C)	34	39	13	3	38	52	18	19	53	53
min H2O (wt%)	1.0	1.1	0.4	0.1	1.1	1.6	0.5	0.5	1.6	1.6

Sample collection depth in core ANL- OBS-A-001	644	825	903
Al ₂ O ₃	0.0	0.0	0.1
MgO	34.7	41.4	44.6
SiO ₂	37.1	39.3	39.1
MnO	0.3	0.3	0.2
Cr ₂ O ₃	0.0	0.0	0.1
CaO	0.2	0.2	0.3
FeO	27.8	17.9	14.5
NiO	0.1	0.2	0.2
Total	100.3	99.4	99.1
Fo#	69.0	80.5	84.6
KD	0.39	0.30	0.29
TMg (°C)	1169	1198	1212
TNi (°C)	1163	1146	1129
ΔT (°C)	6	52	83
min H2O (wt%)	0.2	1.5	2.6

Table 2.4. Olivine phenocryst compositional analysis of the highest Mg olivine phenocryst from each of the thirteen samples collected from the USGS 149 and ANL-OBS-A-001 cores. All error associated with the analytical technique is reported as 2-sigma for each element. For Al, Cr, Ca, and Ni were below +/- 0.02 wt%. For Mg, uncertainties were below +/- 0.14 wt%. For Fe, average uncertainty was around +/- 0.18 wt%; for Si, average uncertainty was +/- 0.08 wt%; for Mn, average uncertainties were below +/- 0.04 wt%. Uncertainties for the thermometer calculations are ± 26 °C and ± 29 °C for the Mg-based and Ni-based thermometers, respectively.

Table 5.1. Wajor Element V	sio.	TiO		Ee O	MpQ	MaQ	0¢)	Na.O	K.O	P.O.
Sample Name	Wt %	Wt %	Wt %	Wt %						
11149-026-15	45.9	2.5	14.1	14.3	0.2	9.4	10.5	2.5	0.6	0.5
11149-068-15	45.9	2.5	12.5	16.9	0.2	5.4	9.6	2.5	1.0	0.5
1149-124-15	43.5	3.5	14.2	15.6	0.2	6.9	9.0	2.7	0.9	0.7
11149-133-15	47.1	3.2	13.0	15.0	0.2	6.4	9.1	2.0	0.9	0.0
1149-159-15	47.5	2.1	14.2	15.5	0.2	7.5	0.9	2.0	0.5	0.7
11149-199-15	40.1	3.1	14.2	16.3	0.2	2.0	9.0 10.3	2.0	0.7	0.7
