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Dynamics of Magma Recharge and Mixing at Mount Hood Volcano, Oregon – Insights from Enclave-bearing Lavas

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Dynamics of Magma Recharge and Mixing at Mount Hood Volcano, Oregon –
Insights from Enclave-bearing Lavas

by

Molly Kathryn Ellowitz

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Geology

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Portland State University
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ABSTRACT

Magma recharge events and subsequent mixing processes are understood to precede volcanic eruptions. Textural evidence of intrusion of hot, mafic magma into a cooler, rheologically locked silicic magma is commonplace. Solidified ‘blobs’ of injected magma, called enclaves, are evidence of magma mixing, but the petrological and mechanical conditions during their formation are debated. Mount Hood, Oregon consistently erupts andesite bearing compositionally similar enclaves. These enclaves are evidence of mingling and mixing of two magmas. However, due to the compositional similarity between enclave and host lava (e.g. $\sim 1 - 5$ wt.% difference in SiO_2), it is unclear whether the preserved enclaves represent; 1) partially hybridized mafic melt remaining after mixing with significant crystal exchange with the host magma or 2) the preserved remnants of the intruding magma during recharge, with no homogenization or crystal exchange with the host magma. The aim of this study is to understand how and why enclaves form in compositionally similar host magmas, such as those at Mount Hood. Building off previous research, we utilize a combination of field observations, chemical analyses, and numerical modeling to constrain the rheology of the magmas prior to and during mixing. The degree of magma mixing is dependent on the viscosity contrast between the host and intruding magmas. Since these magmas are similar compositionally, variations in other magmatic properties such as crystallinity, and therefore temperature, and density may drive the viscosity differences between the host and intruding magmas needed for enclave formation.

The enclaves at Mount Hood are vesicular (13 – 28%), coarse-grained; made up of mainly groundmass crystals (200 – 450 μm) with sparse microlites (< 200 μm), glass (<1 – 5%), and a wide range of phenocryst (> 450 μm) proportions, and rarely contain quenched margins. Additionally, crystals within the host magma show preferential alignment along the margins between host and enclave, suggesting a fluid behavior of the host magma during mixing. Based on textural and compositional evidence, we hypothesize that the intruding magma was buoyant, viscous, and crystalline, due to decompression-induced crystallization and exsolution of volatiles, during recharge and ascent to the shallow magma reservoir. Injection and underplating of the viscous crystalline intruding magma into a hot convecting host magma induces enclave formation. Crystallization temperatures differ by only 6 – 15 $^{\circ}\text{C}$ between host and enclave lavas, derived by the two pyroxene geothermometry method by Putrika (2008). These crystallization temperatures are consistent with crystallization in compositionally similar magmas. However, with such similar crystallization and liquidus temperatures, maintaining a viscosity contrast between the mixing magmas for enclave survival after formation suggests other properties, apart from temperature, must explain the viscosity contrast needed for enclave survival after enclave dispersal and thermal equilibration occurs. The presence of bubbles, from exsolution during crystallization, within the enclave magma increases the viscosity while simultaneously decreasing the density. Therefore, the presence of bubbles increases the viscosity of the intruding magma and maintains the viscosity contrast during the mixing process after thermal equilibration occurs. Additionally, if degassing occurs, rapid crystallization maintains the high

viscosity of the enclaves. The enclaves observed at Mount Hood represent the solidified remnants of the last recharge event prior to eruption. The presence of compositionally similar enclaves and host lavas suggest a transient precursor event just prior to eruption at Mount Hood and can be applied to other recharge-driven arc volcanic systems.

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CHAPTER 1: INTRODUCTION AND BACKGROUND OF MOUNT HOOD, OREGON

INTRODUCTION

Motivation

The most hazardous volcanic eruptions are associated with silicic magmatic systems, and an understanding of the processes that drive these eruptions is essential. The factors responsible for triggering these eruptions are controlled by the processes occurring in magma chambers ranging in depths from 3-15 km below the surface of the Earth (Caricchi and Blundy, 2015). During inactivity, magma reservoirs are in their storage phase where the system is stable and inactive. For eruptions to occur, magma must be able to move and flow in response to applied stresses. Thermal rejuvenation of a magmatic system controls the crystallinity and consequently the eruptibility of the system. Crystals preserve their thermal histories and can provide details of the thermal conditions during storage and prior to eruption of the magmatic system (Eichelberger, 1980). The properties of magma, mainly the temperature, crystallinity, viscosity, and density affect the eruptibility of a magma. To understand the processes that drive volcanic eruptions, constraining these magmatic properties and how they influence the eruptibility of a magma is crucial.

The storage temperature of magmas in the crust is a highly debated topic (Bachmann and Bergantz, 2008; Huber et al., 2011; Cooper and Kent, 2014). Through diffusion chronometry of crystals, it is proposed that some crystal-rich silicic magma chambers may spend more time at near-solidus temperatures, where the system is too

crystalline to be erupted (Cooper and Kent, 2014; Rubin et al., 2017). During this time of inactivity, the system may experience episodic recharge events of hot, new magma from greater depths facilitated by dikes or underplating beneath the magma reservoir. These recharge events provide the mass and heat needed to thermally rejuvenate the cold rheologically locked magma, leading to remobilization and ultimately eruption (Kent, 2013). The processes occurring in magma chambers are widely studied, however the mechanisms and timescales responsible for triggering eruptions remains poorly understood.

The idea of mixing between two or more magmas of distinct magmatic properties is a widely recognized fundamental petrogenetic and volcanologic process and thought to trigger eruptions (e.g. Wilcox, 1999). Episodic recharge events supply magma that differs in some magmatic properties from the magma it intrudes, leading to thermal and density instabilities. The degree of mixing is affected by differences in magma properties and system conditions. The degree of mixing can be thought of as a scale of mixing completeness. At one end, complete mixing, termed hybridization, results in a completely mixed hybrid magma with significant crystal exchange between the two magmas (Eichelberger, 1980). While at the opposite end, incomplete mixing, termed mingling, preserves macroscopic features and textures of the mechanical mixing processes with little to no crystal exchange between the mingling magmas (Pabst, 1928; Didier and Barbarin, 1991; Sparks and Marshall, 1986).

Field evidence of magma mingling consists of a heterogeneous mixture of compositionally and texturally distinct blobs, called magmatic enclaves, entrained within

a host rock (Pabst, 1928; Didier and Barbarin, 1991). In cases where mingling and mixing both occur, compositionally distinct bands or zones occur forming ductile deformation features such as banding and mixed pumices, with some crystal exchange, or partial homogenization (Anderson, 1976; Eichelberger, 1980; Bacon, 1986; Nakamura, 1995; Coombs et al., 2000; Andrews and Manga, 2014). Evidence for mixing of distinct magmas is observed macroscopically and also at the crystal-scale with phenocryst heterogeneities and zoning (Larsen et al., 1938; Fenner, 1926; Eichelberger, 1980). Thermal histories of crystals show that recharge events occur just a few weeks to months prior to eruption (Montagna et al., 2015).

Evidence of mixing, from hybrid magmas to magmatic enclaves, is abundant in volcanic and plutonic rocks, however a key question remains; what controls the degree of mixing? The degree in which magmas differ in composition, temperature, density, crystallinity, will dictate the capability of the magmas to either mix completely or mingle. Importantly, variations in viscosity between the magmas will either inhibit or enable complete mixing. Since viscosity is a function of temperature, crystallinity, density, composition, and the deformation rate, magmas with similar viscosities may hybridize easier than magmas with large viscosity ratios (Manga, 1996; Hodge and Jellinek, 2012).

The overall goal for this study is to utilize field observations; such as enclave abundance and size and shape distributions, as a tool to constrain the rheology between the mixing or mingling magmas. I use these field characteristics coupled with petrologic analyses to parameterize numerical models to simulate enclave formation and cooling. The factors influencing mixing dynamics of the pre-eruptive magmatic system can be

constrained and provide timescales of enclave cooling preceding eruption. Mount Hood, Oregon is a unique location to study enclave formation and interaction because it has compositionally and mineralogically similar enclaves and host lavas. The aim of this study is to build an understanding of how enclaves form at Mount Hood. Particularly, understanding the role of how the viscosity ratio dictates enclave formation based on the characteristics; such as composition, temperature, crystallinity, yield strength, and density of the eruptive products at Mount Hood. The motivation for better understanding enclave formation at Mount Hood is not only to gain knowledge on the subject, but also from a public perspective to understand how these eruptions occur and how to better prepare for such events. The combination of petrology and numerical modeling will provide new insights about the magmatic conditions leading to mobilization and eruption of lavas at Mount Hood.

This introductory chapter includes a brief discussion of the parameters involved in understanding the rheology of a magma and the implications of eruptible versus uneruptible magma. Viscosity is an important rheologic factor in governing the degree of mixing. The presence of enclaves provides rheological constraints on mixing and their significance, both in the plutonic and volcanic record is discussed. Based on the identity of the intruding and host magmas, both chemical and textural characteristics, and constraints of their rheological behavior, consideration of possible mechanisms for enclave production are discussed. A general geologic background of the Cascades Volcanic Arc and Mount Hood Volcano follow these sections.

BACKGROUND

Magma Rheology

The dynamics of mixing between magmas with different viscosities is complex, and vigorously debated (e.g. Eichelberger, 1980; Marsh, 1981; Bacon, 1986; Sparks and Marshall, 1986; Wilcox, 1999). The viscosity contrast between an intruding magma and host magma is seen as one of the most important factors affecting the degree of mixing, resulting in end-member products of enclaves and hybridized magmas. Therefore, a comprehensive understanding of the rheology of the melt and the influence of crystals on a magma's viscosity is essential in assessing the driving mechanisms for enclave formation as a result of magma mixing.

The rheological behavior of magmas is strongly dependent on the melt composition, temperature, the presence of crystals and volatiles, and the deformation rate. With dilute suspensions ($< 30\%$ solid fraction), the effect of crystals on the magma's viscosity is less significant than concentrated suspensions ($> 30\%$ solid fraction). Once the solid fraction increases above about 30%, the crystal packing arrangement begins to inhibit the ability of the suspension to move or flow (Marsh, 1981). Magmas at high crystallinities ($\sim 50\%$ solid fraction) are considered rheologically-locked, in that the magma is unable to flow due to the interlocking connected network of crystals. When magmas are rheologically-locked, they are termed uneruptable and require reheating with significant melt production to be able to erupt, referred to as defrosting.

Episodic recharge events supply the heat and mass needed for thermally rejuvenating a rheologically-locked magmatic system (Kent, 2013; Cooper and Kent,

2014). Consequently, textural and petrologic evidence record the occurrence of recharge events and the subsequent mixing processes that precede eruptions. Enclaves are macroscopic evidence of mixing between magmas with different viscosities and their presence suggests a viscosity contrast between the host and intruding magmas (Eichelberger, 1980; Marsh, 1981; Sparks and Marshall, 1986; Bacon, 1986; Hodge and Jellinek, 2012). The size and shape distributions of entrained enclaves can constrain the rheology of mixing magmas and enclave textures detail the timing of enclave cooling. Therefore, assessing the timing of enclave cooling, specifically if crystallization occurred post or pre-entrainment within the host magma, is essential in understanding the pre-eruptive mixing processes.

Enclave Significance

Enclave characteristics such as their physical appearance, petrographic texture, vesicularity, bulk composition, mineral heterogeneities, and groundmass textures can help constrain the magmatic properties during mixing. The physical properties of enclaves such as shape and size distributions provide evidence for mixing styles, or degree of mixing (Turner and Campbell, 1986; Ventura et al., 2006; Paterson et al., 2004). Enclave abundance provides insight into the volume of recharge magma present or able to mix with the host magma (Barclay et al., 2010).

Enclaves that are compositionally and mineralogically similar to their respective host lavas suggest that variations in viscosity to form the enclaves must be driven by temperature, density, or crystallinity differences rather than compositional contrasts. Quenched margins, evidence of undercooling, and quenched glass within the enclaves

indicate thermal contrasts between the magmas and rapid cooling of the enclave magma, or hotter magma (Frost and Mahood, 1987; Paterson et al., 2004; Hammer, 2008; Mollo and Hammer, 2017). Vesicularity variations between enclave and host lavas suggest density variations either due to variability in dissolved volatiles (i.e. water) or rapid crystallization and exsolution of volatiles trapped by the solid margins of the enclaves, decreasing the density of the enclave magma relative to the host (Coombs et al., 2000; Browne et al., 2006).

Enclaves in plutons

Magma mixing, and the chemical variability of igneous rocks have been extensively studied for the past two centuries (Didier, 1973). The complexity of magma chambers is a central issue in studying igneous rocks and volcanic processes (see Marsh, 2015 for a review). The idea that basaltic melts undergo crystallization and fractionation with decreasing temperature was discovered by Norman Bowen in the early 1900s. In his experiments, it was found that the chemical evolution of magmatic bodies during crystallization progressively evolves the residual melt to ultimately become silicic or granitic in composition (Bowen, 1915, 1928).

The conditions at which magmas interact can be determined based on the shape, composition, and textures of the observed enclaves. In plutons, enclaves are generally observed as more mafic in composition than their host magmas (Figure 1). Enclaves in plutons provide important crystallization histories and processes preceding the solidification of the pluton (Reid et al., 1983). The mafic enclaves and dikes in the Sierra Nevada batholith are excellent examples of magma mixing in plutonic environments

(Didier, 1973; Reid et al., 1983). Compositional zoning of the Sierra Nevada batholith provides cooling timescales of the comagmatic plutons (Bateman and Chappell, 1979). Episodic injection of mafic magma and the subsequent mixing style and solidification history are recorded by the degree of hybridization, shape and size distribution, and textures of the mafic enclaves entrained in the host granite (Reid et al., 1983; Bateman and Chappell, 1979).

Figure 1: Photos of granodiorite and microgranular mafic plutonic enclaves from Little Cottonwood Canyon, Utah. Quarter for scale.

Other enclave-producing volcanoes

In volcanic systems, pre-eruptive magmatic processes are determined by analyzing entrained enclaves and host lavas, like those found at Mount Hood. These processes include; silicic host storage conditions, magma recharge events, remobilization, mixing dynamics, and magma ascent rates (Rutherford and Devine, 2003; Bacon, 1986). Recharge driven volcanic systems that produce enclave-bearing lavas provide a basis for our understanding of enclave formation at Mount Hood. These analog volcanoes include but aren't limited to; Lassen Peak, California, Unzen Volcano, Japan, and Soufriere Hills, Montserrat (Feeley et al., 2008; Clynne, 1999; Browne et al., 2006; Rutherford and Devine, 2003). Compositional variations in mineral assemblages and the textures of the erupted enclaves depict evidence of heating events prior to eruption. Basaltic emplacement into an evolved magmatic system with little hybridization prior to eruption is evident from the eruptive products (Rutherford and Devine, 2003).

Mechanisms for Enclave Formation

The degree of mixing is dictated by the viscosity contrast between the host and intruding magmas (Marsh, 1981). Mechanisms of enclave formation vary and can be divided into two general mixing styles; incomplete mixing, termed mingling (Sparks and Marshall, 1986), and complete mixing, termed hybridization (Eichelberger, 1980). Textural evidence and petrologic analysis of chemical zoning within individual crystals assist in understanding whether crystal exchange occurred during mixing (Eichelberger, 1980; Tepley, 1999; Kent et al., 2010). The presence of enclaves either signifies mingling between the intruded and host magmas with no crystal exchange or represent partially

mixed magma that hasn't reached complete hybridization. Therefore, investigating whether crystal exchange occurred between the mixing magmas and the magmatic properties that give rise to the viscosity variations between the host and intruding magmas to produce enclaves at Mount Hood is the basis of this study.

In cases where mechanical mixing dominates with little to no crystal exchange, the processes of enclave formation can be further subdivided into whether the enclave magma cooled and crystallized before or after being entrained within the host magma (Marsh, 1981; Coombs et al., 2000). Essentially, enclave quenching is related to changes in temperature between the intruding magma and area in which it cools. Enclave cooling may occur at the interface between a cooled host magma or country rock within a conduit or cooled once entrained within the host magma as enclaves. Additionally, the intruding magma may cool in response to decompression-induced crystallization during rapid ascent from recharge events (Mollo and Hammer, 2017). Exsolved volatiles during crystallization may also play an important role in enclave formation, as bubbles may increase the viscosity while simultaneously decreasing the density of the intruding magma (Coombs et al., 2000; Browne et al., 2006).

Textural indicators for enclave cooling, either after entrainment and dispersal within the host magma or prior to incorporation within the host magma, include degree of vesicularity, abundance of phenocryst ($>450\ \mu\text{m}$), groundmass crystals ($450\text{-}200\ \mu\text{m}$), and microlites ($<200\ \mu\text{m}$), presence of quenched margins, quenched glass, and signs of undercooling within the groundmass crystals and microlites. Therefore, not only is the chemical identity and rheology of the intruding and host magmas essential in deciphering

enclave formation, but detailed textural analyses to determine timing of enclave groundmass cooling are also necessary.

LOCATION BACKGROUND

Geologic Background of the Cascade Volcanic Arc

The Cascade Volcanic Arc is located along the Pacific Northwest margin of North America. The arc extends in length about 1000 km stretching from northern California to southern British Columbia, Canada (Leeman et al., 1990) (Figure 2). The continental Cascade Volcanic Arc system was formed approximately 30 million years ago, by the subduction of the Juan de Fuca Plate beneath the North American Plate (Rogers, 1985; Priest, 1990). Currently, the subduction rate is greater (20% faster) along British Columbia than Oregon, with the rate of subduction along the plate ranging from 3.8 to 4.6 cm/year (Rogers, 1985; Priest, 1990). Due to oblique subduction along Oregon, clockwise rotation of the central Cascade Volcanic arc region results in extensional and compressional stresses along British Columbia and Washington (Leeman et al., 1990; Priest, 1990).

Figure 2: Map showing the Cascade Volcanic Arc and locations of tectonic plates. Cascade volcanoes shown as triangles: L = Lassen Peak; Sh = Mount Shasta; M = Medicine Lake Volcano; N = Newberry Volcano; S = Mount St. Helens; R = Mount Rainier; B = Mount Baker. Red triangle indicates Mount Hood (H), the location of interest for this study. Map modified from Mooney and Weaver (1989).

The volcanoes of the modern Cascades were formed mainly during the Quaternary Era and are less than 1 Ma (Priest, 1990). The eruptive products of these volcanoes are predominantly calc-alkaline and compositionally range from basaltic andesite to dacite (Leeman et al., 1990; Cameron and Pringle, 1987). Eruptive activity has decreased over the lifespan of the Cascades. However, several large eruptions during

the Holocene have occurred, including the cataclysmic eruption of Mount Mazama (7,700 BP) forming Crater Lake, Mount St. Helens (1980), Mount Hood (~200 BP), and Lassen Peak (1915) (Rogers, 1985; Priest, 1990).

Geologic Background of Mount Hood

Mount Hood is a stratovolcano located about 80 km east of Portland in the Cascade Volcanic Arc and is the highest peak in Oregon (3,426 m). Mount Hood is built upon Miocene to Pliocene basaltic to dacitic lavas ranging in age from about 1.5 Ma to 600,000 years old (Cameron and Pringle, 1987; Scott and Gardner, 2017). These eruptive products are sourced from poorly constrained pre-Hood composite vents located several kilometers from the current edifice (Scott and Gardner, 2017). Mount Hood has mostly formed during the past 500,000 years (Scott and Gardner, 2017). Over its eruptive history, Mount Hood has erupted compositionally similar calc-alkaline andesites and some low-silica dacites (57.9 – 64.5 wt.% SiO₂) (Cameron and Pringle, 1987; Scott and Gardner, 2017). The recent eruptive history is divided into four eruptive units that are separated by periods of inactivity; Main Stage period (>30 ka), Polallie period (30 - 12 ka), Timberline period (1.5 ka), and the Old Maid period (~230 years). All ages were dated using K/Ar dating (Wise, 1969; Crandell, 1980) (Figure 3).

Figure 3: Preliminary geologic map of study area with six field locations of this study are shown where purple locations indicate Main Stage eruptive unit locations, where H stands for Highway 26 location, Q stands for Quarry location, M stands for Meadows location, and CC stands for Compass Creek location. Timberline eruptive unit (T) locations shown as green pins. Old Maid eruptive unit (OM) location shown by yellow pin. The Polallie eruptive period products were not sampled in this study. Map modified from Sherrod & Scott (1995).

The Main Stage eruptive products are characterized by medium grained, porphyritic andesitic lava flows or pyroclastic debris flows containing plagioclase, orthopyroxene, and minor amounts of clinopyroxene and hornblende phenocrysts. The Polallie and Timberline eruptive products are porphyritic andesite to dacite in

composition characterized by pyroclastic flows, lava domes, tephra and lahar deposits formed from dome building and collapse events. Polallie deposits are primarily found on the east and northeast flanks, whereas Timberline deposits are found primarily on the south flank. The Polallie and Timberline eruptive products contain phenocrysts of plagioclase, orthopyroxene, clinopyroxene, and hornblende. The Timberline and Old Maid eruptive products are similar to the previous products and are characterized by lahar and pyroclastic flow deposits. Crater Rock, located on the south flank of Mount Hood, is the remnant dome of both the Timberline and Old Maid eruptions and is dacitic in composition, rich in plagioclase, orthopyroxene, and hornblende phenocrysts. The eruptive products vary slightly and evolve into more dacitic eruptions, however in general, Mount Hood has produced compositionally uniform products.

Mount Hood erupts compositionally and mineralogically similar entrained enclaves and host andesite (Kent et al., 2010). In this study, we sample deposits from the Main Stage, Timberline, and Old Maid eruptive periods. Kent et al. (2010) argues on the basis of episodic recharge events dominate the eruptive history of Mount Hood, and the host lavas are products of mixing between mafic and silicic end-member magmas. However, the processes of enclave formation at Mount Hood have yet to be investigated. Using previous petrologic data of the host lavas from the Main Stage and Timberline eruptive periods by Woods (2004), petrologic analysis for this study is concentrated on the enclaves of the eruptive products. Enclaves provide insight into the properties of the injected magma from recharge events and mingling and mixing histories and are therefore the focus of this study.

CHAPTER 2: METHODS

FIELD LOCATIONS AND METHODS

Field work was carried out with three objectives in mind: 1) to collect samples for petrographic and chemical analyses; 2) to obtain in situ images of enclaves at each location to determine enclave size and shape distributions; 3) to systematically measure enclave abundance by macroscopic point counting at each outcrop or block.

Sample Locations and Collection

Samples of lavas were collected at six locations during summer of 2017. Sampling locations were selected based on previous work by Woods (2004) along with new locations to analyze more recent eruptive units since 30 ka. Field locations of the Main Stage eruptive products include a road cut along US Highway 26 on the south flank of the volcano, Mount Hood Meadows Ski Area on the southeast flank, an outcrop quarry along the Timberline Road on the south flank, and along Compass Creek near Timberline Trail #600 on the northeast flank (Figure 3). Timberline eruptive products were sampled from blocks on the Timberline fan composed of block-and-ash flow deposits N/NE of Timberline Lodge (Figure 3). Old Maid eruptive products were collected along the White River Drainage on the southeast flank of the volcano (Figure 3).

Table 1 lists each sample location, identification, eruptive unit, and measurements taken for each sample location. Sampling focused on specimens including host and enclave lavas. The minimum diameter of enclaves selected for analyses was 0.5 cm. Samples for petrologic and bulk analysis were collected with minimal weathering surfaces. These samples were collected using a hammer and chisel from *in situ* outcrops

and blocks. At least five enclaves and host lavas were sampled at each location. These samples were later used for either textural or chemical analyses.

Chemical analyses used from Woods (2004) include most Main Stage samples (MH0203, MH0205, MH0210, MH0211, MH0213) and a Timberline sample (MH0212). Chemical analyses conducted from this study includes samples from the Compass Creek (MH_P) location of the Main Stage eruptive period, Timberline (MH_T) locations, and one Old Maid (MH_OM) location (Table 1).

Table 1: All sample locations, sample identifications, and measurements taken from Woods (2004) and this study. Sample locations from Woods (2004) denoted as (W) and locations from this study denoted as (E). Chemical analyses conducted by Woods (2004) are denoted by *. E.U. = Eruptive Unit, Field Ms. = Field Measurements.

Site #	E.U.	Location Name	Lat, Long	Host Name	Enclave Name	Field Ms.?	XRD/ICP?	SEM/EMPA?
1	Main Stage	US Highway 26 (W)	45.288495, -121.733083	MH0203-1 MH0203-2 MH0203-3	MH0203A MH0203C MH0203G MH0203I	Yes	Yes*	Yes*
2		Mt. Hood Meadows (W)	45.342211, -121.670949	MH0205-1 MH0205-2 MH0205-3 MH0205-4	MH0205lef MH0205rig MH0205B MH0205E MH0205L MH0205M	Yes	Yes*	Yes*
3		Laurance Lake (W)	45.460787, -121.636688	MH0210-1 MH0210-2	MH0210B MH0210C MH0210E MH0210F MH0210L	No	Yes*	Yes*
4		Compass Creek (W)	45.397322, -121.673593	MH0211-1 MH0211-2	MH0211A MH0211B MH0211H	No	Yes*	Yes*
5		Compass Creek (E)	45.400382, -121.675351	MH_P1_H MH_P2_H MH_P3_H MH_P4_H	MH_P1_E MH_P2_E MH_P3_E MH_P4_E	Yes	Yes	Yes
6		Cathedral Ridge (W)	45.404013, -121.733378	MH0213-1 MH0213-2	MH0213C MH0213F	No	Yes*	No
7		Quarry (E)	45.308167, -121.705882			Yes	No	No
8	Timberline	Timberline Fan A (E)	45.333580, -121.713810	MH_T1_H	MH_T1_E	Yes	Yes	No
9		Timberline Fan B (E)	45.332400, -121.708150	MH_T2_H	MH_T2_E	Yes	Yes	Yes
10		Timberline Fan C (E)	45.334780, -121.713050	MH_T7_H	MH_T5_E	Yes	Yes	Yes
11		Timberline Lodge A (W)	45.330914, -121.710111	MH0212-1	MH0212A	Yes	Yes*	Yes*
12		Timberline Lodge B (W)	45.331477, -121.709014	MH0212-2	MH0212D MH0212E	Yes	Yes*	Yes*
13	Old Maid	White River Drainage (E)	45.313670, -121.680830	MH_OM1_H	MH_OM1_E	Yes	Yes (only Host)	Yes

Image Analysis

In situ images of enclaves were obtained and used for image analysis to measure the size and shape distributions of enclaves at each location. Our approach was to photograph all enclaves at each location ranging in size, shape, vesicularity, texture, and color. A cumulative dataset of about 450 enclaves from all locations was obtained (Appendix F). Each photo was carefully taken orthogonal to the sample surface (Figure 4).

Figure 4: Image of an enclave from Meadows location of the Main Stage eruptive unit showing image analysis method using ImageJ to quantify the size and shape distributions of each observed enclave at every location.

We used ImageJ to analyze each individual enclave by carefully hand-tracing the edges of each enclave. Based on the area (A), we estimate an effective diameter ($d = \sqrt{A}$) based on Hodge et al. (2012) analyses (Figure 4). Enclave shapes are quantified

based on their circularity ($circ = 4\pi \frac{A}{p^2}$) where p = perimeter (traced length), a circularity of 0 indicates an infinite ellipse, whereas a circularity of 1 is a perfect circle. The aspect ratio based on the major and minor axes of the enclaves also quantifies the shape of the enclave where a large aspect ratio indicates an irregular or ellipsoidal shape, whereas a small aspect ratio indicates more of an equidimensional circle.

