Using Two Coeval Andesites from Middle Sister and South Sister, Oregon, as Clues to Understanding Connectivity Between Adjacent, Coincident Stratovolcanoes

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Using Two Coeval Andesites from Middle Sister and South Sister, Oregon, as Clues to Understanding Connectivity Between Adjacent, Coincident Stratovolcanoes

Undergraduate Thesis

By

James Peale

Advised by Dr. Mai Sas
Abstract

The Three Sisters Volcanic Complex in central Oregon is a cluster of three primary stratovolcanoes and a mafic periphery which lies at the intersection of the Cascade volcanic arc and the Basin and Range extensional province. This project focuses on the two youngest stratovolcanoes, Middle Sister and South Sister. Middle Sister experienced a period of frequent eruptive activity from approximately 27 ka to 14 ka, during which it erupted dacites, andesites, and basaltic andesites. South Sister experienced an intense period of eruptive activity from approximately 36 ka to 22 ka, during which it erupted a diverse suite of magmas ranging from rhyolites to andesites, as well as a single basaltic andesite. During the period of overlapping eruptive activity from 27 ka to 22 ka, both volcanoes erupted compositionally similar units. This study aims to examine a set of similarly aged units to determine if the two adjacent volcanoes could draw on the same magmatic reservoirs. In order to accomplish this, this thesis examines the textures and compositions of major mineral phases in two compositionally similar units that erupted on the eastern flanks of their respective source volcanoes ca. 24 ka, during the period in which eruptive activity was decreasing at South Sister and increasing at Middle Sister. These units are the andesite of Demaris Lake from Middle Sister and the andesite of West Fork Park Creek from South Sister. Analysis of chemical and textural data of plagioclase crystals suggests that the most primitive crystals in both units may have shared origins from a deeper crustal source. However, the units diverged at some point, resulting in distinct populations of intermediate-composition crystals.
# Table of Contents

Abstract ......................................................................................................................................................... 2
Introduction................................................................................................................................................... 5
Background................................................................................................................................................... 6
  Tectonic Setting ........................................................................................................................................ 6
  Three Sisters.............................................................................................................................................. 6
    Mafic Periphery and North Sister ......................................................................................................... 6
    Middle Sister and South Sister .............................................................................................................. 7
  Units of Study ........................................................................................................................................... 7
Methods ........................................................................................................................................................ 8
  Sample Prep .............................................................................................................................................. 8
  Sample Characterization ........................................................................................................................... 8
    Petrography .......................................................................................................................................... 8
    Scanning electron microscope (SEM) ................................................................................................... 8
    Electron microprobe analyzer (EMPA) ................................................................................................ 9
    Whole Rock ........................................................................................................................................ 10
Results......................................................................................................................................................... 11
  Hand Sample Descriptions ...................................................................................................................... 11
    Andesite of West Fork Park Creek (awf) ............................................................................................ 11
    Andesite of Demaris Lake (adl) .......................................................................................................... 12
    Petrography .......................................................................................................................................... 14
    Andesite of West Fork Park Creek (TSO-022) ................................................................................... 14
    Andesite of Demaris Lake (TSO-068) ................................................................................................ 16
  Whole Rock Geochemistry ..................................................................................................................... 18
    Andesite of West Fork Park Creek (awf) ............................................................................................ 18
    Andesite of Demaris Lake (adl) .......................................................................................................... 18
  Mineral Textures and Geochemistry ....................................................................................................... 20
    Plagioclase .......................................................................................................................................... 20
    Clinopyroxene ..................................................................................................................................... 24
    Orthopyroxene .................................................................................................................................... 28
    Olivine ................................................................................................................................................ 31
Discussion................................................................................................................................................... 32
Conclusion .................................................................................................................................................. 33
Introduction

Volcanic systems, particularly in arcs, are often oversimplified. Introductory geology textbooks, as well as illustrations in media and popular culture, depict a single shallow magma chamber feeding into a volcano at the surface. However, a growing body of geophysical, geochemical, and petrological evidence suggests that the simplified model does not provide the full picture (Cashman et al., 2017). Instead, the prevailing model is that of a crystal mush dominated transcrustral magmatic system open to both crustal assimilation and magma replenishment (Cashman et al., 2017), and that most arc lavas, particularly intermediate ones, are mixtures of multiple magmatic components (Kent, 2014). The single shallow magma chamber is replaced by a transcrustral magmatic system, which is composed of a large framework of crystal mush throughout which melt is distributed, and comparatively smaller areas of melt throughout which crystals are distributed (Cashman et al., 2017; Sparks et al., 2019). These areas of melts, known as reservoirs, are stacked vertically throughout the magmatic system, constantly forming and breaking connections with surrounding reservoirs as conditions change (Cashman et al., 2017). Verifying this model via direct observation or sampling is not currently feasible, but each crystal erupted from a volcano contains a textural and chemical record of its growth. This record ultimately reflects the history of the host magma. By comparing crystals found in multiple eruptive units, it is possible to form a picture of the evolution and interconnectivity of the magmatic system.

The Three Sisters Volcanic Complex (TSVC) in central Oregon is an ideal location to test the transcrustral magmatic system model. The complex consists of three compositionally diverse stratovolcanoes surrounded by a mafic periphery. Comprehensive mapping and dating of geologic units in the complex show that Middle Sister and South Sister share a partially alternating eruptive history, where eruptive periods at one align with dormant periods at the other (Calvert et al., 2018). By picking coeval units from each volcano erupted during a period of declining activity at South Sister and increasing activity at Middle Sister, it is possible to compare the evolution of the two units, and to determine if the volcanos are drawing on similar reservoirs.

This thesis examines the question of reservoir interconnectivity at the TSVC via physical and chemical observations of two coeval andesites from the eastern flank of Middle Sister and South Sister. Petrographic observations are used to broadly categorize crystals found within the sample. The crystals in the andesites were sorted into populations, or groups of crystals thought to have the same history, through a combination of textural characterization and chemical analysis (Ginibre et al., 2007; Streck, 2008). If there is a clear overlap between the populations found at Middle Sister and the populations found at South Sister, then it is likely that the two volcanos drew on similar reservoirs during the time the units were erupting (and vice versa). Understanding the subsurface connections between these two adjacent stratovolcanoes has implications both for the greater field of geology, and locally for predicting eruption characteristics and mitigating hazards associated with eruption.
Background

Tectonic Setting

The TSVC is located within the Cascade volcanic arc, a 1,300 km swath of volcanic activity stretching from northern California to southern British Columbia (Fig. 1), formed by the subduction of the Juan de Fuca Plate as it moves north-east into the North American Plate at rates of 29 mm/year in the south to 46 mm/year in the north (Leeman, 2020). The age of the subducting slab varies along the subduction zone, with the southern portion of the slab ranging from Paleozoic to Cretaceous in origin, while the northern portion ranges from Paleozoic to Paleocene (Leeman, 2020). The Oregon Cascades, the regional site of the TSVC, lies 270 km east of the trench of the subduction zone atop 44 km of crust (Leaver et al., 1984). The Oregon Cascades are unusual in their density of volcanic activity, with about 1,050 vents arranged in a roughly north – south alignment (Hildreth et al., 2012). This region also has numerous eruptive units of true rhyolite vents, which is atypical of the Quaternary Cascades (Fierstein et al., 2011).