11140 107 15 194	44.0	2.0	14.0	16.0	0.2	7.0	10.5	2.0	0.0	0.0
0149-197-15-184	45.5	3.0	14.5	10.0	0.2	7.0	10.0	2.5	0.0	0.0
0149-197-LS-194	45.8	3.0	14.3	15.7	0.2	7.8	9.9	2.5	0.6	0.6
U149-197-LS	45.9	3.0	14.1	15.7	0.2	7.8	9.9	2.5	0.6	0.6
U149-197-LS-207	45.8	3.0	14.4	15.8	0.2	1.1	9.9	2.4	0.6	0.6
U149-218-LS-213	45.8	3.0	14.4	15.8	0.2	7.7	9.8	2.4	0.6	0.6
U149-218-LS	45.7	3.0	14.0	15.9	0.2	7.9	9.9	2.5	0.6	0.6
U149-218-LS-220	45.8	2.9	14.3	15.7	0.2	7.9	9.9	2.5	0.6	0.6
U149-218-LS-221	45.9	2.9	14.3	15.7	0.2	7.9	9.9	2.4	0.6	0.6
U149-255-LS	46.1	3.3	13.9	16.3	0.2	7.0	9.6	2.5	0.7	0.7
U149-263-LS-260	46.9	3.2	13.7	16.1	0.2	6.4	9.3	2.5	1.0	1.1
U149-263-LS	47.2	3.3	13.5	16.6	0.2	6.3	9.5	2.5	1.0	1.1
U149-263-LS-266	46.7	3.2	13.7	16.2	0.2	6.4	9.4	2.5	1.0	1.1
U149-263-LS-268	47.0	3.6	13.1	16.6	0.2	5.6	9.4	2.5	1.1	1.2
U149-273-LS	46.2	3.0	13.7	16.2	0.2	6.7	9.5	2.7	1.0	1.0
U149-309-LS	46.4	3.2	13.5	16.3	0.2	6.6	9.4	2.6	1.0	1.0
U149-337-LS	47.2	3.2	13.5	16.0	0.2	6.3	9.2	2.5	1.0	1.1
U149-355-LS	46.4	3.6	13.4	16.5	0.2	6.1	9.5	2.6	1.0	0.8
U149-376-LS	45.3	2.6	14.5	15.0	0.2	8.6	10.4	2.6	0.6	0.6
U149-418-LS	46.1	3.4	13.7	16.9	0.2	6.2	9.2	2.6	1.0	0.9
U149-432-LS	45.0	3.6	13.4	17.4	0.2	6.6	9.6	2.6	1.0	0.9
U149-468-LS	45.8	3.4	13.9	16.7	0.2	6.4	9.4	2.6	1.0	0.9
U149-504-LS	44.4	3.5	13.4	17.9	0.2	6.7	9.6	2.6	1.0	0.9
U149-537-LS	46.5	2.8	14.5	15.1	0.2	7.7	9.8	2.6	0.8	0.6
U149-556-LS	46.6	2.9	14.4	15.1	0.2	7.3	9.8	2.6	0.8	0.6
U149-598-LS	46.4	3.1	13.4	16.4	0.2	6.4	9.7	2.8	1.1	0.9
U149-633-LS	46.7	3.4	13.5	16.4	0.2	6.2	9.6	2.6	0.9	0.9
									Continue	d