Enclave Abundances

Enclave abundances were measured at each location by macroscopic point counting using a 0.508 m² grid with 2.54 cm² (1 inch²) squares on each axis, allowing up to 400 points per area of grid. At each outcrop or block, point counting was systematically measured in a ~1 m² band from edge to edge of the outcrop or block (Appendix E). Percent abundance was calculated using the surface area of the outcrop face, or block, relative to area occupied by enclave lava. While there may be some discrepancies based on outcrop size and deposit (lava flow vs. block-and-ash flow deposit), we determine this approach was the most efficient to quantify enclave abundances. At block-and-ash flow deposits, Timberline and Old Maid locations, selection of blocks was random and at least five blocks were carefully measured.

PETROLOGIC ANALYSES

Sample Preparation

Samples were selected with minimal weathering surfaces and cut into ~2.5 x 4.5 cm billets in house at Portland State University and sent to Spectrum Petrographics, Inc. in Vancouver, Washington to be made into petrographic thin sections. Nine samples were made into ~35 μm thick microprobe polished thin sections for petrographic and geochemical analyses using the petrographic microscope, Scanning Electron Microscopy (SEM), and Electron Microprobe Analysis (EMPA) analytical methods.

Terminology

We classify crystals based on crystal size and texture. Previous work at Mount Hood by Kent et al. (2010) and others discuss various crystal populations based on crystal size distribution and compositional variations of the crystals. However, for this study the terminology for crystal sizes was further subdivided based on size and texture of the crystals. The terminology of crystals for this study are listed in Table 2.

Table 2: Terminology for crystal sizes for this study compared to terminology used by Kent et al. (2010).

Size	This Study		Kent et al. (2010)
	Enclave	Host	Both Host & Enclave
> 710 μm	Phenocryst	Phenocryst	Phenocryst
450 - 710 μm	Phenocryst	Phenocryst	N/A
450 - 200 μm	Groundmass crystal	Micro-phenocryst	Microlite
< 200 μm	Microlite	Microlite/Groundmass crystal	

Petrography and Crystallinities of the Magmas

The thin sections were analyzed using Leica petrographic microscopes. Using petrographic images in ImageJ software, crystal sizes and aspect ratios were measured to quantify crystallinity, or phenocryst proportions ($> 450 \mu\text{m}$), of both the host and enclave lavas (Appendix B). We consider all crystals $< 200 \mu\text{m}$ as microlites that are inferred to nucleate during ascent and emplacement and are therefore excluded from the analysis of crystallinity of the magmas. However, for samples from the Main Stage eruptive unit, consideration of micro-phenocrysts within the host lavas ($200 - 450 \mu\text{m}$) were selected to estimate the approximate micro-phenocryst proportion.

Geochemical Bulk Analysis

Major and trace element analysis were performed on 15 samples at the GeoAnalytical Lab at Washington State University, Pullman, Washington, using X-Ray Fluorescence (XRF) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) using the methods of Johnson et al. (1999). Samples were chipped in house at Portland State University and brought to Washington State University for preparation and analysis. The GeoAnalytical Lab states that the analytical precision for ICP-MS analysis is 5% (Residual Standard Deviation) for Rare Earth Elements and 10% (Residual Standard Deviation) for trace elements. The geochemical data obtained for samples collected during this study are found in Appendix A.

SEM and EMPA Analyses

Scanning electron microscopy (SEM) analysis were conducted in house at Portland State University (PSU) to obtain backscatter electron images of minerals and

textures to assess zoning of minerals and vesicularities (Blundy and Cashmann, 2008). Analyses were carried out using a Zeiss Sigma VP FEG SEM. The data obtained from the SEM were both BSD micrographs for compositional contrast images and EDS micrographs for elemental analyses using 15 kV accelerating voltage, 8.5 mm analytical working distance, high current mode, and a large aperture (60 μm). The elemental analyses were completed using the software application Oxford Aztec. These images serve as a basis for selecting minerals for electron microprobe analysis (EMPA).

Electron Microprobe analyses were conducted at Oregon State University, Corvallis, Oregon. Plagioclase, pyroxene, amphibole, and iron-titanium oxide mineral phases were analyzed on a Cameca SX-100 microprobe with a 2 μm beam. Analyses were carried out using a sample current of 15 nA for feldspar, 30 nA for pyroxene and amphibole, and an accelerating voltage of 15 kV for all mineral phases. Standards used for plagioclase calibration include augite for Mg, magnetite for Fe, K-feldspar for K and Si, anorthoclase for Na, and labradorite for Al and Ca. Standards used for mafic silicate calibration include anorthoclase for Na and Al, chromite for Cr, rutile for Ti, gahnite (Zn-spinel) for Zn, Mn-pyroxene for Mn, sanidine for Si and K, diopside for Si and Ca, forsterite for Mg, magnetite for Fe, and tugtupite for Cl.

Micro-vesicularity

Micro-vesicularity measurements were carried out using the BSD micrographs and EDS elemental maps obtained during SEM analyses. Using ImageJ software, the BSD micrograph images were converted to 8-bit grey-scale images. Thresholding was applied for the images, where threshold values ranging from 0 - 70 allowed for all areas

of vacant space, or vesicles, to be identified and quantified with respect to areas with thresholding values >70 (Appendix C). The average vesicularity percentages were calculated and used to represent the average percentage of vesicularity for each host and enclave lavas.

Geothermobarometry

Geothermobarometry measurements were carried out using the Putirka (2008) two pyroxene geothermometer. The two pyroxene geothermometer uses equilibrium chemical reactions between clinopyroxene and orthopyroxene where large enthalpy and large volume changes exist (Blundy and Cashman, 2008). Calculations for the Main Stage eruptive unit were based on all orthopyroxene compositions obtained during EMPA compared to all clinopyroxene compositions. Since clinopyroxene was only measured in the Main Stage eruptive unit, the average clinopyroxene composition was used to calculate temperatures using all orthopyroxene compositions from the Timberline and Old Maid eruptive units.

NUMERICAL MODELING

Rheology of Crystal-Bearing Magmas

The relative viscosity of a magma depends on temperature, melt composition, the presence of crystals and bubbles, and the deformation rate (Hodge et al., 2012a; Giordano et al., 2008; Dingwell et al., 1993). Profound research since Einstein (1906) has been made to accurately estimate a suspension's viscosity varying in particle concentration, size, and shape (Petford, 2009). In addition, estimating temperature- and strain-dependent viscosity has proven to be an arduous and difficult task (see Chapter 5 for review). To evaluate temperature-, crystallinity-, and strain-dependent effective viscosities of crystal-rich magmas, we use melt viscosities calculated using the approach of Giordano et al. (2008) combined with relative viscosities calculated using the approach of Costa et al. (2009) (see Chapter 5). We relate crystallinity and temperature relationships using a linear relationship for simplicity from Huber et al. (2010).

ASPECT Mantle Convection Code

Using these field observations, petrologic analyses, and estimated effective viscosities for crystal-bearing magmas, the magmatic properties are constrained and used to numerically model magma mixing processes and enclave formation at Mount Hood. The motion of a viscous fluid is dependent on a variety of parameters including pressure, velocity, density, gravity, and temperature. Flow behavior of a viscous fluid is described by the ratio of the inertial and viscous forces, or Reynolds number. In magmas, viscous forces dominate, yielding laminar flow conditions with low Reynolds numbers. We use ASPECT (Advanced Solver for Problems in Earth's ConvecTion) version 2.0, a finite

element code to simulate scenarios in which enclave formation occurs in Mount Hood's magmatic reservoir (Kronbichler et al., 2012; Bangerth et al., 2018). The model solves a system of equations to simulate Stokes flow and is applicable to magmatic fluids with low Reynold's numbers. The model calculates velocity, pressure, temperature, and compositional fields to simulate how magmas of various viscosities are driven by buoyancy forces from differences in density.

Costa Material Model in ASPECT

To consider strain rate-, crystallinity-, and temperature-dependent relative viscosity in our numerical models using ASPECT, we generated a new material model. The Costa material model uses equations 12 – 15 to calculate the effective viscosity of a magma (see Chapter 5). Figure 5 shows the general parameters for input files to set-up and run the numerical models in ASPECT.

Figure 5: Schematic flow chart of ASPECT convection model set-up and dependents for model results. Modified from image taken from ASPECT 2.0 Webinar.

Each model is set-up by prescribing initial and boundary conditions of temperature and compositional constraints to a domain with a specific size. In the mantle, chemical compositions change spatially and temporally, and are therefore tracked using specified compositional fields. Discontinuous composition discretization allows the compositional fields to change discontinuously, improving the accuracy. However, the discontinuous composition discretization is computationally expensive, yielding large degrees of freedom. Global and adaptive mesh refinement breaks down the domain into cells allowing each calculation to achieve high spatial resolution. The Stokes equations are solved to obtain the pressure and velocity fields coupled with conductive heat transfer, advection, latent heat, and internal heat production. Other parameters such as

viscosity, density, gravity, thermal conductivity, specific heat capacity, and thermal expansion are indicated using material models.

For this study, we created a new material model to provide strain rate-, crystallinity-, and temperature-dependent relative viscosities of the magmas in all models. The new relative viscosity equations (Equations 14 and 15) were formulated by substituting temperature dependent crystallinity with solid volume fraction in equations of Costa et al. (2009) based on the linear relationship of temperature and solid volume fraction from Huber et al. (2010). The average melt viscosity is given within the code of the material model, where the generated output yields the effective viscosities of the magmas. Based on the composition, crystallinity, temperature, and density of the enclave and host magmas estimated for each eruptive unit, the model simulates magma mingling, mixing, and enclave formation by common enclave formation hypotheses found within the literature including; 1) the injection of a 1-10 m dike into the crystalline host magma, 2) underplating of recharge magma beneath the crystalline host magma, 3) the injection of a 1-10 m dike into a convecting host magma.

CHAPTER 3: PHYSICAL CHARACTERIZATION OF ENCLAVES

INTRODUCTION

Enclaves observed in both intrusive and extrusive igneous rocks are evidence of magmas with distinct magmatic properties interacting within the same magma chamber (Cantagrel et al., 1984; Clynnne, 1999; Anderson, 1976). The physical attributes of enclaves such as their abundance, shapes, and size distributions vary widely, indicating the complex behavior between the interacting host and intruding magmas (Didier and Barbarin, 1991; Bacon, 1986; Sparks and Marshall, 1986). These physical characteristics provide insights into the rheology of magmas with different magmatic properties and can be used to constrain the style of mixing and mechanisms of enclave formation (Thomas and Tait, 1997; Clynnne, 1999; Feeley et al., 2008).

Shape indicators, such as the circularity and aspect ratios of enclaves provide estimates of the timescales of deformation and constrains the timescales of enclave cooling. Deformation is also directly related to viscosity contrast, where high viscosity contrasts result in circular enclaves showing little deformation (Manga, 1996). Smaller viscosity contrasts result in elliptical enclaves showing more deformation (Manga, 1996). The viscosity contrast suggests whether the enclave was more solidified with a higher viscosity than the surrounding magma, or vice versa where the enclave magma was more liquid with a lower viscosity compared to the surrounding host magma (Manga, 1996).

Enclave abundances provide constraints on the degree of enclave magma break-up and mixing efficiency, which are dependent on the viscosity contrast between the enclave and host magmas. Experimental work has demonstrated that enclave size

distributions are related to the viscosity contrast between the mingled magmas (Hodge and Jellinek, 2012; Andrews and Manga, 2014). Enclave size distributions provide further details about the mixing style and extent of enclave break-up and can help constrain the rheology of the magmas. We quantify the physical characteristics of enclaves at Mount Hood to provide some framework for understanding these field observations and relating them to magma chamber or magmatic properties.

RESULTS

Enclave Abundances

Enclave abundances vary greatly from each eruptive unit (Appendix E; Table 3; Figure 6). For the Main Stage eruptive unit, highway 26 location has the lowest abundance with a value of $0.38 \pm 0.2\%$, the quarry location has an abundance value of $0.93 \pm 0.8\%$, and the Compass Creek and Meadows locations have the highest abundances overall with values of $1.28 \pm 0.35\%$ and $1.34 \pm 0.55\%$, respectively. The two most recent eruptions have abundances of $0.13 \pm 0.1\%$ for Timberline eruptive period, and $0.28 \pm 0.38\%$ for Old Maid eruptive period. The measured outcrops for the Main Stage locations were lava flow deposits, whereas the outcrops for Timberline and Old Maid locations were block-and-ash flow deposits and may contribute to the distinct gap in enclave abundances.

Figure 6: Enclave abundances for each location and eruptive unit with field measurements.

Enclave Size Distributions

Enclave diameters all show a positive skew where most of the data is positioned to the left of the mean diameter, therefore the median enclave diameters are taken to be the representative diameter of each location (Hodge and Jellinek, 2012) (Figure 7 and Figure 8). It is important to note that the area of the enclave observed *in situ* may not always be an equatorial section, therefore measured diameters may not always represent the true diameter of the observed enclaves (Thomas and Tait, 1997). The median diameters for all locations and eruptive units ranged from 1.68 cm to 2.9 cm (Table 3; Figure 9).

Four locations for the Main Stage eruptive period comprised a total of 404 enclaves measured for shape and size analyses (Appendix F; Figure 7). A total of 40 enclaves were analyzed from the highway 26 location from the Main Stage eruptive period, showing a range in diameters from 0.8 cm to 10.7 cm and a median diameter of 2.7 cm (Figure 7A). At the Meadows location, 257 enclaves were analyzed with a range in enclave diameters from 0.3 cm to 11.5 cm and a median diameter of 1.7 cm (Figure 7B). At the Quarry location, 26 enclaves were analyzed with a range in diameters of 1.0 cm to 23.2 cm and a median diameter of 2.9 cm (Figure 7C). At the Compass Creek location, a total of 81 enclaves were analyzed with a range in enclave diameters from 0.4 cm to 8.4 cm and a median diameter of 1.7 cm (Figure 7D).

Figure 7: Enclave size distributions for all Main Stage locations; A) Highway 26, B) Meadows, C) Quarry, and D) Compass Creek locations with total number of enclaves analyzed with median diameters.

A total of 33 enclaves were analyzed from blocks making up the extensive Timberline fan, from the Timberline eruptive unit, with a range in enclave diameters from 1.0 cm to 8.8 cm and a median diameter of 2.6 cm (Appendix F; Figure 8A). At the Old Maid eruptive unit location, 11 enclaves were analyzed ranging in diameter from 1.3 cm to 5.5 cm and a median diameter of 2.5 cm (Appendix F; Figure 8B).

Figure 8: Enclave size distributions for A) Timberline and B) Old Maid locations with total number of enclaves analyzed and median diameters for each location.

Enclave Shape Distributions

Enclave shapes are quantified by their circularity and aspect ratios. These shape identifiers are inversely related to each other. Circularity ranges from 0 (infinite ellipse) to 1 (perfect circle), whereas a small aspect ratio (close to 1) indicates an equidimensional shape similar to a perfect circle and a large aspect ratio (farther from 1) indicates a large major axis value similar to an infinite ellipse.

Like the enclave diameters, the enclave circularity and aspect ratios show a positive skew where most of the data are either positioned to the left or closer to the mean values, therefore the median circularity and aspect ratios are taken to be representative of each location (Figure 10) (Hodge and Jellinek, 2012). The median aspect ratio values for each location varied slightly from 1.4 in the Timberline unit to 1.7 in the quarry location of the Main Stage eruptive unit (Appendix F; Table 3; Figure 10). The median circularity values exhibited a smaller range from 0.7 in the quarry location to 0.8 in the Timberline unit (Table 3). Overall, the trend for all locations show more spherical (> 0.6 circularity and < 2.5 aspect ratio) rather than elliptical shapes. Also, it is observed that there is no trend between shape and diameter of enclaves at all locations (Figure 10).

Table 3: Physical characteristics of all enclaves measured from field locations at Mt. Hood, Oregon.

Physical Characteristics		Eruptive Units					
		Main Stage				Timberline	Old Maid
		HWY 26	Meadows	Quarry	Compass Creek		
Diameter (cm)	Minimum	0.80	0.33	1.01	0.39	1.01	1.26
	Maximum	10.72	11.54	23.24	8.41	8.78	5.53
	Median	2.73	1.68	2.90	1.70	2.64	2.47
Circularity	Minimum	0.31	0.37	0.36	0.41	0.49	0.46
	Maximum	0.88	0.96	0.91	0.94	0.90	0.88
	Median	0.71	0.74	0.70	0.79	0.80	0.79
Aspect Ratio	Minimum	1.06	1.02	1.03	1.04	1.05	1.13
	Maximum	3.51	4.15	2.97	3.45	3.65	4.39
	Median	1.66	1.65	1.68	1.45	1.44	1.60
Abundance (%)		0.38	1.34	0.93	1.28	0.12	0.27
Abundance Std. Error (%)		0.20	0.55	0.84	0.35	0.10	0.38

Figure 9: Enclave images of the locations in this study. The locations are based on eruptive units of Mt. Hood. The Main Stage (> 30 ka), Timberline (1.5 ka), and Old Main (~230 yrs).

Figure 10: Scatterplots showing circularity vs. aspect ratio. Enclave diameter (cm) shown by color shade and size of plotted points. A) Highway 26, B) Meadows, C) Quarry, D) Compass Creek locations of the Main Stage eruptive period. E) Timberline locations, and F) Old Maid location.

CHAPTER 4: PETROGRAPHIC AND CHEMICAL CHARACTERIZATION OF ENCLAVES AND HOST LAVAS

RESULTS

Petrography

Main Stage Eruptive Unit

We analyzed two thin sections from the Compass Creek (E) location of the Main Stage eruptive period and included data from Woods (2004) (Table 1). Host andesites are light to medium gray, occasionally reddish, in color (Figure 9). They are porphyritic with mineralogic assemblages of plagioclase + orthopyroxene $\pm$ clinopyroxene $\pm$ amphibole with phenocryst proportions ($> 450 \mu\text{m}$) ranging from 15 – 24% and micro-phenocrysts ($200 - 450 \mu\text{m}$) from 4 – 7% (Table 4). The groundmass is mainly composed of plagioclase laths, occasional clinopyroxene crystals and needle-shaped amphibole crystals, oxides, and minor amounts of apatite. Areas that do not contain amphibole, either as phenocrysts or groundmass crystals, include those from the Highway 26 (MH0203) and Meadows locations (MH0205). Where amphibole is present, clinopyroxene is either absent or minimal (Wise, 1969; Woods, 2004).

The enclaves entrained within the host andesite are generally lighter in color than their host lavas, light gray to light reddish in color, largely due to larger groundmass crystals and greater micro-vesicularity (Figure 9). The enclaves have the same mineral assemblages than their respective host lavas with phenocryst proportions of 7 – 18%. The groundmass is coarser grained comprised of tabular plagioclase laths with intermittent orthopyroxene, clinopyroxene, and (where present) amphibole crystals, and oxides

(Figure 11). Quenched glass is present in all enclaves ranging from $<1 - 5\%$, by visual estimate. The margins are rarely quenched, but when present the margins are finely-grained. Along the margin between host and enclave, most phenocrysts and microlites of the host lava are aligned parallel to the margin, whereas there is little to no alignment of the crystals within the enclave lavas.

Figure 11: Example of host and enclave interface from the Compass Creek location of the Main Stage eruptive unit, sample MH_P1. Image taken under plane polarized light.

Timberline Eruptive Unit

The host lavas of the Timberline eruptive period are dark to medium gray in color, porphyritic with mineral assemblage of plagioclase + orthopyroxene + amphibole with about 22% phenocryst proportion (Table 4). Amphibole is present in all Timberline samples with clinopyroxene seemingly absent from all samples. The groundmass is composed of plagioclase laths, orthopyroxene crystals, needle-shaped amphibole crystals, and oxides.

The enclaves range in color. Some are lighter in color than their host lavas, like the Main Stage samples, whereas some are darker in color than the host lavas (Figure 9). The amount of quenched glass controls the variation in color of the enclaves and host lavas. With higher proportions of glass, the color appears darker and vice versa. Light-colored enclaves contain about $<1 - 3\%$, whereas a dark colored sample contains up to $\sim 15\%$ quenched glass (Figure 12).

The enclaves contain less phenocrysts ($4 - 13\%$) than their respective hosts and are coarse-grained comprised of tabular plagioclase laths with intermittent orthopyroxene and oxides phenocrysts (Table 4). The enclaves have the same mineral assemblages as their respective host lavas and there is not a mineralogical difference between lighter and darker enclaves. Timberline samples contain the highest abundance of amphibole phenocrysts and microlites compared to the other eruptive unit samples. The Timberline samples also contain the most about of quenched glass in the enclave lavas compared to the other eruptive units. Most plagioclase phenocrysts within the enclave lavas have sieved and resorbed centers. The margins of the enclaves are less crenulated than the Main Stage unit samples. Parallel alignment of the host phenocryst and microlites along the margin between host and enclave lava is also observed within the Timberline samples (Figure 12).

Figure 12: Examples of host and enclave interface from MH_T7 sample from the Timberline eruptive unit. Image taken under plane polarized light.

Old Maid Eruptive Unit

The host lavas of the Old Maid eruptive period are light to medium gray in color, porphyritic with about 20% phenocryst proportion (Table 4). Amphibole is present in all Old Maid samples with clinopyroxene absent from all samples. The groundmass is composed of plagioclase laths, orthopyroxene crystals, needle-shaped amphibole crystals, and oxides. Like the Timberline enclaves, the Old Maid enclaves are darker in color than their host lavas (Figure 9), but have the same mineral assemblages; therefore, the darker color of enclaves observed in both Timberline and Old Maid samples are likely related to the higher percentage of glass present. The enclaves are porphyritic, coarse-grained and contain more abundant phenocrysts (about 22%) than the other eruptive period samples and have slightly more phenocrysts present in their respective host lava (Table 4).

Enclave mineral assemblage consists of tabular plagioclase laths and phenocrysts with intermittent orthopyroxene phenocrysts and microlites, needle-shaped amphibole crystals, and oxides. Most plagioclase phenocrysts within the enclave lavas have sieved and resorbed rims. Some quenched glass is present in all enclaves. Like the Timberline eruptive period samples, the margins of the Old Maid samples are less crenulated than the Main Stage eruptive unit samples (Figure 13). As with the other samples, parallel alignment of the host phenocryst and microlites along the margin between host and enclave lava is also observed.

Figure 13: Example of host and enclave interface of sample MH_OM1 from the Old Maid eruptive unit. Image taken under plane polarized light.

We estimated the amount of interstitial glass in host and enclave lavas by visual estimation under plane polarized light microscopy. Samples from the Main Stage and Old Maid eruptive units contained the least amount of glass ($<1 - 5\%$), where a sample from the Timberline eruptive unit (MH_T7) contained up to 15% glass (Figure 12). It is

important to note that most of the interstitial glass contained submicroscopic crystals with little pure glass preserved except within the Timberline sample with the highest amount of glass (MH_T7). One sample from the Meadows location (MH0210L) of the Main Stage eruptive unit contained a significant amount of glass within the host lava with the amount of glass increasing toward the margin of the enclave and no observable glass within the enclave lava.

Table 4: Estimates of host and enclave phenocryst (> 450 μm) and host micro-phenocryst (200 – 450 μm) abundances for all samples used in EMPA analyses. Crystallinities calculated using ImageJ by calculating total area of phenocrysts for both enclave and host lavas.

Measured Crystallinity		Enclave Phenocryst	Host Phenocryst	Host Micro-Phenocryst
Main Stage	MH0205M	7%	22%	5%
	MH0205L	11%	22%	7%
	MH0211-2	-	15%	4%
	MH_P1	10%	24%	-
	MH_P3	18%	20%	-
Timberline	MH_T2	13%	20%	-
	MH_T7	4%	22%	-
Old Maid	MH_OM1	22%	20%	-

Whole Rock Analyses

Bulk Geochemistry

Lavas from Mount Hood are calc-alkaline and range from high-silica basaltic andesite to low-silica dacite (Appendix A). The lowest silica samples are enclaves from Highway 26 (MH0203C) and Laurence Lake (MH0210E) locations from the Main Stage (>30 ka) eruptive period (Woods, 2004). The highest silica samples are host lavas from the Timberline fan (MH212-1, MH212-2, MH_T1_H, MH_T2_H, MH_T7_H) and the

White River (MH_OM1_H) locations from the two most recent eruptive periods, Timberline (1.5 ka) and Old Maid (~230 ya). Overall, the average gap in silica content between host and enclave lavas is minor, between ~1 - 5 SiO₂ (wt. %).

It is important to note that Scott and Gardner (2017) define Mount Hood rocks as coming from vents within 3 km of the summit. Therefore, composition is somewhat restricted as there are lower silica rocks low on the flank and are in the category of low silica basaltic andesite (52 – 55 wt.% SiO₂). Woods (2004) refers to these lower silica rocks as flank lavas and are also considered separate in analyses of the rocks erupted within 3 km of the summit due to the location of emplacement and the compositional and mineralogical differences.

Table 5: Average XRF major element oxide data (wt.%) for both host and enclave lavas from the eruptive units sampled at Mount Hood.

Avg. XRF (wt.%)	Main Stage		Timberline		Old Maid
	Host	Enclave	Host	Enclave	Host
SiO ₂	61.7	58.7	63.6	59.5	63.0
TiO ₂	0.9	1.0	0.7	0.9	0.8
Al ₂ O ₃	17.3	17.9	16.9	17.9	16.9
FeO*	5.5	6.4	4.9	6.0	5.5
MnO	0.1	0.1	0.1	0.1	0.1
MgO	2.8	3.5	2.5	3.4	2.5
CaO	5.8	6.7	5.4	6.8	5.4
Na ₂ O	4.2	4.1	4.2	3.9	4.2
K ₂ O	1.5	1.3	1.5	1.2	1.5
P ₂ O ₅	0.2	0.3	0.2	0.2	0.2
# of analyses	17	23	5	6	1
Min SiO ₂	60.4	56.8	63.3	58.8	-
Max SiO ₂	62.3	60.4	64.0	60.7	-

Major and Trace Element Trends

With increasing silica, compatible major elements Al_2O_3 , TiO_2 , FeO , MnO , CaO , MgO , and P_2O_5 decrease (Figure 14). There is no trend in Na_2O with increasing silica. However, there is a clear gap in Na_2O between the enclave and host lavas where the host lavas have a higher abundance than the enclave lavas in Na_2O (Figure 14). K_2O is the only major oxide that increases with increasing silica, with the lowest concentration observed in the enclave lavas and highest abundance in the host lavas (Figure 14). The Main Stage locations have the highest concentration of Al_2O_3 , TiO_2 , FeO , MnO , CaO , and MgO for both enclave and host lavas, whereas the Timberline locations have the lowest concentrations for both enclave and host lavas.

Figure 14: Scatter diagrams of major elements vs. SiO_2 (wt.%). Color distinguishes eruptive unit; purple for samples of the Main Stage eruptive unit, green for samples of the Timberline eruptive unit, and yellow for sample of the Old Maid eruptive period. Host lavas are indicated by squares and enclave lavas are indicated by circles.

Overall, the host and enclave lavas do not show a distinct trend in trace element concentrations, except for a positive slope in Rb (ppm) and Ba/Sr, with respect to silica, where enclave lavas are generally lower in Ba/Sr and Rb compared to their respective host lavas (Figure 15). The outliers with high Ba, Sr, La, and Sm are enclaves from the Main Stage eruptive period at the Laurence Lake location (MH0210E) from Woods (2004) (Figure 15). This enrichment in incompatible trace elements seen in enclave samples is mirrored by the host samples that are also enriched, just not as enriched as the enclave samples. A distinct gap in Ta concentration in both enclave and host lavas are observed where all Timberline samples and the Highway 26 samples (MH0203) of the Main Stage eruptive period have low Ta compared to the rest of the Main Stage locations and Old Maid location. A similar trend is observed in Ba/Sr, where the same low Ta locations (MH0203 and Timberline locations) are also low in Ba/Sr with respect to the other locations, with the highest Ba/Sr in the Compass Creek location (Figure 15).