Along with the overall westward movement of the North American Plate, the Cascade forearc is migrating northward along the coast and breaking up into large rotating blocks as it does so (Wells et al., 1998). One such block, which encompasses much of Oregon and western Washington, is rotating clockwise around a Euler pole located in eastern Washington, creating compressional zones in northern Washington and extensional zones in central and southern Oregon (Wells et al., 1998). The TSVC lies along the trailing edge of this rotating block in an area of extension. Directly north of the TSVC lies the High Cascade Graben, a zone where north-south faults drop a block of earth downwards relative to the surrounding blocks (Schmidt and Grunder, 2009). The Basin and Range Province, a zone of crustal extension and thinning, lies directly south of the TSVC (Hildreth et al., 2012). Along the northern margin of the Basin and Range Province lies the Brothers Fault Zone, a shear zone that strikes northwest from the southeastern corner of Oregon and intersects the High Cascade graben at the TSVC (Schmidt and Grunder, 2009). The confluence of the High Cascade Graben, the northernmost corner of the Basin and Range Province, and the northern tip of the Brothers Fault Zone, create a region of immense tectonic complexity, and likely result in the high density and strong north-south distribution of vents surrounding and within the TSVC (Schmidt and Grunder, 2009; Hildreth et al., 2012).

Three Sisters

Mafic Periphery and North Sister

The region surrounding the TSVC is blanketed by older, more mafic edifices and lava flows, such as Trout Creek Butte (ca. 530 ka), The Wife (ca. 375 ka), Broken Top (ca. 300-150 ka), The Husband (at least 150 ka), and many others (Hildreth et al., 2012). The oldest of the Three Sisters, North Sister, is also a mafic stratovolcano, which was primarily constructed during two distinct phases (Schmidt and Grunder, 2009). The first stage of eruptive activity occurred between 400 ka and 300 ka, after which a major unconformity suggests a pause in activity until the second stage, which occurred between ca. 180 ka and 100 ka (Schmidt and Grunder, 2009). These first two stages are estimated to have formed upwards of 90% of the central volcano (Schmidt and Grunder, 2009). Two later stages of eruptive activity occurred, with eruptions ceasing ca. 55 ka (Schmidt and Grunder, 2009). North Sister remained compositionally monotonous throughout its eruptive history, with all four eruptive stages producing basaltic andesites (Schmidt and Grunder, 2009).
Middle Sister and South Sister

Middle Sister experienced eruptive activity from 48 ka to 14 ka; however, the majority of the present edifice was built between 25 ka and 18 ka (Hildreth et al., 2012). Unlike North Sister, Middle Sister did not remain compositionally monotonous during the period of construction. Instead, it began by erupting mostly basaltic andesites to andesites, and even one dacite and one rhyolite units; then, ca. 22 ka, it became strictly bimodal as it erupted basaltic andesites and dacites (Calvert et al., 2018). South Sister experienced construction from 50 to 2 ka, during which time it alternated between erupting rhyolitic and intermediate material (Hildreth et al., 2012). South Sister began erupting rhyolite roughly at ca. 50 ka, but by 37 ka the rhyolitic lava flows began to alternate with dacite and andesite lava flows, and by ca. 27 ka the volcano was primarily erupting andesite (Fierstein et al., 2011). Circa 22 ka, South Sister erupted a sheet of basaltic andesite, after which eruptions ceased throughout the TSVC until ca. 2 ka, when rhyolites began to erupt on the southern flanks of South Sister (Fierstein et al., 2011).

Units of Study

This project examines two compositionally similar units that erupted on the eastern flanks of their respective source volcanoes ca. 24 ka (Fig. 1), during the period in which South Sister was winding down its eruptions and Middle Sister was increasing its eruptions, in order to shed some light on this fascinating shift in edifice activity. The first unit, the andesite of Western Flank (awf), represents one of the two most recent andesites produced by South Sister (Hildreth et al., 2012). The second unit, the andesite of Demaris Lake (adl), is one of the last silicic andesites erupted at Middle Sister as activity began to increase and eruptions shifted from andesites to bimodal compositions of dacites and basaltic andesites (Calvert et al., 2018). According to previous studies, adl is composed of approximately 62% SiO₂, with phenocrysts of 15-20% plagioclase and 3% pyroxene. Texturally, the unit displays joints ranging from blocks to slabs or plates, as well as partially devitrified interior facies (Hildreth et al., 2012). Unit awf is composed of approximately 60% SiO₂, with phenocrysts of 15-20% plagioclase and 3% pyroxenes. This unit is similar in texture to adl, with devitrified facies and blocky to slab or plated joints (Hildreth et al., 2012). The similarities between these two units make them prime candidates for further investigation. Results from this project contribute to our understanding of the magmatic processes taking place below the TSVC and this region of the Cascades.
Methods

Sample Prep

Samples TSO-022 and TSO-023 were collected from unit awf, while samples TSO-066, TSO-068, and TSO-069 were collected from unit adl. Two billets of roughly 4 cm by 2 cm by 1 cm were cut from each sample, with care taken to ensure that the billets were representative of the larger sample. Wherever possible, billets were cut from unweathered portions of the sample; however, variations in the size and cohesion of the samples made this impossible at times. Due to the high percentage of vesicles and resulting weakness, TSO-068 was set in epoxy resin. For each sample, one billet was made into a thin section for petrography, and one was made into a thick section for high-resolution imaging and geochemical analysis. Sample TSO-066 was the exception to this, with only a thin section being made due to budgetary and time restrictions. The billets for thin sections were sent to Burnham Petrographics, while the billets for thick sections were sent to Wagner Petrographics.

Sample Characterization

Petrography

Textural characterization of the samples was completed at Western Washington University (WWU) using a Leica DM750P petrographic microscope.

Scanning electron microscope (SEM)

Scanning electron microscope back scatter electron (SEM-BSE) imaging was completed at WWU for the purpose of identifying ideal crystals for major and minor element analysis via the electron microprobe (EMPA) and trace element analysis via laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Back scatter electron images of awf sample TSO-022 from unit awf were
obtained using a JEOL JSM-7200F Field-Emission SEM. A total of 65 plagioclase crystals, 31
clinopyroxene crystals, 35 orthopyroxene crystals, and 1 olivine crystal were identified and imaged. Back
scatter electron images of adl sample TSO-068 from unit adl were obtained using a Tescan Vega 3 SEM.
A total of 55 plagioclase crystals, 34 clinopyroxene crystals, and 21 orthopyroxene crystals were
identified and imaged. For both samples, an acceleration voltage of 20 kv was used, and contrast and
brightness were adjusted to best highlight zoning in the target crystal.

Electron microprobe analyzer (EMPA)

Ideal crystals from both samples were selected for major and minor element analysis on the
EMPA, with 27 plagioclase crystals, 29 clinopyroxene crystals, 28 orthopyroxene crystals, and 1 olivine
crystal selected from awf sample TSO-022 and 33 plagioclase crystals, 31 clinopyroxene crystals, and 22
orthopyroxene crystals selected from adl sample TSO-068. For each selected crystal, an analysis was
performed at the core and rim of the crystal, as well as the mantle of the crystal where possible. Analysis
was performed on the Cameca SX-100 at Oregon State University. During analysis the acceleration
voltage was 15kv, with a beam current of 30nA. A 5µm analysis spot was used for plagioclase crystals
and a 1µm analysis spot was used for clinopyroxene, orthopyroxene, and olivine. Peak times for
plagioclase were 10 seconds for Na, Si, Al, and Ca, 30 seconds for K and Ti, and 60 seconds for Mg and
Fe. Peak times for pyroxenes were 10 seconds for Si, 20 seconds for Fe, Na, and Mg, and 30 seconds for
Al, K, Mn, Ti, Cr, and Ca. Peak times for olivine were 10 seconds for Si, Mg, Fe, 20 seconds for Mn, 30
seconds for Na, and 60 seconds for Al, Cr, Ni, and Ca. Standards used for calibration are reported in

<table>
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<th>Plagioclase Procedure</th>
<th>Pk Time</th>
<th>HV (kv)</th>
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<tbody>
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<tr>
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<td>10</td>
<td>I (nA)</td>
</tr>
<tr>
<td>Mg Ka</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Si Ka</td>
<td>10</td>
<td>Size (µm)</td>
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<tr>
<td>Al Ka</td>
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<tr>
<td>K Ka</td>
<td>30</td>
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<tr>
<td>Ca Ka</td>
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<tr>
<td>Ti Ka</td>
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<tr>
<td>Fe Ka</td>
<td>60</td>
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<td>Ti Ka</td>
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Table 1. Plagioclase procedure for electron microprobe analysis.
Table 2. Pyroxene procedure for electron microprobe analysis.