Table 3.1. Major Element Whole-Rock Geochemical Analyses of ESRP Basalts.

Major Element Whole-Rock	lajor Element Whole-Rock Geochemical Analyses of ESRP Basalts.												
Sample Name	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅			
Sample Name	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %			
U149-656-LS	46.5	3.8	13.0	16.8	0.2	6.1	9.7	2.6	0.9	0.9			
U149-700-LS-690	46.3	3.1	14.3	16.0	0.2	6.8	9.6	2.6	0.8	0.8			
U149-700-LS-697	46.4	3.0	14.3	15.7	0.2	7.0	9.6	2.7	0.8	0.8			
U149-700-LS	45.1	3.2	13.8	16.5	0.2	7.0	10.1	2.7	0.8	0.8			
U149-700-LS-710	47.2	3.2	14.2	15.8	0.2	6.5	9.2	2.5	0.8	0.8			
U149-727-LS	45.8	3.0	14.0	16.2	0.2	7.2	9.7	2.7	0.8	0.7			
U149-745-LS	42.5	3.6	13.0	18.3	0.3	6.6	11.0	3.2	1.0	0.8			
U149-776-LS	46.2	3.1	14.0	16.1	0.2	7.1	9.5	2.6	0.9	0.7			
U149-853-LS	46.0	2.6	14.5	15.0	0.2	8.2	9.9	2.6	0.7	0.6			
U149-869-LS	45.9	2.4	14.7	14.4	0.2	8.7	10.6	2.5	0.6	0.5			
U149-880-LS	46.3	3.3	13.3	16.6	0.2	6.4	9.5	2.6	1.0	1.1			
U149-915-LS	46.9	2.1	15.0	13.0	0.2	9.1	10.8	2.4	0.5	0.5			
U149-945-LS-928	46.9	2.0	15.2	12.8	0.2	9.4	10.8	2.4	0.5	0.4			
U149-945-LS-941	46.6	2.4	14.8	14.1	0.2	8.6	10.1	2.5	0.6	0.5			
U149-945-LS	43.5	2.4	13.9	15.8	0.2	9.1	11.2	2.9	0.7	0.5			
U149-945-LS-950	46.6	2.4	14.7	14.2	0.2	8.6	10.1	2.5	0.6	0.5			
U149-970-LS-966	46.1	3.1	14.3	16.0	0.2	7.3	9.6	2.5	0.7	0.7			
U149-970-LS-972	46.0	2.9	14.4	15.9	0.2	7.8	9.5	2.5	0.7	0.6			
ANL-1-453_LS	45.7	3.3	14.4	16.8	0.2	6.6	9.3	2.6	0.9	0.8			
ANL-1-501_LS	45.9	3.4	14.3	16.8	0.2	6.4	9.4	2.6	1.0	0.8			
ANL-1-552_LS	45.8	3.6	14.3	16.9	0.2	6.4	9.2	2.7	0.9	0.7			
ANL-1-644-LS	46.6	3.3	14.1	16.2	0.2	6.3	9.5	2.6	0.9	0.9			
ANL-1-825_LS	46.4	2.6	14.9	14.9	0.2	8.2	9.9	2.6	0.6	0.5			
ANL-1-903_LS	46.8	2.0	15.3	13.1	0.2	9.2	10.8	2.4	0.5	0.4			
ANL-1-943_LS	45.8	3.2	14.4	16.4	0.2	6.8	9.8	2.6	0.7	0.7			
ANL-1-966_LS	45.6	2.9	14.6	16.2	0.2	7.7	9.5	2.6	0.7	0.6			
ANL-1-1039_LS	45.4	3.0	14.8	16.1	0.2	7.5	9.7	2.6	0.7	0.7			
143-15.6	44.1	2.9	13.9	16.4	0.2	7.9	10.7	2.7	0.8	0.7			
143-31.2	45.2	3.8	13.2	17.6	0.2	6.3	9.8	2.7	0.8	0.7			
143-56.2	45.1	2.8	14.9	15.5	0.2	7.5	10.3	2.8	0.8	0.5			
143-77.1	46.8	2.4	14.9	14.1	0.2	8.1	10.1	2.6	0.8	0.5			
143-115.4	43.9	3.2	14.4	17.1	0.2	7.3	10.1	2.9	0.7	0.7			
143-134.2	42.7	3.2	14.2	17.7	0.2	7.5	10.5	3.0	0.7	0.7			
143-154.5	44.7	3.2	14.5	16.8	0.2	7.1	9.8	2.8	0.6	0.7			
									Continue	d			