Figure 15: Scatter diagrams of trace elements vs. SiO_2 (wt.%). Color distinguishes eruptive unit; purple for samples of the Main Stage eruptive unit, green for samples of the Timberline eruptive unit, and yellow for sample of the Old Maid eruptive period. Host lavas are indicated by squares and enclave lavas are indicated by circles.

Figure 16: Scatter diagrams showing the sequence of increasing major elements (SiO₂, FeO, and MgO in wt.%) based on the average host lava compositions from each location versus major elements in wt.%. The average host lava compositions from each location are shown as squares with the individual enclave compositions shown as circles. Color distinguishes eruptive unit; purple for samples from the Main Stage eruptive unit locations and green for the Timberline eruptive unit locations.

Figure 16 shows the compositional similarities between the average host compositions (squares) of each location with the respective individual enclave lava compositions (circles). The plots are organized by increasing major elements based on the average host lava compositions, where for SiO_2 (wt.%), the Main Stage locations have the lowest silica concentrations compared to the Timberline locations. The individual enclave sample compositions are connected to their average host compositions by lines, where each line signifies a different sample location. The difference between the individual enclave samples with respect to the average host composition for each location can then be easily compared. The silica concentrations of the enclave samples vary by just $\sim 1 - 5$ wt.% with the average host compositions for each location (Figure 16). For iron oxide concentrations, the individual enclave and average host compositions range from $\sim 0.3 - 1.5$ wt.% (Figure 16). The individual enclave and average host compositions range from $\sim 0.15 - 1.5$ wt.% MgO (Figure 16). Overall, this compositional similarity is observed within most major elements at each location.

Average Mount Hood location host and enclave lava compositions are shown in Figures 17 and 18 with respect to primitive mantle normalized trace element values using values presented by Sun and McDonough (1989) (Figure 17 and Figure 18). The incompatible elements shown along the x-axis of Figures 17 and 18 range from the most incompatible elements on the left and becoming least incompatible towards the right of the x-axis (Sun and McDonough, 1989). Both host and enclave lavas show enrichment in large ion lithophile elements (LILE), such as Rb, Ba, K, Pb, and Sr, and depletions in high field strength elements (HFSE), such as Nb and Ta. These trends in enrichments of

LILE and depletions in HFSE portray typical features observed in subduction zone lavas and is known as a volcanic-arc signature. Host lavas show little variation in incompatible elements (Figure 17), whereas the enclave lavas show more variability in incompatible elements (Figure 18). Samples of the Main Stage locations Laurence Lake (MH0210) and Compass Creek (W) (MH0211) show the highest abundance of incompatible elements in the host lavas, with Laurence Lake (MH0210) showing the highest abundance in the enclave lavas (Woods, 2004). The Laurence Lake location is also the location where the average enclave composition at this location is high Ba, Sr, La, and Sm observed in Figure 14. This indicates that the Laurence Lake location from the Main Stage eruptive period is the most enriched in incompatible elements in both the host and enclave lavas (Woods, 2004).

Figure 17: Primitive mantle normalized incompatible element diagram showing average host lava compositions from each location at Mount Hood. Main Stage samples shown in purple, Timberline samples shown in green, and Old Maid samples shown in yellow.

Figure 18: Primitive mantle normalized incompatible element diagram showing average enclave lava compositions from each location at Mount Hood. Main Stage samples shown in purple and Timberline samples shown in green.

Mineral Phases

Plagioclase

Plagioclase feldspar is the most abundant mineral phase observed in all sample locations. A total of 174 plagioclase crystals were analyzed, 84 plagioclase phenocrysts and 89 plagioclase microlites, using the electron microprobe with a total of 348 analysis points. This study analyzed plagioclase from the Compass Creek (MH_P) location of the Main Stage eruptive period, Timberline (MH_T) locations of the Timberline eruptive period, and Old Maid (MH_OM) location of the Old Maid eruptive period (Table 1). To compare these analyses against previous analyses by Kent et al. (2010), microlite analyses were focused on crystals ranging in size mainly $< 200 \mu\text{m}$, while phenocryst analyses were focused on crystals $> 710 \mu\text{m}$. Prior to microprobe analysis, quantitative SEM data were acquired on all samples measuring the chemical compositions of feldspar, pyroxene, amphibole, and oxide phenocryst and microlites. All phenocrysts and microlites were analyzed with two points placed in the center and at the rim of each crystal.

Data from Woods (2004) were used for most Main Stage locations (MH0203, MH0205, MH0210, MH0211, MH0213) and one Timberline location (MH0212) (Table 1). Woods (2004) obtained data on 76 plagioclase phenocrysts from both host and enclave lavas from the Main Stage and Timberline eruptive periods with 640 analysis points. Most phenocrysts were analyzed with three points, placed in the center, rim, and midway between the rim and center points. Also, some phenocrysts were analyzed using

traverses from center to rim of crystals with step spacings of 4.0 μm to 5.7 μm (Woods, 2004).

Woods (2004) and this study found that the plagioclase compositions ranged from $\text{An}_{30} - \text{An}_{74}$ in the host lavas and $\text{An}_{30} - \text{An}_{80}$ in the enclave lavas of the Main Stage eruptive period samples (Table 6). The plagioclase compositions for the Timberline samples ranged from $\text{An}_{37} - \text{An}_{63}$ and $\text{An}_{39} - \text{An}_{66}$ for the host and enclave lavas, respectively (Table 6; Figure 19). The plagioclase compositions for the Old Maid samples ranged from $\text{An}_{40} - \text{An}_{65}$ for the host lavas and $\text{An}_{39} - \text{An}_{71}$ for the enclave lavas (Table 6; Figure 19). Overall, the anorthite content of the host and enclave lavas are indistinguishable, although the enclave lavas do contain some plagioclase that are just slightly more anorthite-rich than the host lavas (Figure 19).

Table 6: Average plagioclase composition for both host and enclave lavas from the eruptive units analyzed at Mount Hood.

Lava Type	Main Stage	Timberline	Old Maid
Host	$\text{An}_{30} - \text{An}_{74}$	$\text{An}_{37} - \text{An}_{63}$	$\text{An}_{40} - \text{An}_{65}$
Enclave	$\text{An}_{33} - \text{An}_{80}$	$\text{An}_{39} - \text{An}_{66}$	$\text{An}_{39} - \text{An}_{71}$

Figure 19: Plagioclase feldspar data obtained by EMPA. Main Stage samples from both Woods (2004) (W) and this study (E), Timberline, and Old Maid eruptive units. Plagioclase crystals from enclave lavas are shown as diamonds, whereas plagioclase crystals from host lavas are shown as squares.

The range in anorthite and iron oxide concentrations within the plagioclase are listed in Tables 7 and 8. The Main Stage phenocryst centers, both host and enclave, are similar in anorthite and iron oxide concentrations. Overall, the host and enclave phenocrysts vary widely in anorthite and iron oxide concentrations (0.20 – 0.76 wt.%) (Figure 20A and B). Reverse zoning is observed mainly within the Compass Creek (E) location (Figure 20B). Microlites contain slightly higher iron oxide concentrations (0.23 – 0.85 wt.%) and anorthite concentrations (An_{40} – An_{67}) than the phenocrysts (Figure 20A and B). All microlites show little to no zoning.

Overall, the Timberline samples are lower in iron oxide concentration (0.19 – 0.66 wt.%) than the Main Stage samples. The phenocryst centers vary in both anorthite and iron oxide concentrations between the host and enclave lavas. The host phenocryst centers are low in anorthite (An_{39} – An_{58}) and iron oxide concentration (0.19 – 0.40 wt.%), whereas the enclave phenocryst centers show a wide variation with some centers showing similar concentrations to their respective host centers, and some enclave phenocryst centers with higher anorthite and iron oxide concentrations. The phenocryst rims for both the host and enclave lavas vary in anorthite and iron oxide concentrations, without showing a general trend. The microlite centers and rims from the enclave lavas are slightly higher in anorthite than the host microlites (Figure 20C).

The Old Maid samples show similar trends as the Timberline samples, with overall lower iron oxide concentrations relative to the Main Stage samples. The phenocryst centers for both the host and enclave lavas show similar anorthite and iron oxide concentrations. The phenocrysts in both the host and enclave lavas are slightly

reversely zoned or not zoned. The microlite centers and rims are all higher in iron oxide concentration than the majority of the phenocryst centers and rims. The microlite centers and rims from the enclave lavas are slightly higher in anorthite than the host microlites, as observed in the Timberline samples (Figure 20D).

Table 7: Host and Enclave center vs. rim anorthite (%) and FeO (wt.%) of all phenocrysts. Values in parentheses are outliers.

Lava type		Host		Enclave	
Crystal Size		Phenocryst		Phenocryst	
Position		Center	Rim	Center	Rim
Main Stage [W]	Anorthite (%)	An ₄₁ – An ₆₄ (An ₇₁)	An ₃₁ – An ₄₇	An ₃₉ – An ₈₀	An ₃₄ – An ₆₉
	FeO (wt.%)	0.24 – 0.45 (0.54)	0.20 – 0.60	0.23 – 0.62	0.21 – 0.76
Main Stage [E]	Anorthite (%)	An ₄₆ – An ₅₉ (An ₇₅)	An ₄₅ – An ₆₃	An ₄₅ – An ₅₂	An ₅₆ (An ₂₇) – An ₇₇
	FeO (wt.%)	0.27 – 0.37 (0.52)	0.32 – 0.64	0.27 – 0.61	0.47 – 0.64
Timberline	Anorthite (%)	An ₃₉ – An ₅₈	An ₃₇ – An ₆₂	An ₄₀ – An ₆₀	An ₃₉ – An ₆₀
	FeO (wt.%)	0.19 – 0.40	0.22 – 0.55	0.21 – 0.51	0.17 – 0.49
Old Maid	Anorthite (%)	An ₄₃ – An ₅₁	An ₄₀ – An ₅₇	An ₄₁ – An ₅₃	An ₄₂ – An ₄₉
	FeO (wt.%)	0.25 – 0.36	0.28 – 0.52	0.26 – 0.33	0.33 – 0.47

Table 8: Host and Enclave center vs. rim anorthite (%) and FeO (wt.%) of all microlites. Values in parentheses are outliers.

Lava type		Host		Enclave	
Crystal Size		Microlite		Microlite	
Position		Center	Rim	Center	Rim
Main Stage [E]	Anorthite (%)	An ₄₅ – An ₆₃	An ₄₆ – An ₆₀	An ₅₅ (An ₂₄) – An ₆₇	An ₄₇ (An ₂₂) – An ₆₄
	FeO (wt.%)	0.56 – 0.79	0.45 – 0.85	0.46 – 0.75	0.45 – 0.69
Timberline	Anorthite (%)	An ₄₀ – An ₆₄	An ₄₂ – An ₅₈	An ₅₁ – An ₆₅	An ₄₀ – An ₆₄
	FeO (wt.%)	0.30 – 0.66	0.30 – 0.58	0.28 – 0.58	0.23 – 0.56
Old Maid	Anorthite (%)	An ₄₈ – An ₆₆	An ₅₀ – An ₅₈	An ₆₃ (An ₄₆) – An ₇₁	An ₄₉ – An ₆₆
	FeO (wt.%)	0.37 – 0.61	0.39 – 0.65	0.40 – 0.59	0.42 – 0.67

Figure 20: FeO (wt.%) vs. Anorthite content (%) for plagioclase crystals for all samples; A. Main Stage data from Woods (2004), B. Main Stage data from this study at Compass Creek (E) location, C. Timberline data from this study, and D. Old Maid data from this study. Enclave plagioclase crystals shown in pink and host plagioclase crystals shown in blue. All phenocrysts (P) (> 0.45 mm) are shown as squares with phenocryst centers (P > C) shown as shaded squares and phenocryst rims (P > r) shown as outlines of squares. Microlites (M) are shown as diamonds with microlite centers (M > c) shown as shaded diamonds and microlite rims (M > r) shown as outlines of diamonds.

Orthopyroxene

Orthopyroxene is present in samples from all locations and within each eruptive unit as phenocrysts, groundmass crystals, and occasional glomerocrysts with oxides. A total of 69 pyroxene phenocrysts were analyzed using the electron microprobe with a total of 138 analysis points. All pyroxene crystals were analyzed with two points placed in the center and at the rim of each crystal. Of all pyroxene crystals analyzed, just three were clinopyroxene and the remaining crystals being orthopyroxene.

Data from Woods (2004) were used for most Main Stage locations (MH0203, MH0205, MH0210, MH0211, MH0213) and one Timberline location (MH0212) (Table 1). Woods (2004) obtained data on orthopyroxene crystals from both host and enclave with 137 total analysis points. Using data from Woods (2004) and this study (Table 1), the composition of the orthopyroxene in the host lavas of the Main Stage samples is $\text{En}_{56-75}\text{Fs}_{22-43}\text{Wo}_{1-5}$ and $\text{En}_{57-76}\text{Fs}_{21-41}\text{Wo}_{1-5}$ in the enclave lavas (Woods, 2004). For the Timberline samples, the composition of the orthopyroxene is $\text{En}_{56-67}\text{Fs}_{30-41}\text{Wo}_{1-2}$ in the host lavas and $\text{En}_{55-73}\text{Fs}_{25-44}\text{Wo}_{1-3}$ in the enclave lavas. The composition of the orthopyroxene for the Old Maid samples is $\text{En}_{61-65}\text{Fs}_{33-37}\text{Wo}_{1-4}$ in the host lavas and $\text{En}_{62-64}\text{Fs}_{34-36}\text{Wo}_2$ in the enclave lavas (Figure 21). The compositional similarity between the host and enclave lavas that was observed in plagioclase, is also observed in terms of orthopyroxene (Figure 21).

Some subhedral to euhedral orthopyroxene phenocrysts have frayed rims, which is indicative of partial resorption (Woods, 2004). A few orthopyroxene phenocrysts are overgrown with clinopyroxene, one phenocryst from the Laurence Lake location and one

from the Compass Creek location of the Main Stage eruptive period. Growth of clinopyroxene on an orthopyroxene phenocryst could be explained by an increase in temperature or could suggest this is xenocryst not related to the magma batch erupted.

Figure 21: Pyroxene data obtained by EMPA. Main Stage samples from both Woods (2004) (W) and this study (E), Timberline, and Old Maid eruptive units. Pyroxene crystals from enclave lavas are shown as diamonds, whereas pyroxene crystals from host lavas are shown as squares.

Clinopyroxene

Clinopyroxene is present in the Main Stage eruptive unit (Figure 21). It is not observed in samples with abundant amphibole, like the Timberline and Old Maid locations. Where it is found, it is present as phenocrysts and groundmass crystals similar to orthopyroxene. Woods (2004) measured 2 crystals, whereas this study found one clinopyroxene crystal within the Compass Creek (E) sample (MH_P3). The average composition of clinopyroxene is $\text{En}_{43}\text{Fs}_{14}\text{Wo}_{42}$ (Figure 21). The clinopyroxene phenocrysts do not show compositional zoning.

Amphibole

Amphibole is not present at every location, it is sparsely found within the Main Stage eruptive unit and absent from the Highway 26 and Meadows locations of the Main Stage eruptive unit. Where it is found, it is present as subhedral to anhedral phenocrysts that are elongate, or needle-shaped, with spikey ends in both the host and enclave, indicative of rapid growth (Woods, 2004). Typical cleavage planes are observed as well as dark black reaction rims. The chemical composition of the amphiboles, using the method of Deer et al. (1992), shows that the amphiboles range from calcic amphibole (hornblende), pargasite, to tschermakite (Figure 22). Sparse data points that plot into different compositional amphibole field are considered not to be representative.

Figure 22: Amphibole data obtained by EMPA. All samples from Woods (2004) shown by squares and denoted by [W]. All samples from this study shown by circles and denoted by [E].

Micro-vesicularity

Groundmass micro-vesicularities were determined for two samples from the Compass Creek location of the Main Stage eruptive unit, two samples from the Timberline eruptive unit, and one sample from the Old Maid eruptive period using BSE micrographs obtained during SEM analyses. In calculating groundmass micro-vesicularities, all phenocrysts were excluded in the analyses to obtain the best representative groundmass areas. The micro-vesicularity results vary between eruptive units, and in the Timberline eruptive unit, varies within samples (Figure 23; Table 9). The Compass Creek (E) samples contain both the lowest (2.4%) and the highest (28.4%)

micro-vesicularities within the host and enclave lavas, respectively (Table 9). The Timberline samples have distinct micro-vesicularities with 10.8% and 12.5% in sample MH_T2 host and enclave lavas, respectively. Sample MH_T7 host lava micro-vesicularity was calculated to be 20.7% with 20.8% for the enclave lava. Although the Timberline samples micro-vesicularities vary by a factor of two, their respective host and enclave lava micro-vesicularities are very similar to each other, especially in MH_T7 sample. The micro-vesicularity of MH_T7 host and enclave lavas are almost exactly the same and are the closest micro-vesicularities compared to any other sample that was analyzed. The Old Maid sample is unique in that it is the only sample in which the host lava is more vesicular than its enclave lava with 20.4% and 13.6%, respectively (Table 9; Figure 23).

Table 9: Micro-vesicularity measurements for the eruptive units from this study at Mount Hood.

Micro-vesicularities	Main Stage		Timberline		Old Maid
	MH_P1	MH_P3	MH_T2	MH_T7	MH_OM1
Host	3.1%	2.4%	10.8%	20.7%	20.4%
Enclave	28.4%	23.6%	12.5%	20.8%	13.6%

Figure 23: BSE micrographs with thresholding by image analysis for micro-vesicularity measurements. Area shown from Main Stage unit is from sample MH_P1, for Timberline unit is from sample MH_T2, and Old Maid unit is from MH_OM1. Red indicates areas of vacant space, or vesicles.

Geothermometry

Multiple geothermometers have been used to approximate storage, crystallization, and eruption temperatures at Mount Hood, including the plagioclase-hornblende (Holland and Blundy, 1994), Fe-Ti oxide (Ghiorso and Evans, 2008), amphibole (Ridolfi et al., 2010), and Sr diffusion timescales using U-series equilibrium (Cooper and Kent, 2014) (Table 10). Since mafic magmas saturate amphibole at temperatures below 1000°C at upper crustal pressures and after extensive crystallization, the plagioclase-hornblende geothermometry estimates the minimum temperatures for the recharge or enclave magma (Koleszar, 2011; Koleszar et al., 2012; Scott and Gardner, 2017). Due to the relatively rapid equilibration rate of Fe-Ti oxides, the Fe-Ti oxide geothermometry method by Ghiorso and Evans (2008) estimates the approximate temperatures of eruption. Cooper and Kent (2014) investigated the long-term storage temperatures for the host magma at Mount Hood by combining crystal size distribution data, Sr diffusion, and U-series ages.

Table 10 : Previous work by Koleszar et al. (2012) and Cooper and Kent (2014) constrained storage temperatures based on crystal growth and diffusion and crystallization and eruption temperatures based on multiple geothermometry methods.

T (°C)	Host Magma	Enclave Magma
Storage	< 750	min = 1000 - 950
Crystallization	850 - 900	> 950
Eruption	900 - 1050	

To complement the geothermometry that has been obtained at Mount Hood, we use Putirka (2008)'s method for two pyroxene geothermobarometry to obtain pressure and temperature conditions in which clinopyroxene and orthopyroxene liquids are in equilibrium. Temperature and pressure results from the two pyroxene geothermometry

are listed in Table 11. Overall, the temperatures obtained by the two pyroxene geothermometry are consistent with the crystallization temperatures obtained by previous analyses and other geothermometry methods (Table 10). The pressures obtained from Putirka (2008)'s method ranged from 5.1 ± 0.33 kbar to 8.7 ± 0.27 kbar (Table 11).

Table 11: Two pyroxene geothermobarometry results using the method of Putirka (2008) of the host and enclave lavas from the eruptive units at Mount Hood.

Eruptive Unit	Thin Section	Enclave		Host	
		T (°C)	P (kbar)	T (°C)	P (kbar)
Main Stage	MH0210L	916 ± 1.92	7.9 ± 0.20	-	-
	MH0205L	-	-	922 ± 0.69	8.7 ± 0.27
	MH_P3	940 ± 3.87	5.4 ± 0.29	925 ± 3.18	5.9 ± 0.19
	MH_P1	935 ± 9.71	5.1 ± 0.33	925 ± 2.43	5.4 ± 0.15
Timberline	MH_T2	894 ± 7.04	9.3 ± 0.43	904 ± 2.24	7.8 ± 0.60
	MH_T7	927 ± 7.13	6.4 ± 0.59	913 ± 4.24	7.2 ± 0.88
Old Maid	MH_OM1	912 ± 2.86	6.9 ± 0.41	906 ± 2.15	6.3 ± 0.21

CHAPTER 5: RHEOLOGY AND NUMERICAL MODELING

INTRODUCTION

Motivation for Numerical Models

The concept of magma mixing dates back to Robert Bunsen's 1851 theory that mixing of a mafic and felsic magma may account for the variety of chemical compositions observed in igneous rocks, however this theory was not widely accepted until more than a hundred years later (Wilcox, 1999). More recent studies suggest evidence of magma mixing is commonplace throughout the plutonic (Didier, 1973; Reid et al., 1983) and volcanic record (Eichelberger, 1980; Bacon, 1986; Sparks and Marshall, 1986). In these studies, mixing commonly occurs between mafic and felsic magmas where the compositional difference drives the viscosity contrast needed for producing enclaves. However, for mixing of compositionally similar magmas the driving mechanisms responsible for enclave formation are poorly understood.

Two primary variations of magma mixing exist, with a continuum of intermediate types between, these are: 1) incomplete magma mixing, characterized as mingling by means of mechanical mixing and 2) complete mixing, characterized as hybridization of the mixing magmas (Eichelberger, 1980; Bacon, 1986; Sparks and Marshall, 1986; Spera et al., 2016). Mingling results in a macroscopic record (i.e. enclaves) of the mixing process itself with a heterogeneous mixture of discrete blobs, or enclaves, of the intruding magma entrained within a distinct host magma with no crystal exchange or chemical homogenization between the mixing magmas. Hybridization results in chemical and thermodynamic equilibration of the two mixing magmas with significant crystal

exchange generating a new mixed magma with no macroscopic record of the mixing process itself (Spera et al., 2016).

The degree to which magma mixing results in hybridization or mingling is primarily controlled by the viscosity difference between the two interacting magmas. Magmas with similar viscosities will easily mix to produce a homogeneous hybrid magma, whereas large viscosity contrasts inhibit complete mixing, resulting in enclave formation (Hodge and Jellinek, 2012). Magma viscosity is determined by the thermodynamic properties of the system, such as composition, temperature, the presence of crystals and volatiles, and deformation rate.

In many systems compositional differences appear to drive the viscosity contrast needed for enclave formation (Eichelberger, 1980; Bacon, 1986; Sparks and Marshall, 1986). This cannot explain enclave formation however in compositionally similar lavas; therefore, the driving mechanism for viscosity variations must rely on other magmatic properties. At Mount Hood, similarities in host and enclave composition suggest another mechanism. We use textural evidence; such as signs of undercooling, glass and vesicle proportions, crystallinities, and presence of quenched margins, to determine the magmatic property driving viscosity variations. We hypothesize that temperature and/or density variations due to the presence of exsolved volatiles drive the viscosity contrast needed for enclave formation at Mount Hood.

Common mechanisms of enclave formation can be subdivided in terms of mingling or hybridization. Based on the petrologic and textural evidence found in this study (see Chapter 4), we hypothesize that enclave formation at Mount Hood occurred by

mingling of two magmas prior to eruption. To better understand the mechanisms that drive enclave formation at Mt. Hood (i.e. mingling rather than hybridization), a numerical model has been created to simulate three enclave formation scenarios found within the literature which highlight the effect of temperature and density variations on enclave formation:

Scenario 1: A hot intruding magma is injected or emplaced into a cooled, rheologically locked host magma. Through conductive heat transfer, the intruded dike will heat the surrounding host magma while the dike itself cools and crystallizes. Sufficient heating of the host magma by the intruding magma will drive convection in the host magma. As the host magma is heated sufficiently, convection will occur. At the onset of convection, if the dike is solid it will deform in a brittle manner forming enclaves. Otherwise, the dike will deform in a ductile manner forming banding (Andrews and Manga, 2014).

Scenario 2: A hot intruding magma pools beneath, or underplates, a cooled, rheologically locked host magma. Crystallization and exsolution of volatiles occurs at the boundary between the intruding and overlying host magma. Growth of a “foamy” layer of intruding magma at this boundary causes density instabilities where the crystallized intruding magma is less dense than the overlying host. Due to the density differences, this foamy recharge magma layer will buoyantly rise into the overlying host magma with quenched or crenulated margins, trapping the exsolved volatiles within the enclave entrained within the host magma (Eichelberger, 1980; Coombs et al., 2002; Browne et al., 2006).

Scenario 3: The intruding magma is gradually injected into a convecting host magma. As the host magma continues to convect, the intruded magma may form detached droplets that become incorporated into the convecting host magma as enclaves (Hodge et al., 2012)

This study models these scenarios using magmatic parameters constrained by field observations and petrologic results specific to the eruptive products at Mount Hood. All input files are provided in Appendix D.

Rheology of Magmas

Magma rheology describes how magma flows and deforms. How a magma will flow in response to an applied stress is largely dependent upon its viscosity. Physical characteristics of enclaves, such as their size and shape distributions, record the rheology of mixing magmas (Hodge et al., 2012; Albert et al., 2015). We will examine the difference in viscosity of the enclaves and host magma to understand the mixing processes and enclave formation.

Magmas are suspensions of melt, crystals, and in some cases, bubbles. In this study, we consider magma as a two-phase suspension (melt + crystals), due to the scale and depth focus of this research. For magmatic suspensions, viscosity can be described by three terms which relate melt characteristics and volume fraction of crystals to viscosity:

1. The melt or suspending medium viscosity (η). Melt viscosity is dependent on the silicate melt composition, density, temperature, and the amount of deforming stresses and rates of strain applied to the melt (Vogel, 1921; Fulcher, 1925; Shaw,

1972; Bottinga and Weill, 1972; Bird et al., 1982; McBirney and Murase, 1984; Dingwell et al., 1993; Giordano et al., 2008; Mader et al., 2013).

2. The relative viscosity or viscosity of the suspension (η_r). The relative viscosity depends on the amount, shape, size, and packing arrangement of crystals (Einstein, 1906; Roscoe, 1952; Marsh, 1981; Richet, 1996; Costa et al., 2005, 2009; Petford, 2011)

3. The effective viscosity or apparent viscosity of the suspension (η_e) is a function of the melt and relative viscosity of the suspension (Costa et al., 2005, 2009; Petford, 2011).

The effective viscosities of magmas are key to understanding the dynamics and processes of magma mixing. The parameters that influence the melt and relative viscosities, specifically the composition and temperature dependent melt viscosity, deformation rate, and the presence of crystals, will be addressed in greater detail.

Melt Composition and Temperature Dependence

The viscosity of a silicate melt is directly related to the silicate composition or structure (e.g. Bottinga and Weill, 1972). A silicate melt is composed of an extensive structure of silicate tetrahedra interconnected by strong covalent bonds of silicon and oxygen. During flow, these bonds are broken and remade and the melt structure is rearranged. Rearrangement with network forming molecules, such as SiO_2 and Al_2O_3 will increase the strength of the bonds, increasing melt viscosity. Rearrangement with network modifying molecules, such as MgO , CaO , Na_2O , K_2O , and metal oxides results in less oxygen atoms for covalent bonding. With less bonds the structure of the silicate

melt allows for the melt to flow easily with lower viscosity. The addition of dissolved water into the silicate melt decreases the degree of polymerization of the melt, which decreases the viscosity across all temperatures from the solidus to liquidus temperatures.