<table>
<thead>
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<th>HV (kv)</th>
<th>Time/Repeat</th>
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<tbody>
<tr>
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<td>1 (nA)</td>
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<td>Al Ka</td>
<td>30</td>
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<tr>
<td>K Ka</td>
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<td>Size (μm)</td>
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<tr>
<td>Mn Ka</td>
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<tr>
<td>Ca Ka</td>
<td>30</td>
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Whole Rock

Whole rock analyses were done using a Thermo ARL Perform’X X-ray fluorescence spectrometer (XRF) at Hamilton Analytical Lab, New York. Preparation of samples constituted chipping then grounding into a ~3.5 gm powder using a ring mill (tungsten carbide or alumina). The powder was blended with Merck Spectromelt A-10 Li-tetraborate flux in a vortex mixer and fused with Mersen grade UF-4S graphite at 1000°C. The resultant pellets were cleaned, reground, and refused, then cleaned with ethanol.

Trace element concentrations were obtained on chips cut from the pellets, which were mounted in epoxy and micro-polished. Sample preparation and analytical settings followed those of Conrey et al. (2019). The LA-ICP-MS consisted of a Photon Machines Analyte 193 laser ablation system coupled to a Varian 820 mass spectrometer.
Results

Hand Sample Descriptions

Andesite of West Fork Park Creek (awf)

This unit largely makes up a gentle, sparsely grassy plateau on the lower eastern flank of South Sister. Outcrops are spread out as small (<5 m) to medium (>20 m) clusters of broken or rounded boulders that partially protrude from the ground and range from 2 to 10 m in diameter. Some outcrops are tree-covered while others are vegetation-free. Weathered surfaces range from a tan brown to dark grey in color, while fresher exposures are medium grey in color. Outcrops vary in vesicularity from rare (≤1%) to abundant (≤40%), and highly vesicular samples are generally dark grey on a fresh surface. The outcrop of TSO-022 and TSO-023 constitute light gray, fractures, and variably vesicular boulders ranging from 2 m to 10 m in diameter, with the cobbles also present.

TSO-022 is a dark gray rock roughly 14 cm by 11 cm by 10 cm. The hand sample is vesicular, with the interiors of the vesicles containing secondary mineral crystallization. The vesicles range in size from 1 mm to 5 mm and make up roughly 40% of the sample. Vesicles range from circular to elongate to blobby. The sample is aphanitic and porphyritic in texture, with individual crystals ranging up to 3 mm and crystal clots of up to 5 mm that collectively make up about 25% of the sample. The most abundant mineral is plagioclase, which makes up roughly 20% of the sample. The plagioclase crystals are vitreous white to off white, with blocky to tabular habits, ranging in size from under 1 mm to approximately 3 mm. The plagioclase appears both as solitary crystals and in clots with other plagioclase crystals, as well as in clots with pyroxene crystals. The plagioclase crystals are euhedral to anhedral in perfection, with the solitary crystals generally being more perfect than the crystals in clots. The second most abundant mineral is pyroxene, which makes up less than 5% of the sample. The pyroxene crystals are vitreous light greenish brown to dark brown, display a blocky habit, and are under 1 mm in size. The pyroxenes appear within clots with other pyroxene crystals and plagioclase crystals.

The hand sample is a semi-weathered light gray rock roughly 18 cm by 13 cm by 8 cm. TSO-023 includes rounded vesicles, which are under 1 mm in size and make up less than 1% of the sample. The sample is aphanitic and porphyritic in texture, with individual crystals of up to 3 mm and clots of crystals up to 5 mm, and up to 23% total visible crystals. The most abundant mineral is plagioclase, which makes up approximately 20% of the sample. The plagioclase crystals are vitreous white, with blocky to tabular habits, ranging in size from 1 mm to 3 mm. The crystals range in perfection from anhedral to euhedral, with the most euhedral samples exhibiting perfect cleavage. The plagioclase appears both as solitary crystals and in clots with other plagioclase and pyroxene crystals. The solitary plagioclase crystals are generally more euhedral than the crystals in clots. The next most abundant mineral is pyroxene, making up roughly 3% of the sample. The pyroxene crystals are vitreous dark brown, display a blocky habit, and are under 1 mm in size. The pyroxenes primarily appear within clots with plagioclase and other pyroxene crystals; however, some solitary pyroxene crystals are present.
Andesite of Demaris Lake (adl)

Outcrops of this unit can be found along the Demaris Lake Trail on the lower eastern flanks of Middle Sister. Outcrops range from tree- and lichen-covered, cliff-forming outcrops approximately 10 m in height, with talus of <3 m boulders and broken off plates, to discreet, tree and tree-debris covered outcrops that are <2 m. Weathered surfaces frequently exhibit obvious flow banding that alternate from light reddish brown to black, although from afar, weathered surfaces appear reddish brown or light grey. Outcrops also drastically vary in vesicularity, from vesicle-free to ≤50%.

In outcrop, TSO-066 is reddish from weathering and covered in black lichen. Boulder debris near the outcrop is gray and black with flow banding, with flow banding also visible on the outcrop where it not covered by lichen. The hand sample is a light gray rock, roughly 13 cm by 13 cm by 6 cm. The rock is aphanitic and porphyritic in texture, with crystals ranging from under 1 mm to 5 mm, and up to 20% visible crystals. The sample is moderately weathered. Throughout the center of the rock runs a 2 cm thick vesicular band with a similar mineral composition to the rest of the sample. Multiple fractures run parallel to the vesicular band. The plagioclase makes up about 15% of the sample, is vitreous white to off white, anhedral to euhedral, and blocky in habit. The crystals range from 1 mm to 5 mm, with the majority falling in the 2 mm to 3 mm range. The most euhedral crystals, which have apparent cleavage, are found within the vesicular band. Anhedral crystals exhibit irregular fractures and no discernable cleavage.
planes. In comparison to the other two adl samples, there are more individual crystals and less crystal clots; however, the plagioclase crystals form clots with other plagioclase crystals, as well as with pyroxene crystals. Pyroxene crystals make up about 4% of the sample, are vitreous, dark green to black, anhedral to subhedral, with a blocky habit. The crystals range from less than 1 mm to 2 mm, with the majority being around 1 mm. The pyroxene crystals appear both as individual crystals and in clots with plagioclase. Visible magnetite is also noted in this sample. The magnetite crystals make up <1% of the sample, are blocky in habit, <0.5 mm in diameter, and are generally found in clots with plagioclase and pyroxene.