Comple Norma	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅
Sample Name	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %	Wt %
143-184.2	46.2	3.7	12.7	17.3	0.2	5.7	9.6	2.6	1.2	1.1
143-220.0	46.5	3.3	13.6	16.3	0.2	6.6	9.4	2.6	1.0	0.9
143-250.9	45.6	3.3	14.0	16.5	0.2	7.2	9.5	2.6	0.7	0.7
143-264.1	45.6	3.4	14.1	16.5	0.2	7.0	9.6	2.7	0.7	0.7
143-296.6	45.5	3.3	13.9	16.6	0.2	7.5	9.4	2.5	0.7	0.7
143-364.4	45.8	3.1	14.1	16.1	0.2	7.4	9.7	2.7	0.7	0.6
143-392.2	46.1	2.1	14.7	13.6	0.2	9.6	10.9	2.4	0.4	0.5
143-412.6	45.6	2.2	14.7	13.7	0.2	9.7	11.0	2.5	0.4	0.5
143-446.1	47.3	2.6	14.7	14.4	0.2	6.7	9.8	2.7	1.1	0.8
143-466.4	46.7	2.7	14.7	14.7	0.2	6.8	10.0	2.8	1.1	0.8
143-484.3	46.6	3.3	13.8	16.0	0.2	6.0	9.9	2.6	0.9	1.1
143-506.2	46.4	2.7	14.4	15.3	0.2	7.7	9.5	2.5	0.7	0.9
143-522.1	46.1	4.0	12.3	17.3	0.2	5.5	10.0	2.6	1.0	1.3
143-544.5	46.4	2.8	14.3	15.4	0.2	7.5	9.5	2.5	0.8	0.9
143-587.2	46.9	2.9	14.4	15.1	0.2	7.2	9.6	2.5	0.8	0.9
143-606.4	46.5	3.2	14.2	15.7	0.2	6.6	9.6	2.5	0.8	1.0
143-632.5	46.5	2.9	14.5	15.4	0.2	7.1	9.5	2.6	0.7	0.9
143-673.1	45.7	3.3	14.1	16.3	0.2	7.1	9.7	2.5	0.7	0.8
143-693.6	45.8	3.2	14.3	16.0	0.2	7.2	9.7	2.5	0.7	0.8
143-701.2	46.4	2.6	14.8	14.9	0.2	7.9	9.8	2.5	0.7	0.5
143-725.1	45.8	2.8	14.3	15.5	0.2	7.8	10.0	2.7	0.7	0.6
143-746.2	46.4	2.8	14.2	15.1	0.2	7.9	10.0	2.5	0.6	0.5
143-778.3	46.5	2.6	14.8	14.7	0.2	7.9	9.9	2.7	0.6	0.5
143-798.3	46.5	2.5	14.9	14.5	0.2	8.0	10.0	2.7	0.5	0.5
143-817.0	44.2	3.6	12.1	20.2	0.4	4.2	8.2	3.2	1.6	2.5
Microwave_LS	46.1	2.5	14.4	14.2	0.2	9.0	10.4	2.4	0.5	0.6
Topper_LS	45.3	3.6	13.9	17.0	0.2	6.4	9.8	2.5	0.7	0.7
Radiofacility-DC_LS	45.1	3.5	13.1	16.2	0.2	6.1	10.9	2.4	0.7	1.1
Vent5350_LS	47.2	1.9	14.3	12.5	0.2	10.0	10.5	2.3	0.7	0.4

Major Element Whole-Rock Geochemical Analyses of ESRP Basalts.

 Notes:
 Based on repeated analyses of 11 international reference materials, estimates of uncertainty for XRF analysis of these major oxides are less than +/- 0.1% wt% (absolute) (E. Christiensen, personal communication, February 2, 2022)

Table 3.1. Whole-rock major element geochemistry of the 95 basalt samples analyzed in this study.