A silicate melt viscosity can be explained by an Arrhenian temperature dependence at restricted temperatures above or near the liquidus temperature;

$$\ln\eta = \ln A + \frac{E}{RT} \quad (1)$$

Where A is the pre-exponential factor, representing the value of $\ln\eta$ at infinite temperature, E is the activation energy for viscous flow, R is the universal gas constant, T is temperature (K) (Shaw, 1972; Bottinga and Weill, 1972). For a broad range of temperatures below the liquidus and melt compositions, melt viscosity is best described by a non-Arrhenian temperature dependence (Vogel-Tammann-Fulcher equation);

$$\ln\eta = A + \left(\frac{B}{T-C} \right) \quad (2)$$

Where A is the pre-exponential factor which is assumed to be constant for all melts representing the high temperature limit for silicate viscosity. This suggests that all silicate melts converge to a common viscosity at the high temperature limit (Vogel, 1921; Fulcher, 1925; Giordano et al., 2008). The parameters B and C are compositionally dependent adjustable parameters, where B is the pseudo-activation energy, C is the Vogel-Tammann-Fulcher temperature (K). Melt viscosity has an exponential dependence on temperature applicable for a wide range in melt composition, and for temperatures below the liquidus temperature.

Deformation Rate

A general understanding of deforming stresses and rate of deformation is essential in understanding the rheology of a fluid or magma. When the relationship between shear stress and rate of strain of a fluid is linear, the fluid is said to be Newtonian (Figure 24). Otherwise, the fluid is considered non-Newtonian. Magmas are considered incompressible fluids in that changes in hydrostatic pressure, or normal stresses, have no effect on flow, only shear stresses effect the flow of the fluid (McBirney and Murase, 1984; Dingwell et al., 1993). For non-Newtonian fluids, viscosity depends on strain rate and can be explained using a power-law relationship:

$$\tau = \eta \dot{\epsilon}^n, \quad (3)$$

where τ is shear stress, η is the melt viscosity at a specific strain rate, $\dot{\epsilon}$ is the strain rate, n is the flow behavior index, or consistency index. When $n < 1$, viscosity decreases with increasing strain rate. This flow behavior is termed shear-thinning, or pseudoplastic, similar to the flow behavior of blood or paint (Hodge et al., 2012; Mader et al., 2013)(Figure 24). Whereas when $n > 1$, viscosity increases with increasing strain rate showing a shear-thickening, or dilatant flow behavior, similar to corn starch water mixtures and wet sand flow behavior (Hodge et al., 2012; Mader et al., 2013) (Figure 24). Flow behavior for non-Newtonian fluids are further subdivided with a superset of shear-thinning flow behavior. This superset of shear-thinning flow behaviors requires exceeding a finite value of shear stress to flow. This critical value of shear stress is referred to as the yield stress, τ_o . For Bingham plastic flow behavior, after exceeding a

critical yield stress the fluid will flow with a constant viscosity, behaving like a Newtonian fluid:

$$\tau = \tau_o + \eta \dot{\epsilon} , \quad (4)$$

This ideal plastic rheology, called viscoplastic behavior, describes no deformation occurring below the yield stress, such that the material will behave like a solid below this critical yield stress, similar to the flow of ketchup or toothpaste (Bird et al., 1982; Hodge et al., 2012; Mader et al., 2013)(Figure 24). This viscoplastic behavior also exhibits a power-law behavior:

$$\tau = \tau_o + \eta \dot{\epsilon}^n , \quad (5)$$

This viscoplastic flow behavior, known as Hershel-Buckley, requires a critical yield stress, however after this yield stress is exceeded, the flow resembles that of shear-thinning behavior (Figure 24). Shear thinning and viscoplastic flow behaviors are commonly observed in textures of lavas such as parallel alignment of crystals preferential to the direction of flow, bubble deformation, and congested particle clots or slurries (Petford, 2009).

Figure 24: Strain rate vs. stress flow behavior for a) Newtonian fluids, b) Shear-thinning, c) Shear-thickening, d) Bingham, e) Hershel-Bulkley. Image from Mader et al. (2013).

The structural rearrangement of the melt structure and stress relaxation are vital parameters for viscoplastic flow behavior. Unlike elastic behavior where energy is stored in response to deformation, viscoplastic materials disperse energy under deformation (McBirney and Murase, 1984). During constant strain, a material will experience stress relaxation over time (Dingwell et al., 1993). The Maxwell relaxation time approximates the timescale of deformation, or relaxation of a melt between the transition of liquid-like and solid-like flow behavior:

$$\tau_m = \frac{\eta}{E}, \quad (6)$$

where τ_m is the Maxwell relaxation time, η is the Newtonian shear melt viscosity, and E is the elastic shear modulus defined as the ratio of shear stress to strain.

The relaxation time of a silicate melt can be described by the flow relaxation rate ($\dot{\gamma} = \tau_m^{-1}$) (Webb and Dingwell, 1990). The flow relaxation rate varies proportional to the shear viscosity; therefore, the Maxwell relationship provides good estimation of strain rates at Newtonian and non-Newtonian fluid behavior (Figure 24). At low strain rates ($< 10^{-5} \text{ s}^{-1}$) where $\dot{\epsilon} \ll \dot{\gamma}$ the melt is fully “relaxed”, therefore the flow will behave in a Newtonian manner. As $\dot{\epsilon} \sim \dot{\gamma}$, the flow behaves as a shear-thinning behavior, whereas at high strain rates (10^{-4} s^{-1}) $\dot{\epsilon} \gg \dot{\gamma}$ the flow behaves in a viscoplastic manner (Webb and Dingwell, 1990; Gonnermann and Manga, 2007).

The Presence of Crystals

A key aspect of magma rheology is the presence of solid particles, or crystals. Once magmas cool below their liquidus temperatures, crystallization occurs where the amount, shape, and size of crystals affects viscosity. To include the effect of crystals on a magma’s viscosity is complex (e.g. Petford, 2009). This early model from Einstein (1906) is applicable in the limit of spherical, uniform, non-interacting particles, therefore it is applicable for very dilute ($< 30\%$ crystallinity) suspensions only:

$$\eta_r = (1 + B\phi) , \quad (7)$$

where η_r is the relative viscosity defined as the ratio of the suspension viscosity (effective viscosity) and melt viscosity, B is the Einstein coefficient with a nominal value of 2.5, and ϕ is the volume fraction of solid particles, or crystals. This relative viscosity equation is essential for cases with dilute suspensions with non-interacting similar size and shape particles, however in nature rarely do we deal with particles with uniform size

and shape. Roscoe (1952) further complicated this relationship between relative viscosity and volume fraction of solids considering particles of different sizes:

$$\eta_r = \left(1 - \frac{\phi}{\phi_m}\right)^{-2.5}, \quad (8)$$

where ϕ_m is the maximum packing fraction for mono- and poly-dispersed particles. This equation is commonly referred to as the Einstein-Roscoe equation which relates the change in relative viscosity to increasing particle concentration (Petford, 2009). The Einstein-Roscoe equation has been successful in estimating effective viscosities of dilute suspensions of polydisperse particles. Like the Einstein equation, the Einstein-Roscoe equation is derived for dilute (< 30% crystallinity) suspensions. However, for concentrated suspensions (> 30% crystallinity), the effective viscosity of the magma increases and behaves rheologically more complex. Krieger and Dougherty (1959) describe the relative viscosity of a concentrated suspension for monodispersed particles:

$$\eta_r = \left(1 - \frac{\phi}{\phi_m}\right)^{-B_e \phi_m}. \quad (9)$$

Costa (2005) and others (e.g. Petford, 2009) recognized that in transitioning from a dilute to concentrated suspension, the rheology of the suspension shifts from behaving as a Newtonian fluid to a non-Newtonian fluid. For concentrated suspensions, a yield stress is needed for the suspension to flow, otherwise it will behave like a solid. Using experimental results from Lejeune and Richet (1995) of concentrated suspensions, Costa et al. (2005, 2009) and others formulated an empirical relationship between the effective viscosity, volume fraction of solids, and adjustable parameters to show this rheological transition as well as simplify to the Einstein equation in the case for dilute suspensions.

We use the approach of Costa et al. (2009) to calculate the relationship between the relative viscosity and volume fraction of solids between 0 and 1, where we calculate relative viscosity as:

$$\eta_r(\phi) = \frac{1+\phi^\delta}{[1-F(\phi,\xi,\gamma)]^B\phi_*}, \quad (10)$$

Here,

$$F = (1 - \xi) \cdot \operatorname{erf} \left[\frac{\sqrt{\pi}}{2 \cdot (1 - \xi)} \phi \cdot (1 + \phi^\gamma) \right], \text{ and } \phi = \frac{\phi}{\phi_*}, \quad (11)$$

Where γ controls the rapidity of relative viscosity increase, or rate of change in relative viscosity, as the solid volume fraction (ϕ) approaches the critical solid fraction (ϕ_*). As the solid volume fraction increases, the critical solid fraction marks the onset of exponential increase in relative viscosity toward non-Newtonian behavior. The parameter δ controls the increase in relative viscosity when $\phi > \phi_*$, or as ϕ approaches 1, therefore this term is negligible when $\phi < \phi_*$. Also, δ is a function of γ , where $\delta = A - \gamma$, here A is an empirical constant equal to 13. The relative viscosity at the onset of non-Newtonian behavior, or the critical solid fraction (ϕ_*) is determined by the empirical parameter ξ . The empirical parameters (ξ, γ, δ) are described as functions of strain rate ($\dot{\epsilon}$) originally by Caricchi et al. (2007) and re-formatted by Costa et al. (2009) such that;

$$\begin{aligned} \phi_* &= \phi_m + \Delta\phi \frac{(\dot{\epsilon}/\dot{\epsilon}_c)^n - (\dot{\epsilon}_c/\dot{\epsilon})^n}{(\dot{\epsilon}/\dot{\epsilon}_c)^n + (\dot{\epsilon}_c/\dot{\epsilon})^n} \\ \xi &= \xi_m + \Delta\xi \frac{(\dot{\epsilon}/\dot{\epsilon}_d)^n - (\dot{\epsilon}_d/\dot{\epsilon})^n}{(\dot{\epsilon}/\dot{\epsilon}_d)^n + (\dot{\epsilon}_d/\dot{\epsilon})^n} \\ \gamma &= \gamma_m + \Delta\gamma \frac{(\dot{\epsilon}/\dot{\epsilon}_d)^n - (\dot{\epsilon}_d/\dot{\epsilon})^n}{(\dot{\epsilon}/\dot{\epsilon}_d)^n + (\dot{\epsilon}_d/\dot{\epsilon})^n} \\ \delta &= \delta_m + \Delta\delta \frac{(\dot{\epsilon}/\dot{\epsilon}_d)^n - (\dot{\epsilon}_d/\dot{\epsilon})^n}{(\dot{\epsilon}/\dot{\epsilon}_d)^n + (\dot{\epsilon}_d/\dot{\epsilon})^n} \end{aligned} \quad (12)$$

These empirical parameters are adjustable and are functions of strain rate ($\dot{\epsilon}$). Costa et al. (2005) show that a suspension with decreasing particle volume (for $\phi < \phi_*$), equation 10 transforms into the equation formulated by Krieger and Dougherty (1959) (Equation 9). Also, as the particle volume fraction decreases towards 0, equation 10 tends toward the Einstein equation (Equation 7). Therefore, equation 10 most accurately represents relative viscosity that is crystallinity- and strain rate-dependent across a solid volume fraction of 0 to 1.

Since crystallinity increases with decreasing temperatures between the liquidus and solidus, we require a relationship between temperature and crystallinity. We use the temperature and crystallinity relationship described by Huber et al. (2010):

$$\chi = 1 - \theta = 1 - \left(\frac{T - T_s}{T_l - T_s} \right)^b \quad 0 < b \leq 1 \quad (13)$$

We use $b = 1$ where crystallinity and temperature vary linearly for simplicity.

Using this temperature and crystallinity relationship, we then substitute temperature dependent crystallinity (χ) for the solid volume fraction (ϕ) in equations 10 and 11 to generate a crystallinity-, temperature-, and strain-dependent relative viscosity relationship (Figure 25):

$$\eta_r(\phi, T, \dot{\epsilon}) = \frac{1 + \frac{\chi}{\phi_*}^\delta}{[1 - F(\frac{\chi}{\phi_*}, \xi, \gamma)]^B \phi_*}, \quad (14)$$

where:

$$F = (1 - \xi) \cdot \text{erf} \left[\frac{\sqrt{\pi}}{2 \cdot (1 - \xi)} \frac{\chi}{\phi_*} \cdot \left(1 + \frac{\chi}{\phi_*}^\gamma \right) \right], \quad (15)$$

Since these are relative viscosities that are calculated, we relate the melt viscosity determined with the method by Giordano et al. (2008) and relative viscosity that is

crystallinity-, temperature-, and strain-dependent to generate an estimated effective viscosity of both the intruding and host magmas.

Figure 25: Model results for temperature-, crystallinity (volume fraction of solid)-, and strain rate-dependent relative viscosity where log relative viscosity (Pa s) are shown along the y-axes, Temperature (°C) along the top x-axis, and volume fraction of solid along the bottom x-axis. The individual lines distinguish magmas with different strain rates; where the lowest strain rate of $1 \times 10^{-5} \text{ s}^{-1}$ is shown as the blue line, strain rate of $5 \times 10^{-4} \text{ s}^{-1}$ shown as red line, and the highest strain rate of $1 \times 10^{-3} \text{ s}^{-1}$ is shown as the yellow line.

Table 12: List of parameters used in numerical models.

Physical Meaning	Parameter	Value	Units
Relative viscosity	η_r		Pa S
Effective viscosity	η_e		Pa S
Viscosity of suspending magma	η_0		Pa S
Solid fraction	ϕ		%
Critical solid fraction	ϕ^*		%
Maximum packing fraction of particles	ϕ_m		%
Measure of the rapidity of relative viscosity increase as $\phi \rightarrow \phi^*$	γ	Empirical	
Controls the increase in relative viscosity as $\phi \rightarrow 1$	δ	Empirical	
Determines the value of relative viscosity at ϕ^* ($0 < \varepsilon < 1$)	ε	Empirical	
Strain rate	$\dot{\varepsilon}$	$10^{-6} - 10^{-3}$	s^{-1}
Characteristic strain rate	$\dot{\varepsilon}_c$	$10^{-4.30}$	s^{-1}
Characteristic strain rate where $\dot{\varepsilon}_d \approx 10 \cdot \dot{\varepsilon}_c$	$\dot{\varepsilon}_d$	$10^{-3.37}$	s^{-1}
(γ at large $\dot{\varepsilon}$ + γ at small $\dot{\varepsilon}$)/2	γ_m		
(γ at large $\dot{\varepsilon}$ - γ at small $\dot{\varepsilon}$)/2	$\Delta\gamma$		
(δ at large $\dot{\varepsilon}$ + δ at small $\dot{\varepsilon}$)/2	δ_m		
(δ at large $\dot{\varepsilon}$ - δ at small $\dot{\varepsilon}$)/2	$\Delta\delta$		
(ε at large $\dot{\varepsilon}$ + ε at small $\dot{\varepsilon}$)/2	ε_m		
(ε at large $\dot{\varepsilon}$ - ε at small $\dot{\varepsilon}$)/2	$\Delta\varepsilon$		
Einstein coefficient (intrinsic viscosity)	B	2.5	
Crystallinity	χ		%
Melt fraction	θ		%
Temperature	T	750 - 900	$^{\circ}C$
Solidus temperature	T_s	700	$^{\circ}C$
Liquidus temperature	T_l	1200	$^{\circ}C$
Exponent relating temperature and crystallinity	b	1	
Gravity	g	9.81	m/s^2
Density	ρ	2296 - 2453	kg/m^3
Thermal expansivity	α	5.00E-05	1/K
Domain size	b	100 - 1000	m
Reference viscosity	μ	1e2 - 1e6	Pa s
Thermal diffusivity	K	6.31E-06	m^2/s
Specific heat capacity	C_p	130	J/kgK
Thermal conductivity	k	2	kgm/s^3K
Wavelength	λ		m
Injection velocity	U	1 - 100	mm/s
Diameter of injection	D	1 - 10	m
Injection length	l		m
Magmatic overpressure	ΔP		MPa
Elastic Shear Modulus	E	100 - 300	MPa

RESULTS

Scenario 1: Break-up of dike entrained within cold host magma

This model is set up with a magma chamber domain size of 100 m^2 with a 1 – 10 m wide intruded dike. This domain set-up was chosen to focus on the rate of conductive heat transfer between the hot emplaced dike and surrounding cool host magma. Boundary conditions include free-slip and insulating temperatures along all sides of domain with prescribed temperatures of the host and dike compositional fields. Two versions of this model were investigated. The first version (S1.1) models a 1 m dike, whereas the second version (S1.2) models a 10 m dike (Figure 26 and Figure 28). In both models, the dike is hot, 900°C , emplaced about half-way through the domain (50 m). The initial viscosity of the emplaced dike is 10^2 Pa s with a density of 2420 kg/m^3 . The host magma is cool, 750°C , and is considered rheologically-locked with a viscosity of 10^6 Pa s and density of 2438 kg/m^3 . For each model, all magma densities were informed by values obtained using Rhyolite-MELTS with the intruding magma containing about 4 – 5 wt.% H_2O and host magma containing about 3 – 4 wt.% H_2O to account for volatile exsolution in the intruding magma based on vesicularity measurements (Koleszar, 2011; Kent et al., 2010). Additionally, all temperatures were based on storage and crystallization temperatures found by various geothermometry methods (Table 10 and Table 11)

Regardless of dike width, the emplaced dike never breaks up (Figure 27 and Figure 29). Rather, the dike will buoyantly rise through the host magma due to lower densities than the surrounding host magma. The time in which the dike rises depends on the width of the dike. A wider dike (S1.2) will rise faster than a smaller dike (S1.1)

(Figure 27 and Figure 29). The rate of conductive heat transfer is too slow compared to the buoyant rise of the intruded dike. Therefore, heat transfer between the dike and host magma never allows for the dike to cool sufficiently against the host magma to be solidified or to induce convection within the host.

Figure 26: Scenario 1.1 model initial conditions of 1 m dike with a temperature of 900 °C emplaced in a 750 °C host magma. Domain size is 100 m². Four panels are shown where each panel shows a different parameter for the model output. The top left panel shows compositional fields, top right panel shows temperature (°C), bottom left panel shows density (kg/m³), and bottom right panel shows effective viscosity in log scale (Pa s).

Figure 27: Scenario 1.1 model results after 46.35 hrs of 1 m dike with a temperature of 900°C emplaced in a 750°C host magma. Domain size is 100 m^2 . The four panel parameters are the same shown in Figure 26.

Figure 28: Scenario 1.2 model initial conditions of 10 m dike with a temperature of 900 °C emplaced in a 750 °C host magma. Domain size is 100 m². The four panel parameters are the same shown in Figure 26.

Figure 29: Scenario 1.2 model results after 3.38 hrs of 10 m dike with a temperature of 900 °C emplaced in a 750 °C host magma. Domain size is 100 m². The four panel parameters are the same shown in Figure 26.

Scenario 2: Recharge magma underplating host with buoyant rise of enclaves

This model is set-up with a magma chamber domain size of 1 km² with a 30 m and a 60 m thick intruded magma underplating the overlying host magma. Boundary conditions include free-slip and insulating temperatures along all sides of domain with prescribed temperatures of the host and dike compositional fields. Three versions of this model set up were explored. The first (S2.1) and second (S2.2) versions includes a cool host magma at 750 °C with an initial viscosity of 10⁶ Pa s and density of 2438 kg/m³. The

intruding magma is hot at 900 °C, a viscosity of 10^2 Pa s, and density of 2296 kg/m³. The main difference between S2.1 and S2.2 is the thickness of the underplated intruded magma. In S2.1, the intruded magma layer is 30 m thick, whereas in S2.2 the thickness of the intruded magma layer is 60 m (Figure 30 and Figure 33).

The third (S2.3) version of this model considers a hot host magma at 900 °C with a lower initial viscosity of $10^2 - 10^5$ Pa s, where lower viscosities are observed along the interface of the intruding magma with viscosity increasing toward the top of the domain, and density of 2438 kg/m³ (Figure 35). The intruding magma is cooler with a temperature of 800 °C, a viscosity of 10^6 Pa s, and density of 2326 kg/m³. The thickness of the intruded magma layer is 30 m thick in S2.3 (Figure 35). In all versions, the intruded magma is less dense than the host magma to simulate the effect of exsolution of volatiles during crystallization. All magma densities were prescribed using Rhyolite-MELTS using the water contents stated in Scenario 1. The intruding magma temperature for S2.3 was chosen to be lower than crystallization temperatures, obtained by geothermometry methods in Table 10 and Table 11, to account for crystallization prior to encountering the host magma. Therefore, the intruding magma is interpreted to have undergone extensive crystallization and volatile exsolution at the time of mixing, cooling down to temperatures of about 800 °C.

In S2.1, the host magma is cooler than the underlying intruded magma with a thickness of 30 m. After about 3.46 minutes a large (~25 m in diameter) plume rises through the cold host magma (Figure 31). As time progresses, this plume rises toward the top of the domain with smaller (5 – 10 m in diameter) plumes rising below the tail of the

initial large plume. Eventually these smaller plumes break-off forming deformed remnants of the intruded magma. These deformed bands are easily observed in the viscosity panel. The viscosity contrast between the host and enclaves is nearly the same (Figure 32). Therefore, the remnants of the intruding magma will eventually dissipate as thermal equilibration occurs.

Figure 30: Scenario 2.1 model initial conditions of a 30 m underplating intruded magma with a temperature of 900 °C emplaced below a 750 °C host magma. Domain size is 1 km². The four panel parameters are the same shown in Figure 26.

Figure 31: Scenario 2.1 model results after 3.46 minutes of a 30 m underplating intruded magma with a temperature of 900 °C emplaced below a 750 °C host magma. Domain size is 1 km². The four panel parameters are the same shown in Figure 26.

Figure 32: Scenario 2.1 model results after 23.17 minutes of a 30 m underplating intruded magma with a temperature of 900 °C emplaced below a 750 °C host magma. Domain size is 1 km². The four panel parameters are the same shown in Figure 26.

The S2.2 model has the same set up as S2.1, however the thickness of the underplating layer is twice the thickness (Figure 33). With more intruded magma, the underplated layer does not rise into the overlying host magma as individual plumes (Figure 34). Instead, the underplating induces magma chamber overturn. However, the rate at which overturn occurs (3.43 minutes) is not physically reasonable. In this case, the Reynolds number is high (~ 1000), therefore this model is not capturing the right physics for magmatic systems.

Figure 33: Scenario 2.2 model initial conditions of a 60 m underplating intruded magma with a temperature of 900 °C emplaced below a 750 °C host magma. Domain size is 1 km². The four panel parameters are the same shown in Figure 26.

Figure 34: Scenario 2.2 model results after 3.43 minutes of a 60 m underplating intruded magma with a temperature of 900 °C emplaced below a 750 °C host magma. Domain size is 1 km². The four panel parameters are the same shown in Figure 26.

When the host magma is hotter than the intruding magma with an underplating thickness of 30 m, as in the case of S2.3, the buoyant cooler underplating magma rises through the overlying warmer and less viscous host magma (Figure 35). Overtime, the host magma begins to overturn and convect. At this time, the elongated fingers of the intruding magma become stretched to the point of detaching from the base of the underplating layer (Figure 36). After detachment, enclaves form and disperse within the

host magma (Figure 37). The timescale for enclave formation is rapid, between 3.5 – 4 minutes.

Figure 35: Scenario 2.3 model initial conditions of a 30 m underplating intruded magma with a temperature of 800 °C emplaced below a 900 °C host magma. Domain size is 1 km². The four panel parameters are the same shown in Figure 26.

Figure 36: Scenario 2.3 model results after 3.63 minutes of a 30 m underplating intruded magma with a temperature of 800°C emplaced below a 900°C host magma. Domain size is 1 km^2 . The four panel parameters are the same shown in Figure 26.

Figure 37: Scenario 2.3 model results after 4.08 minutes of a 30 m underplating intruded magma with a temperature of 800 °C emplaced below a 900 °C host magma. Domain size is 1 km². The four panel parameters are the same shown in Figure 26.

Though this model is set-up different from experiments by Hodge et al. (2012) (Scenario 3), break-up of a buoyant viscous intruding magma emplaced within a convecting host magma occurs. The style of enclave break-up resembles that of the tension regime described by Hodge et al. (2012), though the set-up of this model is similar to experiments by Coombs et al. (2002) and Browne et al. (2006). The results from S2.3 suggests that underplating of buoyant viscous intruded magma facilitates

enclave formation by buoyant rise into a convecting host magma and break-up may occur similar to the tension regime described by Hodge et al. (2012).

Scenario 3: Convecting host with gradual intrusion of recharge magma

The model is set up with a reservoir magma chamber domain size of 100 m^2 with a 1 m wide intruding viscous dike. Boundary conditions along the top and bottom of the domain are no-slip with prescribed inflow velocity of 10 cm/s at the injection base and corresponding outflow velocity of 10 cm/s at the top of the domain, otherwise velocities are set to 0 mm/s along the boundary domain. The right and left sides of the domain are insulated and free-slip with prescribed temperatures of the host and dike compositional fields. The intruding dike is introduced into the remobilized host magma with a temperature of $800 \text{ }^\circ\text{C}$ with a viscosity of 10^6 Pa s and density of 2453 kg/m^3 . The intruding magma is just slightly hotter ($830 \text{ }^\circ\text{C}$) and less dense (2450 kg/m^3) with a viscosity of 10^6 Pa s (Figure 38). Since the two magmas have such similar viscosities, the intruding magma rises through the host magma and enclaves never form (Figure 39).

Figure 38: Scenario 3.1 model initial conditions of a 1 m dike with a temperature of 830 °C intruding a remobilized host magma with a temperature of 800 °C at a rate of 10 cm/s. Domain size is 100 m². The four panel parameters are the same shown in Figure 26.

Figure 39: Scenario 3.1 model results after 10.8 hours of a 1 m dike with a temperature of 830 °C intruding a remobilized host magma with a temperature of 800 °C at a rate of 10 cm/s. Domain size is 100 m². The four panel parameters are the same shown in Figure 26.

Summary of Key Model Results

In scenario 1, the dikes buoyantly rise through the host magma never heating up the surrounding host magma. Conductive heat transfer occurs where the host magma cools down the dike and never breaks up to form enclaves, regardless of dike width (Figure 27 and Figure 29). Depending on the thickness of the underplating layer, in scenario 2, when the host magma is at storage temperatures of 750 °C underplated by a hot intruding magma at temperatures of 900 °C (S2.1 and S2.2), either large plumes rise

followed by smaller plumes that do not persist or chamber overturn occurs, and enclaves are not formed. However, when the overlying host magma is already heated, or defrosted, and remobilized, and the intruding magma is cooler, and volatile- and crystal-rich, sub-rounded enclaves form. Though the sizes of the enclaves produced in the model are larger (~10 m) than those observed in the field, this model provides an initial step toward understanding the conditions needed for enclave formation.