In outcrop, TSO-068 has less flow banding and more vesicles than other samples of adl. The hand sample is a dark gray rock roughly 14 cm by 10 cm by 4 cm. The sample is composed of ~40% vesicles, with the interiors of the vesicles being slightly lighter gray than the groundmass of the rest of the sample. The vesicles themselves are roughly 1 mm to 5 mm and lack secondary mineral crystallization. The vesicles are mostly rounded and blobby. The sample is aphanitic and porphyritic in texture, with approximately 20% visible crystals and individual crystals of up to 2 mm and clots of crystals of up to 5 mm. The minerals on the surface of the sample are moderately weathered, with fracturing visible on exposed surfaces. The most prominent mineral in the sample is plagioclase, which makes up roughly 15% of the sample. Here, it displays a vitreous white to yellow-white, anhedral, blocky to elongate to habit, irregular fractures, and no discernable cleavage. Variations in color and fractures appear to be due to weathering. It is found either as solitary crystals or larger crystal clots, with clots ranging from 2 to 5 mm and crystals up to 2 mm. The pyroxene crystals, which make up ~5% of the sample, are < 1 mm, vitreous dark brown, and anhedral. They appear primarily in clots with plagioclase and other pyroxenes, although a small number of solitary crystals are present.

In outcrop, TSO-069 is slightly red from weathering and has polished surfaces with glacial striations. The hand sample is a dark gray rock roughly 14 cm 10 cm by 6 cm. The sample is aphanitic and porphyritic in texture, with crystals ranging from 1 mm to 5 mm, and crystal clots ranging from 3 mm to 5 mm. The sample is primarily unweathered apart from small patches where the groundmass is slightly brown. This sample has approximately 20% visible crystals. The most prevalent mineral in the sample is plagioclase, which makes up about 15% of the sample. The plagioclase is vitreous white to slightly off white, with a subhedral to euhedral, blocky habit. The surfaces of the crystals are irregularly fractured, and cleavage planes are harder to discern in crystals found in clots. Individual crystals range from 1 mm to 5 mm, with the majority of crystals falling within the 2 mm to 3 mm range. The crystals are found individually as well as in clots with other plagioclase and pyroxene crystals. The second most abundant mineral is pyroxene, which makes up approximately 5% of the sample. Here, the pyroxenes are vitreous dark green to black, anhedral with a blocky habit, irregular fractures, and no discernable cleavage. The crystals are small, ranging up to 2 mm in diameter, but are more commonly 1 mm in diameter or less. These crystals are easiest to identify in clots with plagioclase, but there are some solitary crystals visible. There do not appear to be any clots of pyroxene without plagioclase.
Petrography

Andesite of West Fork Park Creek (TSO-022)

Sample TSO-022 was selected as the least weathered representative sample of awf for petrography and chemical analyses. The groundmass of TSO-022 makes up ~55% of the sample, and is composed of ~90% plagioclase, ~7% pyroxene, and ~3% oxide. Within the groundmass, the plagioclase is ~0.06 mm long, elongate to acicular, randomly oriented, and displays polysynthetic twinning. The pyroxene in the groundmass is ~0.06 mm, equant, and randomly oriented. The remainder of the groundmass consists of equant oxide crystals ~0.06 mm in size. The phenocrystic plagioclase makes up ~15% of the sample, with crystals ranging from 1 mm to 2.5 mm. The crystals have a tabular habit, are euhedral to subhedral in perfection, and display polysynthetic and simple twinning, with a singular example of crosshatch twinning. The majority of crystals show oscillatory zoning, and some crystals have light sieving. The crystals are randomly distributed and oriented throughout the sample. The clinopyroxene phenocrysts make up ~3% of the sample, with crystals ranging from 0.5 mm to 2 mm. The crystals have a blocky habit, are subhedral to anhedral in perfection, and display simple twinning. The crystals are randomly distributed and oriented throughout the sample. The orthopyroxene phenocrysts make up ~2% of the sample, with crystals ranging from 0.5 mm to 2 mm. The crystals have a blocky
prismatic habit, are subhedral to anhedral in perfection, and display no twinning. The crystals are randomly distributed and oriented throughout the sample. All phenocrysts appear both as solitary crystals and in clots, with plagioclase crystals clotting with other plagioclase crystals and clinopyroxene crystals, orthopyroxene crystals and plagioclase crystals clotting together. Vesicles make up the remaining 25% of the sample, with the vesicles being 2 mm to 5 mm, are generally rounded, and are evenly distributed throughout the sample.

Figure 4. Representative crystals within awf, with petrographic microscope images on the left and backscatter electron images on the right. A and B are plagioclase crystals, C and D are clinopyroxene crystals, and E and F are orthopyroxene crystals.
Andesite of Demaris Lake (TSO-068)

Sample TSO-068 was selected as the least weathered representative sample of adl for petrography and chemical analyses. The groundmass of TSO-068 makes up ~60% of the sample, and is composed of ~98% plagioclase, ~1% oxides, and <1% pyroxenes. Within the groundmass, the plagioclase crystals are 0.02 mm to 0.1 mm, elongate to acicular, randomly oriented, and display polysynthetic twinning. The oxides in the groundmass are <0.02 mm, equant, and randomly oriented. The pyroxene crystals in the groundmass are ~0.05 mm, equant to tabular, and randomly oriented. When viewed through plane polarized light, the groundmass is generally light gray in color, however there are sections of groundmass that are distinctly darker in color. These darker sections are either 0.5 mm to 1 mm freestanding blobs, or as rims around crystals or vesicles, where the darker groundmass will outline the shape of the crystal or vesicle. There are less plagioclase crystals within the darker groundmass compared to the rest of the groundmass. The plagioclase phenocrysts make up ~15% of the sample, with crystals ranging from 0.2 mm to 2.5 mm. The crystals have a tabular habit, are euhedral to subhedral in perfection, and display polysynthetic and simple twinning, with some un-twinned examples. The majority of crystals show oscillatory zoning. The crystals are randomly oriented and distributed throughout the sample. The clinopyroxene phenocrysts make up ~3% of the sample, with crystals ranging from <1 mm to 1.5 mm. The crystals have either an equant or elongate habit, are subhedral to anhedral in perfection, and display simple twinning. The crystals are randomly oriented and distributed throughout the sample. The orthopyroxene phenocrysts make up ~1% of the sample, with crystals under 1 mm. The crystals have a prismatic habit and are subhedral to anhedral in perfection. The crystals are randomly distributed and oriented throughout the sample. The oxide phenocrysts are ~0.2 mm in size and make up ~1% of the sample. The crystals have an equant habit and are subhedral to anhedral in perfection. The oxide crystals are more prevalent within and around other phenocrysts, although there are a number of freestanding crystals. All phenocrysts appear both as solitary crystals and in clots, with the plagioclase crystals clotting with other plagioclase crystals, as well as plagioclase crystals, clinopyroxene crystals, and orthopyroxene crystals clotting together. Vesicles make up the remaining ~20% of the sample. The vesicles range in size from 1 mm to 7 mm and have random morphologies, often taking the form of blobs connected by thin necks. The vesicles are evenly distributed throughout the sample.
Figure 5. Representative crystals within adl, with petrographic microscope images on the left and backscatter electron images on the right. A and B are plagioclase crystals, C and D are clinopyroxene crystals, and E and F are orthopyroxene crystals.
Whole Rock Geochemistry

Andesite of West Fork Park Creek (awf)

Whole analysis of awf yielded 59.5 – 61.0 SiO₂ wt.%, 1.19 – 1.30 TiO₂ wt.%, 16.4 – 16.9 Al₂O₃ wt.%, 6.8 – 7.1 FeO wt.%, 0.12 – 0.14 MnO wt.%, 2.3 – 3.1 MgO wt.%, 5.3 – 6.2 CaO wt.%, 4.1 – 4.7 Na₂O wt.%, 1.4 – 1.6 K₂O wt.%, 0.3 wt.% P₂O₅ wt.%. Whole rock data for awf primarily plot in the andesite field on the total alkali-silica (TAS) diagram (Le Maitre, 1984), with the most silica-rich sample (sample TS187 of Hildreth et al., 2012) plotting slightly into the dacite field. The Mg# (Mg³ = molar Mg/[Mg+Fe*0.85]*100) of the awf samples have a narrow range from 41 to 42. Whole rock compositions are listed in Table A5 and shown in Figures 6-9.