Table 3.2. Trace Elen	nent W	hole-R	ock Ge	ochem	nical Ar	nalyses	of ESR	P Basa	lts.														
Sample Name	Ва	Ce	Cl	Cr	Cu	F	Ga	La	Nb	Nd	Ni	Pb	Rb	S	Sc	Sm	Sr	Th	U	۷	Y	Zn	Zr
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
U149-026-LS	325	59	82	443	40	554	18	29	21	38	87	5	9	0	26	6	283	2	0	257	30	97	211
U149-068-LS	509	90	79	110	40	600	23	45	30	59	61	6	16	40	26	10	320	2	0	288	46	134	303
U149-124-LS	502	78	73	116	32	590	20	39	26	51	68	6	16	94	23	9	314	3	0	253	40	119	271
U149-133-LS	450	75	66	100	37	563	21	38	28	48	54	5	16	114	22	8	299	2	0	257	42	121	283
U149-159-LS	386	73	72	156	43	637	19	37	23	46	66	4	12	86	23	7	287	1	0	257	37	105	240
U149-181-LS	325	62	70	167	45	505	20	31	23	44	80	5	11	19	25	8	287	2	0	277	37	114	224
U149-197-LS-184	327	64	70	200	42	520	21	32	23	44	84	6	11	157	25	7	289	1	0	285	37	117	226
U149-197-LS-194	290	59	74	224	44	414	20	31	24	47	92	4	11	273	28	8	298	1		320	38	134	238
U149-197-LS	323	62	69	175	40	523	20	28	22	45	81	5	11	107	26	8	290	2		278	36	113	223
U149-197-LS-207	277	53	69	235	45	317	19	27	24	46	92	3	10	204	28	8	293			312	37	137	235
U149-218-LS-213	305	59	68	197	42	472	20	30	23	46	79	5	11	154	25	7	280	2	0	282	37	117	227
U149-218-LS	257	53	63	224	45	356	19	26	23	42	87	5	11	196	27	8	277	3	0	295	36	129	223
U149-218-LS-220	312	57	72	217	44	504	20	32	24	45	87	5	12	153	28	9	294	2	0	303	38	126	234
U149-218-LS-221	286	60	70	227	44	458	20	24	24	46	87	4	11	121	27	8	290	1		303	38	129	233
U149-255-LS	467	74	75	126	28	624	21	37	25	51	68	7	13	97	26	9	307	2	0	296	41	127	308
U149-263-LS-260	645	129	92	98	31	787	22	65	46	75	53	9	17	208	25	12	300	4	0	255	57	142	454
U149-263-LS	549	113	79	100	28	588	21	53	42	67	52	7	16	215	23	11	290	5	1	248	52	136	416
U149-263-LS-266	653	131	91	98	28	774	21	63	44	75	54	8	17	159	24	12	304	4	0	255	56	138	446
U149-263-LS-268	611	131	85	103	39	630	22	64	50	82	42	10	19	249	28	13	290	5	1	302	62	161	500
U149-273-LS	602	119	84	105	33	671	22	60	42	71	59	7	16	133	23	11	310	3	0	237	52	138	421
U149-309-LS	681	130	77	104	33	844	22	65	40	74	54	9	18	0	21	12	298	5	1	220	52	120	408
U149-337-LS	609	127	94	100	34	684	21	64	46	79	59	9	19	159	26	13	308	4	1	271	57	151	447
U149-355-LS	622	107	83	88	48	689	21	54	36	65	46	7	18	110	25	9	302	4	0	288	50	132	378
U149-376-LS	354	55	72	253	32	518	20	27	20	38	82	3	12	0	24	6	277	1	0	234	32	97	212
U149-418-LS	802	133	69	89	44	757	22	66	36	78	50	6	15	16	25	11	318	2	0	250	49	131	448
U149-432-LS	771	119	75	81	39	637	21	60	34	74	51	6	14	28	25	12	309	2	0	255	46	128	416
U149-468-LS	795	126	80	109	37	755	22	63	36	75	57	7	15	34	25	13	332	2	0	279	48	139	443
U149-504-LS	825	134	77	105	31	746	23	67	35	81	62	8	15	71	26	12	328	4	1	270	50	142	445
U149-537-LS	491	67	68	152	32	639	20	34	21	42	57	5	15	0	23	8	280	3	0	237	33	95	255
U149-556-LS	529	75	64	147	26	654	20	37	22	44	54	4	16	0	23	7	281	1	0	242	35	96	269
U149-598-LS	585	120	72	98	78	872	22	60	35	66	61	9	23	0	23	11	290	5	1	245	47	117	337
U149-633-LS	544	113	88	89	41	688	21	56	34	67	53	7	17	34	24	11	290	3	0	261	46	120	332
																						Con	tinued