Although the host magma is defrosted and remobilized in scenario 3, the intruding magma and host magma have similar viscosities, or little to no viscosity contrast which will never result in enclave formation. The viscosity contrast between the dispersed enclaves and host magma in S2.3 is about 4 orders of magnitude different, therefore S2.3 provides the most likely scenario for enclave formation and survival. The results from S2.3 suggests that underplating of buoyant viscous intruded magma facilitates enclave formation by buoyant rise into a convecting host magma and break-up may occur similar to the tension regime described by Hodge et al. (2012).

This study provides a foundation for possible enclave producing model scenarios using ASPECT. The caveat to these models includes a limited range of possible parameter space. A more complete treatment of the problem would require many simulations run with systematically varying host magma Rayleigh numbers, buoyancy ratios, and injection rates.

CHAPTER 6: ENCLAVE FORMATION AT MOUNT HOOD

DISCUSSION

The composition, textures, and physical characteristics of the enclaves at Mount Hood provide evidence for their formation. This discussion is organized initially with the interpretation of the origin and identities of the enclave and host magmas followed by an explanation of the physical constraints of the enclave and host magmas using textural evidence of the enclaves. Three conceptual models for enclave formation are examined where supporting textural and compositional evidence lead to the most likely model for enclave formation at Mount Hood. The conceptual models provide insights into recharge dynamics, remobilization of rheologically locked magmas, and enclave formation and survival that can be applied to other arc magmatic systems.

Identity of Enclave and Host Magmas

The enclave and host lavas at Mount Hood exhibit compositional homogeneity across all eruptive periods. Bulk silica and major element chemistry show both the enclave and host lavas are andesitic in composition. Eruptive products have evolved slightly over time, where lavas of the oldest eruptive unit, Main Stage, are less evolved than lavas of the younger eruptive units, Timberline and Old Maid. The enclave bulk silica concentration differs by ~1 – 5 wt.% less than its host lava bulk silica concentration. This compositional contrast could be interpreted to be the minimum compositional contrast needed to allow for enclave formation. The only difference in the mineralogical assemblage across the eruptive periods is the presence of clinopyroxene in lavas, where amphibole is either absent or sparse. The enclave lavas also show this trend

toward higher silica, less clinopyroxene, and more amphibole over time. Compositions of all minerals analyzed are indistinguishable between enclave and host lavas at each location. It is important to note that the Main Stage period encompasses >450,000 years, depending on unit sampled, and the Timberline and Old Maid eruptive periods cover a much shorter time period.

Both the enclave lavas and their hosts show similar incompatible element patterns. If crystal fractionation was the main factor in producing the andesitic host and enclave magmas, the most enriched samples would also be the most evolved in terms of the silica content. Additionally, if the enclave magma is more mafic than the host magmas, the enclave magma should have significantly higher compatible and lower incompatible elements with respect to the host magmas. The trend in enrichment of incompatible elements with respect to silica content is not correlated (Figure 17 and Figure 18). These results suggest that fractional crystallization is not the sole process producing the lavas at Mount Hood and the enclave magma may not have been directly sourced from a mafic magma that underwent minor (~8%) to moderate (~30%) amounts of fractional crystallization.

The compositional endmembers of plagioclase, albite (Na-rich) and anorthite (Ca-rich), record qualitative information about the temperature at which they crystallized. Anorthite-rich plagioclase crystallizes at high temperatures (and/or water contents), whereas albite-rich plagioclase crystallizes at lower temperatures. Therefore, a plagioclase crystal that crystallized from a hot mafic melt will have higher anorthite content, and vice versa for a cooler felsic melt. During the growth of a crystal,

crystallization occurs due to cooling in the surrounding magma, resulting in geochemically zoned crystals. A crystal with a high anorthite center and low anorthite rim is considered normally zoned, whereas a crystal with a low anorthite center and high anorthite rim is considered reversely zoned. The presence of reversely zoned crystals indicates either an influx of high Ca/Na magma or a higher P_{H_2O} . The former would signify a thermal rejuvenation into the magmatic system by magma recharge just prior to eruption. The latter is unlikely the case as the higher P_{H_2O} would require deeper storage. Normally zoned crystals record progressive crystallization in a cooling (and/or degassing) magmatic system. The rims of crystals aid in our understanding of the thermal histories of the magmas just prior to eruption.

The presence of multiple plagioclase populations is evident in both the host and enclave lavas at Mount Hood. These populations are defined based on crystal size and composition. The large ($> 450 \mu\text{m}$) euhedral phenocrysts with low anorthite content at their center record growth within a more felsic melt, or endmember magma, over long periods of time. Also, large phenocrysts of host and enclave magmas showing several high-to-low anorthite oscillations from center to rim of crystals clearly indicate longer term compositional changes during crystallization and recharge cycles (Woods, 2004). The smaller ($200 - 450 \mu\text{m}$) tabular crystals make up the groundmass of the enclaves. Elongate microlites ($< 200 \mu\text{m}$) with slightly higher iron oxide concentrations record rapid growth from a somewhat less evolved, more mafic melt. Microlites are present in both the host and enclave lavas, but most enclaves mainly consist of groundmass crystals. To compare mineral compositions with previous analyses by Kent et al. (2010), we focus

all compositional and elemental analyses on true microlites ($< 200 \mu\text{m}$) and the largest phenocrysts ($> 710 \mu\text{m}$) in both the host and enclave lavas.

Kent et al. (2010) defined crystal populations based on the change in slope of the crystal size distributions and the compositional zonation of the plagioclase crystal populations. In Kent et al. (2010), microlites in both host and enclave lavas are similar in composition and have higher anorthite and iron oxide concentrations, showing characteristics of crystallizing in a high temperature mafic magma. The phenocrysts in both the host and enclave lavas are similar in composition with low anorthite and iron oxide centers, indicative of crystallizing in a low temperature felsic melt. The rims of the phenocrysts are reversely zoned, recording high anorthite and iron oxide concentrations, similar to the compositions of the microlites. Since the microlites in both host and enclave lavas were found to be similar in composition, they are inferred to have originated from a mafic recharge magma, and vice versa for the phenocrysts crystallizing from the felsic host magma. Kent et al. (2010) calculated the hypothetical mafic and felsic endmember magma compositions using regressions of measured mixing fraction of total plagioclase to proportion of plagioclase populations. In Figure 19, we show the iron oxide content of plagioclase expected from the endmember compositions calculated by Kent et al. (2010) with the data obtained in this study.

In this study, slight variations between the microlite and phenocryst anorthite and iron oxide concentrations exist (Table 7 and Table 8). The microlite centers and phenocryst rims plot within the estimated iron oxide concentrations of the “mafic” endmember, calculated by Kent et al. (2010), only for the Main Stage eruptive unit. For

the Timberline and Old Maid eruptive units, the microlite centers and phenocryst rims have lower iron oxide concentrations (Figure 20). The phenocryst centers of the enclave and host lavas show similar low iron oxide concentrations and relatively similar anorthite contents (Figure 20). The enclave and host lava microlite centers are similar in iron oxide concentrations, however they vary in anorthite content where the enclave microlite centers are slightly more anorthite rich relative to the host lava microlite centers (Figure 20). All microlites show either normal zoning or no zonation. The phenocrysts, based on this analysis, show either no zonation or reverse zonation (Figure 20). On the other hand, Woods (2004) found zonation within most phenocrysts using more detailed line traverses of the Main Stage lavas and anorthite ranges within single phenocrysts were those observed here to low-to-high anorthite plagioclase.

The juxtaposition and compositional zoning of these plagioclase populations have been inferred to represent mixing between mafic and felsic endmembers to create a hybrid andesitic magma. Furthermore, the enclaves at Mount Hood are assumed to represent blobs of left over partially hybridized melt from the mafic endmember that have survived the mixing processes prior to erupting (Kent et al., 2010). The compositional spread and the spatial location of compositions observed in plagioclase of this study cast doubt on the model of Kent et al. (2010). Due to the compositionally distinct microlites of the enclave and host lavas found in this study, the microlites in the enclave are inferred to have crystallized within their respective magma bodies and did not exchange crystals during mixing with the host magma. Furthermore, compositional similarities, distinct textures, vesicularities, little glass or quenched margins, and inter-connected groundmass

crystals (200 – 450 μm) within the enclaves call for reexamination of alternate enclave formation hypotheses.

Based on compositional evidence of the bulk rock, mineral, and crystal zonation of both the host and enclave lavas, we conclude that the intruding magma and host magma were both andesitic in composition. Both are mixed magmas prior to enclave formation and enclave magmas did not hybridize or exchange crystals with the host magma, although the opposite, breaking off phenocrysts and microlites from the enclaves and entrainment with the host andesite is observed. The intruding andesite and host magmas are compositionally nearly identical and neither magma carries actual evidence that andesites originated from mixing of rhyolite with basalt endmember magmas (Kent et al., 2010). Therefore, the viscosity contrast needed to produce enclaves must be largely driven by magmatic properties such as temperature variations or the presence of volatiles effecting the density of the magmas, rather than compositional variations. Assessment of the timing of enclave crystallization, either before entrainment within the host magma or after, is essential in understanding how enclaves can quench against a host magma with similar composition.

Physical Constraints on Enclave Formation

The existence of enclaves at Mount Hood illustrate mingling between compositionally similar host and intruding magmas, leading to fundamental questions of how, when, and why do Mount Hood enclaves form? Specifically, what rheological differences are needed to form enclaves in compositionally similar host magmas? If interaction of the magmas occurs in a liquid-liquid relationship, where the host and

enclave magmas have similar viscosities, the viscosity contrast between the compositionally similar mixing magmas would likely not allow for enclave formation, rather banding and hybridization would occur. Otherwise, quenching of intruding magma can be induced by a sharp temperature gradient, if the host was solid (Figure 37). Are the variations in temperature, crystallinity, and vesicularity noted between the host and enclave lavas at Mount Hood enough to form enclaves in compositionally similar magmas?

Next, we examine what enclave size and shape distributions tell us about the rheology of the mixing magmas. A fundamental question is whether the enclave shapes we observe *in situ* represent the shape of enclave formation or deformation during eruption and emplacement. The majority of Mount Hood's enclaves are mainly sub-round to round in shape and range in size with median diameters of 1.68 – 2.9 cm (Table 3). These size distributions are consistent with other enclave-bearing lavas (Coombs et al., 2002; Blake and Fink, 2000; Feeley et al., 2008; Hodge and Jellinek, 2012; Andrews and Manga, 2014). In general, there is no correlation between shape and size distributions (Figure 10). The fluid shapes of the enclaves may imply that the intruding and host magmas mingled as liquids, although true liquid-liquid interaction of mafic with intermediate to silicic magmas reveal textures of banding and contortion rather than rounded and elliptical shapes (Streck and Gruner, 1999). However, the proportion of groundmass crystals and phenocrysts (> 20%) suggests that the intruding magma was somewhat crystalline at the time of mixing. Therefore, the enclave shapes observed at

Mount Hood are likely caused by modification or deformation during eruption and emplacement, rather than the shape during formation of enclaves initially.

Using the two pyroxene geothermometry method by Putrika (2008), crystallization temperatures of the host and enclave lavas were obtained. Overall, the crystallization temperatures of the host magma range from 906 ± 2.15 °C to 925 ± 3.18 °C, and for the enclaves from 894 ± 7.04 °C to 940 ± 3.87 °C (Table 11). These geothermometry results were then compared to those obtained by Rhyolite-MELTS, where the enclave lava compositions with 4 wt.% H₂O and 4 – 22% crystallinities correspond to crystallization temperatures of about 1170 – 975 °C (Figure 40). The host lava compositions with 4 wt.% H₂O and 20 – 24% crystallinities correspond to crystallization temperatures of about 993 - 975 °C (Figure 40).

Figure 40: Rhyolite-MELTS results for magma density (g/cm³) and temperature (°C) vs. total crystallinity (%) for enclave and host magma compositions with 4% H₂O.

The temperatures obtained by Rhyolite-MELTS are slightly higher than the crystallization temperatures obtained by geothermometry methods. However, for hydrous magmas, Rhyolite-MELTS is often not well calibrated (Gualda et al., 2012). The geothermometry indicates that host and enclave equilibration temperatures differ by only 6 – 15 °C (Table 11). The geothermometry used here reveals the temperature at which the pyroxenes crystallized. Magmas with similar melt compositions will record similar

crystallization temperatures, therefore the small range in crystallization temperature variations are consistent with crystallization in compositionally similar magmas.

A thermal gradient is needed for enclaves to quench if temperature is driving the viscosity contrast for enclave formation. The temperatures recorded by the two pyroxene geothermometry represent crystallization temperatures. Since the enclave and host magmas record similar crystallization temperatures, one of the magmas, either host or intruding magma, would have to be more crystallized and cooler to provide the thermal gradient needed for quenching. Textural evidence of rapid cooling is evidenced by when one or more of the following is observed: quenched margins, glass (or remnants of what used to be glass), and textures associated with undercooling, particularly swallowtail crystal edges and/or holes within microlites (Mollo and Hammer, 2017).

The enclaves at Mount Hood rarely show quenched margins, if at all. Very few samples from the Main Stage eruptive unit have fine grained margins along the interface of host and enclave lava. Enclaves from the Timberline and Old Maid eruptive periods do not have quenched margins. Instead groundmass crystals are homogeneous from rim to interior of enclaves. On the other hand, margins often show sections where the enclave lava is distended or a piece is broken off and is in the process of being incorporated into the host lava. Feeley and Dungan (1996) and Feeley et al. (2008) describe similar features along the margins of enclaves from Tatara-San Pedro Volcano in Chile and Mt. Helen dome at the Lassen volcanic center as a result of disintegrations and disaggregation of crystallized enclaves in conduit during eruption and fracturing or shearing of the enclaves during emplacement of lava flows post eruption. Additionally, in most samples, host

crystals are aligned parallel to the enclave margins. These textural characteristics imply the host behaved in a fluid manner relative to a more rigid or solid enclave magma, suggesting that the enclaves were more solid at the time of entrainment within the host magma and the host groundmass crystallization occurred post eruption during emplacement.

The amount of interstitial glass was estimated in the enclave, and host when present. Generally, little interstitial glass ($<1 - 5\%$) is found in the enclave lavas. However, sample MH_T7 from the Timberline eruptive unit contained up to 15% glass. When glass is present, abundant submicroscopic crystals are present with little pure glass. The presence of submicroscopic crystals within the interstitial glass implies the glass was exposed to temperatures above the glass transition temperature for a relatively brief time just prior to eruption. One sample from the Meadows location (MH0210L) of the Main Stage eruptive unit contained a significant amount of glass within the host lava with the amount of glass increasing toward the margin of the enclave and no observable glass within the enclave lava. Glass present within the host lavas, especially along the margin, implies the host magma quenched against the enclave magma at the time of mixing. This would suggest that the host magma was hotter than the enclave magma.

Textural evidence of undercooling, caused by differences between the saturation phase in a liquid between the temperature of the system, are represented as swallowtail crystal margins and holes within crystals (Mollo and Hammer, 2017). Evidence of undercooling is mainly present as swallowtail crystal margins within the microlite ($<200\ \mu\text{m}$) and some groundmass crystals observed in both plagioclase and pyroxenes. Holes

within crystals are also evidence for undercooling, however little if any undercooling holes are present in the host or enclave lavas.

Along with temperature, density variations due to the presence of exsolved volatiles between the enclave and host magmas influence the viscosity contrast needed for enclave formation (Coombs et al., 2000). High vesicularity, or vesicle proportions, causes a decrease in density and may increase viscosity based on the sizes of the bubbles present in the magma. The vesicularity of the enclave lavas ranges from 13 – 28%, where the Main Stage samples show the highest vesicularities and the Timberline samples show the lowest. The host lava vesicularities range from 3 – 21%, where the Timberline and Old Maid samples show the highest host vesicularities and the Main Stage samples are low in vesicularity. The eruptive units with the highest host vesicularities are products of block-and-ash flow deposits, whereas the Main Stage eruptive unit showing the lowest vesicularity is a lava flow deposit.

All phenocrysts show complex oscillatory zoning patterns; therefore, they are inferred to have crystallized during storage conditions. With 20 – 24% phenocryst proportion in the host lavas and 4 – 22 % in the enclave lavas, these phenocryst proportions represent the minimum crystallinities of the magmas at the time of mixing. Combining the amount of glass, vesicles, and phenocrysts, the estimated proportion of groundmass and microlite crystals in the enclaves ranges from 57 – 67%. Generally, groundmass crystals are more prevalent in the enclaves than microlites. Excluding the amount of glass and proportion of vesicles, the total crystallinity of the enclaves is estimated to range from 71 – 83%.

The enclaves at Mount Hood show evidence of rapid cooling with minor amounts of glass and signs of undercooling and contain textural evidence suggesting the enclaves behaved as solid inclusions at the time of entrainment within the host magma. Therefore, the round shapes of the enclaves are likely products of reshaping, or essentially erosion along the margins, during ascent and deformation, rather than formation. Using the compositional and textural evidence obtained in this study, we compare various enclave formation scenarios found in the literature to explain how quenching of enclaves may occur at Mount Hood.

Conceptual Models of Enclave Formation

There are three scenarios that are commonly invoked to explain the formation of enclaves by mingling in volcanic systems: 1) break-up of a dike emplaced in a rheologically-locked magma chamber (Andrews and Manga, 2014), 2) floatation of volatile- and crystal-rich enclaves from a foamy underplating layer (Coombs et al., 2002; Browne et al., 2006), 3) injection of a viscous dike into a convecting host magma (Hodge et al., 2012). These models of enclave formation usually involve mingling between compositionally distinct magmas, where the viscosity contrast needed for enclave formation is driven by compositional and thermal variations of the magmas. All chemical and textural features of the enclaves at Mount Hood require explanation in any enclave formation model.

Scenario 1: Dike emplacement in rheologically locked host magma:

As a 1 – 10m dike of hot intruding magma (~900 °C) intrudes an overlying cooled host magma (~750 °C), the dike begins to cool from the margins of the dike to the center.

As the dike crystallizes, it conductively transfers heat to the surrounding host magma (Figure 41A). As the surrounding host magma is heated, the host is defrosted and able to flow. Once the dike has crystallized completely, the surrounding host magma is able to flow and convect (Figure 41B). The cooled dike is broken up by the convecting host magma and dispersed within the host as enclaves (Figure 41C). If the dike is not effectively solid at the onset of convection, banding will occur. The timescale of cooling of the injected dike depends on the size of the dike and the temperature difference between the two magmas. Supporting textural evidence for this model of enclave formation should form enclaves with angular shapes and show signs of rapid cooling within the enclave, such as quenched margins along the margin of the enclave and host lava, interstitial quenched glass, and microlite crystals ($< 200 \mu\text{m}$) would be abundant throughout the enclave groundmass.

Figure 41: Conceptual illustration of scenario 1. A) A hot dike is intruded into a cooled, rheologically locked host magma. The dike begins conductively transferring heat to the surrounding host magma. B) As the dike cools and crystallizes, the surrounding host magma continues to heat up and remobilized. C) The host magma is heated sufficiently, and convection occurs, breaking-up the crystallized dike to form enclaves. See legend for symbol and color identification.

This model assumes that the host magma has a crystallinity $> 20\%$ and that the intruding magmas are more mafic and volumetrically smaller than the felsic host magma. According to this model, if the intruding and host magma compositions are similar, yet the intruding magma is slightly warmer than the host, after thermal equilibration, the rheological contrast between the magmas disappears and the magmas mix and hybridize rather than mingle to form enclaves (Andrews and Manga, 2014). Additionally, the process of defrosting and remobilizing of the host magma chamber by brittle deformation of an emplaced dike occurs over long timescales, up to one year for the largest dikes (Andrews and Manga, 2014). For compositionally similar magmas, even with large initial temperature variations between the magmas, if brittle deformation occurs to form enclaves the rate of survival after thermal equilibrium is rapid. Based on the evidence and timescales involved in this model, it is unlikely that the compositionally similar enclaves would form or survive the mixing process after formation.

Scenario 2: Buoyant rise of volatile- and crystal-rich enclaves by underplating:

As a hot intruding magma pools beneath, or underplates, a cooled, rheologically locked host magma, crystallization of the intruding magma will occur along the boundary of the overlying host magma (Figure 42A). As crystallization continues, exsolution of volatiles occurs within the underplating magma while heating and remobilizing the overlying host magma (Figure 42B). These volatiles are trapped at the interface between the two magmas due to the quenched interface. The intruding magma will form a foamy volatile-rich crystallizing layer. This foamy layer is less dense than the overlying host magma as volatiles continue to exsolve. Due to the density differences between this

foamy intruding magma and host magma, blobs of the foamy intruded magma will buoyantly rise and disperse within the host magma forming enclaves (Figure 42C). Further dispersal of the quenched volatile-rich enclaves within the host magma heats the host magma sufficiently, inducing convection within the host magma (Coombs et al., 2000). Textural evidence of this model includes quenched margins and glass and high vesicularity of the enclaves relative to the host lavas. The timing of groundmass crystallization occurs prior to dispersal of enclaves entrained within the host magma and the intruding magma is mainly solid at the time of entrainment. If the enclaves crystallized from melt as blobs < 20 cm in diameter entrained within the host, the textures would indicate rapid cooling with abundant glass and microlites. However, in this model the larger groundmass crystals, little glass, and high vesicularities indicate longer crystallization timescales.

Figure 42: Conceptual illustration of scenario 2. A) A hot intruded magma underplates a cool rheologically locked host magma. B) The intruded magma cools and crystallizes while simultaneously heating and remobilizing the overlying host magma. During crystallization of the intruded magma, exsolution of volatiles occurs. C) As the intruded magma continues to crystallize, a foamy layer forms where eventually crystal- and volatile-rich enclaves buoyantly rise through the now convecting host magma. Temperature profiles for each stage (green line) with the intruded magma temperature at 80% and 20% crystallinity as reference. See legend in Figure 26 for symbol identification.

In Coombs et al. (2002), the intruding magma is andesitic intruding into a dacitic host. This model assumes that latent heat of crystallization is linearly approximated and conduction is the primary means of heat transfer within the system (Coombs et al., 2002). Therefore, this model postulates that phenocryst growth in the intruding magma occurs after recharge and underplating, whereas the phenocrysts found within the enclaves at Mount Hood show complex oscillatory zonation patterns indicative of long periods of continued crystallization. Overall, this model is ideal in explaining enclave formation in magmas with compositional variability. If the intruding magma was $\sim 930 - 965^{\circ}\text{C}$ with $\sim 10 - 20\%$ plagioclase feldspar phenocrysts, consistent with geothermometry, phenocryst proportion analyses, and Rhyolite-MELTS results, the intruding magma would have a yield strength at the time of encountering the overlying host magma cooled to $\sim 750^{\circ}\text{C}$ (Andrews and Manga, 2014). As the intruding magma crystallizes, volatiles are exsolved which decreases the density and increases the viscosity, based on the size of the bubbles. However, to defrost the overlying host magma requires a long period of time. As the host is heated the dispersed enclaves may thermally equilibrate with the host magma and the viscosity contrast needed for enclave survival will not be maintained.

Scenario 3: Injection of hot dike into an actively convecting host magma:

In an actively convecting magma chamber, injection of a hot viscous dike occurs (Figure 43A). The dike is buoyant and crystalline (20 - 30% crystallinity) and therefore has a yield strength against the surrounding low viscosity convecting host magma (Figure 43B). Depending on the viscosity ratio between the convecting host and intruding magma, height of the magma chamber, injection width, and convection velocities, the

injected dike may break-up to form enclaves (Figure 43C). The length scale by which enclaves form are controlled by two regimes; 1) the tension regime where the enclaves have a characteristic size dictated by balancing the viscous stresses and impeding yield stresses of the interacting magmas. 2) The Rayleigh-Taylor regime describes the density and viscous instabilities between the two magmas resulting in drips of the intruding magma forming enclaves (Hodge et al., 2012; Hodge and Jellinek, 2012).

Figure 43: Conceptual illustration of scenario 3. A) A buoyant viscous dike is injected into a convecting host magma. B) As the dike intrudes it becomes unstable relative to the surrounding convective forces. C) The crystalline dike is dismembered into enclaves. See legend in figure 26 for symbol identification.

The crystallinity of the intruding magma is essential in determining the regime of enclave formation described by this model. In both regimes, viscous forces and shear strain causes the particles to be stretched away along the margins of the forming enclave. Eventually, the crystals are not interacting together, and the magma behaves as a low viscosity dilute suspension, or Newtonian fluid, decreasing the magmas yield strength. Depending on the size of the enclaves, the interiors may maintain their high crystallinity and along the margins should consist of quenched or microlite-rich rinds (Hodge et al., 2012; Hodge and Jellinek, 2012).

Overall, this model is appealing in that the host magma is convecting and therefore is rheologically eruptible and the injection of recharge magma to form enclaves occurs shortly before eruption, consistent with crystal growth speedometry (Mollo and Hammer, 2017). Also, this model explains common size distributions of enclaves observed in both plutonic and volcanic systems. The rounded or fluid shapes of the enclaves are also explained by both regimes. However, this model assumes compositional variations between the host and intruding magmas with different liquidus temperatures where the host is felsic and intruding magma is mafic. The temperature gradient between the cooled dike ranging from 1 – 10 m wide and the volume of convecting host magma could cause disaggregation of the dike, however for the enclaves to survive entrainment within the convecting host, eruption would have to occur immediately following dike break-up.

Enclave Formation at Mount Hood

Each model for enclave formation has characteristics consistent with some subset of the properties or textures that we observed at Mount Hood. Yet, all models underestimate the time between enclave cooling and eruption and/or consider mingling between compositionally distinct magmas. Due to the compositional similarity between the host and enclave lavas at Mount Hood, the timescale of enclave cooling to eruption will need to be rapid for enclaves to survive the mixing process after thermal equilibrium with the host magma. Otherwise, the enclaves will deform into banded textures and eventually homogenize, erasing any macroscopic evidence of mingling completely. For enclaves to survive the mixing processes after formation, the viscosity contrast between the host and enclave magmas need to be significant. When thermal equilibration occurs prior to eruption, temperature and crystallinity cannot drive the viscosity contrast needed for enclave survival. Other factors, such as bubbles, can increase the viscosity of the enclave magma driving the needed viscosity contrast for enclave survival before eruption.

To account for the high degree of vesicularity observed in the enclaves and compositionally similar magmas, if we assume the intruding magma contains more dissolved volatiles (5 wt.% H₂O) than the host magma (3 wt.% H₂O), crystallization is suppressed allowing for crystallization at lower temperatures (Koleszar, 2011; Kent et al., 2010). As the intruding magma ascends toward the shallow convecting magma chamber, decompression-induced crystallization can occur, associated with volatile exsolution (Shea and Hammer, 2013). As volatiles are exsolved, bubbles are formed, causing an increase in viscosity while simultaneously decreasing the density of the intruding magma.

In terms of scenario 3, if the intruding magma experiences decompression induced crystallization upon ascent during recharge, the crystal- and volatile-rich intruding magma is buoyant and viscous as it is injected within the convecting host. The temperature difference between the cooled intruding magma and surrounding warm convecting host magma facilitates enclave break-up, likely in the tension regime described by Hodge and Jellinek (2012). After breakup of the intruding magma, enclaves disperse, and as thermal equilibration occurs, the volatile-rich enclaves may survive entrained within the host, maintaining higher viscosities and lower densities compared to the surrounding host magma prior to eruption.

The compositional similarities between the magmas and high vesicularities in scenario 2 correlate best with the chemical and textural evidence of the enclave and host lavas at Mount Hood. However, for Mount Hood lavas, the oscillatory zonation within the enclave phenocrysts implies the intruded magma contained phenocrysts prior to underplating. To account for the high vesicularities and groundmass crystal proportions in the enclave lavas, the intruding magma may have undergone decompression induced crystallization during recharge, prior to underplating and continued crystallizing after encountering the host magma. After enclave dispersal and thermal equilibration with the host magma occurs, the entrained bubbles within the enclaves facilitate the necessary viscosity contrast for enclave survival prior to eruption.