Andesite of Demaris Lake (adl)

Whole analysis of adl yielded 61.3 – 63.1 SiO₂ wt.%, 1.0 – 1.2 TiO₂ wt.%, 16.6 – 17.1 Al₂O₃ wt.%, 5.5 – 6.3 FeO wt.%, 0.10 – 0.11 MnO wt.%, 1.9 – 2.1 MgO wt.%, 4.8 – 5.4 CaO wt.%, 4.2 – 4.8 Na₂O wt.%, 1.8 – 2.0 K₂O wt.%, 0.26 – 0.34 P₂O₅ wt.%. Whole rock data for adl plot in the andesite field on the TAS diagram (Fig. 6) (Le Maitre, 1984). The Mg# of the adl samples have a wide range from 41 to 48. Whole rock compositions are listed in Table A5 and shown in Figures 6-9.

Figure 6. Total alkali silica (TAS) diagram of adl (light blue) and awf (dark blue); after Le Maitre (1984).
Figure 7. Spider diagram of minor and trace elements in adl (dark and medium blue) and awf (light blue).

Figure 8. Rare earth element (REE) diagram of adl (dark and medium blue) and awf (light blue).
Plagioclase

A total of five distinct plagioclase populations are observed throughout both awf and adl. Only population 1C is found in both awf and adl. Populations 1B, 4B, and 5 are found only in awf, while populations 1A, 2, 3, and 4A are only found in adl. A summary of plagioclase populations can be found in Figure 10, and BSE images of all analyzed plagioclase crystals can be found in the Appendix. Plagioclase compositions are shown in Figures 11-13.

Population 1A is characterized by normal zoning, with a high An relict cores and moderate to low An rims. Cores range from An83 to An75 and some have boxy to blobby patches with lower An. Most crystals in this population display a distinct boundary that separates the cores from the surrounding mantles, with the rims ranging from An59 to An54. Crystals are tabular to elongate, and euhedral to subhedral in perfection. The crystals range from 0.5 mm to 3 mm, making them the largest phenocrysts found in adl. Population 1A constitutes 36% of the plagioclase crystals in adl, and crystals are found as solitary crystals or in clots with other crystals of plagioclase population 1A.

Population 1B is characterized by normal zoning, with a high An relict cores, moderate to low An outer mantles, and fine, low An rims. Cores range from An82 to An74, and some have boxy to blobby patches with lower An throughout. Crystals in this population display a distinct boundary that separates the cores from the surrounding mantles. Relative brightness in BSE images reveal 1-2 reversely zoned regions between the inner and outer mantles, with the outer mantles ranging from An59 to An52. Crystals
in this population also exhibit fine (<5 µm), low An rims. Although none of the rims were successfully analyzed, these rims resemble the An43 rims of population 4B and An47-36 rims of population 5. Crystals are tabular to elongate in shape and euhedral to subhedral in perfection. The crystals range from 0.5 mm to 3 mm, making them the largest phenocrysts found in awf. Population 1B makes up 44% of the plagioclase crystals in awf, and crystals are found as solitary crystals and in clots with plagioclase populations 1B, 1C, and 4B.

Population 1C is characterized by normal zoning with sieved, high An relict cores, moderate to low An outer mantles, and a fine, low An rim. Only a single crystal of this population was analyzed in adl and it appears to be lacking the fine, low An rim. The cores of population 1C range from An77 to An71, are heavily finely sieved, and contain numerous oxide inclusions. Similarly to populations 1A and 1B, population 1C cores have boxy to blobby lower-An patches, although the cores of population 1C are sieved and make up a much larger portion of the overall crystal. The outer mantles of population 1C range from An62 to An51, and lack both the heavy sieving and oxide inclusions found in the cores. Crystals in this population in unit awf also exhibit a fine (<5 µm), low An rim. Although none of the rims were successfully analyzed, they resemble the An43 rims of population 4B and An47-36 rims of population 5. Crystals are blocky with heavily rounded edges, subhedral to anhedral in perfection, and range from 0.5 mm to 1 mm. Population 1C makes up 16% of awf and 4% of adl. Population 1C clots with clinopyroxene population 4 in adl and is either solitary or in clots with plagioclase 1B in awf.

Population 2 is characterized by normal zoning, with moderate An cores and moderately low An rims. The cores range from An66 to An55 and range from untextured to lightly sieved with oxide inclusions. The crystals are blocky to tabular to elongate, euhedral to subhedral in perfection, and range from 0.4 mm to 1.5 mm in length. Outer mantles range from An57 to An43. Population 2 is only found in adl, where it is found both as solitary crystals and in clots with plagioclase population 2. The population makes up 36% of plagioclase crystals found in adl.

Population 3 is characterized by coarsely sieved, moderately low An cores and moderately low An rims. The population contains both normally and reversely zoned crystals. The cores range from An55 to An53 and contain large, blobby sieves up to 0.3 mm long. Rims range from An57 to An52. The crystals are blocky and euhedral and range from 400 µm to 1.5 mm in length. Population 3 is only found as solitary crystals, and makes up 11% of the plagioclase crystals found in adl.

Population 4A is characterized by reverse zoning with moderately low An cores and moderate An rims. The cores range from An56 to An50, and several crystals exhibit a rounded dissolution boundary between the cores and the surrounding mantles. The rims range from An58 to An51. The crystals are blocky to elongate, subhedral to anhedral, range from 0.75 mm to 2.5 mm in length, and lack any distinguishing textures. Population 4A is only found in adl, where it exists both as solitary crystals and in large clots with plagioclase population 4A, clinopyroxene populations 1B and 2, and orthopyroxene populations 1C and 2A. Population 4A makes up 11% of plagioclase crystals found in adl.

Population 4B is characterized by reverse zoning, with moderately low An cores, moderate An outer mantles, and low An rims. Crystals in this population are also distinguished from population 4A by numerous oscillations throughout the crystal mantles. The cores range from An58 to An49, and there is a dissolution boundary between the cores and surrounding mantles. The mantles consist of rings of alternating An, with a general increase in An from inner mantle to outer mantle. The outer mantle ranges from An60 to An58. Crystals in this population exhibit a fine (typically <5 µm) low An rim, only one of which was successfully analyzed and yielded An43. The crystals are tabular to elongate, euhedral to subhedral, and range from 0.4 mm to 1.5 mm in length. Population 4B is only found in awf, where it
exists both as a solitary crystal and in large clots with plagioclase population 5, clinopyroxene populations 1B and 2, and orthopyroxene populations 1C and 2A. The population makes up 24% of plagioclase crystals found in awf.