	Ba	Ce	CI	Cr	Cu	F	Ga	La	Nb	Nd	Ni	Pb	Rb	S	Sc	Sm	Sr	Th	U	V	Y	Zn	Zr
Sample Name	ppm	ppr																					
U149-656-LS	536	112	74	82	44	810	22	56	35	63	49	6	15	10	25	10	282	3	0	278	47	119	338
U149-700-LS-690	491	98	84	112	47	677	22	49	30	59	69	6	14	0	24	9	304	2	0	265	41	121	300
U149-700-LS-697	398	78	68	142	41	403	19	34	31	54	79	6	13	212	25	9	291	2	0	268	40	133	298
U149-700-LS	482	96	83	113	31	658	22	49	30	59	74	7	15	118	23	10	313	2		250	41	122	30
U149-700-LS-710	404	83	70	122	44	469	20	40	30	54	68	8	17	197	25	9	278	4	1	281	41	136	30
U149-727-LS	488	85	80	137	33	643	21	43	26	55	72	6	15	0	24	9	301	3	0	256	38	119	27
J149-745-LS	467	89	70	98	45	648	21	45	30	56	55	7	16	39	25	9	288	4	0	278	42	126	30
U149-776-LS	476	90	80	124	32	613	20	45	28	54	73	6	15	80	23	9	289	2	0	251	39	120	28
U149-853-LS	395	70	72	207	49	491	19	35	22	45	101	5	12	6	24	8	285	2	0	233	35	106	24
U149-869-LS	340	61	67	206	42	521	19	31	18	37	90	4	10	10	23	7	247	1	0	223	31	90	21
U149-880-LS	352	67	67	221	48	606	18	34	22	44	95	4	12	26	26	7	255	3	0	239	36	102	24
J149-915-LS	300	50	69	280	50	482	18	25	17	30	106	6	11	21	25	5	223	3	0	228	30	86	20
J149-945-LS-928	299	52	67	285	42	455	19	26	18	36	84	4	11	67	26	6	251	2	0	257	33	101	23
J149-945-LS-941	261	47	62	353	49	406	17	26	17	33	134	3	10	90	28	6	230	1		244	30	97	20
J149-945-LS	274	48	63	298	39	479	18	25	18	36	82	5	11	81	26	7	249	2		254	31	102	22
J149-945-LS-950	281	51	64	296	41	451	18	30	17	34	78	3	11	53	26	5	245	3	0	251	32	100	22
J149-970-LS-966	410	71	72	124	44	564	21	35	24	48	74	6	13	107	25	9	287	2		258	38	116	26
J149-970-LS-972	404	66	70	162	45	547	20	35	23	48	93	6	12	95	24	9	294	1		259	37	121	26
NL-1-453_LS	436	71	70	116	39	659	20	35	22	45	72	5	12	29	22	8	274	2	0	230	35	101	24
ANL-1-501 LS	732	110	79	94	30	658	22	55	31	68	55	6	14	41	24	11	317	3	0	249	43	125	39
ANL-1-552_LS	780	119	73	104	20	816	22	59	33	71	58	4	14	0	24	11	330	2	0	261	45	132	41
ANL-1-644-LS	702	107	77	87	34	695	22	53	30	64	69	6	15	111	25	10	312	3	0	272	43	126	36
ANL-1-825_LS	514	104	85	90	40	731	21	52	34	62	56	6	16	32	23	10	291	4	1	252	45	122	33
ANL-1-903_LS	365	60	61	221	37	504	19	30	19	39	95	4	11	10	23	6	274	1	0	235	32	99	22
ANL-1-943 LS	303	50	62	294	42	487	18	25	16	29	103	3	10	0	23	6	223	0	0	207	28	80	19
ANL-1-966 LS	397	72	66	87	46	565	20	36	24	45	59	6	13	15	23	8	277	2	0	241	38	112	26
ANL-1-1039 LS	445	72	73	133	47	604	21	36	21	45	77	5	12	0	21	7	284	2	0	221	35	102	24
43-15.6	410	67	103	186	36	614	18	34	24	47	53	5	14	57	26	8	288	2	nd	271	37	114	26
43-31.2	483	88	88	112	48	775	18	44	29	59	59	6	15	251	28	9	306	4	1	339	46	142	32
43-56.2	440	68	84	136	31	637	19	34	21	43	76	5	14	73	23	7	327	1	nd	249	34	109	23
43-77.1	387	59	82	253	46	508	16	29	21	38	94	5	16	69	26	6	285	2	nd	256	33	108	22
43-115.4	454	71	77	90	34	767	19	35	24	48	61	4	10	24	25	9	307	nd	nd	284	37	117	26
143-134.2	449	74	73	106	23	733	20	37	24	52	59	5	10	32	25	9	311	1	nd	293	37	119	26
143-154 5	458	73	80	99	53	736	19	37	24	48	64	5	9		24	8	305	1	nd	284	38	119	26