Additionally, if the enclave enclaves experience degassing while entrained within the host magma at a certain temperature, the crystallinity of the enclaves increases rapidly. Figure 44 shows results from Rhyolite-MELTS calculations for the host magma

composition at 3 wt. % H_2O compared to the enclave magma composition at 3 and 5 wt. % H_2O . At an eruption temperature of about 950 °C, the host magma has a crystallinity of about 30% and the hydrous (5 wt.% H_2O) enclave magma has a crystallinity of about 20%. At the same temperature, the enclave magma with 3 wt. % H_2O has a crystallinity of about 40%. If the hydrous (5 wt.% H_2O) enclave magma degasses at 950 °C, the crystallinity of the enclave magma may jump to 40%. Though the enclaves lose their bubbles, the high viscosity of the enclaves is now maintained by an increase in crystallinity.

Figure 44: MELTS temperature (°C) vs. crystallinity (%) for a host magma with 3% H₂O and enclave magmas with 3 and 5% H₂O.

Our numerical models support scenario 2 in producing enclaves when the host magma is hot (900 °C) and the intruding magma is crystal- and volatile-rich at temperatures of about 800 °C (Figure 37). Though the initial model set up is different from scenario 2, in that the host is already reheated and remobilized at the time of recharge, enclave formation by the tension regime described by Hodge et al. (2012) is likely the case for formation in the underplating scenario, for example S2.3. Therefore, the buoyant rise of viscous intruding magma into a hot remobilized host magma is the most likely enclave formation model for Mount Hood.

The model here provides a scenario by which compositionally similar host and intruding magmas mingle to create the enclaves observed at Mount Hood. Most enclave formation scenarios throughout the literature consider mixing between compositionally distinct magmas. For compositionally similar magmas, enclave formation and the subsequent mixing processes are inhibited by small thermal gradients and the chance for enclave survival after thermal equilibration is low. The textural features of the enclaves, such as high amount of phenocryst and groundmass crystals, little quenched glass and margins, high vesicularities, and signs of undercooling imply crystallization induced by exsolution of volatiles during decompression and ascent of the intruding magma prior to encountering the convecting host magma.

There is significant time, years, required to reheat and defrost a rheologically-locked magma reservoir by magma recharge. If enclaves formed during an early phase of this defrosting, then the compositionally similar enclaves wouldn't survive as the enclave and host magmas converge to a narrow temperature gradient over the time period to defrost the host andesite. Therefore, the more likely scenario is recharging magmas homogenize with the host magmas until sometime after the host starts convecting, up to a few years after initial recharge. At this time onward, if a more volatile-rich recharge magma, with a temperature at or below the convecting host magma, enclaves may form and only survive if eruption shortly ensues, within days to weeks. Therefore, the enclaves observed at Mount Hood represent the preserved remnants of a final recharge event just prior to eruption.

Arc Magmatism Dynamics Informed by Enclaves

Continental volcanic arc systems are dominated by recharge-driven magmatism (Eichelberger, 1980; Bacon, 1986; Sparks and Marshall, 1986). Recharge events and the subsequent mixing processes are understood to precede eruptions (Kent, 2013; Cooper and Kent, 2014). As a result, intermediate lavas and macroscopic evidence of the mixing processes, such as enclaves, are prominently found at volcanic arc environments throughout the world. Throughout the literature, the processes by which mafic enclaves entrained within felsic host lavas are formed is commonly discussed (Eichelberger, 1980; Bacon, 1986; Sparks and Marshall, 1986; Wilcox, 1999). However, few studies have discussed enclave formation between compositionally similar mixing magmas.

The presence and implications of compositionally similar enclaves can be viewed as a transient precursor event prior to eruption at Mount Hood and can be applied to other arc magmatic systems. The timescale of initial recharge to eruption has been estimated to occur within weeks to months (Kent, 2013; Cooper and Kent, 2014). For magmatic systems like Mount Hood, these timescales apply to the processes of defrosting and remobilization of the host magma by recharge events and may involve longer timescales, within years. However, the timescales of enclave cooling and survival in compositionally similar magmas may be orders of magnitude shorter than timescales of remobilization and eruption, within days to weeks. Hence, the preserved enclaves at Mount Hood represent remnants of final recharge events prior to eruption.

CONCLUSIONS

Recharge-driven magmatism often records macroscopic evidence of magma mixing as enclaves both in the plutonic and volcanic record throughout the world (Eichelberger, 1980; Bacon, 1986; Sparks and Marshall, 1986). Generally, enclaves are compositionally and texturally distinct from their surrounding host magmas or lavas. This compositional contrast between the host and enclave magmas often leads to the viscosity contrast needed for enclave formation. Mount Hood, Oregon is unique in that it consistently erupts andesite bearing compositionally similar enclaves. This research supplements previous studies on the host and enclave lavas at Mount Hood by providing additional bulk and mineral chemical data on samples from three main eruptive units. We also provide new constraints on the enclave size and shape distributions, abundances, vesicularities, calculated temperature data from pyroxene crystals, and crystal proportion estimates of both the enclave and host lavas.

The eruptive products at Mount Hood are andesite, evolving slightly over time from the oldest eruptive unit (> 30 ka) to the youngest (~ 230 ya). The bulk compositions of the enclaves and host lavas differ by $\sim 1 - 5$ wt.% SiO_2 . The median diameters of the mainly sub-round to round enclaves at Mount Hood correspond to those found within the literature ranging from $1.68 - 2.9$ cm (Hodge and Jellinek, 2012). The estimated crystallization temperatures recorded in the host and enclave lavas range from $6 - 15$ °C corresponding to pressures between about $5.1 - 8.7$ kbar. Plagioclase feldspar phenocrysts reveal complex oscillatory zoning in both enclave and host lavas, whereas microlite compositions differ slightly in anorthite content with respect to the host and

enclave lavas. Textural differences are evident between the porphyritic host and coarse-grained enclave lavas. The enclaves are crystalline with abundant groundmass crystals and sparse microlites (57 – 67%), a wide range of phenocryst proportions (4 – 22%). Little glass (<1 – 5%) is present throughout the enclave groundmass, apart from one Timberline sample containing up to 15% glass. Furthermore, the enclaves contain a high proportion of vesicles (13 – 28%). Where the greatest vesicularities are found within lava flows of the Main Stage eruptive period, whereas the lowest vesicularities correspond to enclaves deposited by block-and-ash flows of the Timberline eruptive period. Likewise, quenched margins are sparse, and if present, are found only in samples from lava flows of the Main Stage eruptive unit.

The compositional similarities between the enclave and host lavas suggests that the viscosity contrast needed for enclave formation is controlled by temperature and volatile variations, rather than compositional variations. However, with similar crystallization temperatures inferred from the two pyroxene geothermometry, it is unlikely that temperature alone is responsible for driving the viscosity contrast to quench enclaves. Furthermore, once thermal equilibrium is reached during mixing prior to eruption, enclave survival is hindered by similar compositions and crystallization temperatures. The high vesicularities and high proportions of groundmass crystals of the enclaves suggests crystallization and volatile exsolution occurred before entrainment as enclaves within the host magma. Otherwise, the viscosity contrast would be too small to quench and maintain enclaves during the mixing process. Therefore, we conclude that the intruding magma was quenched with extensive volatile exsolution at the time of coming

into contact with an actively convecting host magma. Thus, the crystal and bubble-rich intruding magma may have been slightly cooler than the convecting host magma at the time of recharge. This temperature difference facilitates enclave break-up as the intruding magma encounters the convecting host magma. The bubbles and extensive crystalline-network within the enclave magma increases the viscosity, while simultaneously decreasing the density, allowing the necessary viscosity contrast for enclave survival during the mixing processes, after thermal equilibration, and during eruption. The timescale from the last recharge event to eruption would need to be short, within a few days to weeks, for the enclaves to survive the mixing and eruption process.

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APPENDIX A – Geochemical Data

Table A1. XRF Results

Sample ID	MH_P1_E	MH_P1_H	MH_P2_E	MH_P2_H	MH_P3_E	MH_P3_H
Lat	45.400382	45.400382	45.400382	45.400382	45.400382	45.400382
Long	-121.675351	-121.675351	-121.675351	-121.675351	-121.675351	-121.675351
Erupt. U	Main Stage	Main Stage	Main Stage	Main Stage	Main Stage	Main Stage
H/E	Enclave	Host	Enclave	Host	Enclave	Host
XRF Normalized Major Elements (Weight %), 100% volatile free:						
SiO₂	59.80	62.41	58.90	62.41	58.12	62.41
TiO₂	0.98	0.83	0.98	0.83	1.02	0.83
Al₂O₃	17.89	17.18	18.27	17.20	18.34	17.12
FeO*	6.38	5.44	6.61	5.44	6.77	5.50
MnO	0.11	0.09	0.11	0.10	0.11	0.10
MgO	3.33	2.67	3.49	2.65	3.55	2.66
CaO	6.13	5.50	6.42	5.49	6.84	5.48
Na₂O	4.00	4.18	3.92	4.16	3.86	4.18
K₂O	1.21	1.53	1.10	1.55	1.17	1.53
P₂O₅	0.20	0.18	0.19	0.18	0.21	0.19
Pre-normalized Total	98.10	99.14	98.02	98.87	98.85	99.23
LOI %	0.95	0.37	1.29	0.39	0.48	0.33
XRF, unnormalized ppm						
Ni	30	22	32	23	33	23
Cr	38	25	41	25	39	25
Sc	14	12	16	12	16	12
V	122	100	124	98	133	102
Ba	394	404	366	401	335	405
Rb	16	21	14	22	15	23
Sr	535	578	553	577	625	577
Zr	160	161	152	162	137	162
Y	18	17	16	16	18	17
Nb	10.8	11.4	10.4	11.7	10.1	11.5
Ga	20	19	20	19	19	19
Cu	58	44	59	37	66	40
Zn	71	62	77	65	70	63
Pb	6	5	6	7	4	5
La	18	18	17	23	19	20
Ce	43	39	39	39	41	43
Th	4	4	4	3	3	3
Nd	20	20	19	18	19	21
U	1	1	1	2	2	1

Table A2. ICP-MS Results

Sample ID	MH_P1_E	MH_P1_H	MH_P2_E	MH_P2_H	MH_P3_E	MH_P3_H
Lat	45.400382	45.400382	45.400382	45.400382	45.400382	45.400382
Long	-121.675351	-121.675351	-121.675351	-121.675351	-121.675351	-121.675351
Erupt. U	Main Stage	Main Stage	Main Stage	Main Stage	Main Stage	Main Stage
H/E	Enclave	Host	Enclave	Host	Enclave	Host
ICP-MS, ppm						
La	21.53	20.72	18.83	21.24	18.49	21.67
Ce	42.07	41.6	37.53	43.14	38.17	44.51
Pr	5.15	5.03	4.55	5.14	4.69	5.29
Nd	19.71	19.74	17.78	20.2	18.66	20.29
Sm	4.21	4.05	3.92	4.18	4.13	4.13
Eu	1.39	1.3	1.35	1.33	1.36	1.3
Gd	3.84	3.54	3.64	3.64	3.79	3.64
Tb	0.61	0.55	0.56	0.57	0.61	0.58
Dy	3.54	3.16	3.36	3.22	3.53	3.2
Ho	0.7	0.62	0.65	0.63	0.69	0.63
Er	1.83	1.58	1.68	1.64	1.78	1.71
Tm	0.25	0.23	0.25	0.24	0.25	0.23
Yb	1.62	1.45	1.54	1.49	1.58	1.51
Lu	0.24	0.22	0.23	0.23	0.24	0.23
Ba	399	410	366	405	336	408
Th	3.16	3.6	2.92	3.64	2.55	3.67
Nb	12	11.3	11.2	11.2	10.28	11.35
Y	17.56	15.85	16.57	16.09	17.16	16.4
Hf	4.23	4.17	3.89	4.23	3.61	4.23
Ta	0.76	0.72	0.69	0.72	0.65	0.72
U	0.99	1.14	0.86	1.13	0.75	1.16
Pb	5.22	4.89	6.14	5.75	5.34	5.52
Rb	14.8	21.1	12.7	20.9	13.8	21.2
Cs	0.32	0.36	0.27	0.27	0.25	0.31
Sr	536	578	552	569	630	575
Sc	15	11.8	15.4	12	15.8	11.5
Zr	166	163	155	161	139	165

Table A1 continued.

Sample ID	MH_P4_E	MH_P4_H	MH_T1_E	MH_T1_H	MH_T2_E	MH_T2_H
Lat	45.400382	45.400382	45.33358	45.33358	45.3324	45.3324
Long	-121.675351	-121.675351	-121.71381	-121.71381	-121.70815	-121.70815
Erupt. U	Main Stage	Main Stage	Timberline	Timberline	Timberline	Timberline
H/E	Enclave	Host	Enclave	Host	Enclave	Host
XRF Normalized Major Elements (Weight %), 100% volatile free:						
SiO₂	59.66	62.39	60.74	63.56	59.03	63.71
TiO₂	0.97	0.82	0.91	0.73	0.98	0.72
Al₂O₃	18.20	17.18	17.71	16.96	17.86	17.02
FeO*	6.34	5.46	5.92	5.00	6.33	4.86
MnO	0.11	0.09	0.11	0.09	0.10	0.09
MgO	3.31	2.66	3.00	2.47	3.48	2.39
CaO	6.07	5.52	6.15	5.32	7.05	5.32
Na₂O	3.96	4.16	4.03	4.22	3.88	4.24
K₂O	1.20	1.53	1.22	1.48	1.09	1.50
P₂O₅	0.20	0.18	0.20	0.15	0.20	0.15
Pre-normalized Total	98.16	98.89	99.32	98.87	99.49	98.85
LOI %	1.27	0.49	0.23	0.63	0.05	0.44
XRF, unnormalized ppm						
Ni	32	22	28	20	36	20
Cr	39	26	35	21	43	19
Sc	14	12	13	12	15	10
V	120	101	105	89	124	87
Ba	394	409	303	347	269	352
Rb	16	22	18	21	16	22
Sr	534	576	692	555	624	558
Zr	163	161	162	157	128	157
Y	18	16	15	16	18	14
Nb	11.2	11.4	8.8	8.2	8.2	8.1
Ga	19	19	20	19	19	20
Cu	78	39	30	21	27	25
Zn	70	62	73	65	68	62
Pb	6	6	7	6	5	7
La	23	20	17	20	15	19
Ce	43	40	36	37	35	36
Th	3	4	3	3	2	4
Nd	20	18	19	17	19	18
U	1	2	3	2	1	3

Table A2 continued.

Sample ID	MH_P4_E	MH_P4_H	MH_T1_E	MH_T1_H	MH_T2_E	MH_T2_H
Lat	45.400382	45.400382	45.33358	45.33358	45.3324	45.3324
Long	-121.675351	-121.675351	-121.71381	-121.71381	-121.70815	-121.70815
Erupt. U	Main Stage	Main Stage	Timberline	Timberline	Timberline	Timberline
H/E	Enclave	Host	Enclave	Host	Enclave	Host
ICP-MS, ppm						
La	21.86	20.79	16.98	18.09	16.36	18.05
Ce	41.88	41.61	34.81	37.3	35.28	37.25
Pr	5.1	5.16	4.44	4.66	4.64	4.63
Nd	19.67	20.09	17.47	18.38	19.38	18.01
Sm	4.16	4.05	3.78	3.78	4.38	3.73
Eu	1.4	1.32	1.11	1.18	1.46	1.21
Gd	3.87	3.57	3.37	3.42	4.03	3.37
Tb	0.61	0.55	0.52	0.52	0.63	0.52
Dy	3.53	3.2	2.97	3.03	3.64	3.08
Ho	0.67	0.63	0.59	0.59	0.71	0.59
Er	1.87	1.65	1.52	1.54	1.81	1.52
Tm	0.25	0.23	0.21	0.22	0.25	0.22
Yb	1.59	1.45	1.37	1.35	1.48	1.34
Lu	0.25	0.23	0.24	0.22	0.23	0.21
Ba	401	417	300	352	271	353
Th	3.12	3.75	2.73	3.48	2.22	3.46
Nb	12.03	11.59	9.75	8.48	8.38	8.44
Y	17.4	17.04	15.63	15.83	18.41	15.61
Hf	4.19	4.29	4.11	4.16	3.51	4.19
Ta	0.74	0.7	0.65	0.63	0.57	0.63
U	0.94	1.17	0.83	1.1	0.68	1.08
Pb	5.08	5.3	5.63	6.2	4.85	6.64
Rb	14.5	22.6	17.2	21.7	15.2	21
Cs	0.32	0.37	0.39	0.5	0.38	0.47
Sr	534	612	723	576	642	562
Sc	15.5	14.2	14.5	11.7	16.4	11.6
Zr	166	170	168	162	129	160

Table A1 continued.

Sample ID	MH_T5_E	MH_T7_H	MH_OM1_H
Lat	45.33478	45.33478	45.31367
Long	-121.71305	-121.71305	-121.68083
Erupt. U	Timberline	Timberline	Old Maid
H/E	Enclave	Host	Host
XRF Normalized Major Elements (Weight %), 100% volatile free:			
SiO₂	58.88	63.95	63.04
TiO₂	0.89	0.72	0.80
Al₂O₃	17.95	16.91	16.94
FeO*	6.18	4.82	5.47
MnO	0.10	0.08	0.09
MgO	3.54	2.38	2.46
CaO	6.97	5.23	5.38
Na₂O	3.88	4.23	4.16
K₂O	1.45	1.52	1.45
P₂O₅	0.16	0.16	0.19
Pre-normalized Total	99.02	98.54	99.23
LOI %	0.58	0.96	0.20
XRF, unnormalized ppm			
Ni	29	19	20
Cr	29	20	23
Sc	14	11	11
V	127	85	71
Ba	276	353	353
Rb	19	22	21
Sr	644	546	535
Zr	128	160	169
Y	16	16	17
Nb	7.0	8.2	9.8
Ga	20	20	20
Cu	36	20	29
Zn	65	61	64
Pb	12	7	4
La	14	17	18
Ce	32	38	42
Th	3	4	4
Nd	18	19	22
U	2	1	2

Table A2 continued.

Sample ID	MH_T5_E	MH_T7_H	MH_OM1_H
Lat	45.33478	45.33478	45.31367
Long	-121.71305	-121.71305	-121.68083
Erupt. U	Timberline	Timberline	Old Maid
H/E	Enclave	Host	Host
ICP-MS, ppm			
La	14.66	18.21	19.92
Ce	31.46	37.29	41.09
Pr	4.01	4.61	5.07
Nd	16.52	18.11	19.83
Sm	3.62	3.74	4.17
Eu	1.23	1.19	1.27
Gd	3.39	3.34	3.72
Tb	0.54	0.51	0.57
Dy	3.05	3	3.3
Ho	0.59	0.58	0.64
Er	1.54	1.53	1.64
Tm	0.22	0.22	0.23
Yb	1.35	1.37	1.45
Lu	0.21	0.21	0.23
Ba	276	357	355
Th	2.34	3.59	3.45
Nb	6.8	8.45	9.7
Y	15.66	15.27	16.69
Hf	3.35	4.26	4.34
Ta	0.48	0.64	0.71
U	0.74	1.14	1.05
Pb	11.35	7.03	4.08
Rb	17.4	21.8	20.4
Cs	0.32	0.51	0.4
Sr	650	547	536
Sc	15.5	11.3	11.4
Zr	129	162	171

APPENDIX B – Crystallinity Images

Figure B1: Crystallinity image for host lava of sample MH0205L from the Meadows location of the Main Stage eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$) and red indicates micro-phenocrysts ($200 - 450 \mu\text{m}$).

1 cm

Figure B2: Crystallinity image for enclave lava of sample MH0205L from the Meadows location of the Main Stage eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

1 cm

Figure B3: Crystallinity image for host lava of sample MH0205M from the Meadows location of the Main Stage eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$) and red indicates micro-phenocrysts ($200 - 450 \mu\text{m}$).

Figure B4: Crystallinity image for enclave lava of sample MH0205M from the Meadows location of the Main Stage eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

Figure B5: Crystallinity image for host lava of sample MH0211-2 from the Compass Creek Location of the Main Stage eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$) and red indicates micro-phenocrysts ($200 - 450 \mu\text{m}$).

1 cm

Figure B6: Crystallinity image for host lava of sample MH_P1 from the location of the Main Stage eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

Figure B7: Crystallinity image for enclave lava of sample MH_P1 from the location of the Main Stage eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

1 cm

Figure B8: Crystallinity image for host lava of sample MH_P3 from the location of the Main Stage eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

1 cm

Figure B9: Crystallinity image for enclave lava of sample MH_P3 from the location of the Main Stage eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

1 cm

Figure B10: Crystallinity image for host lava of sample MH_T2 from the Timberline eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

1 cm

Figure B11: Crystallinity image for enclave lava of sample MH_T2 from the Timberline eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

1 cm

Figure B12: Crystallinity image for host lava of sample MH_T7 from the Timberline eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

1 cm

Figure B12: Crystallinity image for enclave lava of sample MH_T7 from the Timberline eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

1 cm

Figure B13: Crystallinity image for host lava of sample MH_OM1 from the Old Maid eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

1 cm

Figure B14: Crystallinity image for enclave lava of sample MH_OM1 from the Old Maid eruptive period. Yellow indicates phenocrysts ($> 450 \mu\text{m}$).

APPENDIX C – Vesicularity Images

Figure C1: BSD image of host lava from sample MH_P1 from the Main Stage eruptive unit with thresholding (red) for vesicularity analysis.

1 mm

1 mm

Figure C2: BSD image of enclave lava from sample MH_P1 from the Main Stage eruptive unit with thresholding (red) for vesicularity analysis.

Figure C3: BSD image of host lava from sample MH_T2 from the Timberline eruptive unit with thresholding (red) for vesicularity analysis.

Figure C4: BSD image of enclave lava from sample MH_T2 from the Timberline eruptive unit with thresholding (red) for vesicularity analysis.

Figure C5: BSD image of host lava from sample MH_OM1 from the Old Maid eruptive unit with thresholding (red) for vesicularity analysis.

Figure C6: BSD image of enclave lava from sample MH_OM1 from the Old Maid eruptive unit with thresholding (red) for vesicularity analysis.

APPENDIX D – ASPECT input files

Model Scenario 1.1 (S1.1)

```
# Scenario 1.1 - 1 m dike emplaced in host

set Additional shared libraries = ./libcosta.so

set Dimension = 2

set Use years in output instead of seconds = false
set Start time = 0
set End time = 1.0e100
set Output directory = scenario1_5
set Use conduction timestep = true
set Pressure normalization = volume

subsection Geometry model
  set Model name = box
  subsection Box
    set X extent = 100.0 # (m)
    set Y extent = 100.0 # (m)
  end
end

##### Velocity model #####
## Boundary Conditions: free-slip

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, bottom,
top
  set Zero velocity boundary indicators =
  set Prescribed velocity boundary indicators =
end

##### Material Model #####
subsection Material model
  set Model name = Costa

  subsection Costa
    set Minimum viscosity = 12.71879
    set Maximum viscosity = 1.0e6
    set Reference strain rate = 1e-4
    set Minimum strain rate = 1e-6
    set Densities = 2438
    set Reference temperature = 750
    set Reference viscosity = 1e6
    set Thermal expansivities = 5e-5
    set Heat capacities = 130 # From MELTS
```



```

end

    set Material averaging          = harmonic average
end

subsection Gravity model
    set Model name = vertical
    subsection Vertical
        set Magnitude = 10
    end
end

##### Discretization #####
subsection Discretization
    set Use discontinuous composition discretization = true
    subsection Stabilization parameters
        set Global composition maximum = 1.0
        set Global composition minimum = 0.0
        set Use limiter for discontinuous composition solution = true
    end
end

##### Temperature #####

subsection Initial temperature model
    set List of model names = function
    subsection Function
        set Variable names      = x, y
        set Function expression = if(y > 50, 750, if(x < 49.5, 750, if(x
> 50.5, 750, 900)));
    end
end

subsection Boundary temperature model
    set Fixed temperature boundary indicators = bottom, top
    set List of model names = initial temperature
    subsection Initial temperature
        set Minimal temperature = 750
        set Maximal temperature = 900
    end
end

##### Composition #####

subsection Compositional fields
    set Number of fields = 1
end

subsection Initial composition model
    set Model name = function
    subsection Function
        set Variable names      = x, y      # Blob -> 1  Host -> 0

```

```

        set Function expression = if(y > 50, 0, if(x < 49.5, 0, if(x >
50.5, 0, 1)));
    end
end

subsection Boundary composition model
    set Fixed composition boundary indicators = bottom
    set List of model names = initial composition
end

##### Refinement #####

subsection Mesh refinement
    set Initial global refinement          = 8
    set Initial adaptive refinement        = 0
    set Strategy                          = composition approximate
gradient, viscosity
    set Time steps between mesh refinement = 0
end

##### Solution parameters #####

subsection Postprocess
    set List of postprocessors = visualization, velocity statistics,
composition statistics
    subsection Visualization
        set Output format          = vtu
        set Time between graphical output = 0
        set Interpolate output      = true
        set List of output variables = density, viscosity, strain rate,
shear stress
    end
end

subsection Checkpointing
set Steps between checkpoint = 500
end

```

Model Scenario 1.2 (S1.2)

```

# Scenario 1.2 - 10 m dike emplaced in host

set Additional shared libraries = ./libcosta.so

set Dimension          = 2

set Use years in output instead of seconds = false
set Start time         = 0
set End time           = 1.0e100
set Output directory    = scenario1_6
set Use conduction timestep = true

```

```

set Pressure normalization                = volume

subsection Geometry model
  set Model name = box
  subsection Box
    set X extent  = 100.0                # (m)
    set Y extent  = 100.0                # (m)
  end
end

##### Velocity model #####
## Boundary Conditions: free-slip

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, bottom,
top
  set Zero velocity boundary indicators      =
  set Prescribed velocity boundary indicators =
end

##### Material Model #####
subsection Material model
  set Model name                        = Costa

  subsection Costa
    set Minimum viscosity                = 12.71879
    set Maximum viscosity                = 1.0e6
    set Reference strain rate            = 1e-4
    set Minimum strain rate              = 1e-6
    set Densities                       = 2438
    set Reference temperature            = 750
    set Reference viscosity              = 1e6
    set Thermal expansivities            = 5e-5
    set Heat capacities                  = 130      # From MELTS
  end

  set Material averaging                  = harmonic average
end

subsection Gravity model
  set Model name = vertical
  subsection Vertical
    set Magnitude = 10
  end
end

##### Discretization #####
subsection Discretization
  set Use discontinuous composition discretization = true
  subsection Stabilization parameters
    set Global composition maximum = 1.0
    set Global composition minimum = 0.0

```

```

    set Use limiter for discontinuous composition solution = true
end
end

##### Temperature #####

subsection Initial temperature model
  set List of model names = function
    subsection Function
      set Variable names      = x, y
      set Function expression = if(y > 50, 750, if(x < 45, 750, if(x >
55, 750, 900)));
    end
  end
end

subsection Boundary temperature model
  set Fixed temperature boundary indicators = bottom, top
  set List of model names = initial temperature
  subsection Initial temperature
    set Minimal temperature = 750
    set Maximal temperature = 900
  end
end

##### Composition #####

subsection Compositional fields
  set Number of fields = 1
end

subsection Initial composition model
  set Model name = function
    subsection Function
      set Variable names      = x, y      # Blob -> 1 Host -> 0
      set Function expression = if(y > 50, 0, if(x < 45, 0, if(x > 55,
0, 1)));
    end
  end
end

subsection Boundary composition model
  set Fixed composition boundary indicators = bottom
  set List of model names = initial composition
end

##### Refinement #####

subsection Mesh refinement
  set Initial global refinement      = 8
  set Initial adaptive refinement    = 0
  set Strategy                       = composition approximate
gradient, viscosity
  set Time steps between mesh refinement = 0

```

```

end

##### Solution parameters #####

subsection Postprocess
  set List of postprocessors = visualization, velocity statistics,
  composition statistics
  subsection Visualization
    set Output format = vtu
    set Time between graphical output = 0
    set Interpolate output = true
    set List of output variables = density, viscosity, strain rate,
    shear stress
  end
end

subsection Checkpointing
set Steps between checkpoint = 500
end

```

Model Scenario 2.1 (S2.1)

```

# Scenario 2.1 - 30 m hot underplating layer

set Additional shared libraries = ./libcosta.so

set Dimension = 2

set Use years in output instead of seconds = false
set Start time = 0
set End time = 1.0e100
set Output directory = scenario2_8
set Use conduction timestep = true
set Pressure normalization = volume

subsection Geometry model
  set Model name = box
  subsection Box
    set X extent = 1000.0
    set Y extent = 1000.0
  end
end

##### Velocity model #####
## Boundary Conditions: free-slip

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, bottom,
  top
  set Zero velocity boundary indicators =
end

```

```

##### Material Model #####

subsection Material model
  set Model name = Costa

  subsection Costa
    set Minimum viscosity = 12.71879
    set Maximum viscosity = 1.0e6
    set Reference strain rate = 1e-4
    set Minimum strain rate = 1e-6
    set Densities = 2438, 2314 # host, enclave
    set Reference temperature = 750
    set Reference viscosity = 1e6
    set Thermal expansivities = 5e-5
    set Heat capacities = 130 # From MELTS
  end

  set Material averaging = harmonic average
end

subsection Gravity model
  set Model name = vertical
  subsection Vertical
    set Magnitude = 10
  end
end

##### Discretization #####

subsection Discretization
  set Use discontinuous composition discretization = true
  subsection Stabilization parameters
    set Global composition maximum = 1.0
    set Global composition minimum = 0.0
    set Use limiter for discontinuous composition solution = true
  end
end

##### Temperature #####

subsection Initial temperature model
  set List of model names = function
  subsection Function
    set Variable names = x, y
    set Function constants = pi=3.1415926
    set Function expression = if( (y > 30 + 10 * cos(pi*x/30)) ,
750, 900);
  end
end

subsection Boundary temperature model

```

```

set Fixed temperature boundary indicators = bottom, top
set List of model names = initial temperature
subsection Initial temperature
  set Minimal temperature = 750
  set Maximal temperature = 900
end
end

##### Composition #####

subsection Compositional fields
  set Number of fields = 1
end

subsection Initial composition model
  set Model name = function
  subsection Function
    set Variable names      = x, y      # Blob -> 0  Host -> 1
    set Function constants  = pi=3.1415926
    set Function expression = if((y > 30 + 10 * cos(pi*x/30)) , 0,
1);
  end
end

subsection Boundary composition model
  set Fixed composition boundary indicators = bottom
  set List of model names = initial composition
end

##### Refinement #####

subsection Mesh refinement
  set Initial global refinement      = 8
  set Initial adaptive refinement    = 0
  set Strategy                       = composition approximate
  gradient, viscosity
  set Time steps between mesh refinement = 0
end

##### Parameters describing what to do with the solution

subsection Postprocess
  set List of postprocessors = visualization, velocity statistics,
composition statistics
  subsection Visualization
    set Output format          = vtu
    set Time between graphical output = 0
    set Interpolate output      = true
    set List of output variables = density, viscosity, strain rate,
shear stress
  end
end

```

```
subsection Checkpointing
  set Steps between checkpoint = 500
end
```

Model Scenario 2.2 (S2.2)

```
# Scenario 2.2 - 60 m hot underplating layer

set Additional shared libraries = ./libcosta.so

set Dimension = 2

set Use years in output instead of seconds = false
set Start time = 0
set End time = 1.0e100
set Output directory = scenario2_9
set Use conduction timestep = true
set Pressure normalization = volume

subsection Geometry model
  set Model name = box
  subsection Box
    set X extent = 1000.0
    set Y extent = 1000.0
  end
end

##### Velocity model #####
## Boundary Conditions: free-slip

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, bottom,
top
  set Zero velocity boundary indicators =
end

##### Material Model #####

subsection Material model
  set Model name = Costa

  subsection Costa
    set Minimum viscosity = 12.71879
    set Maximum viscosity = 1.0e6
    set Reference strain rate = 1e-4
    set Minimum strain rate = 1e-6
    set Densities = 2438, 2314 # host, enclave
    set Reference temperature = 750
    set Reference viscosity = 1e6
    set Thermal expansivities = 5e-5
```



```

        set Heat capacities          = 130          # From MELTS

    end

    set Material averaging          = harmonic average
end

subsection Gravity model
    set Model name = vertical
    subsection Vertical
        set Magnitude = 10
    end
end

##### Discretization #####

subsection Discretization
    set Use discontinuous composition discretization = true
    subsection Stabilization parameters
        set Global composition maximum = 1.0
        set Global composition minimum = 0.0
        set Use limiter for discontinuous composition solution = true
    end
end

##### Temperature #####

subsection Initial temperature model
    set List of model names = function
    subsection Function
        set Variable names      = x, y
        set Function constants  = pi=3.1415926
        set Function expression = if( (y > 60 + 10 * cos(pi*x/30)) ,
750, 900);
    end
end

subsection Boundary temperature model
    set Fixed temperature boundary indicators = bottom, top
    set List of model names = initial temperature
    subsection Initial temperature
        set Minimal temperature = 750
        set Maximal temperature = 900
    end
end

##### Composition #####

subsection Compositional fields
    set Number of fields = 1
end

```

```

subsection Initial composition model
  set Model name = function
  subsection Function
    set Variable names      = x, y      # Blob -> 0  Host -> 1
    set Function constants  = pi=3.1415926
    set Function expression = if((y > 60 + 10 * cos(pi*x/30)) , 0,
1);
  end
end

subsection Boundary composition model
  set Fixed composition boundary indicators = bottom
  set List of model names = initial composition
end

##### Refinement #####

subsection Mesh refinement
  set Initial global refinement      = 8
  set Initial adaptive refinement    = 0
  set Strategy                       = composition approximate
gradient, viscosity
  set Time steps between mesh refinement = 0
end

##### Parameters describing what to do with the solution

subsection Postprocess
  set List of postprocessors = visualization, velocity statistics,
composition statistics
  subsection Visualization
    set Output format          = vtu
    set Time between graphical output = 0
    set Interpolate output      = true
    set List of output variables = density, viscosity, strain rate,
shear stress
  end
end

subsection Checkpointing
  set Steps between checkpoint = 500
end

```

Model Scenario 2.3 (S2.3)

```

# Scenario 2.3 - 30 m cooler underplating layer

set Additional shared libraries = ./libcosta.so

set Dimension                      = 2

```

```

set Use years in output instead of seconds = false
set Start time                             = 0
set End time                               = 1.0e100
set Output directory                       = scenario2_7
set Use conduction timestep                = true
set Pressure normalization                 = volume

subsection Geometry model
  set Model name = box
  subsection Box
    set X extent  = 1000.0
    set Y extent  = 1000.0
  end
end

##### Velocity model #####
## Boundary Conditions: free-slip

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, bottom,
top
  set Zero velocity boundary indicators      =
end

##### Material Model #####

subsection Material model
  set Model name                        = Costa

  subsection Costa
    set Minimum viscosity                = 12.71879
    set Maximum viscosity                = 1.0e6
    set Reference strain rate            = 1e-4
    set Minimum strain rate              = 1e-6
    set Densities                       = 2438, 2314      # host, enclave
    set Reference temperature            = 900
    set Reference viscosity              = 3e2
    set Thermal expansivities            = 5e-5
    set Heat capacities                  = 130             # From MELTS
  end

  set Material averaging                 = harmonic average
end

subsection Gravity model
  set Model name = vertical
  subsection Vertical
    set Magnitude = 10
  end
end

```

```

##### Discretization #####

subsection Discretization
  set Use discontinuous composition discretization = true
  subsection Stabilization parameters
    set Global composition maximum = 1.0
    set Global composition minimum = 0.0
    set Use limiter for discontinuous composition solution = true
  end
end

##### Temperature #####

subsection Initial temperature model
  set List of model names = function
  subsection Function
    set Variable names      = x, y
    set Function constants  = pi=3.1415926
    set Function expression = if( (y > 30 + 10 * cos(pi*x/30)) ,
900, 800);
  end
end

subsection Boundary temperature model
  set Fixed temperature boundary indicators = bottom, top
  set List of model names = initial temperature
  subsection Initial temperature
    set Minimal temperature = 800
    set Maximal temperature = 900
  end
end

##### Composition #####

subsection Compositional fields
  set Number of fields = 1
end

subsection Initial composition model
  set Model name = function
  subsection Function
    set Variable names      = x, y      # Blob -> 0  Host -> 1
    set Function constants  = pi=3.1415926
    set Function expression = if((y > 30 + 10 * cos(pi*x/30)) , 0,
1);
  end
end

subsection Boundary composition model
  set Fixed composition boundary indicators = bottom
  set List of model names = initial composition
end

```

```
##### Refinement #####

subsection Mesh refinement
  set Initial global refinement      = 8
  set Initial adaptive refinement    = 0
  set Strategy                       = composition approximate
gradient, viscosity
  set Time steps between mesh refinement = 0
end

##### Parameters describing what to do with the solution

subsection Postprocess
  set List of postprocessors = visualization, velocity statistics,
composition statistics
  subsection Visualization
    set Output format          = vtu
    set Time between graphical output = 0
    set Interpolate output      = true
    set List of output variables = density, viscosity, strain rate,
shear stress
  end
end

subsection Checkpointing
set Steps between checkpoint = 500
end
```

Model Scenario 3.1 (S3.1)

```
# Scenario 3.1 - Injection into convecting host - initial temp
perturbation to initiate convection

set Additional shared libraries = ./libcosta.so

set Dimension                = 2

set Use years in output instead of seconds = false
set Start time                = 0
set End time                  = 1.0e7
set Output directory          = scenario3.16
set Use conduction timestep    = true
set Pressure normalization    = volume

set Resume computation        = false

subsection Termination criteria
  set Termination criteria = end step
  set End step = 3000
  set Checkpoint on termination = true
```

```

end

subsection Geometry model
  set Model name = box
  subsection Box
    set X extent = 500.0
    set Y extent = 500.0
  end
end

##### Velocity model #####
## Boundary Conditions: free-slip

subsection Boundary velocity model
  set Tangential velocity boundary indicators = left, right, top,
bottom
  set Zero velocity boundary indicators =
end

##### Material Model #####
subsection Material model
  set Model name = Costa

  subsection Costa
    set Minimum viscosity = 12.71879
    set Maximum viscosity = 1.0e6
    set Reference strain rate = 1e-4
    set Minimum strain rate = 1e-6
    set Densities = 2453
    set Reference temperature = 800
    set Reference viscosity = 1e6
    set Thermal expansivities = 5e-5
    set Heat capacities = 130 # From MELTS
  end

  set Material averaging = harmonic average
end

subsection Gravity model
  set Model name = vertical
  subsection Vertical
    set Magnitude = 10
  end
end

##### Discretization #####

subsection Discretization
  set Use discontinuous composition discretization = true
  subsection Stabilization parameters

```

```

        set Global composition maximum = 1.0
        set Global composition minimum = 0.0
        set Use limiter for discontinuous composition solution = true
    end
end

##### Temperature #####

subsection Initial temperature model
    set List of model names = function
    subsection Function
        set Variable names      = x, y
        set Function constants  = pi=3.1415926
        set Function expression = if( (y > 45 + 35 *cos(pi*x/500)) ,
800, 820);
    end
end

subsection Boundary temperature model
    set Fixed temperature boundary indicators = bottom, top
    set List of model names = initial temperature
    subsection Initial temperature
        set Minimal temperature = 790
        set Maximal temperature = 950
    end
end

##### Composition #####

subsection Compositional fields
    set Number of fields = 1
end

subsection Initial composition model
    set Model name = function
    subsection Function
        set Variable names      = x, y
        set Function expression = 1, 0
    end
end

##### Refinement #####

subsection Mesh refinement
    set Initial global refinement      = 6
    set Initial adaptive refinement    = 0
    set Strategy                       = composition approximate
gradient, viscosity
    set Time steps between mesh refinement = 0
end

##### Solution parameters #####

```

```

subsection Postprocess
  set List of postprocessors = visualization, velocity statistics,
composition statistics
  subsection Visualization
    set Output format          = vtu
    set Time between graphical output = 0.0
    set Interpolate output     = true
    set List of output variables = density, viscosity, strain rate,
shear stress
  end
end

```

```

subsection Checkpointing
set Steps between checkpoint = 500
end

```

```

# Scenario 3.1 - Injection into convecting host - injection onset

```

```

set Additional shared libraries = ./libcosta.so

```

```

set Dimension          = 2

```

```

set Use years in output instead of seconds = false
set Start time          = 0
set End time            = 1.0e9
set Output directory    = scenario3.16
set Use conduction timestep = true
set Pressure normalization = volume

```

```

set Resume computation          = true

```

```

subsection Termination criteria
  set Termination criteria = end time
  set End step = 3000
  set Checkpoint on termination = true
end

```

```

subsection Geometry model
  set Model name = box
  subsection Box
    set X extent = 500.0
    set Y extent = 500.0
  end
end

```

```

##### Velocity model #####
## Boundary conditions: free-slip - left, right and no-slip -
bottom, top

```

```

subsection Boundary velocity model

```



```

    set Tangential velocity boundary indicators = left, right
    set Zero velocity boundary indicators      =
    set Prescribed velocity boundary indicators = bottom y:function,
top y:function      #inflow;outflow
    subsection Function
        set Variable names          = x, y
        set Function expression      = 0; if(x < 249.5, 0, if (x >
250.5, 0, 1e-1))
    end
end

##### Material Model #####
subsection Material model
    set Model name                    = Costa

    subsection Costa
        set Minimum viscosity          = 12.71879
        set Maximum viscosity          = 1.0e6
        set Reference strain rate      = 1e-4
        set Minimum strain rate        = 1e-6
        set Densities                  = 2453
        set Reference temperature      = 800
        set Reference viscosity        = 1e6
        set Thermal expansivities      = 5e-5
        set Heat capacities            = 130      # From MELTS
    end

    set Material averaging              = harmonic average
end

subsection Gravity model
    set Model name = vertical
    subsection Vertical
        set Magnitude = 10
    end
end

##### Discretization #####
subsection Discretization
    set Use discontinuous composition discretization = true
    subsection Stabilization parameters
        set Global composition maximum = 1.0
        set Global composition minimum = 0.0
        set Use limiter for discontinuous composition solution = true
    end
end

##### Temperature #####

subsection Initial temperature model
    set List of model names = function
    subsection Function

```

```

        set Variable names      = x, y
        set Function expression = if(y > 10, 800, if(x < 249.5, 820,
if(x > 250.5, 820, 830)));
    end
end

subsection Boundary temperature model
    set Fixed temperature boundary indicators = bottom, top
    set List of model names = initial temperature
    subsection Initial temperature
        set Minimal temperature = 790
        set Maximal temperature = 950
    end
end

##### Composition #####

subsection Compositional fields
    set Number of fields = 1
end

subsection Initial composition model
    set Model name = function
    subsection Function
        set Variable names      = x, y      # Blob -> 1 Host -> 0
        set Function expression = if(y > 10, 1, if(x < 249.5, 1, if(x >
250.5, 1, 0)));
    end
end

subsection Boundary composition model
    set Fixed composition boundary indicators = bottom
    set List of model names = initial composition
end

##### Refinement #####

subsection Mesh refinement
    set Initial global refinement      = 8
    set Initial adaptive refinement    = 0
    set Strategy                      = composition approximate
gradient, viscosity
    set Time steps between mesh refinement = 0
end

##### Solution parameters #####

subsection Postprocess
    set List of postprocessors = visualization, velocity statistics,
composition statistics

```

```
subsection Visualization
    set Output format = vtu
    set Time between graphical output = 0
    set Interpolate output = true
    set List of output variables = density, viscosity, strain rate,
shear stress
end
end

subsection Checkpointing
set Steps between checkpoint = 500
end
```

APPENDIX E – Enclave Abundance Data

Eruptive Unit	Main Stage				Timberline	Old Maid
Location	Compass Creek (E)	Quarry	HWY 26	Meadows	Timberline fan	White River Drainage
Lat/Long	45.400382, -121.675351	45.308167, -121.705882	45.29537, -121.73433	45.34392, -121.67223	45.33834, -121.71344	45.31367, -121.68083
Point	8.5	1	0	10	1	9
Count	6.5	9.5	0	1	0.75	4
	7	0	2	12	0	2
	0	2.25	2.5	9	0	4
	0	0	5	9	0	0
	7	3	5	13	0	0
	5	1	0	35	1	0
	1	3	6	4	0	0
	3.5	1	0	9	0.5	0
	10.5	1.5	0	8	2	0
	3	4.5	0	7	0	0
	4	4	4	11	0	7
	9	3.5	3	5	2	0
	0	7.5	2.5	1	0.75	0
	5	78	1	11	0	0
	2.5	3.5	4	6	0	2.5
	4	36	0	1	2.75	0
	2.5	6	0	0	0	3
	4.5	0	0	4.5	0	0
	6.5	19	2	7	1	0.25
	2.5	0	9	30	2	0
	6.5	0	4	13	8	0
	1	0	3	3	0	0
	2.5	6	1	2.5	0	1
	5	10.5	0	28	0	0
	5	1	4	9	0	1.5
	0.5	19	3.5	1	0	1.25
	4	0	7.5	8	0	0
	3.5	8.5	0	1.5	0	0
	1	0	8	1	0	0
	2.5	7	1	4	0	0
	4.5	1	1.5	5	1	0
	1.5	6.5	1.5	7	0	
	13	0	4	12	0	
	1	0	1	11.5	0	
	8.5	0	0.5	4	0	
	3	10	0	23	0	
	1	3	0	5	1	
	3.75	5	0	1.75	0	
	0	1.75	0	12	1.25	
	1.5	0	0	3	5	
	1.75	4	0	4	0	

4	0	2.75	0.5	0
7.5	1.5	0	0	0
10	1	0	0	0
8	6	0	2	0
5	0	3.5	0.5	0
10	4	1	0	0
7	12	0	0	0
8	3	0	3	0
10	2.75	0	0	0
5	0	0	0	0
8	3	0	0	11
11	4	0	0	0
2.5	0	0	0	0
13	0	0	1	0
6	7	0	0	0
6	0	0	0	0
7	0	0	0	0
9	0.5	0	0	0
9	7	4	0	1.75
5	0	4.25	0	0
3	0	6.5	0	0
6	4.5	0	2	0
7	3.5	0	1	0
4	0	0	4	0
7	0	0	0.5	0
2	0	0	1	0
5	0	3	9	0
4	0	2	15	0
7	1	1	0	0
4	0	0	1	0
1.75	0	0	4	0
7	0	0	0.5	1
9	0	2	1	4.5
3	0	0	5	1
3	0	0	0	0
4	0	2.5	6	0
3	3	0	8	0
5	0	0	5.5	0
13	0	0	0	0
8	12	3	3.5	0
	0	2	4	0
	33	0	7	1
	6	0	1	0
	2	0	8	0
	1	0	0	1
	0	0	4	3
	0	0	2	0
	3	2	3	4
	8	0	5	2
	0	0	8	0
	2	0	12	0
	0	0	2	1

0	0	5	0
3	0	2	0
3	0	8	0
5	0	9	1.5
0	0	3.5	0
1	0	4.75	0
0	18	7	0
4	0	9	0
0	0	16	0
0	0	13	1
0	0	9	0
0	0	11	1
0	0	7	0
0	3	3	0
2	0	0	0
3	0	0	0
3	0	1	2
2	0	0	0
0	0	0	0
0	4.5	10	0
	0	5	0
	5	14	0
	0	8	0
	0	8	0
	4.75	4	0
	2	5	0
	5	4	1.5
	1.5	5	0
	2.5	4	0
	0		0
	0		0
	3		0
	0		1.25
	0		0
	3		0
	1.5		0
	0		0
	0		0.75
	0		0
	0		0
	6		1
	4		0
	10		0
	3		0
	3.5		0
	4		0
	0		0
	0		5
	10		0
	7		0
	0		0
	0		0

0	0
0	2
7	0
4	0
9	0
0	0
0	0
0	2.5
0	0
0	0
0	0
1	0
0	2.5
0	0
0	0
0	0
0	1
0	3
3	0
12	0
0	0
0	0
0	5
0	0
0	1
2	0
0.5	0
1	0
4	0
0	0
0	0
0	0
0	0
5	0
	0
	0
	0
	0
	0
	0
	0
	0

APPENDIX F – Enclave Size and Shape Data

Eruptive Unit	Location	Area (cm ²)	Diameter (cm)	Perimeter (cm)	Circularity	Aspect Ratio
Main Stage	HWY 26	10.97	3.31	13.02	0.81	1.38
Main Stage	HWY 26	7.50	2.74	12.42	0.61	1.93
Main Stage	HWY 26	19.20	4.38	19.62	0.63	2.40
Main Stage	HWY 26	3.03	1.74	8.41	0.54	1.90
Main Stage	HWY 26	9.30	3.05	12.92	0.70	1.40
Main Stage	HWY 26	38.70	6.22	24.52	0.81	1.18
Main Stage	HWY 26	7.58	2.75	11.34	0.74	1.35
Main Stage	HWY 26	6.16	2.48	13.97	0.40	2.06
Main Stage	HWY 26	1.44	1.20	4.97	0.73	1.66
Main Stage	HWY 26	3.21	1.79	7.88	0.65	1.79
Main Stage	HWY 26	2.13	1.46	5.52	0.88	1.32
Main Stage	HWY 26	2.77	1.66	6.48	0.83	1.15
Main Stage	HWY 26	4.40	2.10	8.82	0.71	1.24
Main Stage	HWY 26	3.12	1.77	8.18	0.59	1.06
Main Stage	HWY 26	3.40	1.84	7.15	0.84	1.45
Main Stage	HWY 26	44.04	6.64	28.82	0.67	1.39
Main Stage	HWY 26	6.74	2.60	11.84	0.60	1.58
Main Stage	HWY 26	114.96	10.72	44.36	0.73	1.78
Main Stage	HWY 26	3.09	1.76	7.07	0.78	1.78
Main Stage	HWY 26	39.87	6.31	28.71	0.61	2.04
Main Stage	HWY 26	35.60	5.97	24.30	0.76	1.80
Main Stage	HWY 26	13.43	3.66	15.34	0.72	1.66
Main Stage	HWY 26	3.44	1.85	7.96	0.68	2.26
Main Stage	HWY 26	7.40	2.72	11.48	0.71	2.01
Main Stage	HWY 26	6.79	2.61	11.12	0.69	1.53
Main Stage	HWY 26	0.65	0.80	3.24	0.78	1.71
Main Stage	HWY 26	2.70	1.64	6.84	0.72	1.59
Main Stage	HWY 26	0.86	0.93	3.65	0.81	1.50
Main Stage	HWY 26	32.45	5.70	24.95	0.66	1.84
Main Stage	HWY 26	14.43	3.80	15.89	0.72	1.65
Main Stage	HWY 26	4.09	2.02	8.84	0.66	2.11
Main Stage	HWY 26	8.61	2.93	12.20	0.73	2.06
Main Stage	HWY 26	7.12	2.67	11.57	0.67	1.61
Main Stage	HWY 26	42.81	6.54	29.12	0.63	1.90
Main Stage	HWY 26	11.08	3.33	13.15	0.81	1.25
Main Stage	HWY 26	7.62	2.76	11.43	0.73	1.33
Main Stage	HWY 26	30.89	5.56	25.75	0.59	2.48
Main Stage	HWY 26	12.84	3.58	15.81	0.65	2.03
Main Stage	HWY 26	14.49	3.81	24.45	0.31	3.51

Main Stage	HWY 26	3.85	1.96	7.98	0.76	1.51
Main Stage	Meadows	64.22	8.01	31.03	0.84	1.58
Main Stage	Meadows	6.82	2.61	10.55	0.77	1.38
Main Stage	Meadows	16.60	4.07	17.64	0.67	1.12
Main Stage	Meadows	1.96	1.40	5.82	0.73	1.97
Main Stage	Meadows	23.64	4.86	20.84	0.68	1.44
Main Stage	Meadows	0.50	0.71	2.95	0.72	2.47
Main Stage	Meadows	1.92	1.39	5.78	0.72	1.92
Main Stage	Meadows	2.14	1.46	6.42	0.65	2.19
Main Stage	Meadows	0.44	0.66	2.71	0.75	1.09
Main Stage	Meadows	0.45	0.67	3.02	0.62	2.35
Main Stage	Meadows	11.14	3.34	14.27	0.69	1.96
Main Stage	Meadows	3.84	1.96	8.76	0.63	2.21
Main Stage	Meadows	4.47	2.11	8.42	0.79	1.38
Main Stage	Meadows	0.65	0.81	3.27	0.76	1.58
Main Stage	Meadows	4.95	2.22	8.92	0.78	1.93
Main Stage	Meadows	3.30	1.82	7.12	0.82	1.05
Main Stage	Meadows	28.04	5.30	21.62	0.75	1.88
Main Stage	Meadows	0.48	0.69	3.52	0.48	2.78
Main Stage	Meadows	3.56	1.89	8.08	0.68	2.03
Main Stage	Meadows	119.38	10.93	45.08	0.74	1.44
Main Stage	Meadows	1.40	1.18	4.70	0.79	1.77
Main Stage	Meadows	7.00	2.65	11.92	0.62	1.18
Main Stage	Meadows	51.94	7.21	34.01	0.56	1.67
Main Stage	Meadows	5.60	2.37	11.79	0.51	2.30
Main Stage	Meadows	2.47	1.57	6.36	0.77	1.61
Main Stage	Meadows	0.98	0.99	4.87	0.52	2.18
Main Stage	Meadows	0.71	0.84	3.44	0.75	1.48
Main Stage	Meadows	0.64	0.80	3.18	0.80	1.23
Main Stage	Meadows	3.98	1.99	8.47	0.70	1.51
Main Stage	Meadows	4.85	2.20	8.71	0.80	1.56
Main Stage	Meadows	2.42	1.56	6.25	0.78	1.48
Main Stage	Meadows	2.99	1.73	7.77	0.62	2.39
Main Stage	Meadows	0.96	0.98	4.15	0.70	2.44
Main Stage	Meadows	1.08	1.04	4.12	0.80	1.15
Main Stage	Meadows	0.34	0.59	2.55	0.67	1.41
Main Stage	Meadows	0.94	0.97	4.75	0.53	1.67
Main Stage	Meadows	0.62	0.79	3.02	0.85	1.45
Main Stage	Meadows	0.64	0.80	3.65	0.60	2.31
Main Stage	Meadows	0.26	0.51	2.31	0.63	1.39
Main Stage	Meadows	0.36	0.60	2.57	0.68	1.25
Main Stage	Meadows	1.35	1.16	5.22	0.62	2.08
Main Stage	Meadows	0.30	0.55	2.10	0.85	1.41

Main Stage	Meadows	0.31	0.55	2.17	0.82	1.25
Main Stage	Meadows	0.44	0.66	2.74	0.73	1.42
Main Stage	Meadows	0.38	0.62	2.42	0.82	1.42
Main Stage	Meadows	2.47	1.57	7.65	0.53	1.61
Main Stage	Meadows	1.87	1.37	5.65	0.74	1.57
Main Stage	Meadows	9.21	3.03	12.70	0.72	1.58
Main Stage	Meadows	0.76	0.87	3.49	0.78	1.59
Main Stage	Meadows	0.34	0.58	2.37	0.76	1.91
Main Stage	Meadows	0.22	0.47	1.99	0.71	2.02
Main Stage	Meadows	0.69	0.83	3.22	0.84	1.16
Main Stage	Meadows	0.82	0.91	4.20	0.59	2.48
Main Stage	Meadows	5.51	2.35	9.66	0.74	1.95
Main Stage	Meadows	1.81	1.34	5.49	0.75	1.19
Main Stage	Meadows	0.93	0.97	3.92	0.76	1.47
Main Stage	Meadows	0.36	0.60	2.56	0.69	2.37
Main Stage	Meadows	5.83	2.41	11.57	0.55	1.50
Main Stage	Meadows	6.15	2.48	10.00	0.77	1.43
Main Stage	Meadows	4.62	2.15	8.45	0.81	1.69
Main Stage	Meadows	1.13	1.06	4.44	0.72	2.09
Main Stage	Meadows	0.67	0.82	3.29	0.77	1.78
Main Stage	Meadows	2.42	1.55	7.18	0.59	1.71
Main Stage	Meadows	0.48	0.69	2.61	0.89	1.13
Main Stage	Meadows	22.35	4.73	21.72	0.60	2.46
Main Stage	Meadows	0.72	0.85	3.46	0.75	1.87
Main Stage	Meadows	8.20	2.86	12.35	0.68	1.42
Main Stage	Meadows	30.83	5.55	29.48	0.45	2.38
Main Stage	Meadows	94.22	9.71	40.78	0.71	1.41
Main Stage	Meadows	4.15	2.04	8.41	0.74	1.80
Main Stage	Meadows	3.67	1.92	8.42	0.65	1.50
Main Stage	Meadows	1.80	1.34	5.31	0.80	1.39
Main Stage	Meadows	2.39	1.55	7.42	0.55	3.43
Main Stage	Meadows	1.57	1.25	5.33	0.69	1.33
Main Stage	Meadows	1.66	1.29	6.36	0.51	3.03
Main Stage	Meadows	2.25	1.50	6.11	0.76	1.67
Main Stage	Meadows	124.45	11.16	45.77	0.75	1.60
Main Stage	Meadows	25.01	5.00	21.40	0.69	1.66
Main Stage	Meadows	1.65	1.28	5.25	0.75	1.68
Main Stage	Meadows	4.85	2.20	8.95	0.76	1.23
Main Stage	Meadows	10.06	3.17	14.21	0.63	1.99
Main Stage	Meadows	4.21	2.05	8.92	0.67	2.13
Main Stage	Meadows	5.02	2.24	8.81	0.81	1.24
Main Stage	Meadows	53.14	7.29	32.81	0.62	1.96
Main Stage	Meadows	68.69	8.29	31.35	0.88	1.28

Main Stage	Meadows	46.43	6.81	29.81	0.66	2.51
Main Stage	Meadows	18.37	4.29	17.24	0.78	1.43
Main Stage	Meadows	1.74	1.32	4.96	0.89	1.18
Main Stage	Meadows	6.64	2.58	10.27	0.79	1.71
Main Stage	Meadows	95.48	9.77	56.85	0.37	2.16
Main Stage	Meadows	1.26	1.12	4.88	0.67	1.84
Main Stage	Meadows	7.35	2.71	11.74	0.67	1.65
Main Stage	Meadows	52.78	7.26	28.05	0.84	1.60
Main Stage	Meadows	1.86	1.36	5.19	0.87	1.22
Main Stage	Meadows	4.58	2.14	8.16	0.86	1.26
Main Stage	Meadows	113.16	10.64	61.70	0.37	3.48
Main Stage	Meadows	3.49	1.87	7.53	0.77	1.60
Main Stage	Meadows	37.41	6.12	24.85	0.76	1.43
Main Stage	Meadows	11.52	3.39	17.48	0.47	2.87
Main Stage	Meadows	24.37	4.94	19.55	0.80	1.42
Main Stage	Meadows	4.28	2.07	7.98	0.85	1.42
Main Stage	Meadows	3.40	1.84	8.16	0.64	2.69
Main Stage	Meadows	0.93	0.96	4.31	0.63	2.38
Main Stage	Meadows	0.51	0.72	2.90	0.77	1.50
Main Stage	Meadows	1.20	1.10	4.62	0.71	1.85
Main Stage	Meadows	2.88	1.70	9.27	0.42	4.15
Main Stage	Meadows	5.51	2.35	9.58	0.75	1.89
Main Stage	Meadows	4.15	2.04	8.60	0.71	1.55
Main Stage	Meadows	0.62	0.79	3.14	0.79	1.91
Main Stage	Meadows	3.06	1.75	6.59	0.89	1.35
Main Stage	Meadows	1.71	1.31	5.37	0.75	1.89
Main Stage	Meadows	1.30	1.14	5.93	0.46	3.16
Main Stage	Meadows	4.95	2.22	10.72	0.54	3.23
Main Stage	Meadows	0.69	0.83	3.30	0.79	1.10
Main Stage	Meadows	133.28	11.54	67.22	0.37	3.11
Main Stage	Meadows	3.71	1.93	7.39	0.85	1.34
Main Stage	Meadows	1.43	1.19	5.06	0.70	1.79
Main Stage	Meadows	1.29	1.14	4.80	0.70	2.49
Main Stage	Meadows	1.84	1.36	5.25	0.84	1.43
Main Stage	Meadows	15.52	3.94	16.94	0.68	1.86
Main Stage	Meadows	5.75	2.40	9.63	0.78	2.00
Main Stage	Meadows	0.97	0.98	4.19	0.70	2.35
Main Stage	Meadows	6.29	2.51	10.05	0.78	1.11
Main Stage	Meadows	5.67	2.38	9.61	0.77	1.53
Main Stage	Meadows	5.75	2.40	10.65	0.64	2.23
Main Stage	Meadows	4.06	2.01	10.32	0.48	2.76
Main Stage	Meadows	6.07	2.46	13.61	0.41	3.92
Main Stage	Meadows	70.16	8.38	34.88	0.73	1.67

Main Stage	Meadows	13.92	3.73	15.26	0.75	1.59
Main Stage	Meadows	4.05	2.01	8.05	0.79	1.35
Main Stage	Meadows	63.81	7.99	39.81	0.51	1.86
Main Stage	Meadows	4.46	2.11	8.07	0.86	1.43
Main Stage	Meadows	5.38	2.32	8.79	0.88	1.24
Main Stage	Meadows	0.71	0.84	3.56	0.70	1.67
Main Stage	Meadows	31.92	5.65	26.28	0.58	1.64
Main Stage	Meadows	0.36	0.60	2.43	0.77	1.35
Main Stage	Meadows	0.35	0.59	2.43	0.74	1.93
Main Stage	Meadows	0.18	0.42	1.67	0.79	1.13
Main Stage	Meadows	0.23	0.48	1.94	0.77	1.42
Main Stage	Meadows	0.20	0.45	1.76	0.82	1.72
Main Stage	Meadows	8.67	2.94	11.39	0.84	1.40
Main Stage	Meadows	2.86	1.69	8.53	0.49	2.95
Main Stage	Meadows	3.82	1.95	7.20	0.92	1.34
Main Stage	Meadows	3.37	1.83	6.99	0.87	1.19
Main Stage	Meadows	0.52	0.72	3.48	0.54	3.25
Main Stage	Meadows	0.76	0.87	3.32	0.87	1.42
Main Stage	Meadows	7.61	2.76	12.99	0.57	1.10
Main Stage	Meadows	8.51	2.92	13.13	0.62	2.40
Main Stage	Meadows	4.17	2.04	8.35	0.75	1.29
Main Stage	Meadows	0.92	0.96	3.69	0.85	1.64
Main Stage	Meadows	4.83	2.20	8.84	0.78	1.67
Main Stage	Meadows	1.60	1.26	5.48	0.67	1.75
Main Stage	Meadows	3.14	1.77	6.69	0.88	1.14
Main Stage	Meadows	0.12	0.34	1.32	0.83	1.71
Main Stage	Meadows	2.26	1.50	5.86	0.83	1.79
Main Stage	Meadows	2.36	1.54	6.26	0.76	1.69
Main Stage	Meadows	3.76	1.94	7.40	0.86	1.55
Main Stage	Meadows	0.49	0.70	2.83	0.77	1.54
Main Stage	Meadows	0.40	0.63	2.33	0.93	1.02
Main Stage	Meadows	0.47	0.69	2.66	0.84	1.50
Main Stage	Meadows	8.69	2.95	16.94	0.38	2.11
Main Stage	Meadows	0.37	0.60	2.41	0.80	1.78
Main Stage	Meadows	0.43	0.65	2.57	0.81	1.71
Main Stage	Meadows	1.40	1.18	4.60	0.83	1.26
Main Stage	Meadows	17.55	4.19	17.82	0.70	1.76
Main Stage	Meadows	1.41	1.19	5.55	0.58	2.09
Main Stage	Meadows	1.14	1.07	5.34	0.50	3.60
Main Stage	Meadows	1.59	1.26	5.41	0.68	2.50
Main Stage	Meadows	7.87	2.80	11.07	0.81	1.24
Main Stage	Meadows	5.97	2.44	9.30	0.87	1.54
Main Stage	Meadows	9.64	3.10	11.97	0.85	1.14

Main Stage	Meadows	14.22	3.77	14.66	0.83	1.16
Main Stage	Meadows	5.87	2.42	10.56	0.66	1.51
Main Stage	Meadows	2.40	1.55	6.24	0.77	2.13
Main Stage	Meadows	0.53	0.73	2.80	0.85	1.61
Main Stage	Meadows	1.16	1.08	4.17	0.84	1.53
Main Stage	Meadows	1.05	1.02	4.80	0.57	1.06
Main Stage	Meadows	2.69	1.64	6.07	0.92	1.22
Main Stage	Meadows	13.85	3.72	16.20	0.66	1.47
Main Stage	Meadows	1.48	1.21	5.56	0.60	1.96
Main Stage	Meadows	0.87	0.93	3.68	0.81	1.64
Main Stage	Meadows	3.28	1.81	8.31	0.60	1.85
Main Stage	Meadows	1.32	1.15	4.33	0.88	1.14
Main Stage	Meadows	8.39	2.90	12.23	0.71	2.26
Main Stage	Meadows	0.83	0.91	4.41	0.54	2.99
Main Stage	Meadows	2.65	1.63	6.82	0.72	1.78
Main Stage	Meadows	11.72	3.42	14.15	0.74	1.31
Main Stage	Meadows	8.27	2.88	11.10	0.84	1.68
Main Stage	Meadows	3.61	1.90	7.30	0.85	1.36
Main Stage	Meadows	1.40	1.18	5.06	0.69	2.73
Main Stage	Meadows	0.88	0.94	3.60	0.86	1.44
Main Stage	Meadows	3.62	1.90	7.34	0.84	1.37
Main Stage	Meadows	8.70	2.95	13.25	0.62	2.41
Main Stage	Meadows	6.48	2.54	9.87	0.84	1.32
Main Stage	Meadows	4.73	2.17	8.37	0.85	1.13
Main Stage	Meadows	1.71	1.31	4.78	0.94	1.10
Main Stage	Meadows	0.78	0.88	3.38	0.85	1.44
Main Stage	Meadows	0.94	0.97	3.84	0.80	1.85
Main Stage	Meadows	0.85	0.92	4.11	0.64	2.84
Main Stage	Meadows	1.47	1.21	5.36	0.64	1.92
Main Stage	Meadows	1.68	1.30	4.86	0.90	1.25
Main Stage	Meadows	8.12	2.85	11.75	0.74	1.46
Main Stage	Meadows	0.43	0.66	2.45	0.90	1.25
Main Stage	Meadows	4.48	2.12	8.45	0.79	2.00
Main Stage	Meadows	4.34	2.08	8.50	0.76	1.55
Main Stage	Meadows	3.58	1.89	7.57	0.79	1.86
Main Stage	Meadows	1.98	1.41	5.92	0.71	1.84
Main Stage	Meadows	0.29	0.54	2.07	0.86	1.65
Main Stage	Meadows	0.18	0.42	1.69	0.79	1.98
Main Stage	Meadows	0.83	0.91	3.53	0.84	1.49
Main Stage	Meadows	0.49	0.70	2.80	0.78	1.40
Main Stage	Meadows	37.75	6.14	25.29	0.74	1.50
Main Stage	Meadows	5.50	2.34	8.88	0.88	1.17
Main Stage	Meadows	1.20	1.09	4.85	0.64	2.09

Main Stage	Meadows	0.84	0.91	3.92	0.69	1.31
Main Stage	Meadows	6.06	2.46	11.42	0.58	3.38
Main Stage	Meadows	2.68	1.64	6.39	0.83	1.71
Main Stage	Meadows	1.31	1.14	5.02	0.65	2.26
Main Stage	Meadows	1.35	1.16	4.35	0.90	1.37
Main Stage	Meadows	22.50	4.74	20.04	0.70	1.95
Main Stage	Meadows	32.95	5.74	23.94	0.72	1.65
Main Stage	Meadows	1.98	1.41	5.59	0.80	1.80
Main Stage	Meadows	5.98	2.44	9.52	0.83	1.47
Main Stage	Meadows	11.15	3.34	14.24	0.69	2.09
Main Stage	Meadows	2.45	1.56	6.71	0.68	1.83
Main Stage	Meadows	1.72	1.31	5.30	0.77	1.85
Main Stage	Meadows	2.49	1.58	6.85	0.67	2.52
Main Stage	Meadows	3.52	1.88	7.96	0.70	1.65
Main Stage	Meadows	4.71	2.17	9.66	0.64	2.78
Main Stage	Meadows	1.46	1.21	4.93	0.75	1.90
Main Stage	Meadows	11.92	3.45	15.77	0.60	1.37
Main Stage	Meadows	7.07	2.66	13.48	0.49	2.39
Main Stage	Meadows	15.86	3.98	16.28	0.75	1.65
Main Stage	Meadows	7.63	2.76	12.03	0.66	1.42
Main Stage	Meadows	3.13	1.77	7.92	0.63	1.98
Main Stage	Meadows	2.62	1.62	6.09	0.89	1.50
Main Stage	Meadows	0.18	0.42	1.73	0.75	2.23
Main Stage	Meadows	0.75	0.86	3.50	0.77	1.46
Main Stage	Meadows	0.11	0.33	1.20	0.96	1.09
Main Stage	Meadows	2.99	1.73	7.00	0.77	1.08
Main Stage	Meadows	2.20	1.48	5.78	0.83	1.43
Main Stage	Meadows	2.59	1.61	6.31	0.82	1.26
Main Stage	Meadows	5.52	2.35	10.02	0.69	2.25
Main Stage	Meadows	4.85	2.20	9.59	0.66	2.34
Main Stage	Meadows	0.51	0.72	2.98	0.73	1.34
Main Stage	Meadows	31.49	5.61	32.26	0.38	2.71
Main Stage	Meadows	1.14	1.07	4.94	0.59	2.99
Main Stage	Meadows	1.40	1.18	5.15	0.66	2.51
Main Stage	Meadows	0.53	0.73	3.93	0.43	3.25
Main Stage	Meadows	2.61	1.62	8.51	0.45	2.05
Main Stage	Meadows	22.90	4.79	22.23	0.58	1.34
Main Stage	Meadows	17.30	4.16	21.08	0.49	1.91
Main Stage	Meadows	17.11	4.14	17.57	0.70	1.75
Main Stage	Meadows	2.61	1.62	7.32	0.61	1.55
Main Stage	Meadows	27.23	5.22	24.32	0.58	1.86
Main Stage	Meadows	3.98	1.99	8.21	0.74	1.52
Main Stage	Meadows	0.56	0.75	3.23	0.68	2.11

Main Stage	Quarry	13.45	3.67	21.79	0.36	1.57
Main Stage	Quarry	48.11	6.94	38.12	0.42	2.97
Main Stage	Quarry	540.07	23.24	99.19	0.69	1.36
Main Stage	Quarry	194.15	13.93	54.97	0.81	1.42
Main Stage	Quarry	2.25	1.50	6.68	0.64	2.11
Main Stage	Quarry	117.07	10.82	41.62	0.85	1.41
Main Stage	Quarry	2.91	1.71	9.04	0.45	1.69
Main Stage	Quarry	10.19	3.19	12.08	0.88	1.45
Main Stage	Quarry	21.77	4.67	17.83	0.86	1.50
Main Stage	Quarry	4.34	2.08	8.31	0.79	1.39
Main Stage	Quarry	3.97	1.99	7.57	0.87	1.32
Main Stage	Quarry	45.39	6.74	28.47	0.70	1.84
Main Stage	Quarry	121.09	11.00	43.44	0.81	1.66
Main Stage	Quarry	4.91	2.22	8.95	0.77	2.09
Main Stage	Quarry	2.39	1.55	6.14	0.80	1.78
Main Stage	Quarry	71.77	8.47	38.07	0.62	1.72
Main Stage	Quarry	4.57	2.14	9.64	0.62	1.03
Main Stage	Quarry	70.16	8.38	37.53	0.63	1.69
Main Stage	Quarry	1.03	1.01	4.37	0.68	2.37
Main Stage	Quarry	1.01	1.01	4.45	0.64	1.69
Main Stage	Quarry	3.62	1.90	7.62	0.78	1.24
Main Stage	Quarry	4.69	2.17	9.45	0.66	2.26
Main Stage	Quarry	7.55	2.75	10.64	0.84	1.40
Main Stage	Quarry	26.21	5.12	24.24	0.56	2.75
Main Stage	Quarry	4.30	2.07	7.70	0.91	1.20
Main Stage	Quarry	9.34	3.06	13.41	0.65	2.03
Main Stage	Compass Creek	3.18	1.78	7.17	0.78	1.62
Main Stage	Compass Creek	5.13	2.27	9.28	0.75	1.62
Main Stage	Compass Creek	15.60	3.95	15.55	0.81	1.91
Main Stage	Compass Creek	15.87	3.98	15.92	0.79	1.09
Main Stage	Compass Creek	3.08	1.75	7.29	0.73	2.17
Main Stage	Compass Creek	14.73	3.84	14.77	0.85	1.54
Main Stage	Compass Creek	21.20	4.60	17.65	0.86	1.20
Main Stage	Compass Creek	49.63	7.04	28.52	0.77	1.40
Main Stage	Compass Creek	11.42	3.38	12.95	0.86	1.15
Main Stage	Compass Creek	3.42	1.85	7.07	0.86	1.20
Main Stage	Compass Creek	3.29	1.81	7.57	0.72	1.66
Main Stage	Compass Creek	2.19	1.48	5.99	0.77	1.46
Main Stage	Compass Creek	2.59	1.61	6.17	0.85	1.29
Main Stage	Compass Creek	8.25	2.87	11.13	0.84	1.31
Main Stage	Compass Creek	3.48	1.86	7.59	0.76	1.93
Main Stage	Compass Creek	33.42	5.78	23.42	0.77	1.91
Main Stage	Compass Creek	13.74	3.71	14.78	0.79	1.84

Main Stage	Compass Creek	0.52	0.72	2.67	0.92	1.29
Main Stage	Compass Creek	1.48	1.22	4.53	0.91	1.47
Main Stage	Compass Creek	1.01	1.01	5.07	0.50	3.21
Main Stage	Compass Creek	10.00	3.16	12.20	0.84	1.21
Main Stage	Compass Creek	4.97	2.23	8.28	0.91	1.04
Main Stage	Compass Creek	2.88	1.70	7.13	0.71	1.83
Main Stage	Compass Creek	1.05	1.02	4.08	0.79	1.14
Main Stage	Compass Creek	1.29	1.13	4.33	0.86	1.48
Main Stage	Compass Creek	2.83	1.68	7.32	0.66	2.52
Main Stage	Compass Creek	1.24	1.11	4.53	0.76	1.24
Main Stage	Compass Creek	0.69	0.83	3.28	0.80	1.45
Main Stage	Compass Creek	1.24	1.11	4.41	0.80	1.67
Main Stage	Compass Creek	48.33	6.95	27.34	0.81	1.07
Main Stage	Compass Creek	70.79	8.41	33.54	0.79	1.59
Main Stage	Compass Creek	1.50	1.22	4.72	0.85	1.41
Main Stage	Compass Creek	6.10	2.47	9.83	0.79	1.56
Main Stage	Compass Creek	4.24	2.06	7.66	0.91	1.09
Main Stage	Compass Creek	19.53	4.42	22.68	0.48	3.45
Main Stage	Compass Creek	3.20	1.79	6.78	0.88	1.63
Main Stage	Compass Creek	4.01	2.00	8.27	0.74	1.49
Main Stage	Compass Creek	4.47	2.11	7.85	0.91	1.20
Main Stage	Compass Creek	13.07	3.62	14.68	0.76	1.11
Main Stage	Compass Creek	7.03	2.65	13.66	0.47	1.55
Main Stage	Compass Creek	12.25	3.50	17.20	0.52	3.23
Main Stage	Compass Creek	3.63	1.91	8.37	0.65	2.42
Main Stage	Compass Creek	0.37	0.61	2.49	0.75	2.26
Main Stage	Compass Creek	10.20	3.19	12.71	0.79	1.16
Main Stage	Compass Creek	3.41	1.85	7.49	0.77	1.94
Main Stage	Compass Creek	5.35	2.31	9.32	0.77	2.02
Main Stage	Compass Creek	2.06	1.43	5.40	0.89	1.07
Main Stage	Compass Creek	0.34	0.58	3.22	0.41	3.23
Main Stage	Compass Creek	0.52	0.72	3.24	0.62	2.48
Main Stage	Compass Creek	3.49	1.87	7.19	0.85	1.11
Main Stage	Compass Creek	0.55	0.74	3.02	0.76	1.38
Main Stage	Compass Creek	0.26	0.50	1.92	0.87	1.45
Main Stage	Compass Creek	2.28	1.51	5.58	0.92	1.06
Main Stage	Compass Creek	0.43	0.66	2.41	0.94	1.08
Main Stage	Compass Creek	0.75	0.87	3.24	0.90	1.16
Main Stage	Compass Creek	0.46	0.68	2.55	0.88	1.15
Main Stage	Compass Creek	0.92	0.96	3.71	0.84	1.28
Main Stage	Compass Creek	3.71	1.93	7.97	0.74	2.25
Main Stage	Compass Creek	0.39	0.62	2.69	0.67	1.37
Main Stage	Compass Creek	0.31	0.56	2.17	0.83	1.60

Main Stage	Compass Creek	0.15	0.39	1.45	0.91	1.09
Main Stage	Compass Creek	2.69	1.64	6.68	0.76	1.76
Main Stage	Compass Creek	0.33	0.58	2.23	0.84	1.42
Main Stage	Compass Creek	0.52	0.72	2.95	0.75	1.69
Main Stage	Compass Creek	0.82	0.90	3.40	0.89	1.19
Main Stage	Compass Creek	1.01	1.00	4.19	0.72	1.16
Main Stage	Compass Creek	1.57	1.25	4.88	0.83	1.27
Main Stage	Compass Creek	1.33	1.15	4.43	0.85	1.24
Main Stage	Compass Creek	2.64	1.62	6.72	0.73	1.16
Main Stage	Compass Creek	0.89	0.94	3.54	0.89	1.19
Main Stage	Compass Creek	31.80	5.64	24.08	0.69	2.12
Main Stage	Compass Creek	0.59	0.77	3.11	0.76	1.08
Main Stage	Compass Creek	8.12	2.85	11.23	0.81	1.40
Main Stage	Compass Creek	20.72	4.55	17.10	0.89	1.12
Main Stage	Compass Creek	10.30	3.21	12.95	0.77	1.27
Main Stage	Compass Creek	10.51	3.24	13.49	0.73	1.72
Main Stage	Compass Creek	0.57	0.75	2.89	0.86	1.31
Main Stage	Compass Creek	1.20	1.09	4.53	0.73	2.11
Main Stage	Compass Creek	0.81	0.90	3.42	0.87	1.50
Main Stage	Compass Creek	0.92	0.96	3.59	0.90	1.45
Main Stage	Compass Creek	48.53	6.97	28.13	0.77	1.48
Timberline	Timberline	3.59	1.90	7.39	0.83	1.18
Timberline	Timberline	4.49	2.12	8.16	0.85	1.14
Timberline	Timberline	8.39	2.90	10.80	0.90	1.39
Timberline	Timberline	9.05	3.01	11.68	0.83	1.26
Timberline	Timberline	1.81	1.35	5.07	0.89	1.32
Timberline	Timberline	2.90	1.70	6.61	0.84	1.65
Timberline	Timberline	1.02	1.01	5.06	0.50	2.11
Timberline	Timberline	4.65	2.16	8.08	0.89	1.35
Timberline	Timberline	15.98	4.00	16.33	0.75	1.19
Timberline	Timberline	6.95	2.64	10.17	0.84	1.23
Timberline	Timberline	6.95	2.64	10.17	0.84	1.23
Timberline	Timberline	6.24	2.50	9.79	0.82	1.48
Timberline	Timberline	10.67	3.27	13.47	0.74	1.56
Timberline	Timberline	3.35	1.83	6.83	0.90	1.12
Timberline	Timberline	9.32	3.05	14.81	0.53	3.65
Timberline	Timberline	21.72	4.66	17.98	0.84	1.64
Timberline	Timberline	8.39	2.90	11.78	0.76	1.24
Timberline	Timberline	10.76	3.28	13.01	0.80	1.12
Timberline	Timberline	3.56	1.89	7.89	0.72	2.26
Timberline	Timberline	16.16	4.02	15.70	0.82	1.34
Timberline	Timberline	12.75	3.57	14.10	0.81	1.31
Timberline	Timberline	14.81	3.85	14.90	0.84	1.44

Timberline	Timberline	77.16	8.78	35.24	0.78	1.40
Timberline	Timberline	2.83	1.68	6.98	0.73	1.60
Timberline	Timberline	21.22	4.61	18.72	0.76	1.68
Timberline	Timberline	2.80	1.67	6.80	0.76	1.58
Timberline	Timberline	5.64	2.38	9.73	0.75	1.93
Timberline	Timberline	15.22	3.90	16.51	0.70	1.58
Timberline	Timberline	6.40	2.53	10.29	0.76	2.02
Timberline	Timberline	1.61	1.27	5.24	0.74	1.94
Timberline	Timberline	2.39	1.55	7.82	0.49	1.05
Timberline	Timberline	18.15	4.26	16.81	0.81	2.02
Timberline	Timberline	13.51	3.68	14.98	0.76	1.83
Old Maid	W. R. Drainage	29.76	5.46	21.40	0.82	1.15
Old Maid	W. R. Drainage	5.78	2.40	9.09	0.88	1.60
Old Maid	W. R. Drainage	13.19	3.63	14.88	0.75	1.63
Old Maid	W. R. Drainage	14.57	3.82	15.23	0.79	1.14
Old Maid	W. R. Drainage	30.55	5.53	22.37	0.77	1.88
Old Maid	W. R. Drainage	4.66	2.16	8.70	0.77	1.96
Old Maid	W. R. Drainage	9.54	3.09	11.85	0.86	1.46
Old Maid	W. R. Drainage	3.96	1.99	7.85	0.81	2.00
Old Maid	W. R. Drainage	1.58	1.26	6.61	0.46	4.39
Old Maid	W. R. Drainage	6.10	2.47	10.20	0.74	1.25
Old Maid	W. R. Drainage	3.30	1.82	6.88	0.88	1.13