Population 5 is characterized by oscillatory normal zoning with moderate An cores, moderate An mantles, and fine, low An rims. The cores range from An69 to An58. The mantle displays oscillatory zoning that range in width from <10 µm to 50 µm. The outer mantle ranges from An64 to An58. All crystals show a thin (<10 µm) rim, which ranges in composition from An47 to An36 and resembles the fine, low An rims found in all awf plagioclase crystals. The crystals are tabular, euhedral to subhedral, range in length from 0.5 mm to 1.5 mm, and lack any distinguishing textures. Population 5 is only found in awf, where it exists in clots with plagioclase populations 4B and 5, clinopyroxene population 2, and orthopyroxene population 2A. The population makes up 16% of plagioclase crystals found in awf.

<table>
<thead>
<tr>
<th>Population</th>
<th>Texture</th>
<th>Description</th>
<th>An</th>
<th>Found in</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td></td>
<td>Sharp normal zoning, high An resorbed core, moderate-low An rim. ~36% of adl</td>
<td>Core: 83 - 74&lt;br&gt;Rim: 59 - 49</td>
<td>Solitary; clots with plg 1A</td>
<td>adl</td>
</tr>
<tr>
<td>1B</td>
<td></td>
<td>Sharp normal zoning, high An resorbed core, moderate-low An rim. ~44% of awf</td>
<td>Core: 83 - 74&lt;br&gt;Rim: 59 - 49</td>
<td>Solitary; clots with plg 1B, 1C, 4B</td>
<td>awf</td>
</tr>
<tr>
<td>1C</td>
<td></td>
<td>Sharp normal zoning, high An resorbed core, moderate-low An rim. Heavily sieved. ~16% of awf ~4% of adl</td>
<td>Core: 76 - 71&lt;br&gt;Rim: 62 - 51</td>
<td>Clots with cpx 4 in adl, solitary or clots with plg 1B in awf</td>
<td>awf, adl</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Normal zoning with moderate An core and moderate-low An rim. ~30% of adl</td>
<td>Core: 66 - 55&lt;br&gt;Rim: 57 - 43</td>
<td>Solitary; clots with plg 2</td>
<td>adl</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Coarse sieving, moderate normal and reverse zoning. ~11% of adl</td>
<td>Core: 55 - 53&lt;br&gt;Rim: 57 - 52</td>
<td>Solitary</td>
<td>adl</td>
</tr>
<tr>
<td>4A</td>
<td></td>
<td>Reverse zoning with moderate-low An core and moderate An rim. ~11% of adl</td>
<td>Core: 56 - 50&lt;br&gt;Rims 58 - 51</td>
<td>Solitary; large clots with plg 4A, cpx 1B and 2, cpx 1C and 2A</td>
<td>adl</td>
</tr>
<tr>
<td>4B</td>
<td></td>
<td>Reverse zoning with oscillations. Moderate-low An core and moderate An rim. ~24% of awf</td>
<td>Core: 58 - 49&lt;br&gt;Rim: 60 - 58</td>
<td>Solitary; clots with plg 5, cpx 1B and 2, cpx 1C and 2A</td>
<td>awf</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Normal zoning with oscillation. Moderate An core and low An rim. ~16% of awf</td>
<td>Core: 69 - 57&lt;br&gt;Rims 47 - 42</td>
<td>Clots with plg 4B and 5, cpx 2, cpx 2A</td>
<td>awf</td>
</tr>
</tbody>
</table>

Figure 10. Summary of plagioclase populations found in adl and awf.
Figure 11. Plot of FeO vs anorthite content in plagioclase, separated by population.

Figure 12. Plot of MgO vs anorthite content in plagioclase, separated by population.
Clinopyroxene

A total of five clinopyroxene populations are observed throughout both awf and adl. Populations 1A and 2 are found in both awf and adl, while populations 1B and 3 are only found in awf and population 4 is only found in adl. A summary of clinopyroxene populations can be found in Figure 14, and BSE images of all analyzed clinopyroxene crystals can be found in the Appendix. Clinopyroxene compositions are shown in Figures 15-17.

Population 1A is characterized by slight normal zoning with moderate Mg# cores, moderate Mg# outer mantles, and a fine, low Mg# rim. The cores range from Mg# 77 to 75, while the outer mantles range from Mg# 74 to 71. All crystals have a thin rim (<5 µm in adl, <20 µm in awf), and a single successful analysis on a rim from awf yielded Mg# 63. The crystals are equant to elongate, euhedral to anhedral, and, in adl only, contain oxide inclusions. A single adl crystal also contains a remnant, blobby orthopyroxene core. The crystals range from 0.4 mm to 1.2 mm in length. Population 1A is found in both awf and adl. The population is solitary in unit adl and is found in clots with clinopyroxene population 1B and orthopyroxene populations 1C and 2A. The population makes up 4% of clinopyroxene crystals found in awf and 15% of clinopyroxene crystals found in adl.

Population 1B is characterized by slight normal zoning with moderate Mg# cores and low Mg# rims. The cores range from Mg# 74 to 70, while the outer mantles range from Mg# 73 to 63. Some crystals show a thin (<5 µm), low Mg# rim that was not successfully analyzed but resembles the Mg# 63 rims observed in populations 1A and 3. The crystals are equant to blobby, euhedral to anhedral, and rarely contain oxide inclusions. The crystals are 0.3 mm or less in diameter. In unit awf, population 1B is found in clots with plagioclase population 4B, clinopyroxene populations 1A, 2, and 3, and orthopyroxene populations 1C and 2A. In unit adl, population 1B is found both as a solitary crystal and in clots with plagioclase populations 2 and 4A, clinopyroxene populations 1B and 2, and orthopyroxene populations.
Population 1B makes up 14% of clinopyroxene crystals found in awf and 19% of clinopyroxene crystals found in adl.

Population 2 is characterized by slight reverse zoning with moderate Mg# cores, moderate Mg# outer mantles, and fine, low Mg# rims. The cores range from Mg# 72 to 69, while the outer mantles range from Mg# 76 to 72. All crystals show a thin (<5 µm), low Mg# rim that was not successfully analyzed but resembles the Mg# 63 rims observed in populations 1A and 3. The crystals are equant to elongate, subhedral to anhedral, and contain oxide inclusions. The crystals range from 0.4 mm to 2 mm in length. Population 2 is found in both awf and adl, where it exists in large clots with plagioclase populations 4A, 4B, and 5, clinopyroxene populations 1B, 2, and 3, and orthopyroxene populations 1B, 1C, and 2A. Population 2 makes up 68% of clinopyroxene crystals found in awf and 50% of clinopyroxene crystals found in adl.

Population 3 is characterized by double reverse zoning in the outer mantle, with moderate Mg# cores, outer mantles with alternating bands of moderate and moderately low Mg#, and fine, low Mg# rims. The cores range from Mg# 72 to 69, while the sequence in the outer mantles alternates between Mg# 72 to 71, followed by Mg# 69 to 65, followed by Mg# 73. All crystals show a thin (<5 µm), low Mg# rim one of which was successfully analyzed Mg# 63. The crystals are equant to blocky, subhedral to anhedral, and generally lack distinguishing textures beyond the complex outer mantle zoning. The crystals range from 0.2 mm to 0.75 mm in length. Population 3 is only found in awf, where it exists in clots with clinopyroxene populations 1B, 2, and 3, and orthopyroxene populations 1C and 2A. The population makes up 14% of the clinopyroxene crystals found in awf.

Population 4 is characterized by patchy and moderately sieved cores, as well as reverse zoning followed by normal zoning, with moderate Mg# cores, moderately high Mg# inner mantles, a moderate Mg# outer mantle, and a fine, low Mg# rim. The cores range from Mg# 78 to 74, while the outer mantles range from Mg# 73 to 72. Unfortunately, no inner mantles were analyzed. All crystals show a thin (<5 µm), low Mg# rim too that was not successfully analyzed but resembles the Mg# 63 rims observed in populations 1A and 3. The crystals are equant, subhedral to anhedral, and contain oxide inclusions. The crystals range from 0.25 mm to 1 mm in length. Population 4 is only found in adl, where it exists in clots with plagioclase population 1C and clinopyroxene population 4. The population makes up 15% of clinopyroxene crystals found in adl.
Figure 14. Summary of clinopyroxene populations found in adl and awf.