Continued

Trace Element Whole	e-Rock	Geoch	emical	Analy	ses of E	ESRP B	asalts.																
Sample Name	Ва	Ce	CI	Cr	Cu	F	Ga	La	Nb	Nd	Ni	Pb	Rb	S	Sc	Sm	Sr	Th	U	۷	Y	Zn	Zr
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
143-184.2	725	144	99	73	36	956	21	72	47	87	44	9	20	107	26	13	301	4	nd	280	62	147	480
143-220.0	630	122	90	110	26	892	21	61	40	72	64	9	17	7	25	11	314	4	1	263	53	141	408
143-250.9	501	86	79	131	34	686	20	43	28	59	80	5	10	6	25	10	330	2	nd	290	43	134	308
143-264.1	547	88	67	105	49	754	20	44	26	57	70	5	9	-	23	9	321	1	nd	245	39	113	282
143-296.6	514	83	79	101	31	681	20	42	26	55	77	5	10	33	23	9	313	1	nd	250	38	117	285
143-364.4	492	71	77	150	50	777	20	35	25	53	95	5	10	17	24	9	318	1	nd	273	39	125	276
143-392.2	300	52	67	417	54	543	18	26	18	36	118	5	7	-	29	5	254	3	1	263	31	97	209
143-412.6	302	52	69	396	57	596	18	26	18	35	117	4	6	-	29	6	255	1	nd	255	32	96	209
143-446.1	668	121	122	111	31	821	20	60	43	64	47	9	20	53	24	11	324	4	1	239	42	120	388
143-466.4	664	119	116	93	31	799	20	59	40	58	42	9	19	-	22	11	309	4	1	215	40	106	364
143-484.3	691	155	116	107	42	957	21	77	47	80	35	9	14	4	25	13	304	4	nd	269	50	123	422
143-506.2	540	112	108	132	31	726	19	56	38	61	61	7	11	55	23	11	307	4	1	230	38	117	335
143-522.1	776	167	128	106	58	1084	22	83	54	89	25	10	16	49	27	14	278	5	1	308	57	129	477
143-544.5	572	115	106	112	27	699	20	58	39	62	56	7	12	28	22	10	305	2	nd	230	40	115	346
143-587.2	503	102	94	129	34	727	20	51	34	57	57	6	15	78	24	10	307	3	nd	241	40	119	323
143-606.4	557	109	93	77	30	763	21	54	34	62	40	6	14	-	23	10	301	2	nd	231	42	109	326
143-632.5	547	103	85	79	25	751	21	52	31	59	49	6	13	-	22	10	309	2	nd	208	39	107	300
143-673.1	499	92	78	103	25	705	20	46	26	52	47	6	9	-	22	9	309	2	nd	254	37	102	270
143-693.6	447	79	204	99	29	659	20	39	26	50	50	5	9	72	23	10	315	1	nd	235	37	111	272
143-701.2	436	57	73	170	54	553	20	29	19	37	74	5	13	126	23	7	295	1	nd	249	31	105	217
143-725.1	491	71	61	148	30	696	19	35	20	42	65	5	13	-	23	7	285	1	nd	238	33	97	230
143-746.2	415	57	71	191	36	583	19	28	18	38	59	4	12	22	24	7	265	2	nd	260	31	92	202
143-778.3	352	58	61	160	37	604	19	29	17	35	49	4	9	9	23	6	279	1	nd	237	30	89	191
143-798.3	346	52	61	184	31	574	19	26	16	34	50	4	9	-	23	6	280	1	nd	229	28	89	182
143-817.0	1402	311	143	nd	17	1352	24	155	95	171	10	18	28	10	22	25	290	10	2	93	125	196	1024
Microwave_LS	242	47	143	719	35	410	16	23	19	32	98	3	17	0	29	6	214	3	0	248	31	91	200
Topper_LS	290	57	103	453	35	480	17	28	21	37	89	5	9	1321	28	6	280	1	0	266	29	101	210
Radiofacility-DC_LS	530	114	253	122	33	723	21	57	45	70	46	8	14	307	28	11	297	4	0	305	52	152	395
Vent5350 LS	455	73	127	103	32	542	22	36	28	52	51	6	12	292	27	9	330	3	0	311	42	146	319
Notes:	All an	alyses	detern	nined (using X	RF at B	righan	1 Youn	g Unive	ersity.	1-sigm	a unce	rtaintie	es: 5.5%	% for B	a, 12.4	% for (Ce and	Cr, 4.8	% for (Cu, 1.8	% for G	ia,
	10.9%	6 for La	a, 3.2%	for Nb	and Y	, 12.6%	6 for N	d and S	5m, 12.	2% for	Ni, 13	.2% for	r Pb, 2.	.5% for	Rb, 8.	3% for	Sc, 2.2	% for s	Sr, 26.6	5% fot	Th, 64.	5% for	U,
	23.19	6 for V	, 1.5%	for Zn,	and 1.	0% re	ported	as 1-si	gma re	lative	standa	rd dev	iation	(RSD) (E. Chri	stiense	n, pers	ional c	ommu	nicatio	n, Febr	ruary 2	,
	2022).																					

Table 3.2. Trace element whole-rock geochemistry for all 95 samples analyzed in this study.

compositional Analysis of the Most Mg-high onlysis from Samples Conected From the Coop Mith. Falebinggletic circle From Your										
Sample	U149_700_LS-690	U149_700_LS-697	U149_700_LS	U149_700_LS-710	U149_945_LS-928	U149_945_LS	U149_945_LS-950	ANL-1-644	ANL-1-825	ANL-1-903
AI2O3	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.1
MgO	39.2	38.4	38.7	40.2	45.2	43.9	42.7	34.7	41.4	44.6
SiO2	38.8	38.0	38.1	38.8	38.5	39.5	38.6	37.1	39.3	39.1
MnO	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.2
Cr2O3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
CaO	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.3
FeO	21.1	21.3	22.2	20.6	14.7	17.1	16.8	27.8	17.9	14.5
NiO	0.1	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.2
Total	99.8	98.5	99.8	100.3	99.1	101.2	98.8	100.3	99.4	99.1
Fo#	76.9	76.2	75.7	77.7	84.6	82.1	81.9	69.0	80.5	84.6
KD	0.29	0.31	0.31	0.27	0.30	0.29	0.31	0.39	0.30	0.29
TMg (°C)	1159	1169	1169	1145	1214	1217	1203		1198	1212
TNi (°C)	1156	1131	1117	1127	1195	1164	1150		1146	1129
ΔT (°C)	3	38	52	18	19	53	53		52	83
min H2O (wt%)	0.1	1.1	1.6	0.5	0.5	1.6	1.6		1.5	2.6

Compositional Analysis of the Most Mg-Rich Olivine Phenocryst From Samples Collected From the Cobb Mtn. Paleomagnetic Chron Flow Group

Table 3.3. Olivine compositional analyses (wt%) of the highest Mg olivine phenocryst analyzed from the Cobb Mtn Paleomagnetic Chron lava flow group observed in both the USGS 149 and ANL-OBS-A-001 cores. Forsterite content (Fo#), ^{Fe2+-Mg}KD partition coefficient, T_{Mg} and T_{Ni} values, Δ T, and minimum dissolved melt H₂O content are reported for each sample. Uncertainties for the T_{Mg} and T_{Ni} are ±26 and ±29 °C, respectively. Note: sample ANL-1-644 is not used to calculate crystallization temperatures, as this sample did not pass the ^{Fe2+-Mg}KD liquidus test.

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