<table>
<thead>
<tr>
<th>Population</th>
<th>Texture</th>
<th>Description</th>
<th>Mg#</th>
<th>Found in</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td></td>
<td>Slight normal zoning with core Mg# greater than 75. Moderate-high Mg cores, moderate-low Mg outer mantles. ~4% of awf 7A</td>
<td>Core: 77-75 Outer mantle: 74-71</td>
<td>Solitary in adl, clots with cpx 1B, cpx 1C and 2A in awf</td>
<td>awf, adl</td>
</tr>
<tr>
<td>1B</td>
<td></td>
<td>Slight normal zoning with core Mg# &lt; 75. Moderate-low Mg cores, low Mg outer mantles. ~14% of awf ~19% of adl</td>
<td>Core: 74-70 Outer mantle: 73-63</td>
<td>Solitary and clots with cpx 1B and 2, cpx 1C and 2A in adl; clots with cpx 4B, cpx 1A, 1C and 2A in awf</td>
<td>awf, adl</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Slight reverse zoning. Moderate-low Mg cores, moderate Mg outer mantles. ~66% of awf ~50% of adl</td>
<td>Core: 72-69 Outer mantle: 76-72</td>
<td>Clots with cpx 1B, 4A, 4B, 6; cpx 1B, 2, 3; cpx 1B, 1C, 2A</td>
<td>awf, adl</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Doubly-reversed zoninig. Moderate-low Mg core, moderate Mg outer core region, low Mg mantle, moderate Mg outer outer mantles. ~14% of awf</td>
<td>Core: 72-69 Mantle: 64-63 Outer mantle: 73-73</td>
<td>Clots with cpx 1B, 2, 3; cpx 1C, 2A</td>
<td>awf</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Reverse and normal zoning. Lightly sieved, reversely zoned core with moderately low Mg outer mantles. ~15% of adl</td>
<td>Core: 78-73 Outer mantle: 73-72</td>
<td>Clots with cpx 1C, cpx 4</td>
<td>adl</td>
</tr>
</tbody>
</table>

Figure 15. Plot of CaO vs Mg# in clinopyroxene, separated by population.
Figure 16. Plot of \( \text{Al}_2\text{O}_3 \) vs Mg\# in clinopyroxene, separated by population.

Figure 17. Plot of \( \text{Cr}_2\text{O}_3 \) vs Mg\# in clinopyroxene, separated by population.
**Orthopyroxene**

A total of five orthopyroxene populations are observed throughout both awf and adl, with populations 1C and 2A being found in both awf and adl, while populations 1A, 1B, and 2B are only found in adl. A summary of all orthopyroxene populations can be found in Figure 18, and BSE images of all analyzed orthopyroxene crystals can be found in the Appendix. Orthopyroxene compositions are shown in Figures 19-21.

Population 1A is characterized by normal zoning, with a high Mg# core, a moderate Mg# outer mantle, and a fine, low Mg# rim. Only one crystal was identified, and it has core Mg# 78 and an outer mantle Mg# 73. The crystal displays a distinct boundary between the mantle and outer mantle, as well as a thin (<5 µm), low Mg# rim which appears brighter in BSE images. Unfortunately, the rim was too thin to analyze but resembles the Mg# 63 rim of population 2A. The crystal is equant, euhedral, and 0.25 mm in length. Population 1A is only found in adl, where it exists as solitary crystals. The population makes up 5% of orthopyroxene crystals found in adl.

Population 1B is characterized by normal zoning, with moderately low Mg# cores and low Mg# outer mantles, and a fine, low Mg# rim. The cores range from Mg# 69 to 68, while the outer mantles range from Mg# 51 to 49. The fine, (<1 µm), low Mg# rim was too thin to analyze but resembles the Mg# 63 rim of population 2A. The crystals are equant to blocky, subhedral, 0.4 mm to 0.5 mm in length, and lack distinct boundaries between zones. Population 1B is only found in adl, where it exists both as solitary crystals and in clots with clinopyroxene population 2. The population makes up 10% of orthopyroxene crystals found in adl.

Population 1C is characterized by slight normal zoning with moderate Mg# cores, moderate Mg# outer mantles, and fine, low Mg# rims. The cores range from Mg# 76 to 70, while the outer mantles range from Mg# 74 to 67. The fine, low Mg# rim was too thin to analyze in adl (<1 µm) and was not successfully analyzed in awf (<15 µm) but resembles the Mg# 63 rim of population 2A. The crystals are equant to blocky, euhedral to anhedral, 0.2 mm to 0.6 mm in length, and lack obvious or sharp boundaries between cores and mantles. Population 1C is found in both awf and adl, where it exists in large clots with plagioclase populations 4A and 4B, clinopyroxene populations 1A, 1B, 2, and 3, and orthopyroxene populations 1C and 2A. The population makes up 21% of orthopyroxene crystals found in awf, and 33% of orthopyroxene crystals found in adl.

Population 2A is characterized by slight reverse zoning, with moderately low Mg# cores, moderate Mg# outer mantles, and fine, low Mg# rims. The cores range from Mg# 73 to 66, while the outer mantles range from Mg# 76 to 69. The fine, low Mg# rim was too thin to analyze in adl (<1 µm), but was successfully analyzed in awf (<20 µm) and yielded Mg# 63. The crystals are equant to elongate, euhedral to anhedral, 0.2 mm to 0.8 mm in length, and lack sharp boundaries between cores and mantles. Population 2A is found in both awf and adl, where it exists in large clots with plagioclase populations 4A, 4B, and 5, clinopyroxene populations 1A, 1B, 2, and 3, and orthopyroxene populations 1C and 2A. The population makes up 79% of orthopyroxene crystals found in awf, and 48% of orthopyroxene crystals found in adl.

Population 2B is characterized by Mg# reverse zoning with a low Mg# core, a moderate Mg# outer mantle, and a fine, low Mg# rim. Only one crystal was observed of this population. This crystal has a core of Mg# 58 and an outer mantle of Mg# 70. The boundary between the core and mantle is diffuse but distinct. The fine, low Mg# rim was too thin to analyze in adl (<5 µm) but resembles the Mg# 63 rim of population 2A. The crystal is elongate, subhedral, and 0.7 mm in length. Population 2B is only found
in adl, where it exists in a clot with an unanalyzed plagioclase crystal. The population makes up 5% of orthopyroxene crystals found in adl.

<table>
<thead>
<tr>
<th>Population</th>
<th>Texture</th>
<th>Description</th>
<th>Mg#</th>
<th>Found in</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Normal zoning. High Mg core, low Mg outer mantle, with defined separation</td>
<td>Core: 78 Outer mantle: 73</td>
<td>Solitary</td>
<td>adl</td>
<td></td>
</tr>
<tr>
<td>1B</td>
<td>Low Mg# normal zoning. Moderate-low Mg core, very low Mg outer mantle.</td>
<td>Core: 69 - 68 Outer mantle: 51 - 49</td>
<td>Solitary, clots with cpx 2</td>
<td>adl</td>
<td></td>
</tr>
<tr>
<td>1C</td>
<td>Slight normal zoning. Moderate-low Mg core, moderate-low Mg outer mantle.</td>
<td>Core: 76 - 70 Outer mantle: 74 - 67</td>
<td>Large clots with pig 4A and 4B; cpx 1A, 1B, 2, 3; cpx 1C and 2A</td>
<td>awf, adl</td>
<td></td>
</tr>
<tr>
<td>2A</td>
<td>Slight reverse zoning. Moderate-low Mg core, moderate-low Mg outer mantle.</td>
<td>Core: 73 - 66 Outer mantle: 76 - 69</td>
<td>Large clots with pig 4A, 4B, 5; cpx 1A, 1B, 2, 3; cpx 1C, 2A</td>
<td>awf, adl</td>
<td></td>
</tr>
<tr>
<td>2B</td>
<td>Low Mg# reverse zoning. Low Mg core, moderate-low Mg outer mantle.</td>
<td>Core: 58 Outer mantle: 70</td>
<td>Clots with unknown pig crystal</td>
<td>adl</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 18. Summary of orthopyroxene populations found in adl and awf.*
Figure 19. Plot of CaO vs Mg# in orthopyroxene, separated by population.

Figure 20. Plot of Al₂O₃ vs Mg# in orthopyroxene, separated by population.
Olivine

A total of two olivine crystals were identified, one in adl and one in awf. BSE images of both crystals can be found in the Appendix.

Population 1 is characterized by normal zoning, with a high Fo core and moderate Fo outer mantle. The core has a forsterite content of 74, while the outer mantle has a forsterite content of 63. The crystal is anhedral, approximately 0.2 mm in length, and is reacting into the surrounding orthopyroxene crystal. The crystal is in a clot with plagioclase population 1B and makes up 100% of olivine crystals identified in awf.

Population 2 is an olivine core with a larger orthopyroxene crystal surrounding it. The core has a forsterite content of 68. The crystal lacks a distinct rim. The crystal is anhedral, approximately 0.25 mm in length, and lacks distinguishing textural features. The crystal is found in a clot with orthopyroxene population 1C and makes up 100% of olivine crystals identified in adl.
Discussion

Both the andesite of Demaris Lake (adl) and the andesite of West Fork Park Creek (awf) contain large crystal clots, which are documented in the summary Figures 10, 14, 18, and 22. Figure 22 shows that plagioclase populations 4A, 4B, and 5 are found in clots with clinopyroxene populations 1B and 2, as well as orthopyroxene populations 1C and 2A. In adl, these clots measure up to 2 mm in length, and populations found in these clots account for 11% of identified plagioclase crystals, 69% of identified clinopyroxene crystals, and 81% of identified orthopyroxene crystals. In awf, these clots measure up to 6 mm in length, and populations found in these clots account for 24% of identified plagioclase crystals, 82% of identified clinopyroxene crystals, and 100% of orthopyroxene crystals. In both units, these populations make up the vast majority of all reversely zoned crystals. In adl, the populations found in the clots make up 83% of reversely zoned plagioclase crystals, 100% of reversely zoned clinopyroxene crystals, and 93% of reversely zoned orthopyroxene crystals. In awf, the populations found in the clots make up 100% of reversely zoned plagioclase crystals, 83% of reversely zoned clinopyroxene crystals, and 100% of reversely zoned orthopyroxene crystals. Generally, reversely zoned crystals result from disequilibrium between the crystal and the melt, indicating additional factors complicated the evolution of the melt (Streck 2008). In both adl and awf, the presence of large clots primarily composed of reversely zoned crystals, combined with the comparatively small numbers of reversely zoned crystals belonging to populations not found in the large clots, suggests that the crystals composing the large plagioclase and pyroxene clots (plagioclase populations 4A, 4B, and 5, clinopyroxene populations 1B and 2, and orthopyroxene populations 1C and 2A) originated from a different source than the crystals of the remaining populations (solitary crystals, plagioclase and plagioclase clots).

The compositional similarities in the cores of the high-An plagioclase in both adl and awf suggests that it is possible that both units shared a magmatic source from which these high-An cores were derived. Crystallization of the high-An cores suggest a mafic source that is likely to be situated deeper in the crust. If the two units indeed share a magmatic source, then there must be some degree of deep reservoir connectivity between Middle Sister and South Sister. In contrast, while overlapping in composition, subtle differences make it unclear whether the cores of moderate-An plagioclase populations and the pyroxene populations could have originated from the same sources. However, the compositional differences in the outer mantles of the moderate-An plagioclase populations and the pyroxene populations found in the large clots indicate that, at the time of outer mantle crystallization, the two units did not share a magmatic source. Based on their moderate compositions, it is probable crystallization of the outer mantles occurred in shallower reservoir. The lack of evidence for a shared source suggests that the reservoirs of Middle Sister and South Sister diverge in the shallower crust, although whether the divergence occurs in the middle or upper crust is unknown. Furthermore, the low Mg# pyroxene rims and low-An plagioclase rims in awf indicate that awf experienced a period of crystallization in a more silicic reservoir that adl did not. When taken together, the compositional data suggests that reservoirs of Middle Sister and South Sister could be connected at depth, but that connection does not persist throughout the magmatic system, and the two volcanoes did not share shallower reservoirs during the ca. 24 ka andesitic eruptions on their eastern flanks.
Conclusion

From 27 ka to 22 ka, Middle Sister and South Sister experienced overlapping and often synchronous periods of eruptive activity. Similarities in both age and composition of many of the erupted units, along with the proximity of the two volcanos, raised the possibility that the two volcanos were drawing on the same reservoirs. This thesis represents the initial efforts in untangling the potential interactions between these two volcanoes. Two units that were identified as ideal candidates for comparing the two volcanoes are the andesite of Demaris Lake (adl), which erupted onto the eastern flank of Middle Sister roughly 24 ka, and the andesite of West Fork Park Creek, which erupted onto the eastern flank of South Sister roughly 23.7 ka. Analysis of the compositional and textural mineral data suggest that reservoirs of Middle Sister and South Sister could be connected at depth, but that connection did not persist throughout the magmatic system, and the shallower reservoirs of the two volcanoes that fed eastern-flank eruptions were not connected ca. 24.

This thesis represents starting efforts in untangling this complicated volcanic system, and the scope of the thesis is therefore limited, with many opportunities for future work. The most critical piece of missing information for this thesis is trace element data, which can act as a fingerprint and allow for more detailed investigations into the origin of each of the crystals. Once trace element work is completed, the scope can be expanded, and the conclusions drawn in this thesis can be compared to the conclusions drawn by other researchers working on Middle Sister and South Sister, resulting in a better understanding of the interaction between these two adjacent volcanoes.
Works Cited


Appendix

Crystal Images

*Andesite of Demaris Lake (adl)*

Plagioclase population 1a:

[Images of crystal images]

Plagioclase population 1c:
Plagioclase population 2:

Plagioclase population 3:

Plagioclase population 4a:

Clinopyroxene population 1a:
 Clinopyroxene population 1b:

 Clinopyroxene population 2:
Clinopyroxene population 4:

Orthopyroxene population 1a:

Orthopyroxene population 1b:

Orthopyroxene population 1c:
Orthopyroxene population 2a:

Orthopyroxene population 2b:

Olivine population 2:
Andesite of West Fork Park Creek (awf)

Plagioclase population 1b:

Plagioclase population 1c:
Plagioclase population 4b:

Plagioclase population 5:

Clinopyroxene population 1a:

Clinopyroxene population 1b:
Clinopyroxene population 2:

Clinopyroxene population 3:
Orthopyroxene population 1c:

Orthopyroxene population 2a:
Olivine: