

Integrating Geochemical and Geophysical Datasets at the Three Sisters Volcanic Complex, OR,
USA

by

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DISSERTATION ABSTRACT

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Doctor of Philosophy in Earth Sciences

Title: Integrating Geochemical and Geophysical Datasets at the Three Sisters Volcanic Complex, OR, USA

Modern volcanology aims to comprehensively understand volcanic eruption processes and mitigate risks for stakeholders to minimize loss of life. Volcanology has advanced significantly in recent decades, improving our understanding of past and present magmatic systems due to technological advances, precision in laboratories, increased computing power, and more experimentation. However, the community advocates for more interdisciplinary volcanology projects, urging geochemists, geophysicists, physical volcanologists, and experimental petrologists to collaborate in investigating the inner workings of volcanoes. My Ph.D. research enters this arena, exploring the magmatic evolution of the Three Sisters volcanic complex in the central Oregon Cascades. First, I examine magmatic storage and timescales at South Sister through zircon geochronology. This work establishes that the two oldest rhyolites are over 10 kyr younger than previously recorded, hypothesizes that the late Pleistocene and Holocene rhyolite sequences originate from distinct reservoirs, and indicates that the increased rate of rhyolite eruption during the late Pleistocene should inform future volcanic hazard monitoring and preparation at South Sister. Second, I investigate questions of magmatic evolution related to the modern-day system of the Three Sisters using a field Bouguer gravity survey and forward gravity model through magma dynamics simulations. This work suggests a magma flux range of $10^{-3} - 10^{-1} \text{ m}^3/\text{m}^2/\text{yr}$ to recreate the past eruptive volumes at the Three Sisters. It highlights that the magmatic system does not have a significant density contrast with the crust, limiting the Bouguer gravity anomaly. Finally, I employ a zircon growth model to investigate the zircon record in magmatic simulations corresponding to the eruptive history of the Three Sisters. These simulations yield a zircon age record that resembles the natural record, suggesting a single magma body with cooling edges and eruptible melt pockets. Overall, this interdisciplinary study of the Three Sisters magma system updates the eruption timeline, indicates a lack of significant mobile melt in the shallow crust, and supports a focused magma

system for zircon crystal growth. Enhancing our understanding of this system aids hazard analysis and monitoring of this high-threat volcanic complex. This dissertation includes previously published and unpublished coauthored material.

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CHAPTER I

CHAPTER 1: INTRODUCTION

1.1 Goals of Modern Volcanology

The US contains 161 potentially active volcanoes, which have experienced over 120 eruptions since 1980. Eighteen of these volcanoes are classified as “very high threat” by the U.S. Geological Survey (USGS) (Ewert et al., 2018). One of the challenges posed to volcanologists is “to document and understand the repose, unrest, precursors, and timing of eruptions during the entire life cycle of volcanoes” to help mitigate volcanic hazards (Committee on Improving Understanding of Volcanic Eruptions et al., 2017). In just ten years, from 1980 to 1990, 620,000

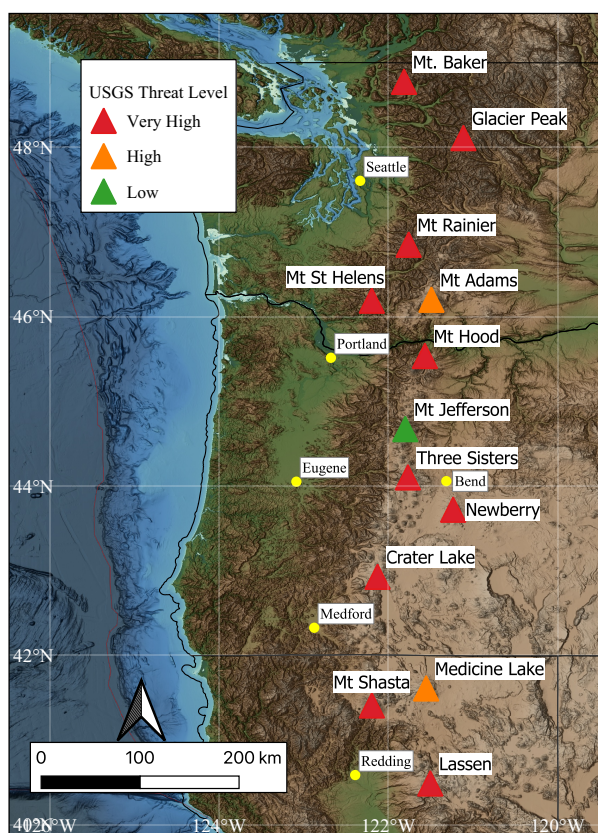


Figure 1: Map of the Cascade Volcanic Arc with volcano symbology representing the USGS threat level following Ewert et al. (2018).

people were directly impacted by volcanic eruptions, and by 2000, at least 500 million people lived within a volcanic risk zone (Tilling and Lipman, 1993; Chester et al., 2000). With potential eruption hazards of pyroclastic density currents, emission of gas, ash plumes, volcanic floods, and lava flows, investigating past volcanic eruptions to inform future eruption hazards is essential. This includes studying eruptive products (e.g., lava compositions, tephra dispersal, dating methods), magmatic storage conditions of the past (e.g., pressure, depth, temperature, composition, volatile content, longevity), and geophysical imaging of the modern system (e.g., magnetotellurics, seismic velocities, gravity anomalies) to inform volcanic hazard

and risk assessments. Inherently, all methods ask and answer distinct questions, but powerful results follow combining methods for a more holistic understanding of a volcano. This dissertation applies interdisciplinary approaches to a “very high threat” volcanic complex: the Three Sisters (Figure 1).

1.2 Three Sisters Volcanic Complex

1.2.1 Indigenous Perspectives

Multiple indigenous groups resided in the central Oregon region, including the Confederated Tribes of Siletz Indians, Confederated Tribes of Warm Springs, Kalapuya, and Confederated Tribes of Grand Ronde (Native Land Digital, 2023). The Confederated Tribes of the Warm Springs have passed down stories and traditions about the peaks of their area—tales of mountains who were once people, fighting over jealousy or carrying food on their journeys. One story archived by Clark (1953) from The Confederated Tribes of the Warm Springs reveals the character of the Three Sisters, without needing to sample any rocks or take any measurements:

Klah Klahnee, the Three Sisters, was once the biggest and highest mountain of all; it could be seen for many miles. One time, the earth shook for days, and the mountain boiled inside. It boiled over, and hot rocks came out of the top of it. Flames and smoke rose high in the air. Red-hot stones were thrown out in every direction. Many villages and many Indians were buried by the rocks. When the mountain became quiet again, most of it was gone. Only three points were left. That is why it is called *Klah Klahnee*, for it means “three points.” You can still see the black rocks all around the base of the three mountains.

This vivid story records the past eruptive hazards posed in the region and discusses how volcanic eruptions directly impacted the Warm Spring tribe. I acknowledge the people of this region and appreciate their vivid description of the land I study through this dissertation. While I will refer to these peaks as the Three Sisters, I appreciate that the original name, Klah Klahnee, or “three peaks,” is an even more descriptive and meaningful name for the volcanoes.

1.2.2 Eruptive History

There has long been interest in mapping and describing the geology of the Three Sisters region. This begins with the first geological overview of the area (Hodge, 1925), followed by a more volcanology-based study (Williams, 1944) that was built upon for a more holistic study of the central Oregon region (i.e., Taylor, 1990; Sherrod et al., 2004). The Three Sisters have been the topic of multiple dissertations (such as this one) (i.e., Wozniak, 1982; Clark, 1983; Hill, 1991; Webster, 1992; Schmidt, 2005). Notably, a U.S. Geological Survey group led a mapping and dating study of the region, laying the base for future, more detailed studies of the volcanic complex (Fierstein et al., 2011; Hildreth et al., 2012; Calvert et al., 2018).

Despite their proximity, each of the three volcanoes in the Three Sisters shows distinct characteristics. In only 20 km running north-south in the central Oregon Cascades lie the major stratovolcanoes North Sister, Middle Sister, and South Sister. The oldest and northernmost of the three main stratovolcanoes is North Sister. North Sister is built of uniform basaltic andesite from 130 – 50 ka (Schmidt and Grunder, 2009). The uniform composition through time is formed by repeated mantle-derived injections of low-potassium tholeiitic basalt, causing low-degree melting of crustal gabbro (Schmidt and Grunder, 2011). Middle Sister is next in space and time, with largely mafic and intermediate eruptions, but also a single rhyolite building the edifice from 49 – 14 ka (Calvert et al., 2018). Finally, South Sister initiated 39 ka, building up the edifice with largely alternating rhyolite, dacite, and andesite until 22 ka (Fierstein et al., 2011; Dechert et al., 2024). After a long pause, South Sister erupted two series of rhyolites around 2 ka on the east and west flanks of the volcano (Scott, 1987). Given the rarity of rhyolite in the high Cascades, numerous studies have postulated mechanisms to produce the more felsic materials with no consensus yet, such as partial melting (Waters et al., 2021), fractional crystallization (Brophy and Dreher, 2000; Parker et al., 2023), melt contributions from dehydration melting of the crust (Hill, 1991; Fierstein et al., 2011), and rejuvenation of residual felsic magmas (Calvert et al., 2018). While such previous work sets the stage at the Three Sisters, many questions remain.

1.2.3 Modern Unrest

In addition to studies of the history of the Three Sisters, efforts have been made to probe the modern-day magmatic system. Deformation to the west of South Sister was first identified by Wicks (2002) suggesting that the uplift was caused by magma intrusion or pressurization of a geothermal system at 6.5 km depth with a volume increase of 0.023 km³. Following studies used InSAR, non-continuous GPS, and leveling methods to explore the deformation that started between 1995 and 1996 (Dzurisin et al., 2006, 2009; Riddick and Schmidt, 2011; Rodríguez-Molina et al., 2021; Lisowski et al., 2021). These studies all have variations in the depths, volumes, and source hypotheses around the inflation. However, the most updated time series suggests that the total uplift of 30 cm (by 2020) is sourced from 5.9 km below the surface and is caused by either 1) persistent magma input causing the surrounding crust to respond elastically to the source-volume increase or 2) an initial injection of magma before 2020 after which the surrounding viscoelastic shell has relaxed (Lisowski et al., 2021). Utilizing another method of geophysical monitoring, Zurek et al. (2012) conducted a microgravity survey over the deforming

area from 2002 to 2009, but did not find evidence of any mass changes, suggesting the ongoing deformation was in response to a past intrusion. To more completely image the hydrothermal or magmatic system at the Three Sisters, Le Mével et al. (submitted) conducted a Bouguer gravity survey, identifying a hydrothermal system of 5 km³ down to 3 km depth, but found no evidence of an eruptible magma body. Instead, they hypothesize that there is a felsic mush with 15-55% partial melt and that the mid-1990s intrusion intersected the base of the mush magmatic system.

Besides geodetic monitoring, spring geochemistry in the Three Sisters also indicates a magmatic source. In the deformation area, low-temperature springs display magmatic carbon, mantle-like helium isotope ratios, and magmatic heat (Evans et al., 2004; Ingebritsen et al., 1994). However, given a chloride anomaly in the area that predates the deformation, Evans et al. (2004) suggest that these geochemical anomalies originate from an intrusion that pre-dates the mid-1990s intrusion.

1.2.4 Unanswered Questions

Even with the fantastic previous research on the Three Sisters volcanic complex, I identify three main groups of unanswered questions: the relationship between the three main volcanoes, the Cascades rhyolite anomaly, and the current magmatic system regarding forecasting future eruptions.

Not only does the Three Sisters Reach of the Cascades arc have one of the highest vent densities with 466 Quaternary volcanoes, three major stratovolcanoes, plus Broken Top, all lie in a 20 km arc segment, which is an anomaly in the arc (Hildreth, 2007). However, each volcano is distinct from the others. Open questions include: What controls the SiO₂ progression to become more felsic to the south (Figure 2a)? Why do we see an age progressing from oldest in the north to youngest in the south, but also see the older Broken Top (300-150 ka) to the east (Figure 2b)? What causes the shift to high eruptive productivity from 50-20 ka, producing coeval Middle and South Sister? Finally, does a single, connected magmatic system form all three volcanoes, or does each system have a physically distinct source? Through this dissertation, I will address the eruptive sequence of South Sister in Chapter 2, creating a clearer picture of the age progression

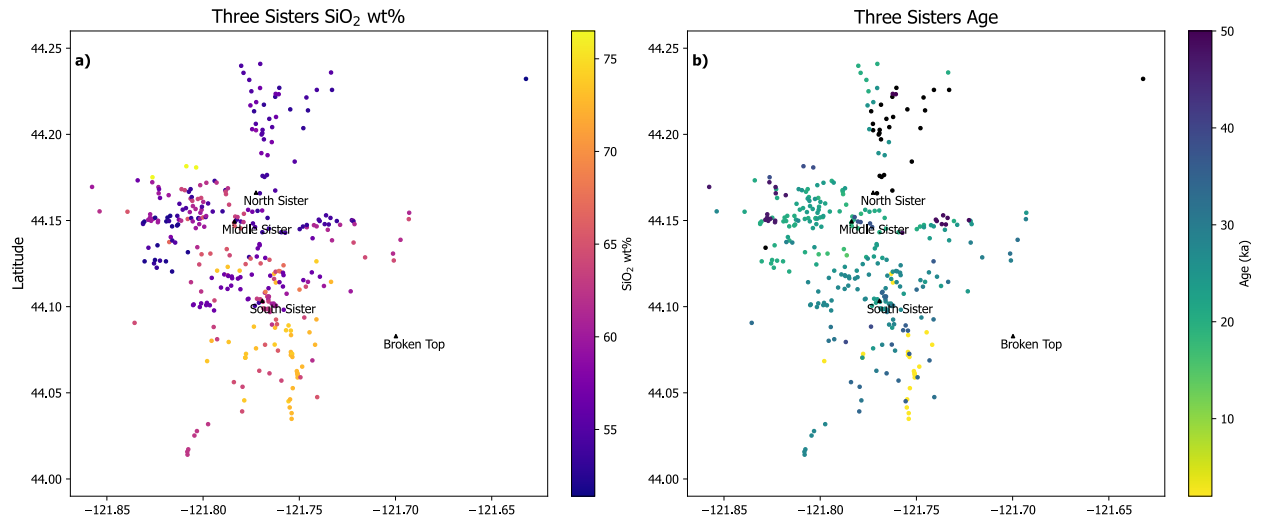


Figure 2: Map showing the age and SiO_2 trends of eruptions in the Three Sisters. a) SiO_2 contents of eruptions from the Three Sisters. Note the more felsic eruptions to the south. b) Ages of eruptions from the Three Sisters. Black dots denote ages >50 ka.

of the system. In Chapter 3, I will address the connectivity of a single or multiple distributed intrusions sourcing the eruptions.

Outside the rear arc, the Three Sisters and Lassen are the only locations with true high-silica rhyolite in the Cascades (Hildreth, 2007). In fact, the scarcity of rhyolites in the front arc settings is true worldwide. Middle Sister has one rhyolite, South Sister erupted 13, and just to the east of the Three Sisters lies a “silicic highland” of the Tumalo Volcanic Field with numerous rhyolites (Sherrod et al., 2004). As Hildreth (2007) says, “there are many roads to rhyolite,” and those roads have been hypothesized at South Sister (Hill, 1991; Brophy and Dreher, 2000; Waters et al., 2021; Parker et al., 2023). However, the root cause of why rhyolites can form here and not elsewhere along the arc is vastly missing. Some studies will suggest that central Oregon is the leading edge of the High Lava Plains rhyolites associated with the presence of the Yellowstone Plume (MacLeod et al., 1975; Jordan et al., 2004; Fierstein et al., 2011). Still, there seems to be no effort to connect that statement to the region's geochemistry or tectonics. As such, I believe the root cause of rhyolites in the Three Sisters region is a significant, outstanding question.

Finally, I believe we have a vague understanding of the current magmatic system beneath the Three Sisters. The geodetic evidence suggests a magmatic intrusion at 6 km depth, but neither a microgravity nor a Bouguer gravity survey has been able to successfully image such a magma body (Zurek et al., 2012; Le Mével et al., submitted). The null hypothesis of Le Mével et

al. (submitted) is an excellent step to understanding the system, highlighting that there is no perceptible, eruptible magma of large volumes in the shallow crust. Additionally, in Chapter 3, I show that even while the Three Sisters are in the highest eruptive state, the possible gravity anomaly due to the magma system is not very different from the modern signal, suggesting a magma system with a density close to the background crust. If this is true, and there is a magma body between 3-6 km with 15-55% partial melt, what sort of recharge event would create an eruptible magma body? More importantly, how would we monitor for a recharge event large enough to remobilize such a magma body (i.e., Cooper and Kent, 2014)? Such questions and answers directly impact the setup of a monitoring network and the interpretation of future unrest.

1.3 Geochronology and Geochemistry

One method regularly utilized to probe the past of volcanic eruptions is a geochronology perspective, or the clocks of volcanoes. In short, we can use the decay of radioactive isotopes in minerals to measure time. The first date calculation through this method is attributed to Bertram Boltwood in 1907, who used the U/Pb series to date a uranium ore sample (White, 2015). Decay systems commonly used in geologic settings include the K-Ar-Ca, Rb-Sr, Sm-Nd, Lu-Hf, and U-Th-Pb systems (White, 2015). A common dating method in volcanology is the $^{40}\text{Ar}/^{39}\text{Ar}$ method, and in unaltered volcanic rocks, the date is interpreted as the eruption age (Schaen et al., 2021a). This is the primary dating method for recording the eruptive history of the Three Sisters (Fierstein et al., 2011; Calvert et al., 2018). However, a single date from a mineral is not necessarily helpful in discerning the evolution of or processes within the magmatic system.

This led to the term petrochronology, or the study connecting time (i.e., ages) with rock and mineral-forming processes and physical conditions (Engi et al., 2017). Zircon is a prime mineral for petrochronology studies, with time from the U-Th-Pb series, temperature from the Ti-in-zircon calculation, and magmatic processes recorded in the crystal's trace elements and rare earth elements (REE) (Watson and Harrison, 1983; Finch and Hanchar, 2003; Hoskin and Schaltegger, 2003; Engi et al., 2017). Zircon studies have focused on large-volume systems (Reid et al., 1997; Simon and Reid, 2005; Rubin et al., 2017) and small-volume systems (Claiborne et al., 2010; Stelten and Cooper, 2012), uncovering the thermal, chemical, spatial, and temporal evolution of magmatic systems (Cooper, 2015). The petrochronologic perspective has revealed magmatic processes such as magma stalling and rejuvenation at Mount St Helens (i.e., Claiborne et al., 2010), independent evolution patterns rather than a long-lived magma body at

Long Valley caldera (i.e., Simon and Reid, 2005), near-solidus crystal storage with only rapid heating events at the Okataina Volcanic Center (i.e., Rubin et al., 2017), and heterogeneous hot and cold magma storage zones of the magmatic system at Laguna del Maule (i.e., Andersen et al., 2019). I utilize this advantageous mineral to explore South Sister volcano's eruptive history and magmatic evolution in Chapter 2.

1.4 Geophysics

While looking to the past of volcanoes through geochronology is useful, another method focuses on probing the magmatic system of the present day: geophysics. Rather than using past eruptive products to understand a volcano, geophysical methods utilize various wave-matter or field-matter methods to image physical differences in the subsurface, identifying magma or hydrothermal fluids beneath active volcanoes. These methods typically use the inverse method, which uses the data collected to infer the subsurface (Blakely, 1995). However, this generally leads to non-unique solutions of the best Earth system model (Magee et al., 2018). However, when used in parallel, these methods are informative about modern magmatic systems. Handy methods include gravity surveys, seismic imaging, and electromagnetic methods. Gravity surveys measure the relative gravitational field at a volcano, and relate the gravity anomaly to the distribution of mass in the subsurface, finding anomalously low-density regions that can be interpreted as melt or fluids (Seigel, 1995). Such a survey identified low-density material ranging from 8-30 km depth in the Campania Active Volcanic Area (i.e., Campi Flegrei, Vesuvius), suggesting long-term magmatic injection and crystallization (Fedi et al., 2018). Seismic imaging techniques measure seismic wave speeds to identify changes in wave arrival times, as S-waves cannot travel through fluids, which also slow down P-waves (Gudmundsson, 2012). A recent effort to image the magmatic systems along the entire Cascade Arc analyzed receiver functions to identify P-to-S wave scattering, finding partial melt under Lassen Peak, Crater Lake, Newberry Volcano, Mount Hood, Mount St Helens, and Mount Rainier (Pang et al., 2025). Electromagnetic techniques measure the resistivity or conductivity variations of the crust to identify higher conductivity melt bodies (Stanley et al., 1990; Magee et al., 2018). In the Altiplano-Puna volcanic complex of the central Andes, a magnetotelluric survey imaged low resistivity melts at 15 km depth and shallow melts, highlighting recent intrusions (Comeau et al., 2015). Geophysical studies of modern magmatic systems provide essential data to support future monitoring efforts. The volume, depth, and melt fraction of an active magmatic system impact

how monitoring networks are built and control the types and magnitude of signals that unrest could produce. I compare the data from a gravity survey of the Three Sisters to simulated gravity anomalies to understand magmatic evolution in Chapter 3.

1.5 An Interdisciplinary Approach

Volcano science is inherently interdisciplinary. One of the main ways to continue strengthening volcanic science is through more multidisciplinary approaches, “integrating diverse types of observations from geophysics, geology, geochemistry, geodynamics, and remote sensing” (Committee on Improving Understanding of Volcanic Eruptions et al., 2017). Successful programs moving towards such endeavors include the Geodynamic Processes at Rifting and Subducting Margins (GeoPRISIMS) Program and the Subduction Zones in four Dimensions (SZ4D), which can help support projects such as imaging Magma Under St. Helens (iMUSH) to uncover the architecture of the Mount St. Helens magmatic system. The utility of such studies is shown at Kīlauea volcano, Hawai‘i, where olivine diffusion timescales and seismic swarms align, connecting real-time monitoring data with timescales of magmatic processes (Lynn et al., 2024). Additionally, an effort to combine petrologic, geophysical, stratigraphic, and modeling approaches displays a fuller picture of the 79 CE Plinian eruption of Vesuvius, Italy, impacts on the surrounding communities, and how such an eruption would impact society today (Doronzo et al., 2022). I believe multidisciplinary approaches are essential for a complete understanding of volcanic processes and specific volcanic edifices. As such, this dissertation considers geochronology and geophysical data, examining the magmatic system at the Three Sisters volcanic complex through an interdisciplinary lens.

CHAPTER II

CHAPTER 2: ZIRCON CONSTRAINTS ON THE ERUPTIVE SEQUENCE AND MAGMA EVOLUTION OF RHYOLITES AT SOUTH SISTER VOLCANO, OREGON

From Dechert, A. E., Andersen, N. L., Dufek, J., & Jilly, C. E. (2024). Zircon constraints on the eruptive sequence and magma evolution of rhyolites at South Sister volcano, Oregon. *Geochemistry, Geophysics, Geosystems*, 25, e2024GC011680. <https://doi.org/10.1029/2024GC011680>

2.1 Introduction

Globally, small volume but frequent explosive volcanic eruptions impact populations and aviation due to eruptive plumes, ashfall, lava flows, and lahars. Therefore, continuing interdisciplinary research at active volcanoes will help inform hazard assessments and mitigation strategies for future eruptions (e.g., Ewert et al., 2018). Geologic and petrologic approaches offer complimentary views of past eruptions and their implications for future behavior. On one hand, geologic studies yield information about the frequency, magnitude, and style of past activity to assess plausible future eruption scenarios. On the other, petrologic methods provide understanding of how the magmatic system has evolved and may offer clues about which past eruptions are more likely to be representative of the modern system and future behavior. The mineral zircon provides coupled temporal and compositional information that can inform both the timing of past eruptions and the evolution of the underlying magmatic system.

The utility of zircon is due to its durability, high compatibility with elements useful for geochronology and petrology (e.g., U, Th, and the rare earth elements), and a well-characterized temperature dependence of saturation (Watson and Harrison, 1983; Finch and Hanchar, 2003; Hoskin and Schaltegger, 2003). Zircon petrochronology has been applied to large eruptive volume systems (Reid et al., 1997; Simon and Reid, 2005; Rubin et al., 2017) as well as small to medium eruptive volume systems (e.g., Claiborne et al., 2010) to distinguish chemical, thermal, spatial, and temporal characteristics of melt evolution and processes (Cooper, 2015). In the Cascade Range, zircon studies have informed models of magma evolution and storage at Mount St. Helens (e.g., Claiborne et al., 2010), South Sister (e.g., Stelten & Cooper, 2012), Crater Lake (e.g., Bacon & Lowenstern, 2005), and Lassen Peak (e.g., Klemetti & Clynne, 2014). However, the dearth of rhyolite and lower U in these arc magmas has, in part, hindered broader application of zircon geochronology in the Cascade Range (Hildreth, 2007). The previous zircon study at

South Sister focused only on the most recent eruptions (Stelten and Cooper, 2012); however, the rhyolites that erupted in the late Pleistocene remain little investigated.

The U.S. Geological Survey has classified the Three Sisters volcanic complex as a “very high threat potential” to the surrounding communities, such as Bend (pop. 100,000), only 50 km away (Ewert et al., 2018). Past eruptions included hazards such as pyroclastic density currents, lava flows, and ash plumes (Scott et al., 2001). South Sister volcano has erupted approximately 12 km³ of volcanic rocks over its lifetime, including 13 rhyolitic eruptions ranging from 51 to 2 ka (Fierstein et al., 2011; Hildreth et al., 2012). Frequent eruption of rhyolite and its modest eruptive volume makes South Sister an ideal system to investigate the origin and pre-eruptive storage of rhyolite in smaller volume magmatic system.

In addition to the recent eruptions, South Sister has experienced ground inflation since the mid-1990s focused 5 km west of the summit and only ~3 km from the late Holocene Rhyolite of Rock Mesa (rrm) vent (Lisowski et al., 2021). InSAR, continuous GPS, leveling, and modeling studies proposed multiple mechanisms of this uplift including the continuing intrusion of basaltic magma (hydraulic), a delayed response of visco-elastic crust to a past magma intrusion (viscoelastic), or the pressurizing of a geothermal system (poroelastic) (Wicks, 2002; Dzurisin et al., 2009; Riddick and Schmidt, 2011). These studies suggest the source of deformation is approximately 5-7 km deep. Additionally, a study of springs near South Sister found He and C isotope ratios and elevated heat flow consistent with contributions from mafic magma (Evans et al., 2004). As such, the working hypothesis suggests an intrusion of basaltic magma 5-7 km below South Sister. This intrusion could lead to a future eruption at South Sister, and understanding how the past magmatic system compares to the modern system can help inform eruption and hazard forecasting.

We present ²³⁰Th-²³⁸U crystallization ages and trace element compositions of zircon crystals from rhyolites at South Sister volcano. Results of this study suggest (a) South Sister hosted a long-lived magmatic system primed for zircon crystallization from 100 to 20 ka, (b) the earliest rhyolite eruptions are more than 10 kyr younger than past studies suggested, (c) South Sister was characterized by a high eruption rate from 40-30 ka, and (d) the Pleistocene and Holocene rhyolites are derived from chemically distinct sources.

2.2 Geologic Background

The Three Sisters volcanic complex comprises three stratovolcanoes (North Sister, Middle Sister, and South Sister) located in the central Oregon Cascade Range, USA (Figure 3). The regional tectonics of this reach of the Cascade Range is complicated by the interaction

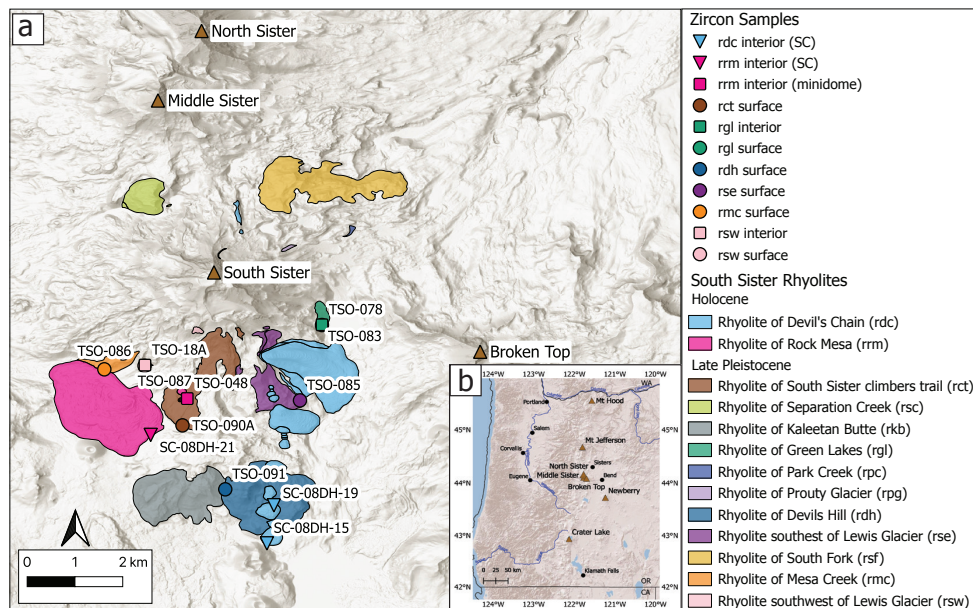


Figure 3: a) Simplified geologic map of the South Sister rhyolites (modified from Hildreth et al., 2012) with locations of samples discussed in this paper. Brown triangles show South Sister, Middle Sister, North Sister, and Broken Top summits. Cyan and magenta triangles denote the samples of Stelten and Cooper (2012). Squares symbolize zircon interior analysis and circles symbolize zircon surface analyses for samples from this study. Colors signify samples from the same eruptive unit. See Dechert (2024) or supplemental data for sample coordinates. b) Inset shows the location of the Three Sisters in the Oregon Cascade Range, other notable Cascade Range volcanoes, and major cities.

between the warm Cascadia subduction zone, the past influence of the Yellowstone plume, the edge of the Basin and Range extension, and may contribute to the unusual abundance of high-SiO₂ volcanism for this region of the Cascade Range (Obrebski et al., 2010; McCrory et

al., 2012; Cheng et al., 2017). The oldest and northernmost of the three, North Sister, erupted basaltic andesite with major cone construction from approximately 120-45 ka (Schmidt and Grunder, 2009; Hildreth et al., 2012). Growth of Middle Sister occurred from approximately 49-15 ka with compositions ranging from basaltic andesite to rhyolite (Calvert et al., 2018). Building of the South Sister edifice alternated between rhyolite and intermediate products from ~51-22 ka, largely coevally with Middle Sister (Fierstein et al., 2011). The growth of all the Three Sisters stratovolcanoes was preceded by the growth of Broken Top stratovolcano, located just 5 km southeast of South Sister. Broken Top erupted 7-10 km³ of basaltic andesite to rhyodacite from approximately 300-150 ka (Hildreth, 2007). In total, the Three Sisters reach of the Cascade Range extends 90 km N-S in Central Oregon, and has at least 466 Quaternary volcanoes (Hildreth, 2007). Postglacial mafic eruptions are more common in this area than

elsewhere in the Cascade Range. These postglacial volcanic centers include the Sand Mountain volcanic field, Blue Lake volcano, LeConte Crater, Fish Lake lava from Nash Crater, Lost Lake cones, Four In One Cone, Yapoah Crater, Collier Cone, and Belknap Crater (Sherrod et al., 2004). Slightly farther south lies Mount Bachelor, which is the largest of approximately 50 N-S aligned basalt to basaltic andesite vents that erupted from 18-8 ka (Gardner, 1994).

The eruption chronology at Three Sisters has largely been established by $^{40}\text{Ar}/^{39}\text{Ar}$ dates (Fierstein et al., 2011; Hildreth et al., 2012; Calvert et al., 2018). However, Fierstein et al. (2011) used the Taylor Creek sanidine standard age of 27.87 Ma while Calvert et al. (2018) used a more recently determined, slightly older age for the Taylor Creek sanidine standard of 28.345 Ma (Fleck et al., 2019). To ensure that all the $^{40}\text{Ar}/^{39}\text{Ar}$ dates are reported on the same basis and are directly comparable, we have recalculated the $^{40}\text{Ar}/^{39}\text{Ar}$ dates using the ArAR software of Mercer & Hodges (Mercer and Hodges, 2016) to an updated Taylor Creek age of 28.447 Ma (equivalent to a Fish Canyon Sanidine age of 28.201 Ma; (Fleck et al., 2019; Schaen et al., 2021a)) and decay constants of Min et al. (2000). For the remainder of this paper, we will report $^{40}\text{Ar}/^{39}\text{Ar}$ ages for South Sister based on this recalculation (Figure A1).

South Sister's eruptive history highlights a range of compositions and one of the rare instances of rhyolite in the Cascade Range (Hildreth, 2007). The oldest exposed lava at South Sister is rhyolitic at 51.4 ± 9.7 ka and eruptions alternated between rhyolitic, dacitic, and andesitic through ~ 37 ka (Fierstein et al., 2011). Then, a broad cone composed of andesitic to dacitic lavas grew from 37 to 30 ka. Activity became concentrated at the summit cone by ~ 27 ka culminating with the final and most mafic South Sister eruption at ~ 22 ka, which formed the present-day summit crater (Fierstein et al., 2011). Finally, two rhyolitic eruptions occurred at approximately 2 ka on the SW and E flanks of the volcano (Scott, 1987). Previous studies have hypothesized that the mechanism for rhyolite production at South Sister could include a) partial melting from different crustal compositions, b) fractional crystallization from mafic precursor magma, or c) the Holocene rhyolites could reflect the rejuvenation of residual rhyolitic magmas related to the late Pleistocene eruptions (Hill, 1991; Brophy and Dreher, 2000; Fierstein et al., 2011; Calvert et al., 2018; Waters et al., 2021; Parker et al., 2023). Hypotheses to explain the compositional gaps in the suite of Three Sisters eruptive products include fractional crystallization (Brophy & Dreher, 2000; Dufek & Bachmann, 2010) and partial melting (Waters et al., 2021); however, these gaps are not as dramatic at South Sister when considering the more

comprehensive data set of Hildreth et al. (2012). These hypotheses highlight the importance of further study as the mechanisms of silicic magma genesis at South Sister and the connection between the late Pleistocene and Holocene rhyolite eruptive episodes remain an open question.

Zircon and plagioclase geochronology and trace element chemistry of the two Holocene rhyolite eruptions suggests two distinct magma sources. Rhyolite of Rock Mesa (rrm) erupted at $2,150 \pm 150$ ^{14}C yr B.P. (preferred ^{14}C age of Scott, 1987) with a main coulee, pumice-fall deposits, and satellite domes on the SW flank of South Sister (Scott, 1987; Hildreth et al., 2012). Rhyolite of Devils Chain (RDC) erupted at $2,000 \pm 200$ ^{14}C yr B.P. in a series of seven lava flows and domes aligned N-S on the southeast flank of South Sister (Scott, 1987; Hildreth et al., 2012). Here, we note different naming of units between sources but consider them superseded by Hildreth et al. (2012). The zircon ^{230}Th - ^{238}U crystal ages are predominantly 80-20 ka for both Holocene eruptions with a small number of grains in secular equilibrium (>350 ka) (Stelten & Cooper, 2012). The zircon crystals with resolvable dates are interpreted to be antecrystic, inherited from the longer-lived system (Stelten and Cooper, 2012). Conversely, bulk plagioclase ^{230}Th - ^{226}Ra crystal ages trend closer to eruption age, 6.8-2.3 ka for rrm and 9.6-4.0 ka for rdc (Stelten and Cooper, 2012). The Ti-in-zircon geothermometer indicates zircon crystallization ranges from 640-837°C (Stelten and Cooper, 2012). The distinct trace element ratio of Hf/Nb of the rrm and rdc zircon crystals suggest these eruptions were sourced from two chemically and physically distinct reservoirs that coexisted temporally in the broader, shared magmatic system (Stelten and Cooper, 2012). While this work focused on the Holocene rhyolites, no such work has included the late Pleistocene South Sister rhyolites.

2.3 Samples and Methods

Samples collected for this work include six late Pleistocene and one Holocene rhyolite from South Sister (Figure 3). The units span the southern spatial extent of the rhyolite eruptions and the known eruption age range. Zircon data were collected for the Rhyolite southwest of Lewis Glacier (rsw), Rhyolite of Mesa Creek (rmc), Rhyolite of southeast Lewis Glacier (rse), Rhyolite of Devils Hill (rdh), Rhyolite of Green Lakes (rgl), and Rhyolite of South Sister climbers trail (rct). These units erupted between 51.4 and 24 ka based on $^{40}\text{Ar}/^{39}\text{Ar}$ ages reported by Fierstein et al. (2011), Hildreth et al. (2012), and Calvert et al. (2018). Ages are based on incremental heating of plagioclase separates (rsw, rmc, and rct) or groundmass (rse, rdh, rgl) separates. Of the Pleistocene rhyolites, rse, rgl, rdh, and rdc are on the southeastern flank of the

volcano, which situates them near Broken Top. Our work also considers the Holocene rrm and rdc rhyolites erupted at $2,150 \pm 150$ ^{14}C yr B.P. and $2,000 \pm 200$ ^{14}C yr B.P. These eruption ages are based on ^{14}C dates of wood fragments within rrm pumice fall and a soil directly underlying rdc tephra (Scott, 1987). We collected a sample of ejecta associated with the rrm satellite minidomes and compare our results to those of Stelten & Cooper (2012) samples from the main rrm coulee and two of the southern rdc domes (Figure 3).

Zircon separates were produced by Zirchron LLC using standard magnetic and density separation techniques, including crushing, electro pulse disaggregation, water table, heavy liquids, and Frantz. Analysis of ^{238}U - ^{230}Th dates and trace element compositions were conducted on the SHRIMP-RG (reverse geometry) ion microprobe co-operated by U.S. Geological Survey and Stanford University in the SUMAC facility at Stanford University during multiple sessions in 2023. Zircons were pressed into indium mounts and left unpolished. For these surface analyses, trace element data were collected followed by ^{230}Th - ^{238}U analysis on the same spot. We also attempted to measure zircon interiors by mounting in epoxy and polishing the mount. A cathodoluminescence image of the polished interiors displays size, shape, and textures of the crystals analyzed (Figure A2). The average c-axis length is 87 μm and the average a-axis length is 49 μm . Crystals are euhedral and the most common shape is equant with additional shapes being tabular and prismatic. Approximately 30% of the crystals exhibit sector zoning, another 30% have patchy zoning, with oscillatory, homogeneous, diffuse, and irregular patterns for the rest. One sample, rrm minidome, does include resorbed cores on 6 of the 22 crystals analyzed. Unfortunately, the small size of most of the zircon crystals frequently resulted in the beam impinging on the epoxy during ^{230}Th - ^{238}U analysis of crystal interiors yielding a significant carbide interference and unusable data.

The U-Th analytical procedure and data reduction procedures follow methods developed by Williams (1997) and Ireland & Williams (2003). An O_2^- primary beam with accelerating voltage of 10 kV was used to sputter secondary ions from the sample surface with a 15-16 nA primary beam current focused to a ~ 37 μm spot. Seven masses were measured, including $^{90}\text{Zr}^{16}\text{O}$, $^{238}\text{U}^+$, $^{232}\text{Th}^{12}\text{C}^+$, $^{230}\text{Th}^{16}\text{O}^+$, background measured 0.050 AMU above the $^{230}\text{Th}^{16}\text{O}^+$ peak, $^{232}\text{Th}^{16}\text{O}^+$, and $^{238}\text{U}^{16}\text{O}^+$. Data were collected over 8 scans per spot, for a total run time of ~ 30 minutes, collected by magnet peak-jumping on an electron multiplier. Zircon U

concentration data were standardized against the well-characterized MAD-559 zircon standard (3940 ppm U; (Coble et al., 2018)).

For trace element analyses, an O_2^- primary beam with accelerating voltage of 10 kV was used to sputter secondary ions from the sample surface with a 1.5 nA primary beam current focused to a $\sim 16\mu m$ spot. The acquisition included analysis of 29 masses, all measured by peak jumping on an electron multiplier: $^{28}Si^{16}O^+$, $^{45}Sc^+$, $^{48}Ti^+$, $^{49}Ti^+$, $^{56}Fe^+$, $^{89}Y^+$, $^{93}Nb^+$, $^{92}Zr^+H^+$, $^{96}Zr^+$, $^{139}La^+$, $^{140}Ce^+$, $^{141}Pr^+$, $^{146}Nd^+$, $^{147}Sm^+$, $^{153}Eu^+$, $^{155}Gd^+$, $^{165}Ho^+$, $^{159}Tb^{16}O^+$, $^{162}Dy^{16}O^+$, $^{166}Er^{16}O^+$, $^{169}Tm^{16}O^+$, $^{172}Yb^{16}O^+$, $^{175}Lu^{16}O^+$, $^{90}Zr^{16}O^+$, $^{180}Hf^{16}O^+$, $^{206}Pb^+$, $^{207}Pb^+$, $^{232}Th^{16}O$, and $^{238}U^{16}O^+$. Count times ranged from 2–18 seconds per mass to optimize counting statistics for each isotope, for a total run time of ~ 13 minutes per spot. See Dechert et al. (2024) Text S1 for additional details of the SHRIMP-RG analytical methods.

Zircon ages are calculated using the decay constant of (Cheng et al., 2013) and the method of Boehnke et al. (2016). The Boehnke et al. (2016) method calculates a date based on a mode equilibrium melt for each zircon spot based on the $^{238}U/^{232}Th$ measured in the zircon, an assumed U/Th partition coefficient ratio between the zircon and the melt, and assumes that melt variance from the equiline is $\pm 15\%$ (1σ). We calculated this mean U/Th partition coefficient to be 5.4 ± 0.8 from the South Sister zircons and sample whole rock compositions (Dechert et al., 2024 Table S4).

The dates reported by Stelten & Cooper (2012) for the Holocene rhyolites were calculated using a two-point model isochron approach (e.g., Reid et al., 1997) using the glass Th isotope ratios of the host rhyolites and the older decay constant of Cheng et al. (2000). To ensure our dates are comparable to those of Stelten & Cooper (2012) we first recalculated their model isochrons using the newer decay constant of Cheng et al. (2013) and find only 5% average difference with the updated decay constant after removing one crystal in secular equilibrium. We then compared these dates to those calculated from their data using the Boehnke et al. (2016) model and employed for our measurements and find a 38% difference for rdc (59% absolute difference within uncertainty) and 30% for rrm (78% absolute difference within uncertainty). Stelten & Cooper (2012) found the Holocene rhyolite whole rock compositions to be in 2% Th-excess. This contrasts to the average of secular equilibrium $\pm 15\%$ that is assumed in the Boehnke et al. (2016) model and is a potential source of bias. We tested the magnitude of this bias by calculating model isochron dates using a whole rock Th isotope composition based on the whole

rock U/Th ratio and assumptions of secular equilibrium with 2% Th excess. We find that assuming 2% Th-excess makes an average difference of 2.2% in the calculated dates, which is less than the analytical uncertainty. In the absence of whole-rock or glass Th isotope compositions for the Pleistocene rhyolites, we prefer the method of Boehnke et al. (2016) and find the assumption that the host melt is in secular equilibrium on average is simpler and no less reasonable than assuming the Th-excess measured for the Holocene rhyolites was homogeneous throughout the magma system and unchanging during the interval of zircon crystallization. All zircon dates discussed for the rest of this paper were calculated by the Boehnke et al. (2016) model without Th excess. Additionally, to also ensure that the trace element measurements from Stelten & Cooper (2012) are comparable to the late Pleistocene data, we recalculated the Holocene data with preferred concentrations of Coble et al. (2018) that intercalibrate MAD-1 (standard of Stelten & Cooper (2012)) and MAD-559 (standard of this work) zircon trace element standards.

2.4 Results

2.4.1 Zircon ^{230}Th - ^{238}U Dates

Individual ^{230}Th - ^{238}U ages are model ages calculated using the Boehnke et al. (2016) model and represent zircon crystallization ages. Our data include 18 analyses in secular equilibrium, and thus unresolvable dates >350 ka. The 228 resolvable zircon dates range from 282.5-3.4 ka, but 199 (87%) are between 100-20 ka (Figure 4). There are three dates from rgl interiors that are nominally resolvable from 344.4-310.9 ka but are within error of secular equilibrium and therefore potentially older. The zircon dates for units rsw, rmc, rse, rdh, and rct all yield probability density maxima around 40 ka (Figure 5). Units rrm (combined) and rdc show a broad distribution with no distinct peaks. The unpolished surface analyses (rsw, rmc, rse, rdh, rgl, rct) yield a narrower range of younger dates compared to the crystal interiors (rdc, rrm coulee, rrm minidome, rgl, rsw). This is especially true for rgl interiors; however, we do not have a complete dataset of interior and surface analyses for the other units. Unit rgl shows two populations of zircon ages, one between 100-20 ka, probability density maxima of ~40 ka, like the other Pleistocene rhyolites, and one >150 ka, probability density maxima of ~250 ka (Figure 5). The coherent >150 ka population was not found in the rgl surface dates, nor the surface dates of the other rhyolites. While we only have four interior analyses for rsw, the zircon crystal date range of 70.2-27.6 ka matches that of the larger surface dataset, 96.7-25.4 ka.

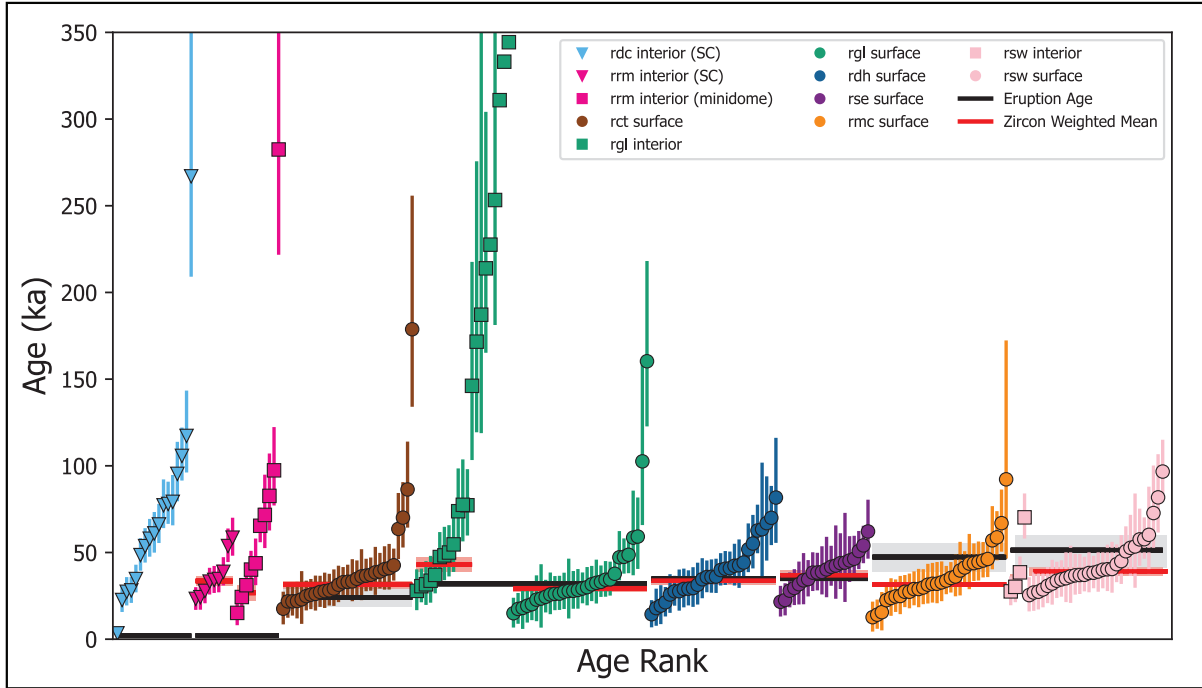


Figure 4: Rank order plot of zircon crystallization ages. Data of Stelten and Cooper (2012) symbolized as triangles and labeled SC. Zircon surface analyses are circles and interior analyses are squares. Black horizontal lines with gray fields show the associated ^{14}C date (rdc and rrm) or $^{40}\text{Ar}/^{39}\text{Ar}$ date (all others) with 1σ uncertainty (Fierstein et al., 2011; Scott, 1987). Red horizontal lines with salmon fields show the zircon weighted mean date with 1σ uncertainty of the youngest group of zircons that yield an acceptable mean square weighted deviation. Note that the zircon weighted mean age for rmc and rsw are younger than the $^{40}\text{Ar}/^{39}\text{Ar}$ date at 1σ . Geologic unit abbreviations are as in Figure 3.

In addition to individual zircon dates, we calculate weighted mean dates for the youngest distinguishable group of dates. We calculate this weighted mean age by including progressively older zircon crystal dates until the mean square weighted deviation (MSWD) exceeded the critical value. Given the spread of ages and the size of the dataset, we are not able to calculate a zircon weighed mean age for rdc (Figure A4). The zircon weighted mean age for the rrm main flow, rrm minidome, rct, and rgl interiors are all older than the associated $^{40}\text{Ar}/^{39}\text{Ar}$ or ^{14}C date. The

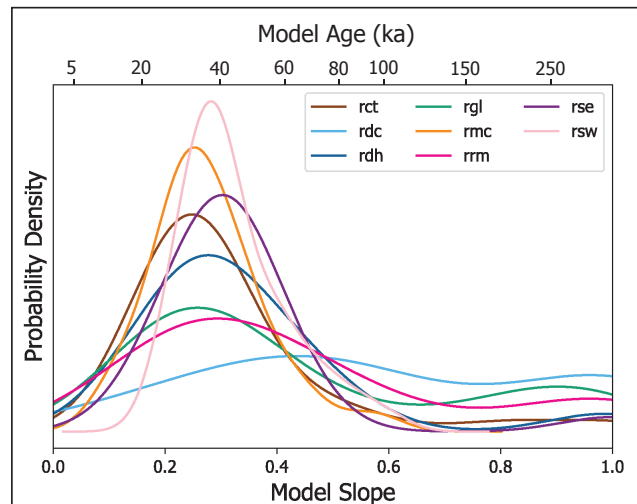


Figure 5: Probability density functions of the zircon populations by unit based on model isochron slope calculated by the method of Boehnke et al. (2016). Surface and interior data are combined for each unit. Geologic unit abbreviations are as in Figure 3.

zircon weighted mean date for rgl surfaces, rdh, and rse are equivalent to the associated $^{40}\text{Ar}/^{39}\text{Ar}$ date. However, the zircon weighted mean date for rmc and rsw surface and rsw interior are younger than the associated $^{40}\text{Ar}/^{39}\text{Ar}$ dates at the 1σ level (Figure A4). The $^{40}\text{Ar}/^{39}\text{Ar}$ eruption date for rmc is 47.4 ± 8.2 ka and the zircon weighted mean date is 31.5 ± 2.1 ka ($n = 30$, MSWD = 1.02). The $^{40}\text{Ar}/^{39}\text{Ar}$ date for rsw is 51.4 ± 9.7 ka and the zircon weighted mean date for surfaces is 39.1 ± 2.4 ka ($n = 30$, MSWD = 0.89). For both rmc surfaces and rsw surfaces, the $^{40}\text{Ar}/^{39}\text{Ar}$ eruption date and the zircon weighted mean age are differentiated at 1σ confidence level, such that the propagated uncertainty of the difference is less than the difference, but not at the 2σ confidence level.

2.4.2 Composition Trends

Nearly all the zircon crystals have U contents lower than 500 ppm (Figure S5); only 18 have higher concentrations up to 2,610 ppm. Ti concentrations cluster between 3 and 10 ppm, some reach up into low to mid 20s ppm Ti (Figure 6). Eu/Eu* is generally low, ranging from 0.02 to 0.34 (Figure 6). Outside of a few outliers, the Hf concentrations ranges between approximately 6,000 to 11,000 ppm.

Zircon Hf concentrations correlate with some trace elements. We see decreasing Ti concentrations and Eu/Eu* with increasing Hf concentrations (Figure 4, Figure A5). However, elements such as Y, Sc, Nb, and ratios such as U/Th are not correlated with Hf concentrations, producing sub-vertical arrays (Figure A5). These elements and ratios that do not correlate with Hf do show some correlation with each other. For example, higher ratios of U/Th correlate with higher ratios of Hf/Nb and Yb/Gd. There is no apparent correlation between zircon age and composition for any of the Pleistocene rhyolites (Figure 7).

2.4.3 Zircon Temperatures

Crystallization temperatures are calculated using zircon Ti concentrations and the Ti-in-zircon geothermometer calibration of (Ferry and Watson, 2007). This calibration requires activities of SiO_2 and TiO_2 . However, determining these values is not straightforward for the South Sister rhyolites. We consider a range of these two activities, how those ranges impact the Ti-in-zircon temperature, and how phases in the South Sister system would impact these activities (see Dechert et al., 2024 Supplemental Text S1). The most reasonable assumptions are an activity of 1 for SiO_2 and 0.7 for TiO_2 , and zircon temperatures presented here use these activities. The temperature range for all zircons spans from 647-855°C (Figure A6). The

Pleistocene eruptions all show a similar average Ti-in-zircon temperature from 724-768°C (Figure A6). Of these Pleistocene units, rgl yields the highest average while rmc and rdh show

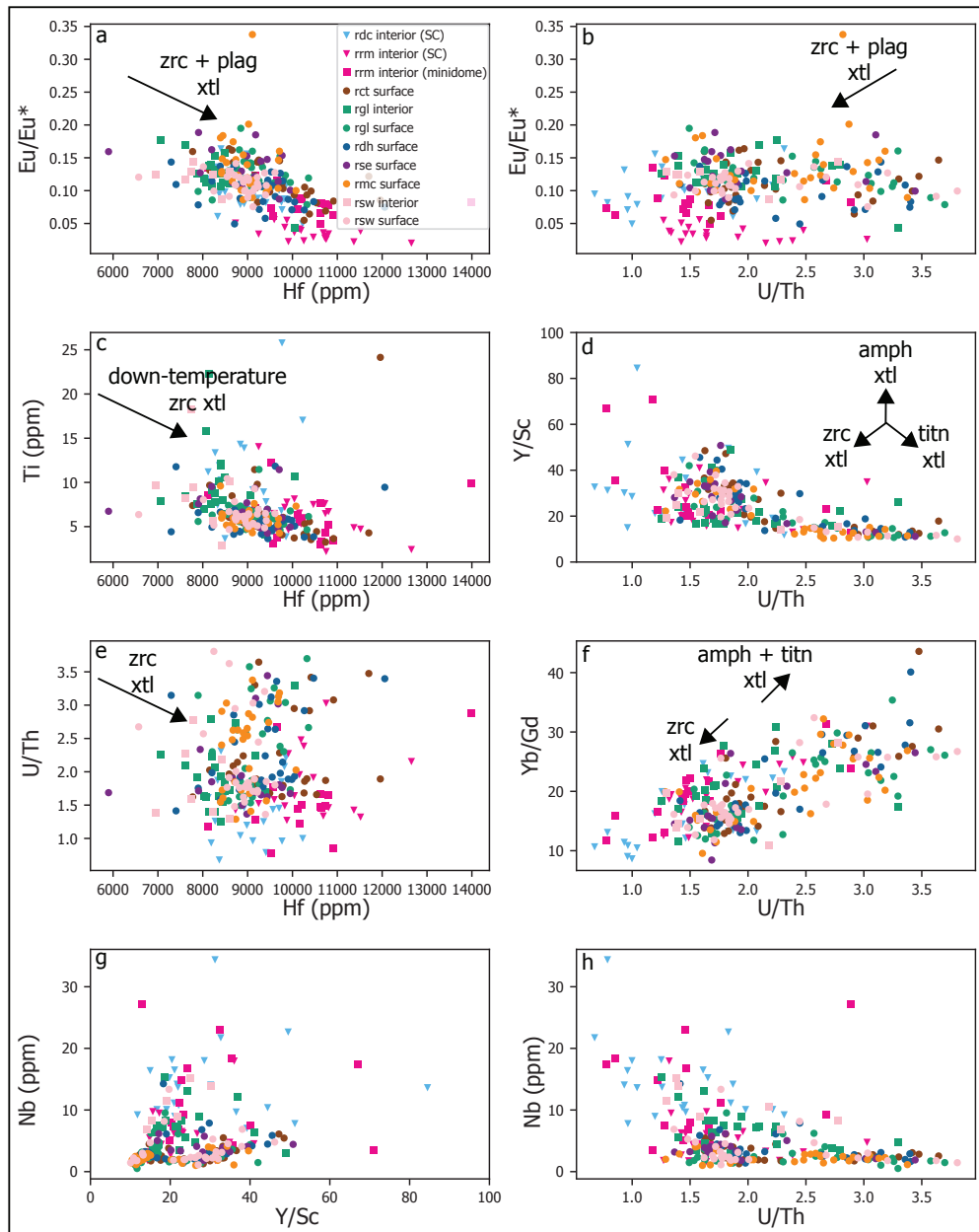


Figure 6: Variation of selected zircon trace elements and ratios. One anomalously high Hf/Nb ratio and Y/Sc ratio plots off scale. zrc = zircon, amph = amphibole, titn = titanite, xtl = crystallization. Geologic unit abbreviations are as in Figure 3.

In addition to calculating the Ti-in-zircon temperature, we can use the whole rock compositions to determine the temperature at which the melt would have reached zircon saturation (Boehnke et al., 2013). The range of temperatures that these melts reached saturation is 743-781°C (Figure A6). We also considered the calibration of (Watson and Harrison, 1983);

the coolest temperatures. For the Holocene rhyolites, rdc has the highest average temperature. Interestingly, rrm collected from the main coulee has a slightly higher average temperature than the sample we collected from the minidome ejecta (Figure 3). There is no correlation or trends between temperature and zircon age.

however, the range of temperatures calculated is higher (791-824°C) and are not consistent with the Ti-in-zircon temperature onset as the saturation temperatures using Boehnke et al. (2013). We do not calculate saturation temperatures using Crisp & Berry (2022) because their experiments only go down to 750°C, which is not a low enough temperature for this

system, and the model includes H₂O values, which we do not have a constraint for.

2.5 Discussion

2.5.1 Revisited Eruption Chronology and Eruption Rate

2.5.1.1 Updated Eruption Chronology

In addition to utilizing zircon for information about the magmatic system, zircon surface dates can represent an eruption age if zircon crystallization continued to the time of eruption, and growth was rapid enough to produce a thick enough rim that could be analyzed by ion probe (~4 µm for ²³⁰Th-²³⁰U dating). Examples include Lava Creek Tuff in Yellowstone National Park (Matthews et al., 2015) and Wilson Creek Formation of Mono Lake, California (Vazquez and Lidzbarski, 2012).

Whereas a majority of the Pleistocene zircon dates are older than or indistinguishable from the associated ⁴⁰Ar/³⁹Ar date, in accordance with the typical assumptions of ⁴⁰Ar/³⁹Ar and ²³⁸U-²³⁰Th systematics, the weighted mean age of the youngest zircons from rsw and rmc are significantly younger than the corresponding ⁴⁰Ar/³⁹Ar date at the 1σ level, regardless of the standard used. The ⁴⁰Ar/³⁹Ar dates for rsw and rmc are plateau ages of bulk plagioclase separates. The low K contents and low radiogenic yields make the ages susceptible to excess Ar—i.e., ⁴⁰Ar

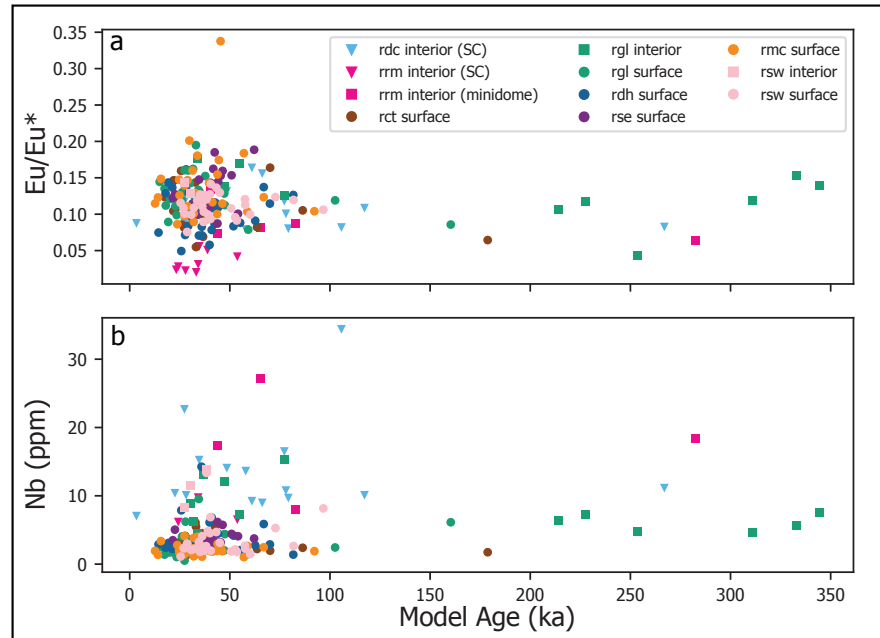


Figure 7: Comparison of South Sister zircon crystallization ages to zircon trace element ratios. There are no clear trends between zircon crystal age and compositions for these, or other, trace elements. Geologic unit abbreviations are as in Figure 3.

that is not attributable to in situ decay or atmospheric Ar (Kelley, 2002). The inverse isochron intercepts of the incremental heating experiments for rsw and rmc are within uncertainty of the $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of atmospheric Ar; however, particularly the larger uncertainty of the isochron intercept for rsw may not be sufficiently sensitive to the small quantities of excess ^{40}Ar needed to produce a spurious date due to the low ^{40}Ar * yields of the plagioclase separates. Moreover, we note that the incremental heating spectra for rmc is somewhat “saddle shaped” (i.e., the ages of intermediate heating steps are consistently lower than the lower and high temperature heating steps), which is often interpreted as reflecting the presence of excess Ar (Kelley, 2002). It is also possible that inherited plagioclase crystals contributed to the older dates; however, we do not find consistent textural evidence that the plagioclase was inherited, and ^{230}Th - ^{226}Ra ages for the two Holocene rhyolites suggest the plagioclase record near-eruption growth (Stelten & Cooper, 2012).

While the $^{40}\text{Ar}/^{39}\text{Ar}$ plagioclase ages and ^{238}U - ^{230}Th ages overlap at the 95% confidence level, we propose that the more precise, and younger, zircon surface weighted mean dates of 31.5 ± 2.1 and 39.1 ± 2.4 ka for rmc and rsw, respectively, represent the better determinations of the eruption age for these units. Zircon crystallization occurs in the melt body, and thus cannot occur after eruption, therefore, the zircon age must be a more accurate representation of eruption age. These younger eruption ages are consistent with field relationships. Because rws and rmc are the oldest known eruptions of South Sister, this revision of their eruption ages inverts the relative timing of the initiation of Pleistocene volcanism at South Sister and Middle Sister and compresses the overall period of cone building at South Sister (Figure 8).

2.5.1.2 Implications of Updated Eruption Chronology

Early work at Three Sisters suggested that North Sister is the oldest of the three, Middle Sister started erupting next, and after Middle Sister was no longer erupting, South Sister’s eruptive sequence began (Wozniak, 1982; Clark, 1983; Hildreth et al., 2012). However, new mapping and dating by Fierstien et al. (2011), Hildreth et al. (2012), and Calvert et al. (2018) found the oldest Middle Sister lava eruption age of 48.5 ± 10 ka (mnf) and the oldest South Sister lava of rsw at 51.4 ± 9.7 ka were of similar age. They concluded that North Sister is still oldest, but that South Sister was the next edifice to be active, followed by Middle Sister as the last edifice to have its first eruption, noting that these dates are not distinguishable, and that activity at South and Middle Sisters largely spanned a similar period in the late Pleistocene. Our

revised eruption age for rsw, 39.1 ± 2.4 ka, now postdates the earliest known eruption from Middle Sister (Figure 8) but does not change the broader point that the Pleistocene South Sister

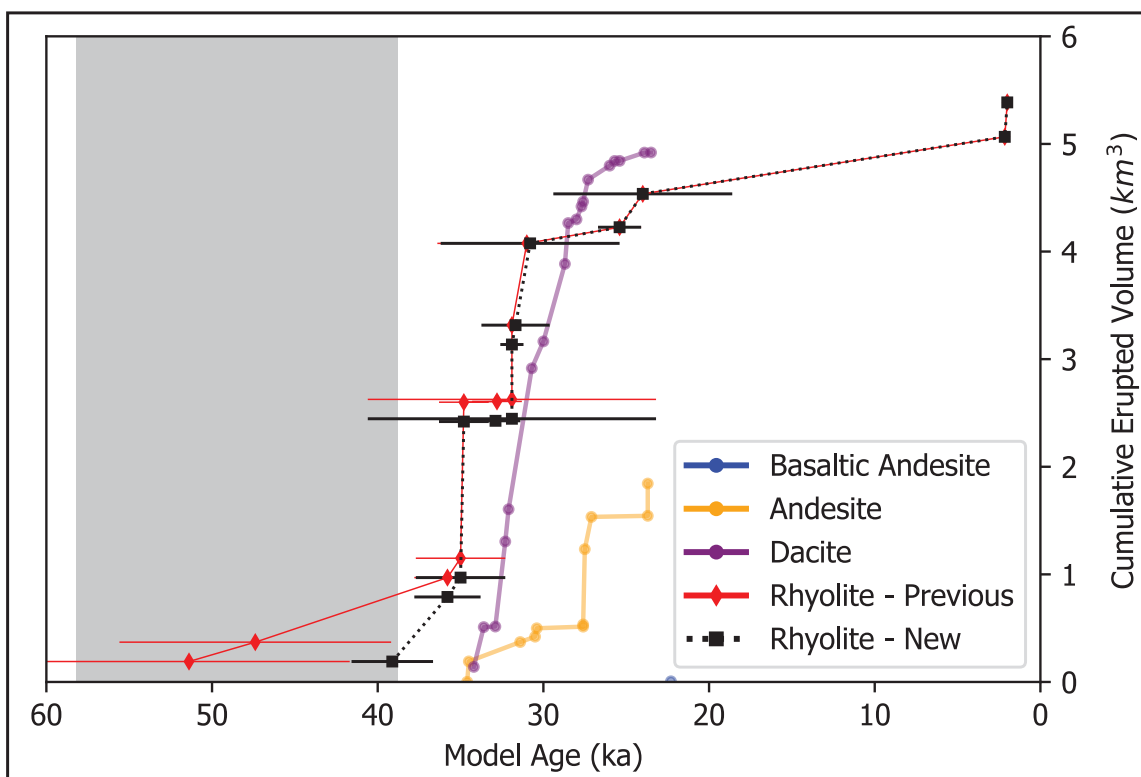


Figure 8: Age (ka) and volume (km^3) plot of South Sister for all erupted lava types. The y-axis shows the cumulative South Sister lava exposed (km^3) (Fierstein et al., 2011). The previously adopted timeline (Calvert et al., 2018; Fierstein et al., 2011; Hildreth et al., 2012) suggests South Sister erupted before Middle Sister initiated (gray box, 1σ) and the first South Sister eruptions was 51.39 ka (red diamonds). Our zircon dates suggest that volcanism at South Sister began erupting after Middle Sister and South Sister experienced a higher rate of rhyolite eruptive productivity from 40-30 ka than previously recognized (black squares).

and Middle Sister eruptions were largely contemporaneous. Products of earlier eruptions from both edifices that would further refine this timeline may have been removed by glaciation and/or buried, but our new dates indicate that Middle Sister initiated before South Sister. The revised rsw and rmc eruption ages fall in the general pause of Middle Sister activity ranging from approximately 37 to 27 ka (Fierstein et al., 2011). While Middle Sister and South Sister have overlapping eruptive periods, this shift in the South Sister eruption timeline suggests a higher productivity of silicic eruptions at South Sister while Middle Sister was eruptively quiet.

The new, younger eruption ages of rsw and rmc condense the eruption sequence such that nine rhyolites erupted from 40-30 ka, rather than just seven, increasing the eruptive rate of the system significantly during this timeframe, and all the Pleistocene rhyolites erupted within 15.1

kyr rather than 27.4 kyr. To evaluate the changes in eruptive rate at South Sister due to the revised eruptive sequence, we consider the cone building phase of the late Pleistocene that concluded at ~ 22 ka (i.e., excluding the Holocene eruptions). Based on the $^{40}\text{Ar}/^{39}\text{Ar}$ dates, the eruptive rate for all lava types is $0.39 \text{ km}^3/\text{kyr}$ and for rhyolite lava is $0.17 \text{ km}^3/\text{kyr}$ over the cone building stage. However, with the updated eruption ages, the eruptive rate for all lava types is $0.67 \text{ km}^3/\text{kyr}$ and for rhyolite lava is $0.30 \text{ km}^3/\text{kyr}$ over the cone building stage, almost doubling the eruptive rate during this time interval. Calculated for all eruptions over the lifetime of the volcano, the eruptive rate of South Sister is $0.4 \text{ km}^3/\text{kyr}$, which is a moderate rate compared to other well-characterized Cascade Range volcanoes: Mount Baker is $0.1\text{-}0.2 \text{ km}^3/\text{kyr}$, Mount St. Helens is $2 \text{ km}^3/\text{kyr}$, Mount Adams is $0.4\text{-}0.6 \text{ km}^3/\text{kyr}$, and Mount Shasta is $0.75 \text{ km}^3/\text{kyr}$ (Hildreth, 2007).

2.5.2 Trace Element Fingerprints of Magma Reservoir Structure

Correlations among zircon trace element compositions are commonly interpreted to reflect the compositional evolution of the host melt resulting from the crystallization or destabilization of zircon or other co-existing phases. The Hf composition is a common index of zircon crystallization, whereby an increase in Hf suggests progressive zircon crystallization (Hoskin & Schaltegger, 2003; Claiborne et al., 2006). Likewise, the Eu anomaly is used as a differentiation index for plagioclase, where a decrease in the Eu/Eu^* ratio tracks a melt crystallizing plagioclase, and thus the fractional crystallization of the melt more generally. The partitioning of Ti in a zircon is temperature sensitive and as such, the concentration of Ti in zircon is used to understand the temperature of the system (Ferry and Watson, 2007). Additionally, U has a higher partition coefficient than the still compatible Th, and with high partition coefficients for the heavy rare earth elements (HREE) in zircon, progressive zircon crystallization should also decrease the U/Th ratio and the abundance of HREE relative to MREE and LREE (Hoskin and Schaltegger, 2003; Claiborne et al., 2018).

The decrease in Ti and Eu/Eu^* with increasing Hf concentrations for the Pleistocene rhyolite's zircon data is consistent with down-temperature co-crystallization of zircon and plagioclase (Figure 6a, 6c). In contrast to Ti and Eu/Eu^* , we do not see a correlation between Hf and the U/Th or rare earth elements (REE) ratios that would be expected if zircon crystallization was the principal process affecting these ratios (Figure 6e). Moreover, we do not see a zircon crystallization trend in the generally flat U/Th versus Eu/Eu^* trend (Figure 6b). However, the

U/Th ratio and REE ratios such as Yb/Gd are correlated to each other, but not with the indication of zircon crystallization or general crystallization, suggesting that another process exerts greater leverage on the evolution of these elements.

Processes that could also influence these concentrations outside of zircon crystallization include the crystallization or destabilization of phases such as amphibole, clinopyroxene, titanite, and/or Fe-Ti oxides. Broadly speaking, clinopyroxene and Fe-Ti oxides do not incorporate U, Th, or the REE in high enough concentrations to have a large impact on their evolution. Importantly we note that $K_D^{U/K_D^{Th}} < 1$ and $K_D^{MREE/K_D^{HREE}} > 1$ in titanite and amphibole while $K_D^{U/K_D^{Th}} > 1$ and $K_D^{MREE/K_D^{HREE}} < 1$ in zircon, so crystallization of these phases drives the U/Th and Yb/Gd ratios of the residual melt in opposite directions. The evolution produced by U/Th versus Yb/Gd could be caused by either zircon or titanite/amphibole crystallization. However, the lack of correlation with Hf, the flat U/Th versus Eu/Eu* trend, and the negative correlation between U/Th versus Y/Sc (which is the opposite trend if zircon crystallization were controlling the evolution of these elements (Bachmann et al., 2005)) suggests that zircon is not leveraging control of the evolution of these elements. Additionally, we see higher Nb concentrations and Y/Sc ratios at low U/Th ratios that indicate zircon fractionation, but this is not consistent with the whole rock compositional evolution (Hildreth et al., 2012). These data trends rule out zircon crystallization as the main influence on these trace elements so instead, we propose that the trends in U/Th and the REE are consistent with the involvement of amphibole and titanite (Figure 6f).

While the trace element compositions of the surfaces are largely indistinguishable, some zircon interiors are marked by higher concentrations of Nb, Ti, and Sc. Most Nb concentrations are <5 ppm, Ti concentrations are ~2-10 ppm, and Sc concentrations are ~50-100 ppm (Figure 6, Figure A5). However, the zircon interiors for rgl and rsw reach higher concentrations of 15, 26, and 150 ppm for Nb, Ti, and Sc, respectively. Comparing Y/Sc versus Nb shows two distinct trends: one with lower Nb values and one with higher Nb values (Figure 6g). Nb can be moderately incompatible or compatible in zircon and amphibole, but is always compatible in titanite (Berlo et al., 2004; Bachmann et al., 2005; Tiepolo et al., 2007). Due to these differences in the affinity for Nb, we interpret the higher Nb trend to be due to titanite destabilization, and the lower Nb trend to be caused by amphibole destabilization (Bachmann et al., 2005). The high-Nb titanite signature is found more often in zircon interiors.

As such, we suggest that the destabilization of amphibole and titanite in response to magma recharge deeper in the magmatic system is the principal driver of the U, Th, and REE ratios thereby decoupling them from zircon and plagioclase co-crystallization. Very rare amphibole is present in the Holocene lavas, and its cryptic involvement in the Pleistocene lavas is inferred from trace element trends and is a common feature of intermediate to silicic arc magmatic systems more generally (Davidson et al., 2007). While titanite has not been identified in the South Sister lavas, cryptic titanite destabilization in the magma could still be contributing to these zircon compositions. Titanite is a common late-stage accessory mineral in felsic calc-alkaline plutons, thus, its presence in the cooler, more crystallized mush would be not surprising (Kohn, 2017).

Various vocabulary and schematics have been postulated to describe the anatomy of the magmatic system beneath a volcano informed by both geophysical and geochemical evidence (e.g., Annen, 2009; Bachmann & Bergantz, 2004; Bacon & Druitt, 1988; Charlier et al., 2005; Cooper & Kent, 2014; Hildreth, 1981, 2004; Huber et al., 2009; Marsh, 1981). Here, we propose a framework involving a mush zone and melt-rich holding chambers. We consider a mush zone located in the upper crust where silicic melts focus and crystallize to a high-crystal content, the crystallinity, longevity, and temperature of which can vary (Hildreth, 2004; Dufek and Bachmann, 2010; Kent and Cooper, 2018). The melt-rich holding chambers represent the melt-segregation from the mush that can more readily be erupted (Bachmann and Bergantz, 2004; Hildreth, 2004). It has been suggested that there is magma distributed throughout the upper crust beneath South Sister (e.g., Brophy & Dreher, 2000; Hill, 1991) as well as in the lower crust (e.g., Hildreth, 2007; Hildreth et al., 2012). The presence of rare amphibole in the Holocene rhyolites, but not in the late Pleistocene rhyolites, suggests some level of interconnectivity between a slightly deeper melt body and the shallow, more evolved mush that is tapped for rhyolitic eruption. The common mush zone fingerprints the indistinguishable trace element trends across the Pleistocene eruptions, and interconnectivity of the magma system provides transport of amphibole and titanite into the crystal mush (Cashman et al., 2017). Periodic intrusions needed to maintain melt in the upper crust (Dufek and Bergantz, 2005; Karakas and Dufek, 2015) may periodically destabilize amphibole and titanite as is recorded by the trace element trends. The resulting melts are then assimilated into the larger magma reservoir. The locus of amphibole and titanite destabilization need not be coincident in space or time with the zircon crystallization, but

apparently was volumetrically significant to dominate the REE and U/Th budget of the magma system.

2.5.3 Integrated Perspective of the Late Pleistocene Magma System

2.5.3.1 Longevity and Structure

In addition to the trace element fingerprints of the structure of the magma system, we can utilize the zircon dates to consider the longevity of the Pleistocene magma system. The continuity of zircon crystal dates for all Pleistocene rhyolites falling from 100-20 ka suggests a long-lived mush zone of silicic magmas and zircon crystallization. We suggest that this mush zone allowed for the destabilization of amphibole and titanite, catalyzed by new arrivals of more mafic magma from depth of the interconnected magmatic system and melt-rich holding zones of more readily eruptible material. These holding chambers could be distinct, one getting tapped for each Pleistocene eruption, or more interconnected and tapped over the Pleistocene rhyolite eruptions. The clustering of zircon surface dates around the eruption ages suggests that the magma body remained at zircon saturation composition and temperatures up to eruption, or long enough to grow the $\sim 4\ \mu\text{m}$ zircon depth to be analyzed, suggesting hundreds to thousands of years of storage based on zircon growth and dissolution kinetics (Watson, 1996).

This common mush zone is also supported by the lack of temperature, temporal, or spatial trends in the zircon crystal ages and compositions. We can distinguish neither individual Pleistocene rhyolites nor geographic clusters of eruptions, for example, those east versus west of the summit, based on their zircon trace element compositions. While we do see a range of Eu/Eu* and Yb/Gd ratios, there is no systematic increase or decrease through time to suggest major melt body processes or evolution in the system. Additionally, using the Ti-in-zircon thermometer, we see no thermal correlation with zircon model age. The shortened interval of rhyolite eruptions in the Pleistocene suggested in this work and a lack of temporal or spatial trace element trends supports a single reservoir that was repeatedly tapped over the eruption sequence. Conversely, multiple physically distinct reservoirs could have been tapped and emptied via a single eruption. The zircon data cannot distinguish between a melt-rich or a mushy extraction source. No matter the process of eruption, the mush zone was likely a dynamic system that was continually replenished via the interconnected system but remained constant chemically through the Pleistocene rhyolite eruption sequence.

2.5.3.2 Regional Connections to the Magma System

In addition to the proposed magma system beneath South Sister, there is evidence of xenocrystic zircons in one eruptive unit from a nearby volcano. While most of the zircon crystal populations range from 100-20 ka, Rhyolite of Green Lakes (rgl) includes an older subset of zircon ages ranging from 150 ka to secular equilibrium (>350 ka). The extent of the exposed rgl is on the eastern flank of South Sister with proximity to Broken Top volcano (Figure 1). While other lavas, such as rse and rdc, are also on the eastern flank, rgl has the most complete dataset including both surface and interior zircon analyses. Broken Top eruptive activity lasted from 300-150 ka and compositionally ranges from basalt to rhyodacite (Hildreth, 2007). The correlation between the older rgl zircon age population and the Broken Top eruptions suggests that either: (a) rgl inherited xenocrysts from the solidified Broken Top magma system or (b) the Broken Top magma system remained active for more than 100 ky following the final eruptions from Broken Top and also fed the rgl eruption. Scenario (a) is favored due to the bimodal age distribution of interior zircon model ages (Figures 4 and 5), whereas scenario (b) would have produced a more continuous age distribution from secular equilibrium through to 20 ka. Currently, Broken Top is an understudied volcano. Further mapping, geochronology, and petrologic investigation at Broken Top would allow an improved understanding of its magmatic system and support comparison to that of South Sister. Other volcanic centers in the area such as Todd Lake volcano, Tam McArthur Rim, and the Tumalo volcanic complex could also be the source of these older zircon crystals; however, the overlapping ages and proximity suggest Broken Top is the more likely candidate (Hill, 1991; Hildreth, 2007; Klemetti et al., 2023).

2.5.4 Comparing the Late Pleistocene and Holocene Magma Systems

In addition to the Pleistocene dataset collected for this project, we can include comparison of the Holocene dataset of Stelten & Cooper (2012) to infer the state of the magmatic system over time. As discussed above, the Pleistocene rhyolites largely cannot be distinguished from one other based on zircon compositions, except for the higher Nb interiors of rgl and rsw. However, zircons from the Holocene rhyolites show a distinction in compositions when compared to those from the Pleistocene rhyolites (Figure A7). The highest Nb concentrations occur in the Holocene zircons and the Holocene zircons have predominately lower Eu/Eu* (Figure 9).

This distinction of trace element concentrations between the two main Holocene lavas and the Pleistocene lavas suggests that the mush zone and melt-rich bodies that fed these two eruption sequences are distinct. The overlap in zircon crystal dates from all units implies that the mush zones that fed these eruptions were largely coeval in the crust and likely relatively restricted in spatial area of the system. As such, it is likely that the melt source for the two main Holocene lavas was present during the Pleistocene eruptive sequence but was not tapped for an

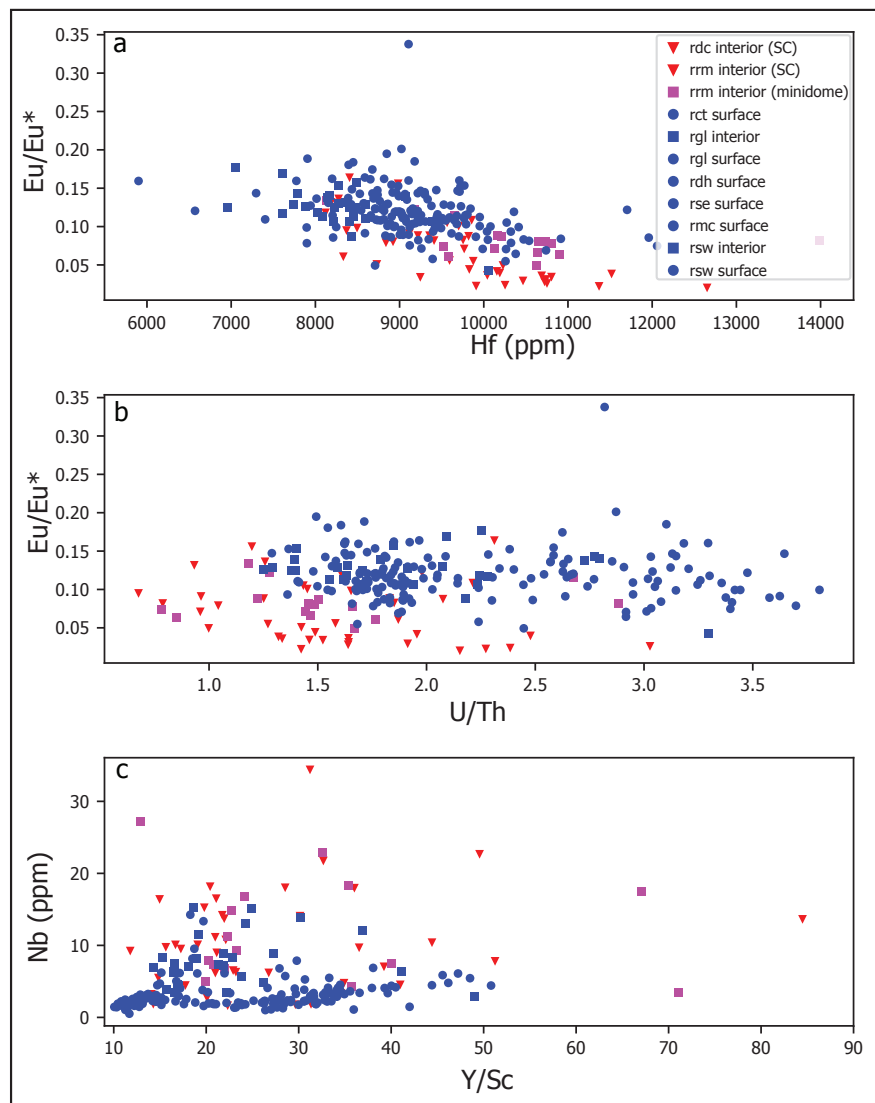


Figure 9: Comparison of the trace element compositions and ratios for the main Holocene rhyolite lava (data from Stelten and Cooper, 2012) (red), the rrm mini dome (pink), and the Pleistocene rhyolites (blue). The zircons from the Holocene and Pleistocene lavas can be distinguished based on their trace element compositions, except for the rrm minidome (pink squares), which displays some chemical affinity to both groups, see text. Geologic unit abbreviations are as in Figure 3.

eruption. These could be two physically distinct melt-rich bodies (e.g., Stelten & Cooper, 2012) or a single body that was tapped for both Holocene eruptions.

Additionally, compared to the late Pleistocene zircon crystals, the Holocene samples tend to have higher Nb compositions, reflecting likely more titanate dissolution (Figure 9c). The erupted Holocene magmas may have been derived from a slightly more fractionated source than the late Pleistocene magmas. Such constraints could also suggest that the late

Pleistocene rhyolites reflect a deeper part of the magmatic system relative to the Holocene rhyolites.

While the compositional distinction between the Pleistocene eruptions and the two main Holocene eruptions is clear, the rrm minidome complicates the story. The rrm minidome is located just east of the main rrm coulee vent and shares compositional trends with both the main Holocene and late Pleistocene groups of lavas. In U/Th, Nb, and U, the rrm minidome compositions matches that of the Holocene group (Figure A7). In Eu/Eu* and Ti, the rrm minidome has similar values to the Pleistocene rhyolite zircons. However, there is also considerable overlap between the rrm minidome with both the late Pleistocene and Holocene groups in other compositions. While we do not have enough data to make a concrete conclusion, causation for these trends include cooling along the edge of the rrm reservoir that erupted as the rrm minidome or the interaction of the rrm reservoir with a remnant of the Pleistocene system.

2.5.5 Holocene Implications

Not only does this work help us understand the evolution and structure of the past rhyolitic magmatic system at South Sister, but it can give us clues to how a modern rhyolitic magma system could evolve. Specifically, we highlight how the Pleistocene rhyolite eruptive sequence could be repeated in the Holocene. The Pleistocene rhyolite magmas all originated from the common South Sister magmatic system, evolved in a long-lived partially crystallized mush, and erupted from melt-rich region(s) for each eruption. The updated South Sister eruption chronology suggests a higher rhyolitic eruptive rate of $0.30 \text{ km}^3/\text{kyr}$ during the 39-22 ka cone building stage. Notably, the recurrence interval of rhyolitic eruptions from 40-30 ka is just over a thousand years, during which time nine of the 11 Pleistocene rhyolites erupted.

The inflation at South Sister since the mid-1990s and the spring geochemistry suggest that magmatism continues beneath South Sister (Evans et al., 2004; Lisowski et al., 2021). Therefore, it must be considered if the Holocene eruptions are the beginning of a cluster of rhyolite eruptions similar to the Pleistocene episode. Continuing and additional efforts, such as additional monitoring and geophysical imaging to identify and characterize an active reservoir that could feed multiple future eruptions is currently beneath South Sister, would help explain if the late Pleistocene episode is a relevant guide to future volcanism. If so, this would suggest the eruptive volume, sequences, hazards, and hazard zones from the 40-30 ka eruptions would

become an important reference for mitigation and monitoring of future volcanic hazards at South Sister.

2.6 Conclusions

1. The two oldest South Sister rhyolites (rsw and rmc) are 12.3 and 15.9 kyr younger than previously thought, making South Sister the most recent of the Three Sisters to initiate eruptive activity. The resulting shorter duration of the edifice building stage at South Sister almost doubles the eruptive rate during this stage.
2. Zircon compositions record magma evolution by down-temperature plagioclase and zircon co-crystallization. However, they also record the influence of destabilized amphibole and titanite in the magma system. The destabilization of these phases exerted compositional leverage on U, Th, and REE composition of the melt and decoupled these elements from the down-temperature zircon and plagioclase crystallization recorded by Hf, Ti, and Eu/Eu*.
3. The Pleistocene rhyolites were derived from a shared crystal mush that imprinted the compositional similarities of all lavas. This mush remained at zircon saturation composition and temperature for hundreds to thousands of years for zircon rim crystallization prior to eruption of the melt-rich region(s).
4. The main flows and domes of the Holocene rhyolites have zircons with similar ages but distinctly lower Eu/Eu* ratios than zircons from the Pleistocene rhyolites, suggesting they crystallized from melts that underwent more plagioclase fractionation than the Pleistocene rhyolites. As such, these Holocene eruptions come from a separate reservoir or mush body than the Pleistocene eruptions.
5. The Holocene rhyolite eruptive sequence is distinct from the Pleistocene rhyolite eruptive sequence and thus could follow a unique eruptive future. Conversely, the Pleistocene rhyolite eruptive sequence could be repeated in the Holocene. If volcanic history repeats itself, we can expect a rhyolitic eruption recurrence interval of just over a thousand years and an eruptive rate of 0.30 km³/kyr. The Pleistocene rhyolite eruptive sequence is an important reference for evaluating future hazards at South Sister while acknowledging South Sister could be in a new, rhyolitic eruption sequence.

2.7 Bridge

In Chapter 2, I utilized a petrochronology lens to explore rhyolites at South Sister volcano. This not only revealed updated eruption ages for two units, making South Sister the most recent of the Three Sisters to initiate, but also reveals long term magmatic storage and evolution. The magmatic system was primed for zircon crystallization since 100 ka and underwent zircon and plagioclase down temperature crystallization, in addition to retaining evidence of dissolved amphibole and titanite of the magmatic system. Finally, trace element compositions support that distinct melt pockets were tapped for the late Pleistocene and Holocene eruptions.

This leads us to considering the Three Sisters from a more geophysical lens in Chapter 3. Here, I will utilize a Bouguer gravity survey, a magma dynamics model, and a forward gravity model to highlight magmatic evolution that not only matches the modern Bouguer gravity anomaly, but also the eruptive history of the Three Sisters. This methodology explores magmatic evolution and magmatic spatial conclusions from Chapter 2, testing how more focused or distributed magmatic intrusions supply eruptions, exploring the distinct melt pockets tapped in the zircon crystallization record. Chapter 3 seeks to connect the eruptive history of the Three Sisters to the modern-day magmatic system through geophysical methods.

CHAPTER III

CHAPTER 3: MAGMA DYNAMICS AND ERUPTION MODELING LINKED TO THE MODERN BOUGUER GRAVITY ANOMALY REVEALS MAGMATIC EVOLUTION AND STRUCTURE OF THE THREE SISTERS VOLCANIC COMPLEX, OR, USA

3.1 Introduction

The Three Sisters volcanic complex has been designated a “very high threat” potential to central Oregon and the nearby city of Bend (population ~105,000), given eruption hazards of lava flows, pyroclastic density currents, lahars, and ash plumes (Scott et al., 2001; Ewert et al., 2018). Two rhyolitic eruptive episodes, approximately 2,000 kyr, included air-fall tephra, pyroclastic flows, snow-melt lahars, lava domes, and lava flows (Scott, 1987). Additionally, deformation and spring geochemistry studies suggest the presence of mafic magma under one of the volcanoes in this complex, South Sister (Evans et al., 2004; Lisowski et al., 2021). Despite clear signs of volcanic unrest, the magmatic system has not yet been imaged because a microgravity survey came back inconclusive, seismic receiver functions cannot identify any melt under the volcanoes, and the recent Bouguer anomaly survey does not conclusively identify any eruptible melt at depth, although the presence of magmatic mush is consistent with the most recent gravity survey (Zurek et al., 2012; Pang et al., 2025; Le Mével et al., submitted). Therefore, questions remain about the current state of the Three Sisters magmatic system and how the modern state compares to the past magma system during high eruptive productivity levels.

Great effort has gone into describing and understanding the eruptive products at the Three Sisters (i.e., Hill, 1991; Brophy and Dreher, 2000; Schmidt and Grunder, 2009; Fierstein et al., 2011; Hildreth et al., 2012; Stelten and Cooper, 2012; Calvert et al., 2018; Waters et al., 2021; Dechert et al., 2024) and the modern inflation event (i.e., Wicks, 2002; Dzurisin et al., 2006, 2009; Riddick and Schmidt, 2011; Zurek et al., 2012; Rodríguez-Molina et al., 2021; Lisowski et al., 2021). Still, no studies have tried connecting the past magmatic system to the modern one. However, combining study methods can provide a more holistic insight into a volcano's character (Committee on Improving Understanding of Volcanic Eruptions et al., 2017). The power of combining methods has been highlighted at systems such as Kīlauea, Vesuvius, Mt. Etna, and Stromboli. At Kīlauea, olivine diffusion timescales align with a seismic swarm west of the summit caldera in 2020, identifying a magmatic intrusion into the summit through

both the petrologic and the geophysical records (Lynn et al., 2024). At Vesuvius, historical accounts, a stratigraphic lens of sedimentology, petrology studies, geophysical methods, and modeling of explosive eruptions are integrated for a global understanding of Plinian eruptions based on the 79 AD eruption (Doronzo et al., 2022). At Mt. Etna, a posteriori results find that seismic activity, anomalous soil gas emissions, and soil temperatures are related to magma migration in 2001, suggesting structural directions likely to act as preferential paths for future eruptions (Alparone et al., 2004). At Stromboli, analysis of thermal images, seismic records, geodetic signals, and geochemical data highlights that the 2017-2018 eruptive episode is attributed to more gas-rich magma in the shallow system than is common (Giudicepietro et al., 2019). Many of these, and other, multidisciplinary studies of volcanoes combine geophysics and petrology. However, this study presents a physically consistent picture of magmatic evolution that compares both the geological and geophysical records at the Three Sisters volcanic complex.

Here, we combine evidence from geophysics, petrology, and the geologic record along with physics-based models to better understand how the past record of intrusions and eruptions have set the stage for the current magmatic system at the Three Sisters volcanic complex. In incorporating multiple, distinct methods at the Three Sisters, we harness both the eruptive geologic record and a Bouguer gravity survey for the geophysical record of the modern system (Hildreth et al., 2012; Le Mével et al., submitted). We explore the plausible magmatic system evolution through a magma dynamics numerical simulation and compute the gravity signal at the surface consistent with the intrusions to identify the simulated gravity anomaly produced. This allows for comparison of the simulated and natural eruptive products and gravity signal, connecting the past to the present. While we do not find a single solution, suggesting the exact evolution to the modern state, we highlight a range of magma fluxes, compositions, and melt distribution under the Three Sisters.

3.2 Geologic Background

The Cascade Arc is formed by the subduction of the Juan de Fuca oceanic plate under the North American Plate, creating the Cascadia Subduction Zone. Subduction rate estimates across the arc are between 30 mm/yr and 45 mm/yr (Riddihough, 1984; Wilson, 1993, 2002). The Cascadia subduction zone geometry varies greatly along arc, with the subducting slab being imaged down to ~300 km in the southern and northern ends but only ~150 km in central Oregon, with a dearth of detectable deep seismicity (Severinghaus and Atwater, 1990; McCrory et al.,

2004, 2012; Cheng et al., 2017). Tearing of the slab could have occurred around 48 Ma during the Siletzia terrane accretion, evidenced by the missing slab (Humphreys, 2008). It has been hypothesized that the Yellowstone Plume interacted with the subducting Juan de Fuca plate, tearing and weakening it, which is supported by the lack of deep seismicity in the central Oregon slab (Humphreys and Coblentz, 2007; Xue and Allen, 2007; Obrebski et al., 2010). Additionally, the central Oregon region experiences the northernmost extension of the Basin and Range via the Brothers fault zone and the Eugene-Denio zone (i.e., Lawrence, 1976; Sherrod et al., 2004), and this extension has been hypothesized to be linked to the relatively rare Cascade rhyolites that are observed in the Three Sisters region (Sherrod et al., 2004; Wells et al., 2014; Camp and Wells, 2021; Humphreys and Grunder, 2022).

These interactions create the setting for the Three Sisters volcanic complex. The Sisters Reach of the Cascade Range spans the 90-km-long N-S segment between South Cinder Peak and Crane Prairie Reservoir and extends 35-45 km E-W inland, 270 km east of the Cascadia subduction zone (Hildreth, 2007; Hildreth et al., 2012c). The plate convergence rate for the region is around 35 mm/yr (McCaffrey et al., 2007). The Three Sisters region and the Lassen segment of the Cascade arc are the only locations (outside of the rear-arc centers) with true rhyolite ($> 72\% \text{ SiO}_2$) products (Hildreth, 2007). The Three Sisters are located at the very edge of the westward 16-Myr younger age progression of rhyolites in the High Lava Plains across Oregon. The processes responsible for the High Lava Plains rhyolites may also be the cause the Three Sisters rhyolites, such as the presence of the Yellowstone Plume in the area, or interactions between the Yellowstone Plume and the complex lithosphere of the Pacific Northwest (MacLeod et al., 1975; Jordan et al., 2004; Fierstein et al., 2011).

Despite their proximity, the stratovolcanoes of the Three Sisters volcanic complex (North Sister, Middle Sister, and South Sister) are distinct (Figure 10 inset). The northernmost, North Sister, was built from approximately 130-45 ka of only basaltic andesite (Schmidt and Grunder, 2009; Hildreth et al., 2012c). Middle Sister was formed from approximately 49-37 ka, paused, and then resumed from 27-14 ka with a composition range from basaltic andesite to one rhyolitic eruption (Calvert et al., 2018). The southernmost, South Sister, was built of basaltic andesite to rhyolite from 39-22 ka, paused for 20 ka, and then had two rhyolitic dome sequence eruptions approximately 2 ka (Fierstein et al., 2011; Dechert et al., 2024). With a total exposed eruptive

volume of 26 km^3 and an eruption rate of $0.2 \text{ km}^3/\text{kyr}$, the Three Sisters is a small volume but active system with the potential for future eruptions.

Additionally, just east of the Three Sisters is Broken Top, a $7\text{-}10 \text{ km}^3$ stratovolcano active long before the Three Sisters, 300-150 ka, built of basaltic andesite to rhyodacite (Hildreth, 2007). Postglacial mafic eruptions are most common in the Three Sisters reach than other

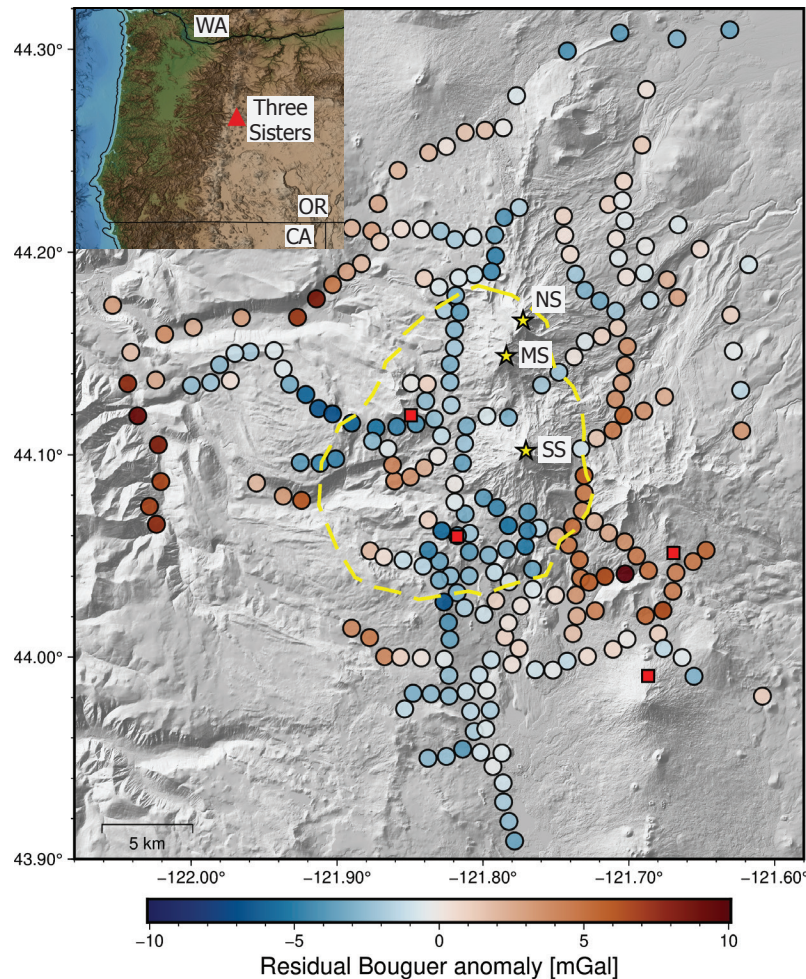


Figure 10: Residual Bouguer gravity anomaly data (mGal) for a crustal density of 25000 kg/m^3 after removing the regional trend (Le Mével et al., submitted). Yellow dashed line shows area of inflation, yellow stars highlight the three main summits of South Sister (SS), Middle Sister (MS), and North Sister (NS). Inset shows the regional location of the Three Sisters.

regions in the Cascade Arc, including lava flows, shields, monogenetic cones, and distributed fields such as Nash Crater, Blue Lake Cone, Sand Mountain chain, and Belknap shield complex (Sherrod et al., 2004; Hildreth, 2007). Just to the north of the Three Sisters in the McKenzie and Santiam Passes area, there are more than a dozen distinct mafic eruptions dated between 4.5 and 1.1 ka with a total of 15 km^3 pulse of distributive mafic volcanism in the late Holocene (Hildreth, 2007). There are additional mafic units in the

periphery of the Three Sisters, such as Cayuse Crater, LeConte Crater, The Wife, and The Husband,

highlighting the eruptive production not only of the main stratovolcanoes but also the less focused, distributed mafic flux of magmas to the surrounding area.

In addition to understanding the eruptive timeline of the Three Sisters, understanding the types of eruptions (i.e., lava flow, lava dome, ash plume) and the volume of each eruption helps

identify the history we can apply to future hazard maps. As such, a USGS group completed a geologic map of the Three Sisters over nine summers of field work on foot, utilizing a topographic map and a GPS to map the region and collect samples (Hildreth et al., 2012c). Lava flow volumes were then calculated using the field-thickness estimates and the areal extent of the mapped lavas (Calvert et al., 2018). However, given the glaciation history of this region, there is uncertainty in these estimates. As such, there are recordings of the exposed volume and the maximum estimated volumes due to the unknown amount of glacial erosion. The cumulative exposed volume of the Three Sisters is 26 km^3 , but the maximum estimate could be as large as 40 km^3 of erupted material (Fierstein et al., 2011; Hildreth et al., 2012c; Calvert et al., 2018). With the exposed and maximum estimated eruptive volumes, there has been 1.3 kyr between eruptions and an eruptive volume of $0.2 - 0.3 \text{ km}^3/\text{kyr}$ (Fierstein et al., 2011; Hildreth et al., 2012c; Calvert et al., 2018; Dechert et al., 2024).

In addition to the geological evidence of recent eruptive activity, studies in geodesy, geophysics, and geochemistry of the region highlight modern unrest at the Three Sisters. Geodesy has identified modern deformation, with inflation beginning in the mid-1990s, centered approximately 5 km west of South Sister's summit (Wicks, 2002, Figure 10). As of 2020, the total uplift of the center of the bulge is 30 cm and continues to rise at around 3 mm/yr (Lisowski et al., 2021). This activity has been monitored via multiple methods: InSAR (Wicks, 2002; Riddick and Schmidt, 2011); InSAR and GPS (Rodríguez-Molina et al., 2021); and GPS, leveling, and InSAR (Dzurisin et al., 2006, 2009; Lisowski et al., 2021). All studies identify the source of inflation as being 5-7 km below South Sister, and hypotheses for the cause include a continuing intrusion of basaltic magma, a delayed response of the visco-elastic crust to a past magmatic intrusion, or the pressurization of a geothermal system. In an attempt to geophysically capture magmatic intrusion, Zurek et al. (2012) conducted a microgravity survey between 2002 and 2009, focused on the area of uplift. However, this gravity time series did not capture evidence for a mass increase or the addition of basaltic magma and instead supports the hypothesis of a delayed response of the crust as the cause of the inflation (Zurek et al., 2012). To further test the hypothesis of continued magma intrusion at the Three Sisters, a geochemical study of dilute, low-temperature springs near the uplift of South Sister was conducted (Evans et al., 2004). Evidence of $^3\text{He}/^4\text{He}$ ratios higher than the air, transport of magmatic heat, and evidence of magmatic carbon suggest the presence of magma beneath the surface. However, the

area's CO₂ emission rate and long-term heat budget suggest that these anomalous features were caused by previous intrusions, not the intrusion identified by InSAR in the mid-19990s (Evans et al., 2004). Based on these studies, the leading hypothesis suggests there is an intrusion of magma at 5-7 km depth to the west of South Sister. However, a recent effort that identified magma storage under many of the Cascade volcanoes using receiver functions did not find magma under the Three Sisters, likely due to sparse data coverage around these volcanoes (Pang et al., 2025).

To map any hydrothermal or magmatic systems in the shallow crust Le Mével et al. (submitted) conducted a Bouguer gravity survey of the Three Sisters from 2019 – 2024. Inversion of this data reveals three zones of a negative anomaly from -4 to -8 mGal extending from the surface down 3 km, mostly to the southwest and west of South Sister, within the area of recent inflation. Given the density contrast between the assumed crust and these anomalies, the leading hypothesis is that these anomalies are an extensive hydrothermal system that could hold ~5 km³ of water. While this gravity survey does not image any magma, thermodynamic modeling finds that up to 15-35% partial melt of rhyolitic composition or 35-55% partial melt of dacitic composition could be present at a depth of 5 km and not create a discernable gravity anomaly compared to the assumed density structure of the crust. There is likely some variation in these numbers, considering the trade-offs of larger or smaller, a deeper or shallower magma body in geophysical imaging. Previous hypotheses of deformation caused by a small-volume intrusion at 5.9 km depth are still supported, as an intrusion of such size ($67 \times 10^6 \text{ m}^3$) would only create a -6 microgal anomaly, suggesting it would not be discernible with the mGal-level Bouguer gravity survey resolution (Le Mével et al., submitted). There are also positive gravity anomalies imaged in the periphery of the main stratovolcanoes that could suggest a difference in crustal density or solidified plutons (Figure 10).

In this project, we consider time-dependent intrusion scenarios through physics-based simulations and evaluate the family of solutions that best match both the documented eruptive history of the Three Sisters and the modern Bouguer gravity anomaly. We use a 3D magma dynamics model that calculates the thermal, chemical, and mechanical evolution of the magmatic system and extracts melt for explosive or effusive eruptions from an energy conservation perspective. The simulated eruptive volumes and time periods are then compared to the eruptive timeline of the Three Sisters. Next, a forward gravity model calculates what surface Bouguer

gravity anomaly the magmatic simulation would produce. This allows comparison between the simulated gravity anomaly and the modern-day field gravity survey of Le Mével et al. (submitted). This enables a comparison between the simulated data and the Three Sisters' past (eruptive history) and present (gravity anomaly), emphasizing the magmatic systems that align most closely with the field data. By combining these methods, we explore the intrusion compositions, intrusion depths, style of magmatic focusing, and range of magmatic intrusion fluxes that most closely fit at the Three Sisters.

3.3 Methods

3.3.1 Bouguer Gravity Survey

This project utilizes the 2019 – 2024 gravity survey of the Three Sisters volcanic complex, and details of measurements and results are described in Le Mével et al. (submitted). Briefly, gravity measurements were made every ~1 km, focusing on the area of recent inflation as well as road and hiking trail access. This includes one base to the north and one to the south outside of the study area, measured at the beginning and end of every field day for regional and instrument drift tie points. We used a Trimble GeoExplorer unit to collect GNSS data to reach elevation confidence of 10 cm for precise location and elevation. The gravity data were collected using a Scintrex CG-6 relative spring gravimeter. A local absolute gravity station is used to convert the relative gravity measurements of this survey to absolute gravity values. Corrections within the gravimeter include internal temperature, tilt, and tide. Post-processing included calculating the free-air gravity anomaly. The Bouguer anomaly is calculated for different crustal densities between 2,400 and 2,700 kg/m³, but a uniform 2,500 kg/m³ crustal density is chosen because it minimizes the correlation between the Bouguer anomaly and the topography. Many trends were tested to remove the regional gravity field, but the final correction is a 1st order polynomial. This postprocessing reveals the final residual Bouguer anomaly utilized in this study (Figure 10). See Le Mével et al. (submitted) for a more detailed explanation of the methods.

3.3.2 Magma Dynamics Model

We consider the magmatic system via a three-dimensional magma dynamics model, calculating the evolution of melt fraction, composition, mineral phases, and temperature through space and time. This approach has been modified from previous studies that have considered the crustal response of basaltic magma injection (Dufek and Bergantz, 2005; Karakas et al., 2017), melt extraction given melt-crystal dynamics (Dufek and Bachmann, 2010), the interaction of

tectonics and magma flux on the thermal state of the upper crust (Karakas and Dufek, 2015), and zircon crystallization histories in the plutonic record (Schaen et al., 2021b).

Separate equations for the conservation of mass and energy are solved for both the magma and the surrounding crust, the balance of heat advected into the system by prescribed intrusions, and the three-dimensional conductive heat transfer determines the time-dependent structure of melt bodies and temperatures throughout the crust (Dufek and Bachmann, 2010). The model computes the enthalpy balance, composition, and displacement of intrusions into the system in three dimensions to conserve mass in response to these successive intrusions. The magma intrusions into the model space are accommodated via crustal thickening by advecting the crust below the intrusion to account for mass conservation. Thermodynamics closure relations from the rhyolite-MELTS software calculate the sensible and latent heat enthalpy balance for melting, crystallization, and mass partitioning during phase changes (Gualda et al., 2012). The embedded rhyolite-MELTS calculations also determine the mineral assemblages and the physical properties of the melt (such as density) based on pressure, temperature, and major oxide composition. As such, we record composition and phase information at each location in the entire computational volume (Dufek and Bachmann, 2010). We do not resolve any spatial information about the mineral phases below the grid scale and assume that the melt and solid are homogeneous internally within this grid.

For the Three Sisters, the computational domain extends 45 km in depth and both horizontal axes, with ~0.2 km spatial resolution. Each model runs for 130 ky with 50-year timesteps, matching the main stratovolcano eruptive period of the Three Sisters. The user sets these model parameters (Figure B1). Model outputs include 18 mineral phases, water content, overall density, melt fraction, melt density, temperature, magma flux volumes into the system, eruption times, and eruption volumes.

In addition to the methodology outlined in the previous works, the model has been updated to include (1) a focusing mechanism allowing the user to set the model area of magma flux rather than random intrusions throughout the entire system, (2) the ability to run the same modeling scenario for a number of timesteps before testing multiple realizations of perturbations into the same system, (3) the ability to only intrude magma into a built magma body rather than anywhere in the model for a focused single magma body, (4) explosive eruptions that remove

melt that reaches a user-set criteria from the model, and (5) effusive eruption scenarios that remove melt from the magma system and deposit it on the model surface.

3.3.3 Eruption Modeling and Comparison to Three Sisters Eruptive History

Eruptions are considered from a thermal and mass transfer perspective in a subset of simulations by removing eruptible melt and either transferring it to the surface (for the effusive case) or removing it from the system (explosive case). In the explosive case, this assumes broad dispersal of the erupted tephra with minimal surface thermal effects, and minor thinning of the crust to accommodate the mass transfer. The effusive case transports melt to the near surface but does not include radiative cooling and lava spreading dynamics, and hence will tend to be on the slower cooling endmember for surface lavas. Every 500 model years, we check if there are contiguous melt bodies greater than 0.4 km^3 with a critical melt fraction of 0.4, and if so, this melt is extracted for an eruption. We document the modeled volume and timestep of each eruption that occurs and compare these volumes to field-based volumes from the Three Sisters. Rather than trying to match the exact eruption age or recurrence interval of individual eruptions, we group the eruptions into four main episodes: North Sister eruptions from 130 – 50 ka, Middle Sister eruptions from 50 – 40 ka, Middle Sister and South Sister major cone building from 40 – 10 ka, and Holocene eruptions from 10 – 0 ka. We consider a good eruption misfit if the model eruptive volume exceeds 20% less than the exposed eruptive volume and less than 20% more than the maximum estimated eruptive volume (Fierstein et al., 2011; Hildreth et al., 2012c; Calvert et al., 2018). Due to erosion, there is uncertainty about the maximum volume of lavas erupted, and we believe this method accounts for that uncertainty while not over-constraining the model workflow.

3.3.4 Background Crust and Intrusion Compositions

The thermodynamic and physical properties of the crust used in the model are dependent on the inferred compositional structure. The magma dynamics model utilizes the rhyolite-MELTS software to determine sensible and latent heat balance during melting and crystallization, as well as mass partitioning during phase change for the composition of the surrounding crust and all magmatic intrusions based on specified major oxide compositions that follow (Gualda et al., 2012). Here, the modeled background crust is based on a general Cascades Range crustal structure with a Three Sisters region focus, where the data are available. We utilize geophysical studies of gravity (Couch et al., 1982; Couch and Riddihough, 1989),

magnetotellurics (Livelybrooks et al., 1989; Stanley et al., 1990), and seismic refraction (Leaver et al., 1984; Stanley et al., 1990) in the High Cascades to highlight crustal depths of composition changes. Despite the complexity of the structures and incomplete data in the Three Sisters, we simplify these general results into four main crustal layers representative of the crustal structure in a Cascade Arc-type setting. The uppermost layer from 0-4 km depth is composed of variable Holocene volcanics and modeled with a composition of dacite based on experimental petrology work to identify potential crustal assimilant compositions in the Three Sisters region (Schmidt and Grunder, 2011b). Porosity is included in this upper layer via Ingebritsen and Manning (2010) with a decaying porosity profile with depth, so while we do not explicitly model the circulating hydrothermal system of Le Mével et al. (submitted), the density effect of fluids in the pore space in the upper crust is still included. We assume the pore space is saturated with water for these density calculations. The second layer, from 4-12 km depth, comprises various plutons in the greenschist metamorphic facies (e.g., Conrey, 1985; Miller et al., 2009; De Bari and Greene, 2011; Bedrosian et al., 2018) and is an augite quartz diorite based on mineral constituents. Continuing with depth into more amphibolitic facies, layer three extends from 12-30 km and has a model composition of gabbroic diorite in the plutonic record based on experimental petrology work to identify potential crustal assimilant compositions in the Three Sisters region (Schmidt and Grunder, 2011b). The fourth layer is from 30 - 44 km depth. Based on the type of analyses (i.e., regional gravity, magnetotelluric, seismic refraction, heat, and boreholes) the boundary of the Moho in the central Oregon Cascades ranges from 35 to 47 km depth (Thiruvathukal et al., 1970; Couch et al., 1982; Leaver et al., 1984; Catchings and Mooney, 1988; Couch and Riddihough, 1989; Livelybrooks et al., 1989; Stanley et al., 1990; Bostock et al., 2002). Our choice of modeling this boundary at 44 km best fits the ranges hypothesized. Falling into the granulite metamorphic facies, the composition of this lowest layer of gabbroic diorite is based on olivine xenolith melt inclusions from North Sister (Ruscitto, 2011). See Table 1 for the major oxide compositions of each background crust layer. Since the intrusions into this background crust occur at either 6 or 15 km, the upper half of this model crust is the most important for modeling results, and the density of the background crust has the most significant impact on the gravity calculations (Figure 11).

Table 1: Table of the compositions for the modeled background crust and magmatic intrusions.

	Layer 1	Layer 2	Layer 3	Layer 4	Mafic Intrusion	Intermediate Intrusion
Depth (km)	0-4	4-12	12-30	30-44		
Rock Type	Dacite	Augite Quartz Diorite	Gabbroic Diorite	Gabbroic Diorite	Basaltic Andesite	Andesite
SiO ₂ (wt%)	72.4997	56.4453	55.2	53.2049	53.2640	62.1674
TiO ₂ (wt%)	0.6529	1.0896	1.53	0.9603	1.4420	0.9829
Al ₂ O ₃ (wt%)	12.9983	18.5533	17.3	16.7132	19.9457	15.8646
Fe ₂ O ₃ (wt%)	0.7901	4.6487	3.56	0.7938	1.9732	1.8816
Cr ₂ O ₃ (wt%)	0.0	0.0	0.0	0.0	0.0	0.0
FeO (wt%)	2.326	4.6487	5.34	7.6572	8.4868	6.289
MnO (wt%)	0.0989	0.0	0.0	0.1455	0.1579	0.1073
MgO (wt%)	1.4739	3.6321	4.0	5.1992	4.6207	1.642
NiO (wt%)	0.0	0.0	0.0	0.0	0.0	0.0
CoO (wt%)	0.0	0.0	0.0	0.0	0.0	0.0
CaO (wt%)	4.0063	7.2152	7.7	8.4197	3.9681	3.9413
Na ₂ O (wt%)	3.2941	3.8775	4.1	3.0943	4.2207	4.1851
K ₂ O (wt%)	0.8705	1.1191	0.93	0.7081	0.4631	1.9638
P ₂ O ₅ (wt%)	0.0	0.0	0.0	0.2037	0.0	0.0
H ₂ O (wt%)	0.3	0.3	0.2	0.46	0.9896	0.9751
CO ₂ (wt%)	0.0	0.0	0.0	0.0	0.0	0.05
Source	Schmidt and Grunder, 2011	Conrey, 1985	Schmidt and Grunder, 2011	Ruscito, 2011	Brophy and Dreher, 2000	Brophy and Dreher, 2000
Sample Number	77	RC-77	NS-03-115 C initial	FO0803-D3 Xb	SS-18	Andesites average
Correction	Yes	Yes	No	Yes	Yes	Yes

We consider the impact of two major compositions of intrusions into the upper crust. In the suites of separate realizations, we intrude two different composition magmas into the system based on the majority of erupted compositions: a basaltic andesite or an andesite (Table 1; Brophy and Dreher, 2000). The basaltic andesite is on the mafic end-member composition of erupted materials from the Three Sisters, and the andesite falls in the middle of the more

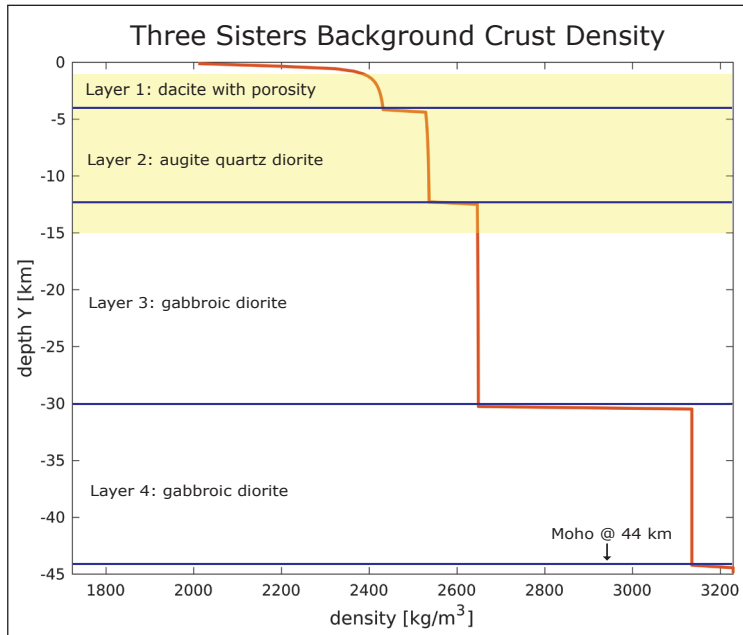


Figure 11: Density versus depth profile for the modeled background crust of the Three Sisters. Yellow box highlights depths at which intrusions can occur (between 1 to 6 km or 1 to 15 km based on the realization).

intermediate compositions erupted (Figure B2). The basaltic andesite explores the more primitive flux into the system that is hypothesized to be the cause of South Sister's deformation (i.e., Lisowski et al., 2021), past intrusions that have not erupted (i.e., Evans et al., 2004), and the parental magma (basalt) that, through partial melting, leads to dacite eruptions at South Sister (i.e., Waters et al., 2021). We add volatiles to a dacite of Brophy and Dreher (2000) and after

normalizing, the composition is

placed in the andesitic field. This intrusion composition explores the hypothesis that the felsic eruptions at South Sister are formed by extracting evolved interstitial liquid of a parent magma through a standard fractionation model, suggesting the presence of basalt, andesite, and rhyolite magma at any time under South Sister (Brophy and Dreher, 2000). This work will refer to the basaltic andesite as the mafic intrusion and the andesite as the intermediate intrusion. See Table 1 for the major oxide compositions of the two magma intrusions. The intrusions into the background crust are considered stochastic, as the user does not set the exact time and location of the intrusion. Instead, we set that on average, intrusions will occur into the system every 250, 500, 750, 1000, or 1500 years. This creates a relatively steady long-term magma flux into the system. The timescale between individual intrusions is computed by sampling a uniform deviate distribution, which creates a consistent and steady average magma flux into the system. This

tests the hypothesis that the flux into the upper crust of the Three Sisters does not vary significantly in time but will match the eruptive productivity throughout the entire history of the stratovolcanoes. In the model, the style of the intrusion locations varies between the focused and distributed model runs (Figure 12). To remove any boundary effects by intrusions occurring too

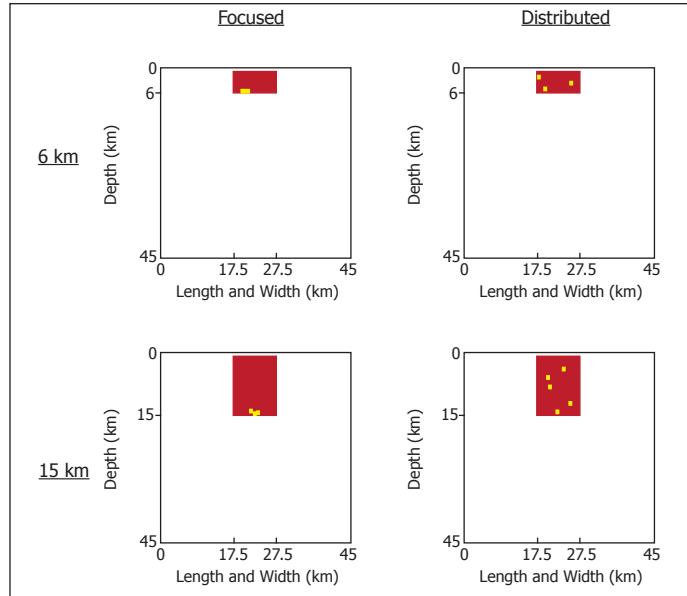


Figure 12: Schematic setup for the intrusions of magma into the modeling space. All three dimensions are 45 km. Red area shows volume where intrusions can occur for each intrusion style (focused versus distributed) and depth factor (6 km versus 15 km). Focused style has intrusions (yellow boxes) that continue to occur in the same crustal region. Distributed style intrusions can occur anywhere in the highlighted domain. Intrusions (yellow boxes) are 600 m thick, and 800 m in length and width, with small variations in these measurements.

close to the edge of the modeling space, we limit the area of intrusions to only the middle 10 km of both horizontal directions. For the focused realizations, the first intrusion occurs, and then all subsequent intrusions are into the area directly connected to the first intrusion. For the distributed realizations, the random intrusions are generated anywhere in the 10x10 km plane in the central area of the 3D background crust.

For the distributed intrusions, all ly likely to occur at any location in the two different depth profiles. The 1-15 km depth, exploring the via deformation or a more transcrustal the magmatic system, or the plutonic

system, over which we run the forward geophysical models, calculating the gravity, conductivity, and seismic anomalies produced by the simulated magmatic system.

3.3.5 Modeling Space Explored

The realization space considers 109 distinct model runs (see Figure B3). We run three styles of models: plutonic (20 realizations), explosive eruptions (49 realizations), and effusive eruptions (40 realizations). These runs allow us to compare the geophysics to the modern day and the geologic history of eruptions. Within each of these styles, we also consider two different styles of magmatic intrusions: focused and distributed (Figure 12). In the focused style, the magmatic intrusions continually occur in a specified region, building up a single magma body. In the distributed style, the magmatic intrusions occur in random locations in the middle 10 km of

the two horizontal modeling dimensions. This tests the hypothesis of whether the Three Sisters are generally erupting from a single magma body or if intrusions spread throughout the crust have produced the eruptions and modern gravity anomaly. Within each of these focusing runs, we explore both mafic and intermediate magma flux into the system. Considering two flux compositions addresses hypotheses about magma genesis and evolution at the Three Sisters. For each flux composition, intrusions occur at either 6 km or 15 km depth. For the distributed style intrusions, the random intrusion location will be between 1- 6 km depth or 1 - 15 km depth. The shallow intrusions represent the source of recent inflation, while the deeper intrusions explore a more transcrustal system. Finally, we test a range of lower to higher volumes of magma flux into the system at each depth. We can directly compare the required magma flux of this system with that of other volcanoes along the Cascade Arc. Within each of the 49 explosive realizations and the 40 effusive realizations, we split into mafic and intermediate intrusions that are focused or distributed at the two different depths. We then run a range of intrusion flux scenarios. Due to the 3D nature of these simulations, we cannot complete a comprehensive suite of these parameters. See Figure B4 and Figure B5 for the ranges of magma fluxes and the erupted volumes produced for all model realizations. Still, this set of realizations provides a guide to the general trends expected for the natural variability of the intrusion styles considered here. It also allows us to answer the primary hypotheses of magmatic flux and magmatic system focusing. The aim of these simulations is not to determine the exact sequences of intrusions, as this is not feasible given the constraints. All magma dynamics and forward geophysical models are run on the University of Oregon's HPC cluster, Talapas. Each model run takes up 100-150G of space, and in total, these realizations take up 16.6T of storage.

3.3.6 Forward Geophysical Model

Seismic imaging, gravity surveys, and electromagnetic techniques are common geophysical efforts to probe the modern magmatic system of active volcanoes (i.e., Gudmundsson et al., 1994; Hill et al., 2009; Represas et al., 2012; Bagnardi et al., 2014; Comeau et al., 2015; Cordell et al., 2018; Wespestad et al., 2019; Pang et al., 2025). Individual geophysical data acquired typically can have non-unique solutions and uncertainty related to surface station coverage, uncertain subsurface structures, and knowledge of the physical properties of rock and partial melt. Ultimately, geophysical measurements infer subsurface structure indirectly through modification of wave-matter or field-matter interactions with specific

approaches having variable sensitivity to different subsurface structures. Many geophysical modeling studies of volcanic systems use inverse methods, using collected field data to calculate the source solutions. Still, the non-uniqueness of these solutions can broaden the range of plausible source solutions. Here, we employ a forward modeling method, starting with the source model based on a specified intrusion history to calculate and compare against observable measurements (Blakely, 1995). By considering numerous realizations in the magma dynamics model encompassing a range of intrusion geometries, we can assess the implications of gravity as measured at the surface. Because the density of each location is determined in the 3D domain, the gravity anomaly produced at the surface station location can be computed and compared to the measured value. Given the modeled magmatic system, this forward methodology has been developed for multiple geophysical approaches, including the surface gravity anomaly, electrical resistivity structure of the crust, and velocities of seismic waves propagating through the crust. The methods of this study follow those of Eggers and Dufek (2018), and an explanation of the streamlined methods follows.

3.3.6.1 Gravity

Static field gravity surveys can identify the subsurface mass distribution and density variations, mapping gravity anomalies and highlighting negative anomalies that can image hydrothermal and magmatic systems (Seigel, 1995). To utilize this method in the numerical model, we utilize Newton's law of gravitation to calculate the gravitational acceleration at some exterior point given the contribution of a specific mass (or density) (Turcotte and Schubert, 2002). For a given cell on the surface of the simulation domain, we calculate the combined vertical gravitational acceleration due to every cell in the 3D model domain. This calculation occurs over the domain to create a reference and again for each timestep as magmatic intrusions and solidification alter the crust. The difference between these two produces the gravity anomaly for the simulation. Thus, the subsurface mass variations in the 3D model space create the surface expression of a gravitational anomaly in 2D (Blakely, 1995). Since the model surface does not include topography, the simulated gravitational anomaly is directly comparable to a residual terrain-corrected Bouguer gravity anomaly with the regional field removed.

The simulated gravity anomaly is directly compared to the field gravity anomaly data of Le Mével et al. (submitted). The simulation space has no geographic connection, so to put the simulation and field data in the same context, we translate the center of the modeling space to the

center of inflation (to the west of South Sister’s summit) since this is the most likely geographical location where magma is present (Lisowski et al., 2021). After this geographic translation, the simulated magmatic system and corresponding simulated gravity anomaly are rotated in increments of 15° through all timesteps to find the smallest misfit between the simulated and field gravity anomaly. The rotation angle that produces the smallest misfit is then applied to all timesteps and considered the optimal scenario. The misfit calculation is the root-mean-square error between the simulated and field gravity measurement at each field station, normalized by the number of stations.

3.3.6.2 Conductivity

Electromagnetic, or magnetotelluric, techniques explore electrical resistivity (or electrical conductivity) variations in the subsurface based on the naturally occurring magnetic fields and can find the less resistive (or higher conductivity) melt bodies (Stanley et al., 1990; Magee et al., 2018). For the entire 3D model domain, the electrical conductivity is calculated for every timestep on a cell-by-cell basis. This calculation depends on the physical parameters of each cell: solid, melt, or partial solid and partial melt. The conductivity of solid rock is calculated based on the crystal phases and temperature (Partzsch et al., 2000). Composition is the main control of melt conductivity, and empirical relationships describe the conductivity based on silica content, varying with pressure, temperature, and water content. To account for this silica control, different calculations occur for basalt (Ni et al., 2011), andesite (Guo et al., 2017), dacite (Laumonier et al., 2015), and rhyolite (Guo et al., 2016) based on the total alkali silica diagram of the melt composition. As expected, the conductivity of a partial melt is a combination of the solid and melt conductivity and can be calculated as a modified Archie’s law (Glover et al., 2000; Gaillard and Marziano, 2005).

Currently, there is no detailed magnetotelluric data for the Three Sisters region. Should such a survey be completed in the future, this model can compare the simulated conductivity to the field conductivity study. For now, we only consider the conductivity model outputs of the best-fit simulations based on the eruptive history and gravity evaluation methods.

3.3.6.3 Seismic Velocities

Seismological techniques can identify the presence of partial melt through a local reduction of seismic wave speed, an increase in anisotropy, or an increase in attenuation, given that S-waves cannot travel through fluids and can cause delays in P-waves (Gudmundsson et al.,

1994). The seismic shear velocities of the entire 3D model domain are calculated for every timestep on a cell-by-cell basis. The seismic wave speeds are calculated based on the solid mineral and rock properties at elevated pressures and temperatures (Hacker and Abers, 2004; Abers and Hacker, 2016). This methodology requires magma dynamics model outputs of 18 individual mineral phases and thermodynamic calculations within the code based on rhyolite-MELTS (Gualda et al., 2012). This creates a bulk composition of the cell, and the composite density, bulk, and shear moduli are used to calculate the seismic velocities for the solid rock model space. To consider partial melt, we implement Chu et al. (2010) for a theoretical shear velocity curve of a silicic mush based on the melt fraction.

Currently, no detailed seismic velocity study for the Three Sisters region has been published. If such a study occurs, this model can compare the simulated seismic velocity structure of the crust to the field seismic velocity study. We only consider the seismic velocity model outputs of the best-fit simulations based on the eruptive history and gravity evaluation methods.

3.4 Results

3.4.1 Example Realization

We walk through one realization to acquaint our readers with the modeling approach and workflow. This realization, R021, has sufficient magmatic flux to build up a magma body over the simulation, which creates a larger gravity misfit between the simulation and the field. In this example, R021, we explore mafic intrusions into a focused magma body at 15 km depth and allow for explosive eruptions once the eruption threshold has been met for at least 0.4 km³ of melt in the upper 15 km of the model space. This realization has a relatively higher flux of 0.02 m³/m²/yr. The flux value is calculated by computing the volume intruded in time, normalized by the crustal footprint, giving units of m³/m²/yr (or m/yr), which can be compared with a range of other previous modeling approaches including 1D approaches. Here we focus on a moment in time 50 kyr after the initiation of intrusions, which in our simulation framework would occur at 80 ka in the past geologic record at the Three Sisters (or see Figure B6 for a timeseries example of the evolution). Figure 13 displays key magma dynamics outputs. The images in 3D (Figure 13a, 13c, and 13e) display only the intrusions into the system for the top 20 km of modeling space. In comparison, the 2D images show the top 20 km of the modeling space, contrasting the background crust and the magmatic intrusions (Figure 13b, 4d, 4f). Overall, this built-up magma

body exhibits a lower density than the surrounding crust. Additionally, the presence of sustained melt is demonstrated with higher melt fractions at the interior of the magma body, with partial melt (mush) around the exterior. Finally, we can see where the 1000°C mafic intrusions occur and see the cooling of the magma moving away from the center of the magma body.

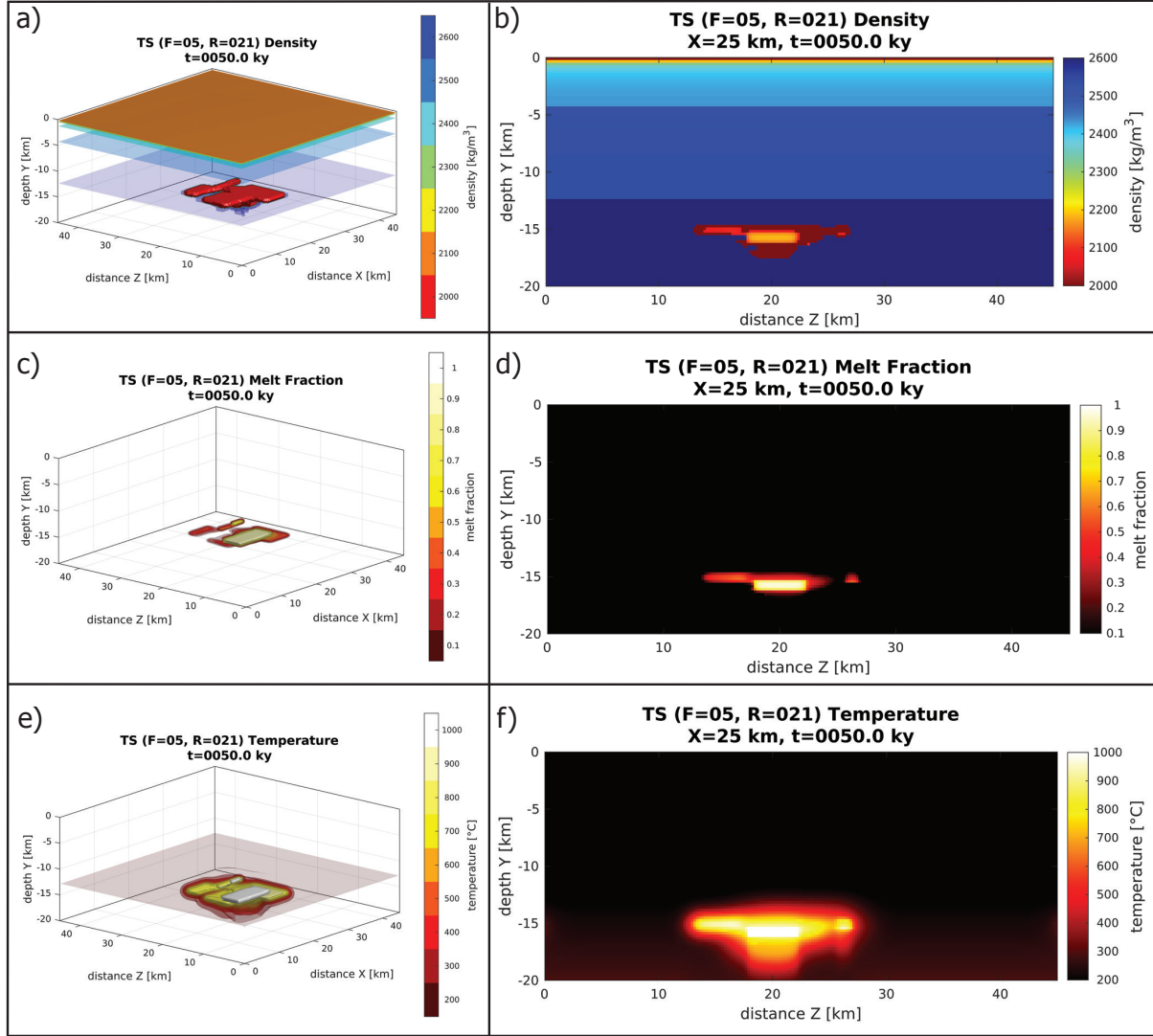


Figure 13: Example magma dynamics model outputs for a single realization at model timestep 50 ky or Three Sisters geologic time of 80 ka. a) 3D image of the density of the built-up magma body via focused intrusions for the top 20 km. b) 2D image of the density of the background crust as well as the built-up magma body for the top 20 km, sliced down the center of the x-axis. c) 3D image of the melt fraction for the top 20 km. d) 2D image of the melt fraction for the top 20 km, sliced down the center of the x-axis. e) 3D image of the temperature for the top 20 km. f) 2D image of the temperature for the top 20 km, sliced down the center of the x-axis.

We use the magmatic simulations' chemical, physical, and thermal output to compute the forward gravity anomaly as measured at the surface coincident with the locations of the gravity anomaly survey (Figure 14a). The gravity anomaly produced by the background crust is calculated (2.89 mGal) and removed from the intrusion timestep to reveal the Bouguer gravity anomaly. At this timestep, there is a diffuse -6 to -4 mGal anomaly in the center of the modeling space, but it does not cover the entire model surface. The simulated gravity anomaly can then be directly compared to the measured field gravity anomaly. We center the modeled gravity anomaly with the point of inflation just west of South Sister to center the evaluation between the two at the best-known location of magma. The field data is interpolated to create the colored map of Figure 14b, and the overlain contours display the simulated gravity survey anomaly. The modeled magmatic system is rotated 360° to find the lowest misfit between the simulated and field gravity data. If the misfit between the field and simulated gravity anomaly is zero, or a perfect fit, the simulation contours would match the pattern of the field data interpolated in the background. For this example, the best rotation angle is 150°, producing an overall gravity misfit of 4.46 mGal. With this realization, while the size of the gravity anomaly does fit the field data, the center location of the anomaly does not match. However, the diffuse simulated ~ -2 mGal

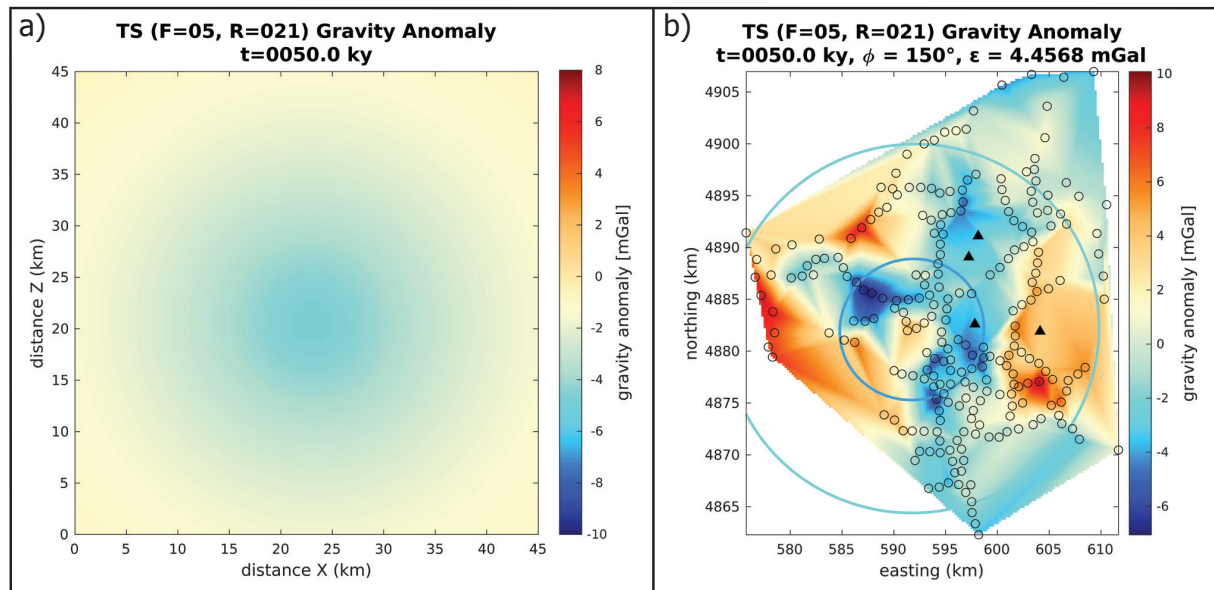


Figure 14: Forward gravity model outputs for the example realization. a) Surface gravity anomaly produced by the magmatic intrusions. b) The solid background map color shows the interpolated field data, with the data locations shown with black circles. The contours display the simulated gravity anomaly from the model realization. Black triangles show Broken Top, South Sister, Middle Sister, and North Sister.

gravity anomaly does match the anomaly to the north and south of the main stratovolcanoes but disagrees with the positive field anomaly displayed to the east and west.

Finally, we can compare the modeled eruptive history of this realization to the four eruptive episodes of the Three Sisters. For this realization, we see that the North Sister modeled eruptive volume (118 km^3) does not fit the eruptive record (Figure 15). However, the modeled

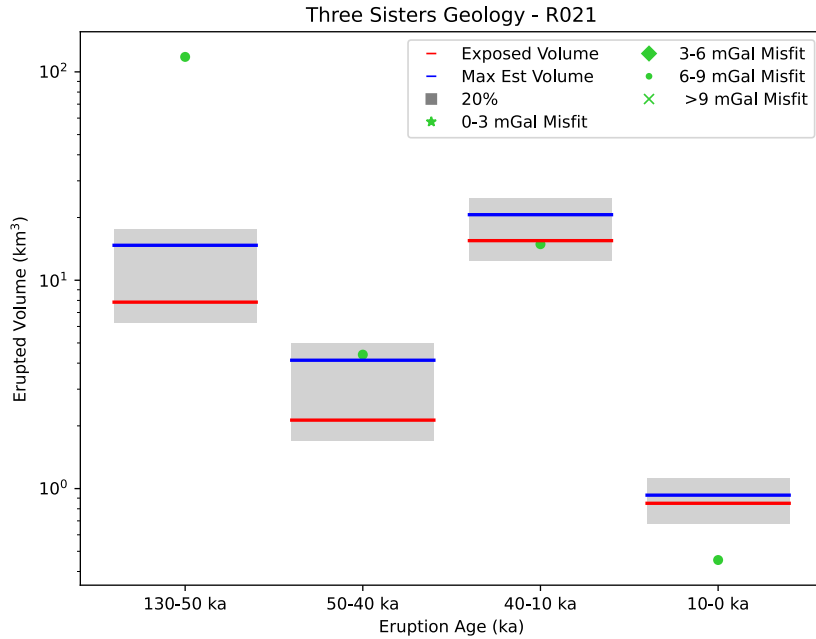


Figure 15: Eruptive volumes during the four eruptive episodes. Gray boxes highlight volumes with 20% of the known geology; red lines show the exposed and mapped volumes and blue lines show the field-estimated maximum volumes. This realization erupts at a higher volume during the North Sister episode (130-50 ka) and falls within the misfit for both the Middle Sister (50-40 ka) and coeval Middle and South Sister episodes (40-10 ka). However, the Holocene has insufficient eruptive material to match the final episode (10-0 ka). The gravity misfit at the end of the model run, representing the modern-day system, is between 6-9 mGal of the field gravity data.

eruptive volume when just Middle Sister was erupting (4.4 km^3) and then during the high productivity of Middle Sister and South Sister (14.9 km^3) fits the geology very well.

Conversely, the model eruptive product of the Holocene (0.5 km^3) is lower than the exposed geology. Since this

realization fits the eruptive history of two of the four episodes, we consider this one of the best-fit realizations.

3.4.2 Model Sensitivity for Forward Gravity Models

To explore the sensitivity of the forward gravity model to variations in the magmatic system, we complete three spherical magma body tests: a sphere at a depth 6 km with a melt fraction of 0.4 and a radius ranging from 0.5 – 5.0 km, a sphere of a 2 km radius with a melt fraction of 0.4 and depth ranging from 4 – 13 km, and a sphere of a 2 km radius with a depth of 6 km and a melt fraction ranging from 0.1 – 1.0. We compare the gravity signal created by these spheres to the field gravity survey. While the depth and melt fraction gravity misfit hover near 3.3 mGal, the radius shows more variability as the magma body increases in size (Figure B7).

From a radius of 0.5 – 2.5 km, the misfit is around 3.3 mGal, but as the size of the sphere continues to increase, the misfit rises to 9.2 mGal

3.4.3 Plutonic Models

3.4.3.1 Gravity

Before considering eruption realizations, we first explore the plutonic record, allowing the magmatic system to build up over the 130 kyr model run, without the thermal impact of removing melt. We explored ten plutonic models of distributed magma intrusion scenarios without eruptions. These include a range of intrusion depths and total magma flux into the system over the two intrusion compositions. Comparing the gravity anomaly of all timesteps to the modern field data for the mafic intrusions (Figure B8a) displays that even for the higher flux realizations, the gravity misfit between the simulation and the modern-day system is always less than 10 mGal. To understand the type of anomaly produced by the simulations, we average the model surface anomaly at each timestep to find if it produces an overall positive or negative anomaly. An overall negative anomaly would highlight a low-density anomaly, suggesting melt or magma. An overall positive anomaly would highlight a high-density anomaly, suggesting solidified, dense intrusions. The plutonic distributed mafic intrusion models show a split of both on-average positive and negative anomalies produced by these simulations (Figure B8b-c). Comparing the gravity anomaly of all timesteps to the modern field data for the intermediate intrusions (Figure B8d) displays that the higher flux realization has the highest gravity misfit, but the range of lower flux values all have gravity misfits around 3 mGal. For the plutonic distributed intermediate intrusion models, we see mostly negative average gravity anomalies produced by these intrusions (Figure B8e-f).

Additionally, we run ten plutonic models with a focused magma system without eruptions. Considering the gravity anomaly of all timesteps compared to the field data for the mafic intrusions (Figure B9a) shows that the higher flux realizations ($0.5 - 0.75 \text{ m}^3/\text{m}^2/\text{yr}$) have a much higher gravity misfit, reaching over 40 mGal at some timesteps. However, the lower flux realizations still cluster at a misfit under 10 mGal. Almost all the focused magma bodies exhibit a negative average gravity anomaly indicative of a sustained melt presence (Figure B9b-c). Considering the focused intermediate intrusions for the plutonic system, the gravity misfits are much lower, only up to ~15 mGal, even over the same range of total magma flux as the mafic

realizations (Figure B9d). Like the focused mafic intrusions, almost all intermediate timesteps exhibit a negative average gravity anomaly (Figure B9e-f).

3.4.4 Effusive Models

3.4.4.1 Gravity

Eruptions can play a dramatic role in reshaping the subsurface magmatic realm, and here, we primarily focus on examining some of the thermal implications of eruptions. We start considering 20 models of effusive eruptions from distributed intrusions. For both the mafic and the intermediate higher magma flux realization, the gravity misfit for all timesteps to the modern system is larger than for the lower flux realizations, up to 60 mGal of misfit (Figure B10a and d). However, the gravity misfit for the range of magma flux from 10^{-3} to 10^{-2} $\text{m}^3/\text{m}^2/\text{yr}$ is relatively uniform around 3 mGal for both magma flux compositions. Additionally, the average model gravity anomaly for both flux compositions is positive for most of the model time, likely reflecting the very near-surface solidified melt (Figure B10b-c and e-f).

We also explore effusive eruptions but with a focused magma body formed by either mafic or intermediate intrusions. For both the mafic and intermediate higher magma flux (~ 10 $\text{m}^3/\text{m}^2/\text{yr}$) realization, the highest gravity misfit reaches 25 mGal. But for the realizations with a magma flux around 10^{-2} $\text{m}^3/\text{m}^2/\text{yr}$, the gravity misfit hovers around 3 mGal (Figure B11a and d). Also, the average model gravity anomaly for both flux compositions is negative (Figure B11e-f).

3.4.4.2 Eruptive History

In addition to considering the misfit between the simulated and field gravity survey, we can compare the simulated eruptive timeline and volumes to the data from the Three Sisters to identify magmatic simulations that match the eruptive history. Again, the 130 ka eruptive history of the Three Sisters are broken into the four main eruptive episodes of North Sister (130-50 ka), Middle Sister (50-40 ka), coeval Middle and South Sister (40-10 ka), and the Holocene (10-0 ka). For the effusive eruptions produced by distributed magmatic intrusions, both the ten mafic flux realizations and ten intermediate flux realizations, all models have at least one eruption during the North Sister episode, but then there are no further eruptions of the system (Figure B12). Further, none of the eruptions during the North Sister period fall within the error of the field geology volume. 18 of the gravity misfit values between the field and model modern day are between 3-4 mGal.

The eruptive history of effusive eruptions with a focused magma body is a different story. Of the ten mafic realizations, four do not match any of the field volumes of eruption episodes, three match one eruption episode, and three match two eruption episodes (Figure B13). There are no realizations that match the Holocene eruption episode. Nine mafic realizations have a final gravity misfit between 3-4 mGal. Of the ten intermediate realizations, four do not match any of the field volumes of eruption episodes, three match one eruption episode, and three match two eruption episodes. Again, there are no realizations that match the Holocene eruption episode. Additionally, nine intermediate realizations have a final gravity misfit between 3-4 mGal.

For all effusive model runs, we can compare the final gravity misfit and the eruption volume misfit for each of the four eruptive episodes. The eruption volume misfit is calculated as the absolute difference between the volume of model erupted material

for the episode time range and the volume of exposed material mapped at the Three Sisters during that same time range. For the effusive eruptions, we see overall low gravity misfit values for the entire range of eruption volume misfits from 0.01 km³ to 100 km³ (Figure 16c-d).

3.4.5 Explosive Models

3.4.5.1 Gravity

We can also explore realizations of distributed magma intrusions with explosive eruptions that remove erupted material from the modeling space for 20 different models. For the mafic input, the two highest flux realizations (~ 0.05 m³/m²/yr) have gravity misfits up to 12

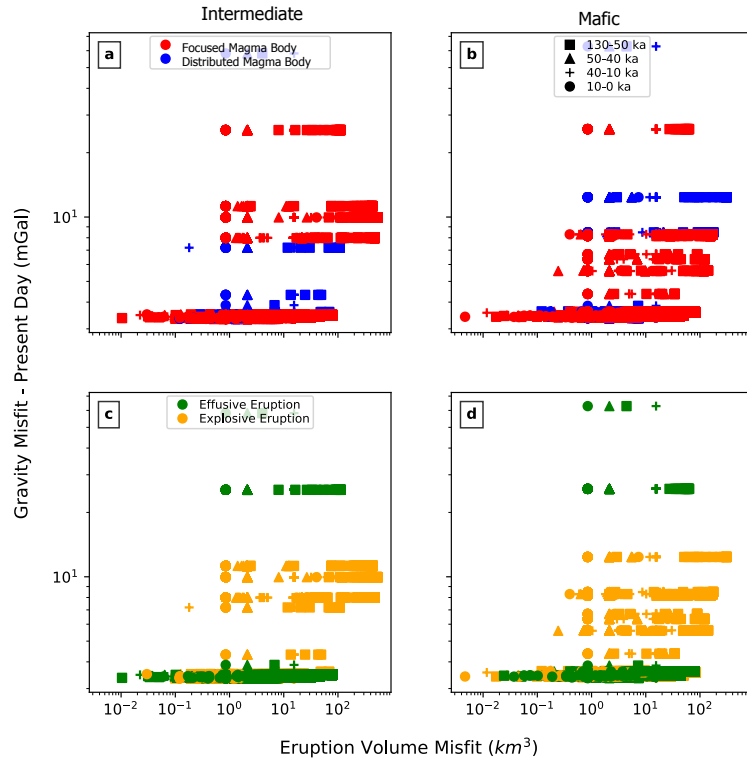


Figure 16: Eruption volume misfit (km³) compared to the gravity misfit (mGal) for the modern-day system for all eruption realizations. Note the bimodal gravity misfit clustering. Even with high eruption volume misfits, the final gravity misfit is around 3.4 mGal for many realizations.

mGal while the lower flux values have gravity misfits of ~ 3 mGal (Figure B14a). Conversely, the intermediate models all have gravity misfits between 3-6 mGal, no matter the flux values (Figure B14d). There is a mix of positive and negative average gravity anomalies for the mafic and intermediate magma intrusions (Figure B14e-f).

Explosive eruptions with a focused magma body composed of either mafic or intermediate input compositions have a higher range of flux values explored (up to $0.2 \text{ m}^3/\text{m}^2/\text{yr}$) and a small range of gravity misfits. For both the mafic and intermediate model runs, the gravity misfit never exceeds 9 mGal (Figure B15a and d). Most timesteps for both flux compositions exhibit an average negative gravity anomaly (Figure B15e-f).

3.4.5.2 Eruptive History

With this understanding of the model gravity data, we can also consider the modeled eruptive history for the explosive eruptions, first for the distributed magmatic intrusions. Eight of the ten mafic flux realizations do not match any of the four eruptive episodes (Figure B16). One realization matches one eruptive episode (Holocene), and one realization matches two eruptive episodes (North Sister and Middle Sister). Eight of these mafic realizations have final gravity misfits from 3-4 mGal. Of the ten intermediate flux realizations, two realizations do not match any of the four eruptive episodes, four match one eruptive episode, and four match two eruptive episodes. Four realizations well overshoot the eruptive volume of the North Sister episode, and eight realizations erupted much less than what is present on the field. We note that four realizations match the Holocene eruption episode with the same volume of erupted material for all four realizations, 0.729 km^3 . Nine of these intermediate realizations have a gravity misfit of 3-4.5 mGal.

Next, we consider the explosive eruptive history for the focused magma body realizations. Of the 19 mafic realizations, eight do not match any of the four eruptive episodes, six match one eruptive episode, and five match two eruptive episodes (Figure B17). The most-matched episode is Middle Sister with six realizations falling in the range of field-matched eruptive volumes between 50-40 ka. Generally, the non-matching realizations produce too much eruptive volume for the North Sister and Holocene episodes, with a mix of both over- and under-producing for the most active Middle Sister and South Sister episode of 40-10 ka. 11 of the 19 mafic realizations have a final gravity misfit of 3-4 mGal. Of the ten intermediate realizations, three realizations match none of the four eruptive episodes, six realizations match one eruptive

episode, and one realization matches two eruptive episodes (Figure B17). The realization that matches two episodes fits the North Sister and Middle Sister periods, and the Holocene episode is never matched. All the realizations that match one or two eruptive episodes have a gravity misfit of 3-4 mGal.

For all explosive model runs, we can compare the final gravity misfit and the eruption volume misfit for each of the four eruptive episodes. The eruption volume misfit is calculated as the absolute difference between the volume of model erupted material for the episode time range and the volume of exposed material mapped at the Three Sisters during that same time range. For the explosive eruptions, we see overall low gravity misfit values around 3 mGal for the entire range of eruption volume misfits from 0.01 km³ to 100 km³ (Figure 16c-d). However, there is a subset of realizations with a gravity misfit closer to 10 mGal with a slightly higher range of eruption volume misfit from 10 to 100 km³.

3.5 Discussion

3.5.1 Good Fits – Eruptive Volumes

We have created an empirical hierarchy to the simulation results based on how well they reproduce eruptive history and gravity measurements. To consider a realization a good fit, at least one of the modeled total eruptive volumes must fall within the 20% error of the Three Sisters geology eruptive episodes (Figure 17). Overall, 40 realizations match this requirement (Figure B18). The eruption volume misfit for these 40 realizations over the four eruptive episodes ranges from 0.05 km³ to 110.2 km³. The North Sister episode is matched the most, followed by the Middle Sister, coeval Middle Sister and South Sister, and the Holocene episodes. The focused magma system matches the eruptive volumes better, with 30 good realizations having a focused magma body. The explosive eruptions produce more good fits, 28, than the effusive eruptions, 12. Conversely, there is little difference between the mafic or intermediate magma flux variable, as the mafic flux produced 19, and the intermediate flux produced 21 of these good fits. There is also little distinction between the depth of intrusions, as the 6 km depth models produce 21 good fits, and the 15 km depth models produce 19 good fits. The magma flux into the system ranges from $\sim 10^{-3}$ to 10^{-1} m³/m²/yr. The mafic flux realizations tend to create an overall average negative gravity anomaly for these realizations throughout the model time. However, the intermediate flux realizations can create both an overall average negative or positive gravity anomaly, depending on the timestep. This is true for the full flux parameter

space represented and for overall low gravity misfit values. However, gravity misfit at the final model timestep representing the modern-day system ranges from 3.33 – 8.3 mGal, with 37/40 realizations falling between 3-4 mGal misfit.

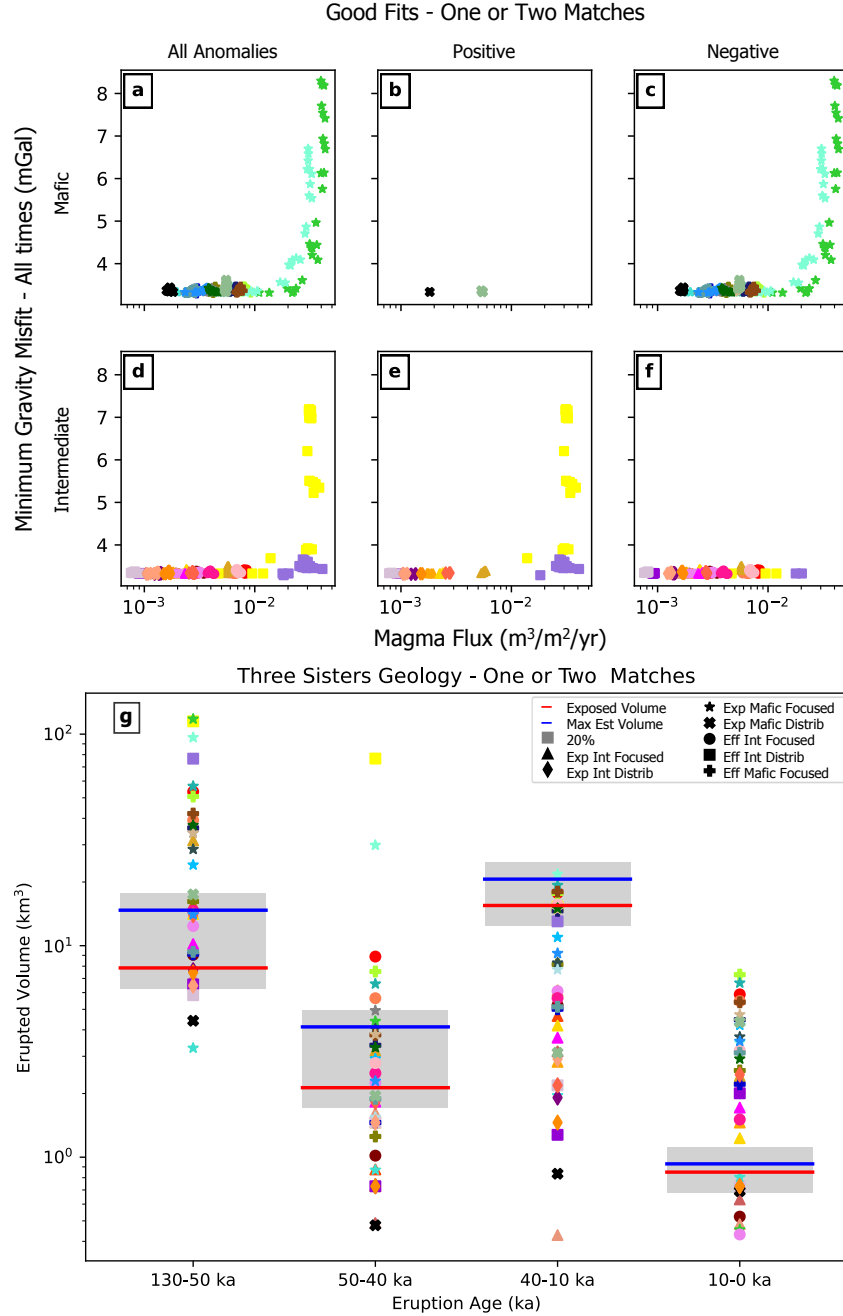


Figure 17: Gravity and geology results for the 40 realizations that fit at least one modeled eruptive volume within the Three Sisters eruptive episodes. Colors throughout a-g represent a single realization. a-f) Magma flux for each timestep and the gravity misfit between the simulated and measured Bouguer gravity survey. a-c) Mafic realizations. d-f) Intermediate realizations. g) Simulated eruptive volumes compared to each of the four eruptive episodes. Symbols represent the type of eruption, intrusion composition, and focusing style. All realizations have a final gravity misfit of less than 8.3 mGal.

3.5.2 Best Fits – Eruptive Volumes

There are no realizations that match three or all four eruptive episodes. So, to consider the best-fit realizations, two of the modeled total eruptive volumes must fall within a 20% error of the Three Sisters geology eruptive episodes (Figure 18). Overall, 17 realizations match this requirement (Figure B18). The eruption volume misfit for these 17 realizations over the four eruptive episodes ranges from 0.11 km³ to 110.2 km³. The most matches occur between the North Sister and Middle Sister eruptive episodes (seven realizations), the Middle Sister and coeval Middle Sister and South Sister episodes (seven realizations), and the North Sister and Holocene eruptive episodes (three realizations). No realizations match North Sister and coeval Middle Sister and South Sister, Middle Sister and Holocene, or coeval Middle Sister and South Sister and Holocene eruptive episodes. Still, the focused magma body realizations produce more best fits, 12, compared to the distributed intrusion realizations, five. The explosive eruptions still produced more best fits, 11, compared to only six for the effusive eruptions. Again, however, there is very little difference between the mafic or intermediate magma flux, with nine and eight realizations, respectively. This is also true for the depths of the intrusions, with 6 km depth producing ten best fits and 15 km depth intrusions producing seven best fits. The magma flux into the system ranges from $\sim 10^{-3}$ to 10^{-1} m³/m²/yr. Almost all timesteps for the mafic flux realizations create an on-average negative gravity anomaly. The intermediate flux realizations created both positive and negative overall gravity anomalies through time. Additionally, other than the one higher flux and higher gravity misfit realization, these best-fit realizations have a gravity misfit between 3-4 mGal throughout all the model time. At the final model timestep, the gravity misfit varies from 3.4 – 8.3 mGal, with 16/17 realizations falling between 3-4 mGal misfit.

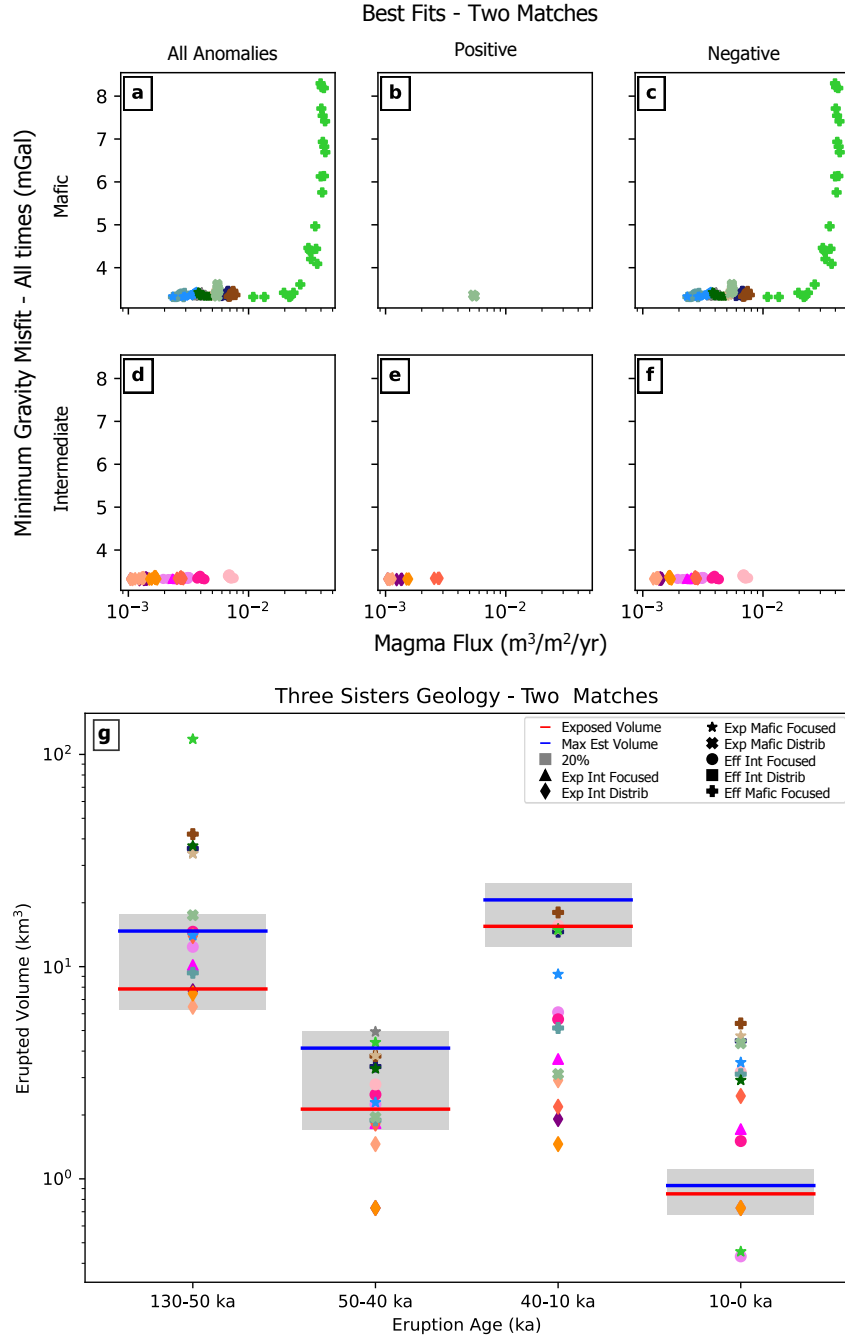


Figure 18: Gravity and geology results for the 17 realizations that fit two modeled eruptive volume within the Three Sisters eruptive episodes. Colors throughout a-g represent a single realization and match those represented in Figure 6. a-f) Magma flux for each timestep and the gravity misfit between the simulated and measured Bouguer gravity survey. a-c) Mafic realizations. d-f) Intermediate realizations. g) Simulated eruptive volumes compared to each of the four eruptive episodes. Symbols represent the type of eruption, intrusion composition, and focusing style. All realizations have a final gravity misfit of less than 8.3 mGal.

3.5.3 Structure of the Magmatic System

Realizations with distributed magma intrusions have different erupted volume fits based on the eruptive style. Distributed magmatic intrusions with effusive eruptions cannot build enough eruptible magma to match the Three Sisters geology. However, distributed magmatic intrusions with explosive eruptions can build up enough eruptible magma. Given that the Three Sisters have seen explosive eruptions producing ash plumes and more effusive lava flows and domes (Scott et al., 2001), we believe this outcome is likely due to the modeling of the two different eruption styles. Modeled effusive eruptions do not include radiative cooling or flow dynamics, resulting in unphysically thick and slower cooling melt bodies at the surface. In contrast, the explosive case represents the fastest possible end-member for cooling. Overall, we do see distributed intrusion model realizations with eruptions that can match the Three Sisters geology, which is of greater importance than the specific type of eruptions.

While the distributed intrusion model realizations can match the Three Sisters' eruptive history, the focused intrusion realizations create more of the best-fit models. After the first intrusion of these realizations, all following intrusions are into the same region of the crust, supplying replenishment of high-temperature liquid melt that is eruptible. So even as eruptions occur, removing the higher melt fraction magma, the magma supply into an eruptible region continues. This suggests the development of a central reservoir associated with summit eruptions of the Three Sisters, although there are obvious signatures of distributed mafic volcanism on the periphery, suggesting a hybrid of central focusing and less focusing in the periphery (Sherrod et al., 2004; Hildreth, 2007).

In general, past studies have focused on individual stratovolcanoes in this cluster rather than trying to connect the petrology and structure of the entire Three Sisters system. The basaltic andesites of North Sister are supported by repeated injection of low-K tholeiites from the mantle and low-degree melting of the gabbroic crust, suggesting lower crustal processes and no stalling in the shallow crust (Schmidt and Gruner, 2011b). However, a study of North Sister lavas and tephra olivine melt inclusions found entrapment pressures of 2-5 kbar, suggesting continuous degassing and olivine crystallization from <5 kbar, and supporting shallow magma storage as shallow as ~0.1 km (Mordensky and Wallace, 2018). These shallow storage pressures could indicate stalling for potentially brief periods prior to eruption. A few entrapment pressures are up to 30 kbar, suggesting depths closer to 7 km, possibly the longer-term storage system,

highlighting interaction and multiple magma storage locations in the shallow crust (Mordensky and Wallace, 2018). We do not test magma evolution from intrusions directly from the mantle at 44 km depth. However, our results of the low gravity misfit with realizations intruded at 6 km depth do support Mordensky and Wallace (2018), suggesting shallow storage and entrapment pressures for mafic magmas.

At South Sister, the range of compositions produced along with a Daly gap suggests crystal fractionation with eruptions of the evolved interstitial melt, including multiple independent solidifying magma bodies of basalt, andesite, and rhyolite present through time (Brophy and Dreher, 2000). This hypothesis is questioned by Waters et al. (2021) who suggest that the South Sister dacites are products of partial melt extraction from mid- to lower-crustal basalts that stall for a short window in the shallow crust, undergoing rapid cooling and crystallization. While our model does not explicitly explore felsic magma production via partial melting or fractionation, we assume one of these processes is acting, given our modeling of intermediate injection at 6 or 15 km depth. Our model results do not explicitly support the Brophy and Dreher (2000) hypothesis suggesting multiple, independently solidifying magma bodies as, generally, our distributed intrusion realizations cannot reproduce the eruptive volumes of the Three Sisters.

A study of the two Holocene South Sister rhyolites hypothesizes that the eruptions were sourced from coeval but physically distinct melt pockets accumulated in a heterogeneous crystalline reservoir based on zircon and plagioclase petrochronology (Stelten and Cooper, 2012). Rhyolite melt extraction from a common mush zone is also supported for the Pleistocene rhyolites; however, Dechert et al. (2024) suggests that a different mush zone sourced the Pleistocene and Holocene rhyolites. Additional support for isolated magma pods comes from a range of TiO_2 and FeO^T concentrations in olivine melt inclusions from North Sister, suggesting that the basaltic andesites underwent fractional crystallization in distinct magma bodies within the main system prior to eruption (Mordensky and Wallace, 2018).

Our modeling results broadly match those of the South Sister magmatic system evolution. First, our focused intrusions support building a magmatic system rather than many random intrusions into the shallow crust. This supports crystal fractionation and partial melting hypotheses from different perspectives. Additionally, the more built magma body can better support the eruptive volumetric history of the area, while also including solidification, creating

more of a magma mush body. Such a mush body, with low eruptability, is supported by the modern Bouguer gravity anomaly. One missing piece connecting to the natural system is the many more peripheral, distributed vents in the Three Sisters area. The distributed intrusion simulations generally cannot produce enough eruptive volume to match the Three Sisters' history. A single magmatic body may primarily support the Three Sisters magmatic system, and tertiary distributed intrusions occur in the periphery, supporting the more distributed mafic field.

We explored two depths of magmatic intrusions to explore the gravity anomaly produced by two magmatic structure hypotheses. Modeling of the modern inflation event suggests that $49 \times 10^6 \text{ m}^3$ (elastic crustal response) or $21 \times 10^6 \text{ m}^3$ (relaxation of a viscoelastic shell) of magma has been intruded into the crust at 5.9 km depth west of South Sister's summit since the mid-1990s (Lisowski et al., 2021). Exploring this inflation event prompted the realizations of 6 km depth. Past geochemical studies have also suggested a more transcrustal magmatic system connected in depth throughout the crust. Zircon U/Th and REE ratios from South Sister rhyolites have signatures of destabilized titanite and amphibole, but only rare amphibole are present in the Holocene lavas and no crystalline titanite (Dechert et al., 2024). This suggests that amphibole and titanite were present in the magma body at some point, but likely were dissolved into the melt due to deeper magma recharge. Additionally, Brophy and Dreher (2000) consider a more interconnected magmatic system of crystallizing magma bodies and melt extraction to continually evolve the magma, suggesting an interconnected magmatic system with depth. We acknowledge that for the intermediate intrusions at 6 km depth, we assume the magma has become more evolved prior to this shallow intrusion, so these models do inherently consider a certain amount of overall magmatic system interconnectivity. However, the mafic realizations could include transport from depth directly to shallow storage prior to eruption. As such, we cannot say that a transcrustal magmatic system is required at the Three Sisters. However, it seems most likely given the best fit realizations and assumptions inherent to the intrusion depths and compositions.

3.5.4 Magmatic Flux

We can use this magma dynamics modeling tool to directly compare the modeled eruptive volume output to the geologically based eruptive production in the field. We set the general composition of what will erupt for the mafic and intermediate magma input compositions, and this major oxide composition will vary based on the melt fraction extracted

and the extraction pressure. The crystal fraction must be above 0.6 to be considered eruptible; following that, 50-70 vol% crystals are the most efficient for crystal-liquid separation, supporting eruption (Dufek and Bachmann, 2010). Additionally, the pressure range for eruptions is set to 1-4 kbar, corresponding to the top 15 km of the crust. For the mafic realizations, the erupted magma is an andesite; for the intermediate realizations, the erupted magma is a dacite to a rhyolite. We acknowledge this is an assumption for the geology of the area, given the range of eruptive products from basaltic andesite to rhyolite in the Three Sisters. This is especially true for any of the best-fit realizations with intermediate intrusions matching the North Sister eruptive volumes, and we know that North Sister only produced basaltic andesite for the entirety of its eruptive history. However, the model magmatic system successfully evolves to the more intermediate compositions found at both Middle Sister and South Sister.

Realizations with magma flux values over $0.1 \text{ m}^3/\text{m}^2/\text{yr}$ tend to have higher gravity misfit values ($> 4 \text{ mGal}$) for the modern system. The best-fit realizations have magma flux values ranging from $10^{-3} - 10^{-1} \text{ m}^3/\text{m}^2/\text{yr}$, with all but one realization falling between $10^{-3} - 10^{-2} \text{ m}^3/\text{m}^2/\text{yr}$. An arc-scale study of volcanic geochemistry linked to the physical and thermal properties of the crust and magma suggests the Quaternary Cascade Arc volcanism has a magma flux range of 4×10^{-5} to $4 \times 10^{-4} \text{ m}^3/\text{m}^2/\text{yr}$, but this range varies by latitude along the arc and width of the magmatic zone (Hildreth, 2007; Till et al., 2019). The magma flux range for this study is slightly higher, however, in the Three Sisters region of the Cascade Arc, as it is known to have a large distribution of Quaternary vents (not only the main stratovolcanoes). A more focused exploration of the thermal consequence of magma flux into the Three Sisters region over one million years finds that magma fluxes $< 10^{-3} \text{ m}^3/\text{m}^2/\text{yr}$ produced distributed volcanism, while magma fluxes $> 10^{-3} \text{ m}^3/\text{m}^2/\text{yr}$ can produce a magmatic mush (Dufek et al., 2022). Our study directly aligns with this conclusion. The plutonic record of the crystalline core of the North Cascades suggests between 96 – 89 Ma, the greatest addition of magma in the system, the volume flux was between $3.9\text{-}12 \text{ m}^3/\text{m}^2/\text{yr}$ (Paterson et al., 2011). However, thermal modeling of melt evolution in rift settings shows that upper crustal mush bodies can be built with a magma flux $> 0.004 \text{ m}^3/\text{m}^2/\text{yr}$ (Karakas and Dufek, 2015). Our flux results are lower than the plutonic record and values considered in rifting settings. However, volumetrically, the Three Sisters, considered individual stratovolcanoes and not the entire region, are small in the Cascade Arc. Averaged over the edifice timeline, the Cascade volcanoes range from 0.1 to $0.6 \text{ km}^3/\text{kyr}$

eruptive volumes, with Mount St Helens much higher at $2 \text{ km}^3/\text{kyr}$ (Hildreth, 2007). When considering the main stratovolcanoes at the Three Sisters, the maximum eruptive rate is $0.3 \text{ km}^3/\text{kyr}$, and the minimum is $0.2 \text{ km}^3/\text{kyr}$ (Hildreth et al., 2012c). As such, our best-fit magma flux values fit the general trend of the Three Sisters eruptive products concerning other Cascade volcanoes.

Considering the eruption modeling in this study, we see two distinct changes in magmatic flux in the timeline of the Three Sisters. Ten of the 17 best-fit realizations match the eruptive volume of the North Sister episode between 6.3 and 17.7 km^3 , with seven also fitting the Middle Sister episode of $1.7 - 4.9 \text{ km}^3$ and three fitting the Holocene episode between $0.7 - 1.1 \text{ km}^3$. The seven remaining best-fit realizations fit the Middle Sister and the coeval Middle Sister and South Sister episodes. These results suggest a change in the magmatic system at 50 ka and 10 ka . Distinctly, model results can match North Sister and Middle Sister eruptive episodes as well as the Middle Sister and coeval episodes, but cannot match all three. If there were no change in the magmatic flux from $130 - 10 \text{ ka}$, one would anticipate the model being able to reproduce the eruptive volumes of all three eruptive episodes of the main cone-building phases. Additionally, the realizations that match the higher eruptive volumes prior to the Holocene generally produce too much eruptive volume in the Holocene. There is a caveat that there is very little volcanism in the Three Sisters from $10 - 0 \text{ ka}$ (0.68 km^3), highlighting the overall shift in magmatic flux or change to the magmatic system. These four eruptive episodes were chosen very deliberately, attempting to capture the distinct characteristics of each volcano in the complex, so it is not surprising that the modeling also displays the distinctions between these volcanoes. Not only was there a shift after the North Sister eruptive episode ended around 50 ka , but there was also a significant decline in magma flux around 10 ka once Middle Sister was no longer erupting (last eruption at 14 ka).

We can compare all the best-fit realization parameters with the average magma flux per realization and the total modeled eruptive volumes for each realization (Figure 19). This highlights that the realization with the highest average magma flux that still fits two of the Three Sisters eruptive episodes produces substantially too much eruptive volume in total through the entire eruptive history of the region (i.e., approximately $10^{-1} \text{ m}^3/\text{m}^2/\text{yr}$ and 140 km^3). Overall, the lower flux, intermediate distributed intrusions with explosive eruptions cannot produce the total eruptive volume history at the Three Sisters. However, there are three realizations with just under

$10^{-2} \text{ m}^3/\text{m}^2/\text{yr}$ average magma flux that successfully reproduce the overall Three Sisters eruptive volumes through time, even though they only correctly match two of the true eruptive episodes. Each of these realizations has magma bodies intruded at 6 km depth, two are mafic intrusions, and two form via focused intrusions. Interestingly, the depth of these three realizations, 6 km depth, matches the hypothesized depth of intrusion causing the deformation event that began in the mid-1990s (Lisowski et al., 2021).

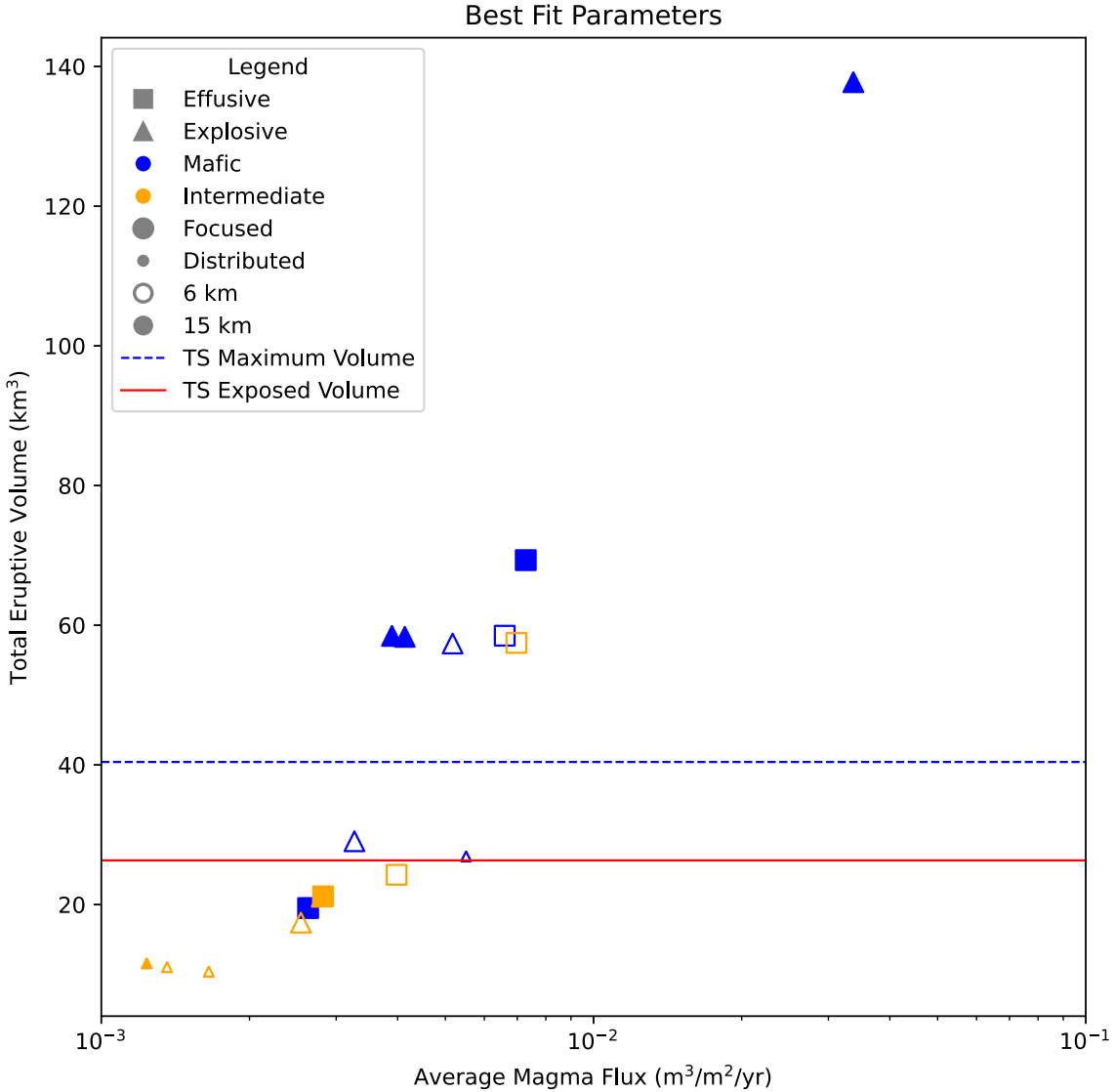


Figure 19: Modeled average mantle flux ($\text{m}^3/\text{m}^2/\text{yr}$) and modeled total eruptive volume (km^3) for the 17 best-fit realizations. All realizations match two of the four volume-timing Three Sisters eruptive episodes. Effusive eruptions are squares; explosive eruptions are triangles. Mafic magmatic intrusions are blue; intermediate magmatic intrusions are orange. Focused magmatic are the larger symbols; distributed magmatic intrusions are smaller symbols. Intrusions at 6 km depth are open faces; intrusions at 15 km depth are fully colored. Blue dashed line shows the maximum estimated volume of erupted products of the Three Sisters; red solid line shows the mapped volume (Hildreth et al., 2012).

We conducted four additional realizations to test if the magmatic system could match the older eruption episodes and the Holocene episode, and have a better gravity misfit. Here, we ran previous realizations that correctly matched the North Sister, Middle Sister, and coeval eruption episodes for the first 120 ka of the model run. Then, we only allowed for one or no magmatic intrusions for the final 10 ka of the model. However, despite this decrease in magma flux, the gravity misfit values only improved by 0.01 mGal.

The only realizations to have one of their two eruptive episode matches include the Holocene episode are three intermediate realizations with distributed magmatic intrusions. This could signify a change in magma flux into the system or the style of intrusions that occurred at 10 ka. The two Holocene eruptions at South Sister are on the opposite flanks of the volcano, rather than building up the main summit sequence, so maybe these rhyolite domes are products of more random intermediate intrusions scattered about the west and east sides of South Sister.

3.5.5 Past, Present, and Future Gravity Anomaly Patterns

While we only have the modern gravity signal, we can compare that signal to the simulated gravity anomaly over time to understand how the magmatic system could have evolved to the present state. The data shows two gravity misfit trends. First, the realization has a considerable variation in the gravity misfit over time, generally with the largest misfit at the modern day because the magma system has grown much larger and produced a greater negative gravity anomaly than is present in the Bouguer gravity anomaly (such as the focused mafic plutonic realizations, Figure B8). Alternatively, the gravity misfit value collapses to a stable value very quickly. It remains at this approximate value throughout the model time (such as the lower intermediate magma flux effusive focused realizations, Figure B9). Both of these trends are represented in the best-fit realizations, with one example of a realization moving from lower to higher gravity misfit, while the others all very quickly reach and stay at a gravity misfit value around 3.4 mGal (Figure 18a-f).

Additionally, some realizations produce an on-average positive gravity anomaly. This is most common with distributed magmatic intrusion realizations and occurs with intermediate and mafic intrusions. These intrusions occur randomly within the model space and likely do not have a large enough volume or high enough temperature to remain at an eruptible melt fraction for a long time. As such, unless these intrusions have quickly erupted, they likely solidify. This solidification of denser material than the background crust can create a slight positive gravity

anomaly. This is not unexpected, given the density ranges for the four modeled crustal layers compared to the intrusion densities (Figure B19). As such, the positive gravity anomalies represent stalled, solidified intrusions that did not erupt.

The goal of this study is not to match the simulated to the field gravity survey perfectly, but rather to find a range of plausible scenarios that match the eruptive history and modern gravity survey. Of the 17 best eruption volume fits, 16 realizations have a gravity misfit ranging from 3.3-3.5 mGal between the present anomaly and the modern-day model timestep. The same 16 realizations also collapse to that small misfit value almost immediately after model initiation. The gravity misfit between the background crust with no intrusions and the field survey is 2.89 mGal. Given the low volume flux into the system and how small the intrusions are, the misfit calculation only picks up the system's perturbations in a small area compared to the total model surface. Thus, the most common misfit value represented is that of the background crust at 2.89 mGal.

To consider this scenario, we recalculate the gravity misfit values but remove all positive gravity anomaly field measurements from the calculation. Most positive anomaly measurements are east of the main Three Sisters and are likely attributed to the nearby Broken Top volcano (Figure 10). Broken Top was largely mafic and active from 300 – 150 ka, a period not considered in these models (Hildreth, 2007). As such, removing these data points does not remove the data most closely related to the Three Sisters volcanism. With this new misfit calculation for the best-fit realizations, the gravity misfit decreased across the board to values between 2.17 and 6.01 mGal, with the percent change ranging from -1.3 to -36.9. These values better represent the difference between the modern and simulated anomalies based on the system's magmatic perturbations. However, when considering this misfit over time, the main trend of the misfit collapsing to a single value is no longer present (Figure B20a). For 15 realizations, the misfit decreases to today, one realization steadily increases, and one realization at first decreases and then increases to today (Figure B20a).

We zoom into a single timestep for the higher-flux explosive, mafic, focused realization R021 to understand the modeled scenario that best matches the modern gravity anomaly. At the 40 ky timestep or 90 ka, the gravity misfit value is 1.57 mGal to the present-day signal, not considering the positive field gravity measurements (Figure B21d). When removing the positive field data, this is the smallest gravity misfit of any model realization and of any timestep for the

best fit runs. The magma body is at 15 km depth and has a footprint of approximately 13 km in length and 4 km in width. There is 221.9 km³ of melt fraction > 0.005, 207.76 km³ of melt fraction > 0.1, 112.45 km³ of melt fraction > 0.4, 63.53 km³ of melt fraction > 0.6, and 0.07 km³ of melt fraction > 0.99. This creates a diffuse negative gravity anomaly of -2 mGal covering ~25 km of the model surface (Figure B21c). This -2 mGal anomaly seems to fit the diffuse, small negative gravity anomaly surrounding the Three Sisters. This is distinct from the more clearly defined larger magnitude negative anomalies that Le Mével et al. (submitted) attribute to the hydrothermal system down to 3 km depth under South Sister. If this is correct, there could be a magma body of 63 km³ at 15 km depth with a melt fraction of > 0.6 that was not clearly identified in the inversion of the Bouguer gravity anomaly. The depth and density contrast of this modeled magma body is beyond the detection limit of the field Bouguer gravity survey and is only identified when removing part of the field data. Additionally, we acknowledge that this is a much larger magma body than expected at such a small to modern-volume system. Further, suggesting a single-timestep answer for the magmatic system under the Three Sisters deviates from the forward modeling method used in this study, we still postulate that this realization could broadly mimic the present-day magmatic system at the Three Sisters, of a more diffuse, low-value negative gravity anomaly.

3.5.6 Seismic and Resistivity Models

While we do not have field data of seismic velocities and electrical resistivity to compare to like with gravity, we can still run the forward geophysical models for these two methods to forecast what future geophysical surveys might reveal. Given the minimal perturbations to the system for the 17 best-fit scenarios, there are no large structures imaged with these forward methods in many realizations. Even for the more focused intrusions, a small magma body is produced, not very large. As such, the best fits tend to create small structures in the model space of conductive melt and low S-wave seismic velocities. How well such structures could be imaged in the field relies on the field data's resolution. For example, distributed intermediate intrusions with explosive eruptions (R071) and distributed mafic intrusions with explosive eruptions (R061) both displays scattered, small electrically conductive bodies ranging from 1-10 Ω m and seismic velocities of 0 km/s for small melt bodies and higher 4 km/s velocities for solidified intrusions (Figure B22). One of the outlier realizations, focused mafic intrusions with explosive eruptions R021, creates a larger magmatic system, and thus geophysical signals, than

the other best-fit realizations. From an eruptive perspective, it matches the Middle Sister and then the coeval Middle and South Sister eruptive episodes, but erupts too much volume for the other two episodes. Additionally, this realization has the highest total magma flux through time as well as the highest gravity misfit at the modern timestep of 8.3 or 6.0 mGal when considering all field data or only negative field data, respectively. With this higher flux, a more built magma body reveals a conductive melt body ranging from 1 – 10 Ωm and seismic velocities of 4 km/s around the solidifying outer edge and no S-wave velocity through the middle of the magma body (Figure B22). Given the large gravity misfit with R021, we do not believe this represents the current magma system. As such, we suggest that modern magnetotelluric and seismic velocity surveys would reveal a system more similar to R071 and R061: very minimal melt at high melt fraction.

3.5.7 Comparison to Modern Inflation

Finally, we completed three tests of magma dynamics and forward gravity modeling to directly test the leading hypothesis for the cause of modern inflation at the Three Sisters. First, we create a uniform crust density of 2,500 kg/m³, matching the value of Le Mével et al. (submitted). We then create a sphere at 6 km depth, a volume of 0.067 km³, a radius of 0.227 km, and a density contrast of -500 kg/m³ as is the geometry hypothesized by Lisowski et al. (2021) and tested by Le Mével et al. (submitted). With this geometry, we find a gravity misfit of 3.33 mGal when considering all field data, the same value as most of our best-fit realizations. When changing the background crust to our modeled crust (Table 1) and keeping the same sphere geometry, the gravity misfit is, again, 3.33 mGal. Just as in Le Mével et al. (submitted), the magnitude of the intrusion to cause the inflation event at the Three Sisters is not large enough to be largely distinguishable in the field Bouguer gravity survey or the forward geophysical gravity anomaly simulations.

3.6 Conclusions

Through this work, we have explored a magma dynamics model that considers eruption scenarios compared to the Three Sisters volcanic complex. We also run a forward gravity model to compare the simulated gravity anomaly to the field-based one. Seventeen realizations match the eruptive record of two eruptive episodes and are considered the best fit. Model parameters that best match the eruptive histories are more focused magmatic intrusions with a flux range of $10^{-3} - 10^{-1} \text{ m}^3/\text{m}^2/\text{yr}$ and suggest changes in the magmatic flux of the system around 50 ka and 10

ka. Additionally, through time, the gravity misfit values for these best realizations generally do not change much, highlighting that the crustal geophysical signals are likely not incredibly varied between eruptive and non-eruptive periods. We also suggest that a magmatic body with a melt fraction > 0.6 and a volume of 63 km^3 at 15 km depth could be the cause of the diffuse, low-value, negative gravity anomaly in the region, which was not detected by the Bouguer anomaly inversions, but does support the hypothesis of a “hidden” mush body. Finally, we note that the hypothesized volumetric magma flux causing the inflation event would not create a large enough perturbation in our modeling scenario to be captured. In conclusion, we highlight a range of magmatic system evolution that could produce the eruptive volumes and the modern Bouguer gravity anomaly, suggesting that the magmatic system of the Three Sisters is unlikely to produce significant geophysical anomalies, and that utilizing other monitoring efforts at this volcanic complex is key.

3.7 Bridge

In Chapter 3, I employed a geophysical lens to probe the modern magmatic system at the Three Sisters, while also considering the eruptive past of the complex. This approach highlights a constant volume flux of magma that could produce some of the eruptive episode volumes, but not all, suggesting changes in the magmatic flux around 50 ka and 10 ka. Additionally, we find that the simulated and field gravity misfit for the simulations matching the eruptive history are small, indicating that even during high eruptivity, the magmatic system does not have a significant density contrast with the surrounding crust.

Chapter 4 utilizes magma dynamics simulations that most successfully match the eruptive history of the Three Sisters and the modern gravity anomaly of Chapter 3 through a geochronological lens. A zircon growth model calculates the size, age, and composition of zircon crystals based on magmatic evolution. I then compare the simulated zircons to those analyzed in Chapter 2. Overall, there was success in matching these ages, suggesting that the modeled magmatic systems correctly aligned with the Three Sisters’ eruptive history and modern gravity survey also reproduced the geochronological data. This underscores the multidisciplinary perspective of my dissertation.

CHAPTER IV

CHAPTER 4: MATCHING MODELED ZIRCONS TO NATURAL SAMPLES REVEALING MAGMA STORAGE AT SOUTH SISTER VOLCANO

4.1 Introduction

With global volcanic hazards threatening hundreds of millions of people from ash fall to lava flows to pyroclastic density currents, it is crucial to understand active volcanoes' eruptive and magmatic history to prepare for future hazard mitigation (Ewert et al., 2018). This can include studying magmatic storage conditions of the past (pressure, depth, temperature, longevity, volatile content) and/or geophysical imaging of the modern system (magnetotellurics, seismic velocities, gravity anomalies) and then using this information to inform volcanic hazard maps and risk assessments. Understanding the state of the magmatic system (volume, longevity, temperature, proportion of solid to melt to volatiles) prior to past eruptions aids in interpreting current monitoring data. In this study, we seek to explain the magmatic evolution as deciphered through the zircon crystal record and hypothesize about the current magmatic system at the Three Sisters volcanic complex in the central Oregon Cascades, USA.

The Three Sisters volcanic complex is considered a “very high threat potential,” yet has outstanding questions about the current and past state of the magmatic system (Ewert et al., 2018). The Three Sisters, composed of three main stratovolcanoes, all show distinct characteristics. North Sister is the oldest (130-50 ka) and erupted only basaltic andesite (Schmidt and Gruner, 2009; Hildreth et al., 2012). Middle Sister erupted mostly basaltic andesite to dacite, with one rhyolitic eruption, between 49-15 ka (Calvert et al., 2018). South Sister was built of alternating rhyolite and intermediate products from 39-22 ka, before two rhyolite sequences around 2 ka (Scott, 1987; Fierstein et al., 2011; Dechert et al., 2024). While magmatism at North Sister is thought to have been caused by repeated mantle recharge, with little crustal melting, the production of felsic materials at South Sister is debated (Schmidt and Gruner, 2011a). Hypotheses include (1) partial melting from different background crust compositions, (2) fractional crystallization from mafic magmas, (3) rejuvenation of residual magmas from the late Pleistocene for the Holocene rhyolites, or a combination of these processes (Hill, 1991; Brophy and Dreher, 2000; Fierstein et al., 2011; Calvert et al., 2018; Waters et al., 2021; Parker et al., 2023). In addition to the complex's geologic studies, ground inflation was identified about 5 km west of South Sister's summit beginning in the mid-1990s (Lisowski et al., 2021). However,

hypotheses for the cause of this inflation range from a continuing intrusion of basaltic magma, a delayed response of the crust to a past magma intrusion, or the pressurization of a geothermal system (Wicks, 2002; Dzurisin et al., 2009; Riddick and Schmidt, 2011). The root cause of this deformation impacts future monitoring efforts. The monitoring network and the signals to watch for are different, if there was truly a magmatic intrusion at shallow depths in the mid-1990s, or if there has not been any new intrusion into the system since the eruptions two thousand years ago. Spring geochemistry further muddles these hypotheses, with evidence of $^3\text{He}/^4\text{He}$ ratios, magmatic heat, and magmatic carbon signatures suggesting magma is stored under South Sister (Evans et al., 2004). A recent Bouguer gravity survey indicates the presence of a hydrothermal system of up to 5 km³ from 0-3 km depth under South Sister (Le Mével et al., submitted). Finally, mineral barometry only exists for South Sister and North Sister, with few analyses. Melt inclusion studies only exist for North Sister, with no vapor bubble analyses, leaving the geochemical constraints on magma storage at the Three Sisters sparse (Schmidt and Gruner, 2011a; Mordensky and Wallace, 2018; Waters et al., 2021; Wieser et al., 2023).

A valuable mineral for considering the magmatic history of a volcano is zircon due to its weathering durability, high compatibility with elements used in geochronology and petrology (i.e., U, Th, and rare earth elements), and a calibrated temperature dependence of saturation (Watson and Harrison, 1983; Finch and Hanchar, 2003; Hoskin and Schaltegger, 2003). Zircon has been widely used to record the protracted thermo-chemical evolution of magmas in diverse intermediate-felsic magmas (i.e., Reid et al., 1997; Bacon and Lowenstern, 2005; Stelten and Cooper, 2012; Klemetti and Clynne, 2014; Andersen et al., 2019; Dechert et al., 2024). For example, zircon has been used at caldera complexes such as Taupo, New Zealand, to understand long-term magma residence times and identify near-solidus crystal storage prior to rapid heating and cooling (Rubin et al., 2017). At stratovolcano Mount St Helens, zircons suggest magma stalling and cooling before rejuvenation via increasing intrusion of mafic magmas over time, highlighting the magma cycles at the most active volcano in the Cascade arc (Claiborne et al., 2010). As such, this small trace mineral can help distinguish a magmatic systems' temporal, chemical, and thermal history (Cooper, 2015; Schmitt et al., 2023).

Despite the extensive application of zircon petrochronology and continued improvement of analytical methodology, questions remain about the timescales of physical processes zircon crystals can record, how dutifully they record the entire thermal and rejuvenation history of

magma bodies, and how the spatiotemporal distribution of zircons in a magma reservoir give rise to the populations samples in eruptions (Kent and Cooper, 2018). First, zircon crystals do not act as passive recorders of the overall history of the magmatic system, as zircon growth is temperature dependent, thus only recording a portion of the magmatic thermal evolution (Watson and Harrison, 1983). This temperature-dependence also suggests zircon dissolution if the magmatic temperature rises past zircon saturation, therefore losing zircon and magmatic history (Watson and Harrison, 1983; Boehnke et al., 2013; Bindeman and Melnik, 2016). Additionally, the time to form the zircon crystals in the magmatic system is likely shorter than the analytical uncertainties from laboratory methods, suggesting we will miss short-term evolution details (Kent and Cooper, 2018). As such, we address the disconnection between a known magmatic system and the natural zircon samples by running a zircon growth model in parallel with a physics-based magma model, directly calculating the temperatures, ages, and compositions of modeled zircon crystals.

Through this study, we utilize a magma dynamics model run in parallel with a zircon growth model for realizations that reproduce the eruptive volumes of the Three Sisters. Then, by comparing age, temperature, and trace element data between the simulations and zircon data from South Sister rhyolites, we explore the magmatic evolution and processes most likely controlling the Three Sisters.

4.2 Methods

4.2.1 Magma Dynamics Model

The magmatic system is modeled in three dimensions, accounting for the magma's physical, chemical, and thermal evolution by conserving mass and energy for the system's solid, melt, and volatiles (Dufek and Bachmann, 2010). Equations for the conservation of mass and energy are solved for both intruded magma and the surrounding modeled crust, and the balance of heat advected into the system through the intrusions and conductive heat transfer determines the time-dependent structure of the magma bodies and temperature throughout the crust (Dufek and Bachmann, 2010). The evolution of crystallization, melting, mass partitioning during phase changes, and exsolution is parameterized in internal rhyolite-MELTS thermodynamic modeling, tracking the melt major oxides, density, viscosity, and the mineral phases formed (Gualda et al., 2012). This embedded rhyolite-MELTS scheme calculates the mineral assemblages and physical parameters of the melt (i.e., density) based on pressure, temperature, and major oxide

compositions. Model outputs include density, melt fraction, pressure, temperature, water content, and melt major oxides at each location in the computational domain (Figure 20). The computational domain extends 45 km in all three-dimensions, with ~0.2 km spatial resolution. Each realization runs for 130 ky (matching the eruptive history of the Three Sisters) with 50-year timesteps. The user sets the background crust depths and compositions (discussed below) and the magmatic intrusion compositions.

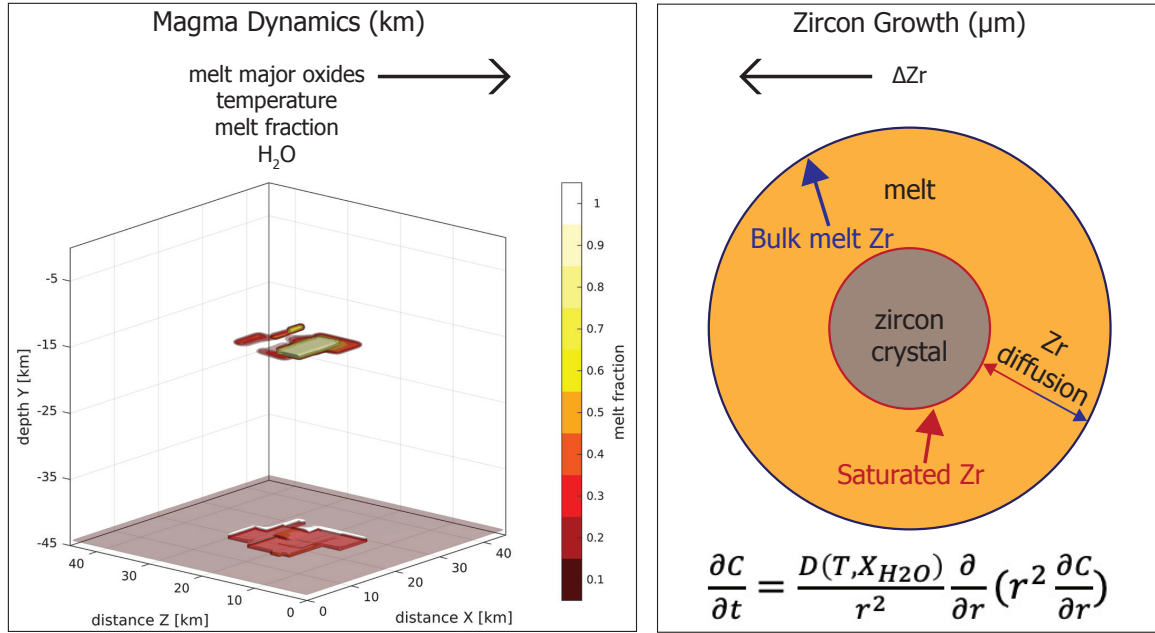


Figure 20: Schematic of the magma dynamics and zircon growth model. The magma dynamics model couples the thermal and chemical evolution of the kilometers-scale magmatic system. Outputs of melt major oxides, temperature, melt fraction, and water are read into the zircon growth model. The zircon growth model calculates diffusion-limited spherical zircon growth based on Zr saturation (Bindeman and Melnik, 2016; Andersen and Dufek, in prep). Zircon diffusivity (D) depends on the temperature (T) and water content (X_{H2O}) of the melt. The Zr concentration (C) is modeled along the radial distance (r) that changes with the zircon radius and melt fraction. The Zr concentration is coupled back to the magma dynamics model. Outputs include the crystal radius, U concentration, and growth rate.

Simulated magmatic intrusions are intruded randomly into the background crust model domain. We set that on average, magmatic intrusions will occur every 250, 500, 750, 1000, or 1500 years, maintaining a relatively fixed long-term average flux for each simulation. We test two styles of intrusions, focused and distributed. For focused intrusions, the first intrusion occurs, and then all following intrusions occur into the same area directly connected to the first intrusion. This creates a more built-up, single, focused magma body. For the distributed intrusions, the location of the intrusions is random about the central region of the model space, thus, generally not building up a long-lived magma system. Both the first focused and all

distributed intrusions occur in the central 10 x 10 km area of the model space to limit boundary effects. Additionally, the depth is set between 1- 6 km or 1-15 km, based on the realization. Mass addition into the system via intrusions is accommodated via crustal thickening through advection of the crust below the intrusion.

Additionally, we consider the thermal implications of eruptions in two simplified end-members to evaluate the first-order effects of explosive or effusive eruptions. Namely, every 500 years, we check if contiguous bodies are above 0.4 km^3 , and a critical melt fraction of 0.4 are present. If so, they are ‘erupted’ by removing the melt above this critical melt fraction. This effectively removes mass and energy from the magmatic system. In the explosive case, this mass and energy is lost to the immediate model domain aimed at mimicking the broad dispersal of tephra. For the effusive end member, melt is brought to the surface (but we neglect radiative heat loss and lava flows, so this end member will cool more slowly than lava flows). In this way, we anticipate that these simulated conditions act as end-members where the explosive case will tend to overestimate cooling and the effusive case will underestimate cooling.

4.2.2 Background Crust

Thermal properties of the surrounding crust are determined through an assumed idealized layered crustal structure and composition. We model a Cascade-like crustal structure based on gravity surveys (Couch et al., 1982; Couch and Riddihough, 1989), magnetotelluric studies (Livelybrooks et al., 1989; Stanley et al., 1990), seismic refraction (Leaver et al., 1984; Stanley et al., 1990), and geochemical studies. These suggest a simplified structure of four main crustal layers. The uppermost layer from 0-4 km depth is dacite; the second layer from 4-12 km is an augite quartz diorite; and the subsequent two layers are gabbroic diorites of different compositions from 12-30 km, and the deepest layer from 30-44 km (Conrey, 1985; Miller et al., 2009; De Bari and Greene, 2011; Ruscitto, 2011; Schmidt and Grunder, 2011b; Bedrosian et al., 2018). While there is some variability in the depth of the Moho in the Cascades between 35 and 47 km, we model the Moho at 44 km depth (e.g., Thiruvathukal et al., 1970; Couch et al., 1982; Leaver et al., 1984; Catchings and Mooney, 1988; Couch and Riddihough, 1989; Livelybrooks et al., 1989; Stanley et al., 1990; Bostock et al., 2002). See Table 1 for the major oxide compositions of each background crust layer.

To explore a range of melt genesis and evolution hypotheses, we use two different melt compositions for the magma flux into the modeling space (Table 1). The mafic composition is

basaltic andesite based on the mafic summit composition modeled in rhyolite-MELTS to find stable conditions (Brophy and Dreher, 2000; Gualda et al., 2012; Ghiorso and Gualda, 2015). The intermediate composition is andesite based on major oxides of the main cone andesites at South Sister (Brophy and Dreher, 2000). After intrusion, these melts evolve to higher SiO₂ values due to crystallization processes. Through this evolution, the SiO₂ wt% composition of the erupted magma ranges from 59.7 to 60.4, or an andesite for the mafic intrusions, and from 73.2 to 75.7, or a dacite to rhyolite for the intermediate intrusions. As such, the compositional evolution of the system is also tracked. Through this work, we will continue referring to the two intrusion types of mafic (basaltic andesite) and intermediate (andesite), even though their eruptive products are more evolved.

4.2.3 Zircon Growth Model

We compute zircon crystal growth as a one-way coupled process using the conditions from magma simulations and simulating the local transport of chemical species near the crystal-melt boundary. The rate of zircon crystal growth or dissolution is limited by the diffusion of zirconium (Zr) in and out of the crystal-melt interface. This diffusion is controlled by the zircon solubility in the melt, the diffusivities of compositional components in the melt, and how much the system deviates from saturation equilibrium (Watson, 1996). Diffusion-limited zircon crystallization or dissolution is modeled via spheres within a shell of melt, and the melt at the crystal boundary maintains the concentration of Zr required for zircon saturation (Figure 20; Watson and Harrison, 1983; Boehnke et al., 2013). The radius of the melt surrounding the zircon crystal is based on the host magma compositions calculated in the magma dynamics model, and this radius varies throughout the simulation as it evolves. A finite difference algorithm solves the double-moving boundary (zircon crystal, melt shell) (Bindeman and Melnik, 2016; Andersen and Dufek, in prep). An important variable to set is the zircon nucleation density, or how many zircon crystals we initiate in the modeling volume. This value is set to 10⁷ crystals per m³ of model space, falling in the range explored by Bindeman and Melnik (2016), primarily focused caldera eruptions. This is one of the major assumptions of this model setup; however, initial exploration of a range from 10⁵ to 10¹¹ crystals per m³ shows no significant change in zircon age data. Additionally, we set the initial zircon nucleation radius to 2 μm so we do not immediately have high crystallinity, but allow for this by the end of the model run. The Zr oversaturation factor in the melt shell surrounding the zircon crystal is at 10 ppm, which is required for the

zircon to nucleate (Bindeman and Melnik, 2016). The background crustal Zr concentration is 150 ppm and U concentration is 2 ppm, in the ranges of the average trace element compositions of the middle and upper continental crust (Rudnick and Fountain, 1995).

The magma dynamics and zircon growth models connect a kilometers-based magmatic system and microns-based crystals. The magma dynamics model computes melt major oxides, water content, mineral phase proportions, melt fraction, and temperature, which are read into the zircon growth model to calculate the saturation condition and temperature dependence on zircon growth. The zircon growth model tracks the Zr budget in the bulk melt.

From these modeled zircons, it's essential to calculate comparable data to laboratory analysis, such as secondary-ion mass spectrometry (SIMS) ages, Ti concentration, and U concentration. First, the Ti concentration in the zircon crystals is computed using the Ti-in-zircon thermometer since we have the temperature data from the magma dynamics outputs, assuming an SiO_2 activity of 1 and a TiO_2 activity of 0.7 (Ferry and Watson, 2007). With this zircon Ti concentration, we calculate the U partition coefficient based on the U concentration in the melt, and can then calculate the U concentration in the zircon crystal (Claiborne et al., 2018). With this data, we can then calculate the SIMS-based zircon age for different profiles of the zircon crystal. First, we set the size of the model SIMS beam to a radius of 10 μm , which is on the smaller end of the standard analytical beam size, and the depth of the sample the beam will analyze to 3 μm (Ireland and Williams, 2003). Then, based on the size of the zircon crystal compared to the beam radius, we calculate just a single age (only one growth zone), a rim and core age (at least two growth zones), or a rim, interior, and core age (when the zircon crystals is over 20 μm in radius). To calculate these ages, we calculate the volume of U in the zircon crystal based on the U concentration, beam radius, and beam depth. Then, we calculate the Pb volume based on the U concentration, beam radius, beam depth, and the decay of ^{238}U to ^{206}Pb . Thus, with the volume of ^{238}U , volume of ^{206}Pb , and the decay constant of ^{238}U , we calculate the SIMS age that would be recorded in a laboratory for the modeled zircons (Cheng et al., 2000). As such, we have age, Ti concentration, and U concentration data for the modeled zircons that can be directly compared to the zircons from South Sister rhyolites.

4.2.4 Modeling Space Explored

The model realizations considered in this work build upon the work of Chapter 3 of this dissertation. This study aimed to explore modeled eruptive history and geophysical signals to understand the structure and flux of the magma system, constrained by the eruptive volumes of the Three Sisters and the modern-day gravity survey. The original study considered 109 model simulations of the plutonic record as well as simulations accounting for the thermal budget of explosive and effusive eruptions. Additionally, the study explored focused and distributed magma bodies, intermediate and mafic composition magmatic intrusions, intrusion depths of 6 or 15 km, and a range of magma flux volumes. This study first compared the gravity misfit between the simulation magmatic system's simulated gravity anomaly and the field gravity anomaly of Le Mével et al. (submitted). This allows for comparison between the modeled and natural magmatic system. Next, this study compared the field eruptive volumes to the modeled eruptive volumes for each realization. Total eruptive volumes are considered for the four main eruptive episodes at the Three Sisters: North Sister from 130-50 ka, Middle Sister from 50-40 ka, coeval Middle and South Sister from 40 -10 ka, and the Holocene from 10-0 ka. These simulations assumed that the mean flux into the crust remained the same throughout the Three Sisters magmatic history. While no model realizations matched all four eruptive episodes, 17 matched two episodes. In Chapter 3, we suggest that the most likely explanation for this is that the incoming magmatic flux into this system has changed over time. We build upon this study by exploring the zircon populations of the magmatic system of these 17 best-fit realizations (Figure 21). With these realizations, we consider 11 explosive eruption and six effusive eruption scenarios; 12 focused, single magma bodies and five distributed magmatic intrusion scenarios; ten intrusions at a depth of 6 km and seven intrusions at a depth of 15 km; and an intrusion magma flux volume range from approximately 10^{-3} to 10^{-1} m³/m²/yr. As such, we only run the zircon model on magma dynamics models that most closely match the eruptive history and the modern gravity anomaly of the Three Sisters.

Eruption Style	Input Composition	Focusing Style	Realization Number	Avg Timestep Between Intrusions	Depth (km)	Gravity Misfit (mGals)
Effusive	Felsic	Focused	R081	10	6	3.432
Effusive	Felsic	Focused	R080	15	6	3.3669
Effusive	Felsic	Focused	R084	20	15	3.3714
Effusive	Intermediate	Focused	R069	10	6	3.4604
Effusive	Intermediate	Focused	R101	10	15	3.458
Effusive	Intermediate	Focused	R098	20	15	3.4124
Explosive	Felsic	Focused	R111	20	6	3.3555
Explosive	Felsic	Distributed	R072	10	6	3.3739
Explosive	Felsic	Distributed	R071	15	6	3.3814
Explosive	Felsic	Distributed	R049	20	6	3.3491
Explosive	Felsic	Distributed	R053	20	15	3.3561
Explosive	Intermediate	Focused	R021	5	15	8.2976
Explosive	Intermediate	Focused	R063	10	6	3.466
Explosive	Intermediate	Focused	R062	15	6	3.4386
Explosive	Intermediate	Focused	R030	20	15	3.4329
Explosive	Intermediate	Focused	R034	30	15	3.4289
Explosive	Intermediate	Distributed	R061	5	6	3.6222

Figure 21: Major variable set for each of the magma dynamics realizations. Eruption style, input composition, realization number, average number of timesteps between magmatic intrusions (one timestep is 50 years), and depth (km). Additionally, the final simulated gravity anomaly misfit to the field gravity anomaly of Le Mével et al. (submitted). Each of these realizations fits two of the four eruptive episodes of the Three Sisters and has a final gravity misfit less than 8.3 mGal, making these the best-fit realizations matching the modern gravity anomaly and the eruptive history of the Three Sisters.

4.2.5 South Sister Zircon Data

In addition to the past modeling efforts to explore the magmatic system of the Three Sisters, we leverage South Sister zircon data (Stelten and Cooper, 2012; Dechert et al., 2024). These studies explore eight of the 13 South Sister rhyolites: Rhyolite southwest of Lewis Glacier (rsw, 39.1 ka), Rhyolite of southeast Lewis Glacier (rse, 35.6 ka), Rhyolite of Devils Hill (rdh, 35.4 ka), Rhyolite of Green Lakes (rgl, 32.4 ka), Rhyolite of Mesa Creek (rmc, 31.5 ka), Rhyolite of South Sister climbers trails (rct), Rhyolite of Rock Mesa (rrm, 2,150 14C yr B.P.), and Rhyolite of Devil's Chain (rdc, 2,000 14C yr B.P.) (Scott, 1987; Fierstein et al., 2011; Hildreth et al., 2012; Calvert et al., 2018; Dechert et al., 2024). Zircon ages for these rhyolites generally range from 100-20 ka, suggesting the longevity of the magmatic system. Additionally, trace element variations suggest that distinct magma bodies fed the Late Pleistocene and

Holocene rhyolites (Dechert et al., 2024). Further, even the two Holocene rhyolites come from likely distinct melt bodies (Stelten and Cooper, 2012). Trace element and REE patterns suggest down-temperature zircon and plagioclase crystallization, but also evidence for destabilized amphibole and titanite. Overall, we can utilize the zircon crystal ages, sizes, and compositions from these studies to compare with the modeled zircons to identify if the model realizations that correctly fit the broader Three Sisters eruptive volume history also match the eruptive zircon crystal ages history.

4.3 Results

4.3.1 Zircon Ages

One of the most powerful data types from zircon crystals is the crystallization age, which illuminates long-term magma storage. Dechert et al. (2024) calculated zircon model dates for zircons from South Sister rhyolites with the method of Boehnke et al. (2016). The zircon crystal data is calculated based on the mode equilibrium melt for each zircon spot based on the measured $^{238}\text{U}/^{232}\text{Th}$ of the zircon, an assumed U/Th partition coefficient ratio between the zircon and melt, and assumes a $\pm 15\%$ (1σ) melt variance from the equiline (Boehnke et al., 2016). Based on South Sister zircons and whole rock compositions, the U/Th partition coefficient used is 5.4 ± 0.8 (Dechert et al., 2024). The dates of Stelten and Cooper (2012) were calculated using a two-point model isochron, but these dates are recalculated in Dechert et al. (2024) by the Boehnke et al. (2016) method, so all dates are directly comparable. This data shows interior age spots for 24 rdc, 22 rrm, 24 rgl, and four rsw crystals. Surface age spots account for 30 rsw, 30 rct, 30 rdh, 31 rgl, 21 rse, and 30 rmc crystals. There are 18 zircons in secular equilibrium with unresolvable dates > 350 ka and 228 resolvable zircon dates. We combine interior and surface ages for each unit and consider the normalized probability density calculated via the Silverman binning method for the zircon dates (Silverman, 1986).

All modeled zircon crystals also have a crystallization date calculated. The SIMS ages are calculated based on the spot radius, measurement depth, and the volume-weighted $^{238}\text{Pb}/\text{U}$ ratio based on the U concentration of the beam spot on the zircon crystal (Andersen and Dufek, in prep). The age calculations occur for the zircon crystal's core and the zircon crystal's rim, because not all zircon crystals have a radius larger than $20\text{ }\mu\text{m}$, or twice the distance of the SIMS beam radius. We measure interior or surface analyses for the South Sister zircons, which would be a core or rim analysis in the modeling space, respectively. To compare the simulated crystals'

core and rim SIMS age calculations to the South Sister samples, we also model how dating these zones would impact the recorded age. Figure 22 shows the South Sister sample normalized probability density ages for each unit (solid lines) and the modeled normalized probability density ages via SIMS cores or rims (dashed lines) for the mafic intrusion realizations. In contrast, Figure 23 displays the same for the intermediate realizations. The South Sister data show the highest probability dates around 40 ka and some variability to 150 ka with units rdc, rrm, and rse. Modeled zircon ages will not be older than 130 ka, given the length of our magmatic simulations. Mafic realizations R069, R089, R101, R062, R063, and R034 generally match the peak age calculation around 40 ka for the core and rim age calculations (Figure 22). Intermediate realizations R080 and R081 also match the South Sister age distribution (Figure 23). Broadly, the model age calculated via cores or rims matches the other. However, mafic

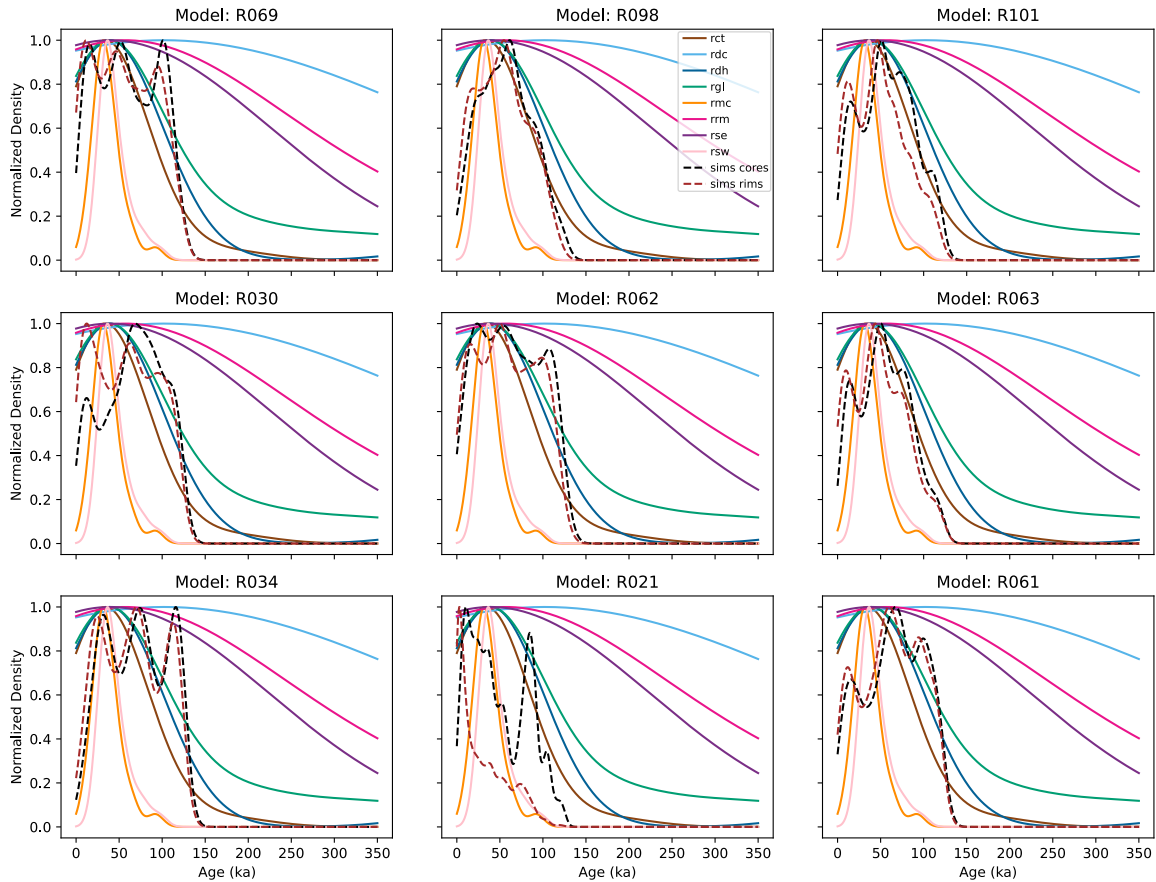


Figure 22: Age data for South Sister zircons and for mafic model realizations. Normalized probability density functions of the zircon population age data by unit from Dechert et al. (2024) in solid lines. Black dashed line shows the age data for each model realization based on a SIMS core age. Brown dashed line shows the age data for each model realization based on the SIMS rim age. The first eight realizations are formed by focused intrusions, and the final realization is formed by distributed intrusions.

R021, intermediate R049, intermediate R053, intermediate R071, and intermediate R072 display younger rim ages than the cores and have a probability maximum near age 0 ka, or the present day.

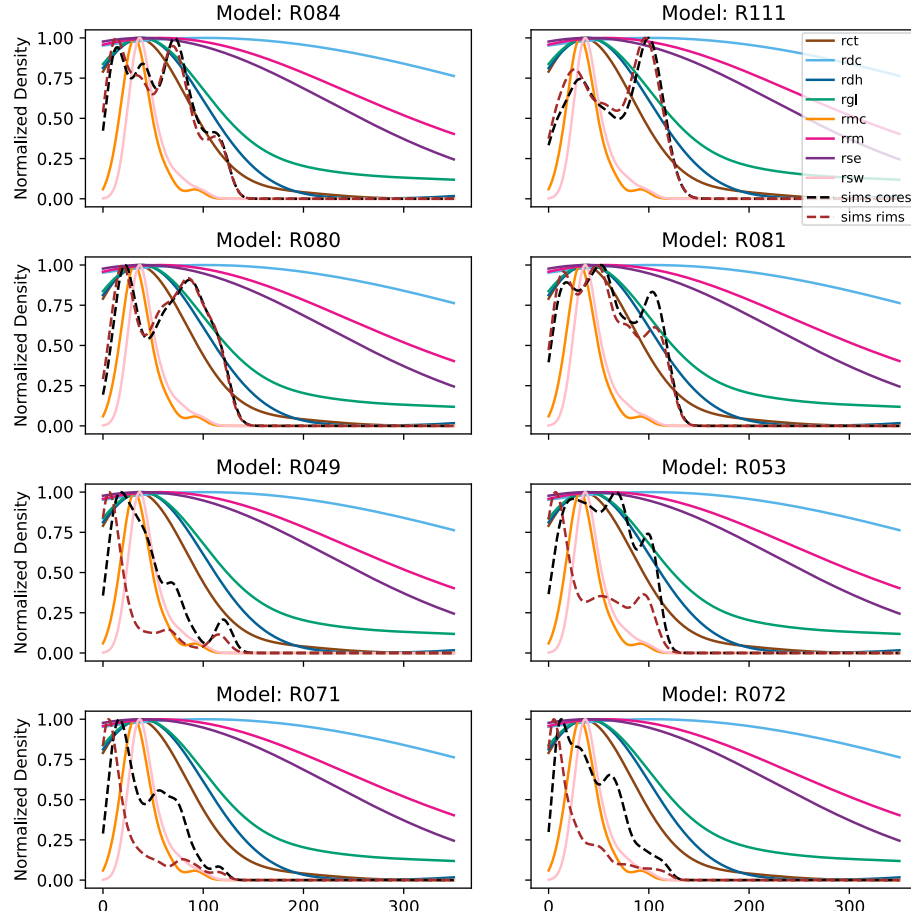


Figure 23: Age data for South Sister zircons and for intermediate model realizations. Normalized probability density functions of the zircon population age data by unit from Dechert et al. (2024) in solid lines. Black dashed lines shows the age data for each model realization based on a SIMS core age. Brown dashed line shows the age data for each model realization based on the SIMS rim age. The first four realizations are formed by focused intrusions, and the final four realizations are formed by distributed intrusions.

4.3.2 Zircon Sizes

Zircon crystal sizes are an essential consideration when planning laboratory analyses. For SIMS analyses via Cameca 1270, the $^{16}\text{O}^-$ beam is in the size range from 10-30 μm in diameter, while for the SHRIMP-RG analyses, the O_2^- beam is 15-40 μm in diameter (Ireland and Williams, 2003). This is important when deciding what mount to consider, as the beam contacting an epoxy mount makes the analysis unusable with a carbide interference; in contrast, analyses with some beam interaction with an indium mount can still be used. Due to these size and mount considerations, Dechert et al. (2024) zircon sizes are only available for rgl (37), rrm minidome (29), and rsw (11). While this sample size does not represent the entire dataset, the eruption ages of rhyolites at South Sister are represented with rsw, the oldest rhyolite at South Sister (39.1 ka), and rrm is one of the youngest (2,150 ^{14}C yr B.P.) (Scott, 1987; Dechert et al., 2024). Finally, we note that the South Sister zircons will be biased towards larger crystals needed

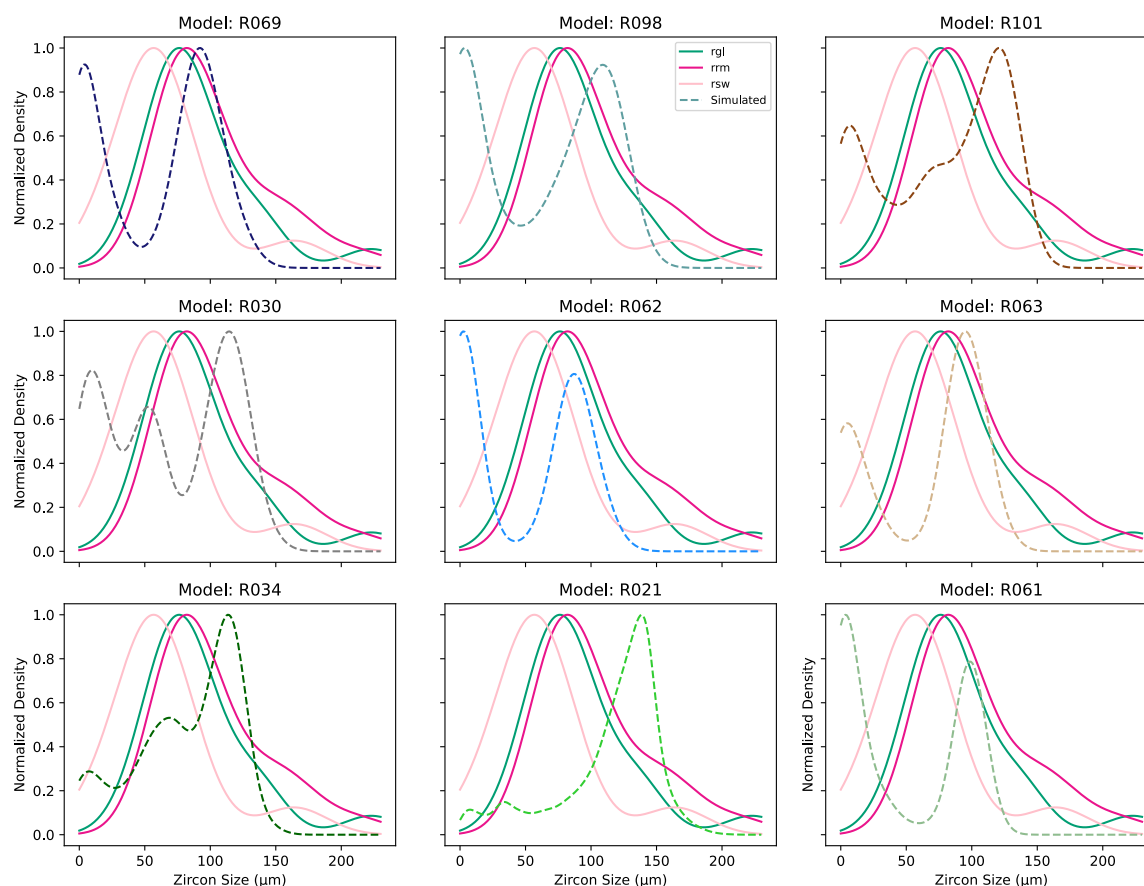


Figure 24: Size data for South Sister zircons and for mafic model realizations. Normalized probability density functions of the zircon population size data by unit from Dechert et al. (2024) in solid lines. Dashed line shows the size data for each model realization. The first eight realizations are formed by focused intrusions, and the final realization is formed by distributed intrusions.

for the laboratory methods (i.e., Schmitt et al., 2023). From picking these zircon crystals, we acknowledge that there is a subset of small zircon sizes within these units, but those are not usable for SIMS analyses and thus, not measured.

We compare the South Sister zircon sizes to the modeled zircon sizes. Figure 24 shows the normalized probability density for zircon sizes ranging from 0 to 200 μm , with units in solid colors and the modeled zircons in a dashed line for the mafic realizations. Conversely, Figure 25 displays the same for the intermediate realizations. The maximum range of natural samples is approximately 50 to 100 μm in the longest c-axis. Realizations that match this same trend include mafic R069 and mafic R063. Multiple mafic realizations show a more bimodal

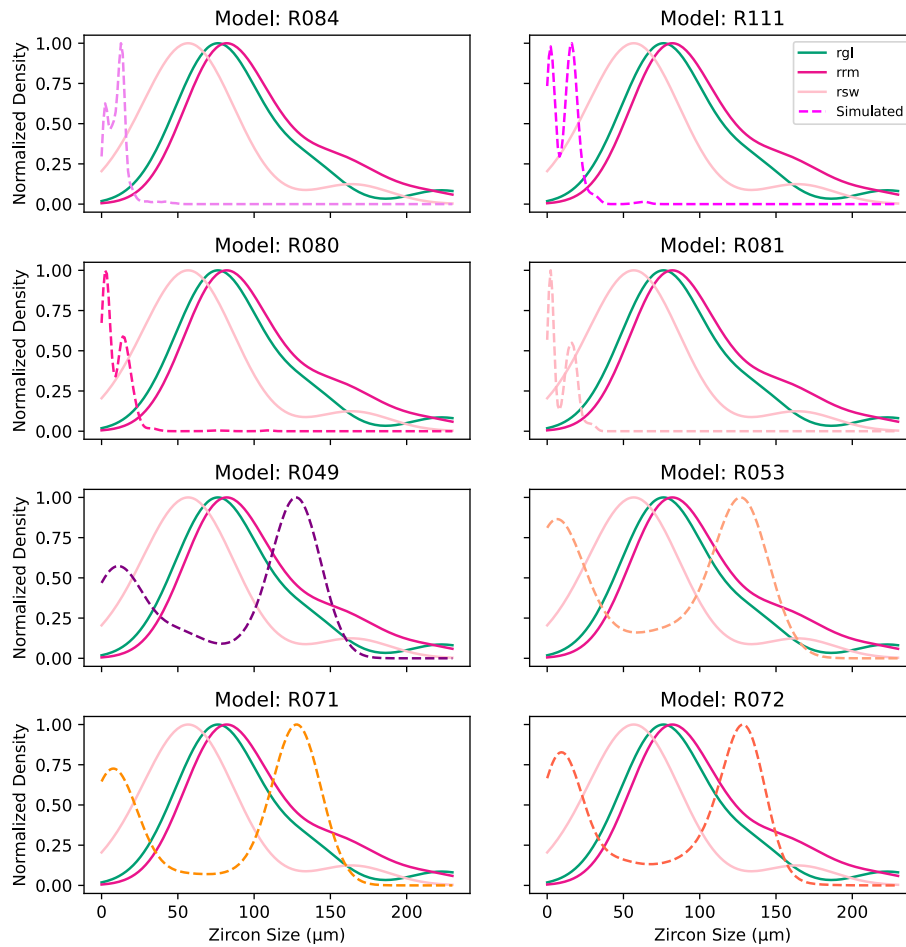


Figure 25: Size data for South Sister zircons and for intermediate model realizations. Normalized probability density functions of the zircon population size data by unit from Dechert et al (2024) in solid lines. Dashed line shows the size data for each model realization. The first four realizations are formed by focused intrusions, and the final four realizations are formed by distributed intrusions.

distribution of sizes found in the natural samples. Four intermediate realizations create only 0-20 μm zircon crystals, much too small for SIMS analyses. The other four intermediate realizations have a bimodal size distribution larger than and smaller than the natural samples.

4.3.3 Zircon Trace Elements

The Ti concentration in zircon allows for calculating crystallization temperatures by the Ti-in-zircon geothermometer calibration (Ferry and Watson, 2007). This calculation requires values for the activities of TiO_2 and SiO_2 , neither of which we have a precise way of finding for the South Sister rhyolites. An a_{SiO_2} equal to 1 suggests the presence of quartz, which we do not see in the South Sister rhyolites. However, basic MELTS modeling of the whole rock values of the South Sister rhyolites suggests an a_{SiO_2} between 0.3 to 0.9 (Gualda et al., 2012), so without an accurate way to calculate a_{SiO_2} , we assume it's equal to 1. We first modeled the TiO_2 activity in a range from 0.6 to 0.9 to find a plausible temperature range, but found the assumption of 0.7 to be best (Watson et al., 2006; Hayden and Watson, 2007; Ferry and Watson, 2007; Dechert et al., 2024). To complete these calibrations, we assume SiO_2 (1.0) and TiO_2 (0.7) activities for both the natural samples and the model calculations, as are typical values used. Ti measurements

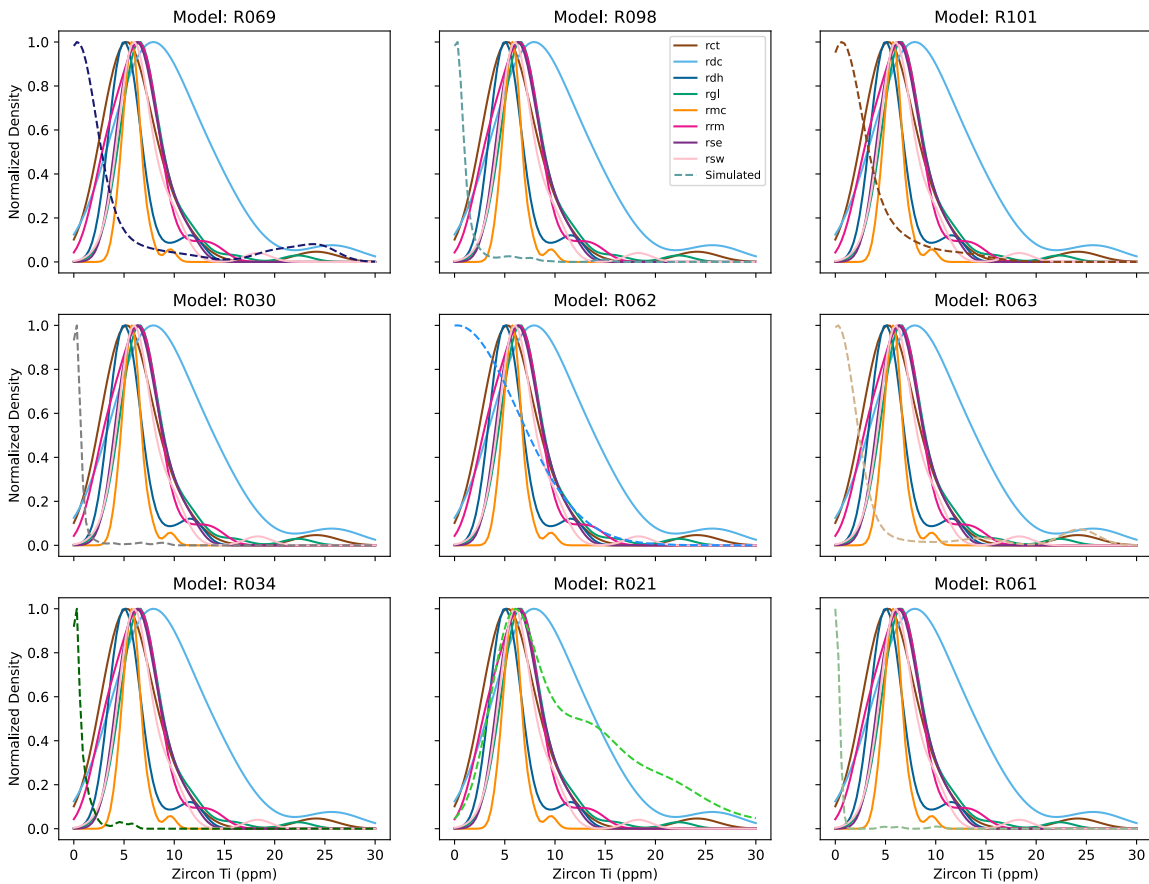


Figure 26: Ti ppm data for South Sister zircons and for mafic model realizations. Normalized probability density functions of the zircon population Ti data by unit from Dechert et al. (2024) in solid lines. Dashed line shows the Ti concentration for each model realization. The first eight realizations are formed by focused intrusions, and the final realization is formed by distributed intrusions.

from South Sister rhyolite zircons cluster between 5-15 ppm, corresponding to approximately 625-775°C at crystallization. The only realization that matches this trend is mafic R021 (Figure 26). Other mafic realizations contain too little Ti, suggesting much lower temperatures than is likely in a natural system. Four intermediate realizations

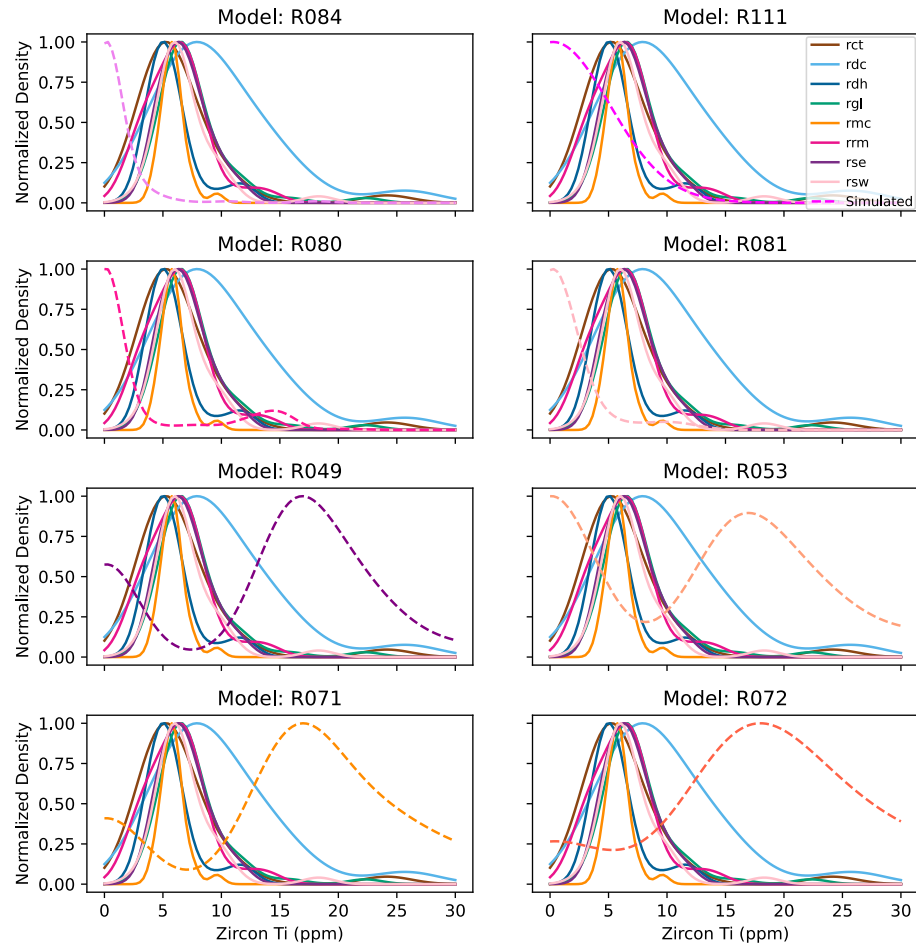


Figure 27: Ti ppm data for South Sister zircons and for intermediate model realizations. Normalized probability density functions of the zircon population Ti data from Dechert *et al.* (2024) in solid lines. Dashed line shows the Ti concentration for each model realization. The first four realizations are formed by focused intrusions, and the final four realizations are formed by distributed intrusions.

produce too little Ti, while four suggest higher Ti than the natural system, correlating to crystallization temperatures near 800-850°C (Figure 27).

The U concentration in zircon crystals is essential for the date calculation because the U-series disequilibrium can date younger zircons (>350 ka) via the U-Th series (Burnham, 2018). The Late Pleistocene lava from South Sister clusters around 100 ppm U, and the two Holocene lavas have higher concentrations, up to 500 ppm. The U content in the simulated zircon crystals is calculated based on zircon partitioning behavior of U from the melt with respect to Ti (Claiborne *et al.*, 2018). Ti is calculated given the Ti-in-zircon temperature with the temperature output from the magma dynamics model (Ferry and Watson, 2007). For all but one of the realizations, the modeled U concentration reaches 1 wt% U, which does not match the natural

systems (Figure C1, C2). However, mafic R021 has a probability density maximum around 100 ppm U, which does match the trends from the late Pleistocene South Sister samples (Figure C1).

4.3.4 Zircon Saturation Temperature

Another method of understanding the longer-term magmatic system using zircon crystals is calculating zircon saturation temperatures. The whole rock compositions for the natural samples, or the melt major oxides for the simulations, determine the temperature at which the melt reaches zircon saturation (Boehnke et al., 2013). The zircon saturation temperatures calculated for the South Sister samples range from 743-781°C (Boehnke et al., 2013) or 791-824°C (Watson and Harrison, 1983). Given the Ti-in-zircon temperatures of Dechert et al. (2024), the Boehnke et al. (2013) model is preferred. However, the current zircon growth model uses Watson and Harrison (1983) for this calculation. The calculated zircon saturation temperatures for each realization have a large range of temperatures, but the South Sister sample range falls within the realization ranges (Figure C3). Notably, the minimum saturation temperatures for the realizations are below the natural system range by ~50-100°C, while the maximum saturation temperatures for the realizations are 200-300°C higher than the natural system.

4.3.5 Zircon Survivability

To explore the durability of zircon crystals in a magma body, we model the zircon survivability within each realization. We define zircon survivability as a ratio of dissolving and nucleating zircon crystals, comparing the current and previous timesteps, meaning a ratio of 1 has no dissolving of the zircon crystal. Almost all mafic realizations have a high zircon survivability, meaning the zircon crystals do not dissolve away after they are formed (Figure C4). This is true within the plutonic record, but also in the low melt fraction magma (not eruptible) and the eruptible high melt fraction (>0.6) magma. One mafic realization, R062 has some zircon dissolution in the high melt fraction magma. Notably, mafic realization R021 shows evidence of zircon dissolution in both the high and low melt fraction magma, dissolving more and more zircon through time, leading to almost no remaining zircon crystals near the present day. Zircon survivability remains high in all melt portions for five intermediate realizations (Figure C5). However, intermediate R053, R071, and R072 have a decreasing zircon survivability through time in the high melt fraction, eruptible magma.

4.4 Discussion

4.4.1 Zircon Modeling Matches South Sister Age Data

Of all the data compared between the natural South Sister zircons and the modeled zircons for 17 realizations, the most matches are for the zircon ages. A built-up, single magma body is one common factor between all realizations that generally fit the probability maximum age distribution for the South Sister zircons. However, the model age distributions are more bimodal than the natural samples, having multiple local maxima of ages rather than only one maximum age distribution. This bimodality is true for both the mafic and the intermediate realizations. One hypothesis for this bimodality is that zircon crystals grow after initial magmatic intrusions begin cooling, but then dissolve away after future intrusions, causing the age loss, on a cycle. However, the zircon survivability calculated for such realizations reveals that once a zircon is formed, it generally does not dissolve away (i.e., R069). Alternatively, after a significant spike in zircon growth, there might not be enough Zr remaining in the melt to form zircon crystals right away, causing the pause in ages and growth. Another possibility is that the magma body does not stay at a zircon saturation temperature for the entirety of the model time, causing the starts and stops of zircon growth based on the modulating temperature of the magma body. Finally, these realizations include the eruption of melt of volume $> 0.4 \text{ km}^3$ and crystal fraction 0.6, meaning that the eruptible melt of the model continues to be added through intrusions, but is removed through eruptions. The bimodality of the zircon ages in the model runs is likely because the model can capture all the melt composition, melt temperature, and water content variations that happen throughout the modeling space, for thousands of zircon crystals. However, the natural samples only account for a few hundred zircon crystals that are also large enough for laboratory analysis. Given the nature of sample collection, zircon crystal separation, and laboratory methods, the minor changes and details recorded in the model space are likely lost in the natural samples.

One suite, intermediate distributed realizations, has the worst age fit to the natural samples and shows the most distinction between age calculations. Realizations R049, R071, and R072 have the maximum probability of zircon ages for the SIMS cores near modern day, around 10 ka (Figure 23). However, unlike other realizations, the SIMS rims show a distinctly younger age (5 ka) than the SIMS cores, and do not follow the SIMS core probability. Realization R053 has a broader peak of zircon ages recorded in the SIMS core, but also has the ~ 5 ka probability

maximum recorded in the SIMS rims. Additionally, three of these intermediate distributed realizations have the worst zircon survivability, showing that over time, zircons formed in the eruptible melt generally dissolve away more in these realizations than in others (Figure C5). When looking at the magma dynamics outputs of these realizations, it appears that the intrusions of andesite stay hot and at liquid melt fractions for thousands of years after intrusion, rather than beginning to solidify immediately. This could mean that the zircon crystals we initialize in the modeling space are dissolved immediately after intrusion, rather than growing, creating the negative slope of zircon survivability. The length in model time at higher temperatures of the intermediate intrusion melts is also supported by the higher zircon saturation temperatures recorded for the intermediate realizations compared to the mafic realizations (Figure C5). Spatially, these realizations do not have a solidifying region around the edge of the melt body. This means that the intrusions are either pure melt or very quickly solidify. This could also explain the younger ages recorded in the SIMS rim measurements. If it takes longer for the intrusions to cool to zircon saturation temperatures, the outer edge of the zircon crystals will record dominantly younger ages. This is an unexpected result, considering that both Holocene South Sister rhyolitic eruptions are more distributed. Rhyolite of Devils Chain (rdc) consists of seven main lavas and seven minidomes spanning 5 km north-south along the southeast flank of South Sister (Hildreth et al., 2012). Rhyolite of Rock Mesa (rrm) has a main coulee and a nearby chain of minidomes on the west flank of South Sister (Hildreth et al., 2012). Additionally, zircon compositions suggest these two eruptions are sourced from chemically and physically distinct melt pockets (Stelten and Cooper, 2012). Both geologically and geochemically, this could indicate that two different, distinct intrusions into the shallow crust created these eruptions, such as the distributed intrusions explored via modelling. However, the modeling of zircon ages does not support the distributed intrusions but suggests a more focused magma body.

4.4.2 Zircon Sizes and Model Assumptions

While the size of natural zircon crystals is not significant for final geochronology conclusions, it does impact the type of laboratory analyses possible. It also provides another direct comparison between the natural and simulated crystals. Only two mafic realizations produce a similar size distribution to the South Sister zircons, with the probability maximum around 50-100 μm (Figure 24). More common for the mafic realizations is a bimodal size range of larger (150 μm) and smaller (10 μm) crystals. If we were to have more holistic measurements

of all zircons from the South Sister rhyolites, we also would have a subset of smaller crystals. However, the smaller crystals were not mounted (and thus not measured) as the SHRIMP-RG beam could not analyze them. None of the intermediate realizations produces zircon sizes similar to the natural data. The focused magma bodies (R084, R111, R080, R081) all produce too small zircons, ranging from 0 – 20 μm (Figure 25). Conversely, the distributed intrusion realizations (R049, R053, R071, R072) produce bimodal zircon sizes, with one maximum around 150 μm and the other around 10 μm , neither fitting the natural data. Overall, both the South Sister and the model zircon sizes fall in the typical size range for igneous zircons of 20-250 μm (Hoskin and Schaltegger, 2003).

One of the critical user-defined inputs for the zircon growth model is the zircon nucleation density. This value sets the number of zircon crystals present in the model per model volume. The zircon nucleation density for these realizations is 10^7 crystals/ m^3 . This value is slightly lower than the density suggested by Bindeman and Melnik (2016) for Toba Tuff, but the size and amount of zircon crystals is generally lower in stratovolcanoes than for large calderas (Bindeman, 2003). Additionally, speaking from experience, collecting the samples and trying to pick crystals, zircons are sparse at South Sister. Similarly, we set the size of the initial zircon nucleation radius to be 2 μm . However, we acknowledge that both input parameters are part of the model's assumptions.

4.4.3 Modeled Zircon Trace Element Compositions Differ from South Sister Data

Across all but one realization, the modeled zircon Ti concentrations do not match the natural samples from South Sister. In the intermediate focused intrusions (R084, R111, R080, R081), the Ti content is lower than in the natural zircons, correlating to lower zircon crystallization temperatures. However, the intermediate distributed intrusions (R049, R053, R071, R072) show a more bimodal Ti density with one maximum around 20 ppm and another lower ~ 2 ppm maximum (Figure 27). Generally, the higher Ti concentration for the intermediate distributed intrusions does not match these realizations, with the magma remaining at a higher temperature through time, as the higher Ti concentration shows higher crystallization temperatures. All mafic realizations, except one, have much lower Ti concentrations than the South Sister zircons (Figure 26). However, R021 with focused intrusions is a great fit for the Ti concentration, with a maximum probability around 5-10 ppm Ti. It is possible that since this realization is the most built-up single magma body, portions of this melt can cool and remain at a

higher silica content long enough to better match the natural system Ti concentration. It is important to note that the modeled Ti concentrations are calculated from the melt temperature output from the magma dynamics code. Conversely, the Ti concentrations are directly measured for the South Sister samples, with the crystallization temperatures calculated after the fact. So, the difference could be in the calculation method in the model, even though we utilize the same Ti-in-zircon geothermometer in both cases.

As with Ti, all but one model realization does not fit the U concentration from the South Sister samples. In all but mafic R021, the U concentration approaches 1 wt% in the modeled zircon crystals. While U is one of the more abundant elements in zircon, this is more than expected, as the typical abundances for igneous zircons range from tens to thousands of ppm (Hoskin and Schaltegger, 2003). Again, we note the difference in the natural samples by directly measuring the U content versus the zircon growth model, calculating the U content of the crystal based on zircon partitioning behavior of U from the melt with respect to Ti (Claiborne et al., 2018). As noted above, there might be a difference in the partitioning of Ti in the model compared to what was expected. However, the U concentration of one mafic focused realization, R021, matches the trend of a probability maximum around 100-200 U ppm (Figure C2). While U does tend to be incompatible in silicic melts, it is compatible with trace minerals such as monazite and titanite (Stepanov et al., 2012; Kohn, 2017). While monazite is not likely in this system, zircon REE ratios from Dechert et al. (2024) find signatures of dissolved titanite from the past magmatic system. Titanite crystals can record hundreds of ppm U (Kohn, 2017). Since titanite is not one of the mineral phases considered in the magma dynamics model, it is possible that some of the U from the melt could be partitioned into titanite, thus lowering the concentration in the zircon crystals.

Since the past focus of the zircon growth model has been the zircon ages produced, we have not yet fully explored the trace element evolution of the system. Future efforts will explore how Ti and U evolve in the zircon crystals and the melt. If we continue finding evidence for unexpected U evolution in the zircon crystals, we will reassess the partitioning of U into the zircon. However, if we see unexpected evolution in the melt through time, we will reassess compositions and U concentrations set in the input files.

4.4.4 Evolution and Structure of the Magmatic System

When comparing the simulated zircons to the natural zircons from South Sister, three realizations match the real samples in two data sets: zircon crystal model age, zircon size, Ti concentration, and U concentration. All three best-matching realizations form via basaltic andesite intrusions into a single, focused magma body (R069, R063, R021). One of the realizations has effusive eruptions, but the other two have explosive eruptions. One realization has the magma body forming at 15 km, and the other two at 6 km depth. Importantly, all three realizations produce eruptive volumes that match the eruptive episodes of Middle Sister and coeval Middle Sister and South Sister. However, none of these realizations match the eruptive volumes of the Holocene episode, and natural zircon data are from the coeval period of South Sister with Middle Sister and the Holocene.

As one of only two locations in the high Cascades arc to erupt true rhyolite (outside of the rear arc), magmatic storage and the production of intermediate and felsic magmas are essential to consider, but still highly debated (Hildreth et al., 2012). One study suggests that the rhyolites resulted from dehydration melting of basaltic amphibolite in the deep crust (Hill, 1991). The crustal impact is also hypothesized for dacite production, suggesting they are produced at depth through partial melting of mafic crust, such as gabbro (Waters et al., 2021). While this focus is on the Daly Gap and production of dacites, Waters et al. (2021) suggest melt generation via partial melting and a short period of crystallization and transport to the surface also produced the South Sister rhyolites. However, another study does not consider crustal melting and instead suggests that the silicic lavas from South Sister and Middle Sister can be related through fractional crystallization (Brophy and Dreher, 2000). In this model, Brophy and Dreher (2000) hypothesize the presence of multiple, independent solidifying magma bodies at depth, representing the evolved, interstitial liquid from the parent magma. From a multiphase numerical modeling perspective, the intermediate Daly Gap is also supported by crystal fractionation, given the high efficiency of crystal-melt separation between 50 and 70 vol% crystals (Dufek and Bachmann, 2010). In addition to the suggested processes forming the intermediate and felsic materials, zircon studies indicate that the two Holocene rhyolite eruptions tap physically and chemically distinct melt bodies, which is supported by evidence that the Holocene and late Pleistocene rhyolites are also sourced from physically and chemically distinct melt pockets in a shared broader magma system (Stelten and Cooper, 2012; Dechert et al., 2024).

The best-fit model simulations of this work highlight a focused, single magma body created by intrusions of basaltic andesite in the mid to shallow crust. Our model shows no direct evidence of partial melting of the surrounding crust to produce the extracted melt. Thus, we do not support the partial melting hypothesis of Waters et al. (2021). Additionally, our model results do not directly support the hypothesis of Brophy and Dreher (2000) that there are magma pockets of progressively more evolved magma with shallowing depths, since our model results only suggest the presence of a single magma body. However, crystal fractionation is likely the dominant process in the evolution of these melts. The intrusions are of basaltic andesite, and the SiO₂ contents of the erupted products above 15 km depth are andesites for a 0.6 crystal volume fraction, but up to a dacite with higher crystallinity values. As such, we do see evidence for crystal fractionation of the intruded magmas, just not in the same spatial assumptions of Brophy and Dreher (2000).

These modeling results demonstrate plausible magmatic evolution at the Three Sisters. From Dechert et al. (2024), there is some sort of amphibole sponge in the crust where amphibole and titanite form and dissolve through magmatic recharge for traces present in erupted zircon chemistry (Davidson et al., 2007). As the intrusions continue, the interior of the magma body remains hot and at a high melt fraction, while the outer edges of the magma body are cooling, allowing for zircon crystallization to occur. This central magma body creates the general trace element fingerprints of the zircon crystals, but smaller pockets of magma evolution allow for slight differences to form. As these eruptible melt pockets are extracted, they can show the differences between the late Pleistocene and Holocene rhyolites, or even between the two Holocene rhyolites (Stelten and Cooper, 2012; Dechert et al., 2024). This partial melt evolution and extraction can also support the modern deformation, suggesting a magmatic intrusion at 6 km depth (Lisowski et al., 2021). The basaltic andesite intrusion could be in the shallower crust, or a pocket of melt from a deeper storage system could have been extracted, but not have led to an eruption. The one caveat is that the eruptive products of the basaltic andesite intrusions are andesites or maybe a dacite, and the zircons from South Sister come from rhyolite lavas. The intermediate andesite intrusions do produce dacites to rhyolites, but none of these model realizations fit more than just the age distribution of the natural samples.

4.5 Conclusions

Through this study, we have run a parallel magma dynamics and a zircon growth model to explore the magmatic system at the Three Sisters volcanic complex, comparing simulated evolution to the zircon data from South Sister rhyolites. First, we have successfully utilized the modeling workflow in connection with real-world samples, which has yet to be done with this tool. Additionally, we successfully matched the modeled and natural zircon ages for eight of the 17 realizations, highlighting the ability of zircon crystals to retain much of the age data from the magma system. When considering the trace element compositions in the modeled zircons, we have identified significant differences from the natural system, raising questions about melt evolution and element partitioning into the crystals in the model workflow. Finally, our results support felsic magma generation at South Sister via fractionation, with zircon crystallization in the cooling outer edge of the magma body, where pockets of eruptible melt are extracted to the surface for eruption, or stall in the shallow crust, producing deformation signals. This suggests that future efforts should focus on understanding the magma storage depth (as through melt inclusion or geobarometry studies) and monitoring for geophysical signals suggesting magma ascent.

CHAPTER V

CHAPTER 5: CONCLUSIONS

Through this dissertation, I have studied the magmatic system at the Three Sisters with an interdisciplinary lens, applying field work, laboratory analysis, and numerical modeling to petrochronology and geophysical methods. Overall, my efforts have uncovered essential findings that will aid in more informed monitoring and hazard forecasting for this very high threat volcanic complex.

Chapter 2 explores zircon geochronology of rhyolites at South Sister, highlighting magmatic evolution. First, zircon surface ages reveal that rsw and rmc are over 10 kyr younger than previously dated, indicating that South Sister is the most recent edifice of the Three Sisters to start erupting. By shortening the total cone-building period of South Sister, the eruptive rate nearly doubles. Additionally, zircon trace elements suggest standard down-temperature crystallization of zircon and plagioclase in the magma, but they also display trends of destabilized amphibole and titanite in the system. Since titanite is not found in any of the lavas, and only a small amount of amphibole is found in the Holocene rhyolites, this finding highlights magmatic evolution lost in the whole rock data. Finally, a distinctly lower Eu/Eu* ratio in the Holocene zircons suggests they crystallized from more fractionated melts than the late Pleistocene rhyolites, suggesting rhyolites from the two time periods originate from separate reservoirs or mush bodies. While the late Pleistocene and Holocene rhyolite eruptive sequences are distinct, we believe the higher eruptive rate of the late Pleistocene should be considered in aiding the assessment of future hazards at South Sister. While this effort uncovers more information about the magmatic system producing rhyolite eruptions, I do not consider why rhyolites exist in this part of the Cascade Arc. As such, I still believe not the question of how rhyolite, but why rhyolite, is left unanswered in central Oregon.

Chapter 3 uses a Bouguer gravity anomaly to probe the modern magmatic system of the Three Sisters while also considering the eruptive history. First, magma dynamics and eruption modeling can only match the general eruptive history of the Three Sisters for two of the main eruptive episodes, highlighting a significant shift in the magmatic flux into the system around 50 ka and 10 ka. Of the models that best fit the eruptive history, the magma flux ranges from 10^{-3} – 10^{-1} m³/m²/yr. Additionally, we compare the simulated Bouguer gravity anomaly based on the magmatic simulations to the field Bouguer gravity anomaly of the Three Sisters. The misfit

between the simulated and field gravity surveys ranges from 3.4 to 8.2 mGal for realizations that match the eruptive history. Given the low magma flux into the system, the background crust with no perturbations largely controls this misfit value, suggesting that any perturbation to the crust would result in a low gravity anomaly just above the background crust of 2.89 mGal. Finally, the inflation event that began in the mid-1990s is too small to be visible in this model space. Overall, we find that even during the high eruptive state, the Three Sisters gravity anomaly was likely not very large, suggesting the magma of the system generally remains near background crust density. This raises the question of whether other geophysical techniques could image the modern magmatic system, or if it is not distinguishable from the crustal structures.

Chapter 4 utilizes the conclusions from both Chapters 2 and 3 to explore whether the magma dynamics simulations also match zircon crystal trends, connecting the petrochronology and geophysical perspectives. A zircon growth model considers the magma dynamics realizations that best match the eruptive history of the Three Sisters to model the zircon age, size, and composition of these systems. This project is the first use of the zircon growth tool connected to natural samples. Not only do the magmatic simulations match the eruptive history and have a low gravity anomaly misfit, but over half of the best fit realizations also successfully reproduce the South Sister rhyolite zircon age distribution discussed in Chapter 2. Zircon crystallization occurs in the cooler regions of the magma system, such as along the solidifying outer edge, where eruptible melt pockets can be extracted. In this chapter, I establish a consensus on the Three Sisters magmatic system that accurately correlates with the eruptive history of the Three Sisters, the current gravity anomaly, and the zircon ages of South Sister, thereby successfully applying a multidisciplinary approach in volcanology.

In closing, this dissertation contributes to the volcanology community's movement towards more multidisciplinary studies of active volcanoes. The efforts of this dissertation (and the overall Three Sisters project), projects like iMUSH, and programs such as SZ4D represent the future of volcanology. Harnessing the combined expertise of experimental petrologists, volcano seismologists, science communicators, computer scientists, and physical volcanologists enhances our understanding of active volcanoes, fostering a more robust and comprehensive awareness of their dynamics. Finally, this more multidisciplinary approach in volcanic hazard mapping and forecasting efforts ensures that both the past eruptive history and modern systems

are considered when producing such products for stakeholders and the community. The outcomes of my dissertation directly support such efforts at the Three Sisters volcanic complex.

APPENDIX A

SUPPLEMENTAL MATERIAL FOR CHAPTER 2

Unit	$^{40}\text{Ar}/^{39}\text{Ar}$ Date (ka)	Uncertainty (ka)	Updated $^{40}\text{Ar}/^{39}\text{Ar}$ Date (ka)	Uncertainty (ka)	Preferred Source
aeg	27.50	3.30	27.50	3.30	Calvert et al., 2018
ahi	23.70	6.40	23.70	6.40	Calvert et al., 2018
alg	27.10	1.10	27.10	1.10	Fierstein et al., 2011
alh	30.40	1.30	30.40	1.30	Fierstein et al., 2011
apc	31.40	8.70	31.40	8.70	Fierstein et al., 2011
awf	23.70	1.30	23.70	1.30	Fierstein et al., 2011
dca	30.70	2.60	30.70	2.60	Fierstein et al., 2011
dcl	26.00	2.10	26.00	2.10	Fierstein et al., 2011
ddl	32.30	1.80	32.30	1.80	Fierstein et al., 2011
dgc	31.60	2.00	31.60	2.00	Fierstein et al., 2011
dkb	27.30	2.60	27.30	2.60	Fierstein et al., 2011
dlg	25.70	1.40	25.70	1.40	Calvert et al., 2018
dml	33.60	1.20	33.60	1.20	Fierstein et al., 2011
dmn	27.70	1.00	27.70	1.00	Fierstein et al., 2011
dnt	23.50	1.10	23.50	1.10	Fierstein et al., 2011
drm	28.70	0.80	28.70	0.80	Fierstein et al., 2011
dwp	34.20	3.40	34.20	3.40	Calvert et al., 2018
mtp	22.30	12.90	22.30	12.90	Fierstein et al., 2011
rct	24.00	5.40	24.00	5.40	Fierstein et al., 2011
rdh	34.80	1.50	34.80	1.50	Fierstein et al., 2011
rgl	31.90	0.70	31.90	0.70	Fierstein et al., 2011
rkb	30.80	5.40	30.80	5.40	Calvert et al., 2018
rmc	47.40	8.20	47.39	8.20	Fierstein et al., 2011
rpc	31.90	8.70	31.90	8.70	Calvert et al., 2018
rpg	32.80	1.50	32.80	1.50	Fierstein et al., 2011
rsc	25.40	1.30	25.40	1.30	Fierstein et al., 2011
rse	33.60	0.50	35.00	2.70	Fierstein et al., 2011
rsf	35.80	2.00	35.79	2.00	Fierstein et al., 2011
rsw	51.40	9.70	51.39	9.70	Calvert et al., 2018

Figure A1: Table of recalculated $^{40}\text{Ar}/^{39}\text{Ar}$ dates. Fierstein et al. (2011) used the Taylor Creek sanidine standard age of 27.87 Ma while Calvert et al. (2018) used a more recent age for the Taylor Creek sanidine standard of 28.345 Ma. To ensure that all the $^{40}\text{Ar}/^{39}\text{Ar}$ dates are reported on the same basis and are directly comparable, we have recalculated the $^{40}\text{Ar}/^{39}\text{Ar}$ dates using the ArAR software (Mercer and Hodges, 2016) to an updated Taylor Creek age of 28.447 Ma (equivalent to a Fish Canyon Sanidine age of 28.201 Ma; (Fleck et al., 2019; Schaen et al., 2021a)) and decay constants of (Min et al., 2000). Very little has changed, and if so, in the hundredths place generally.

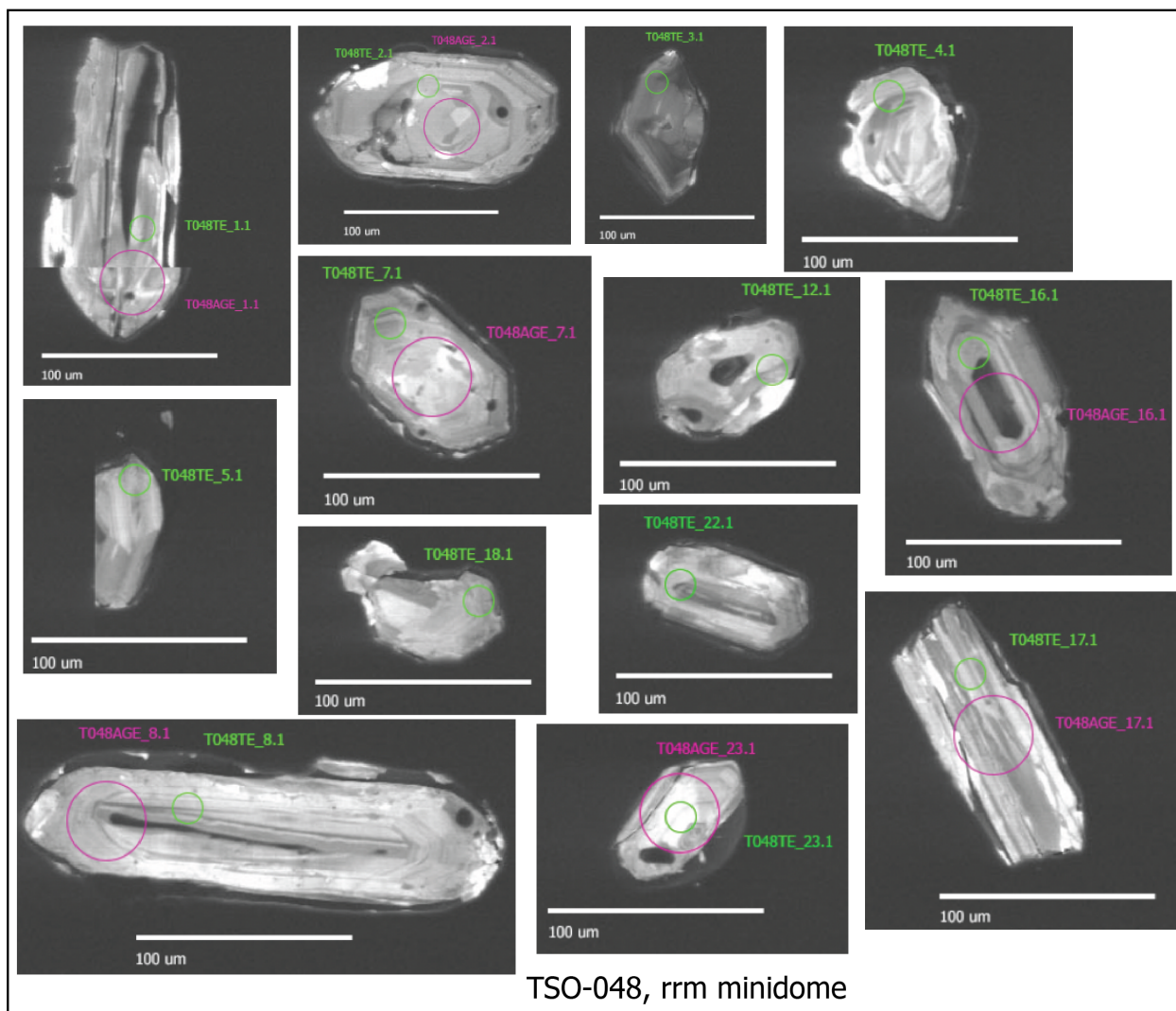
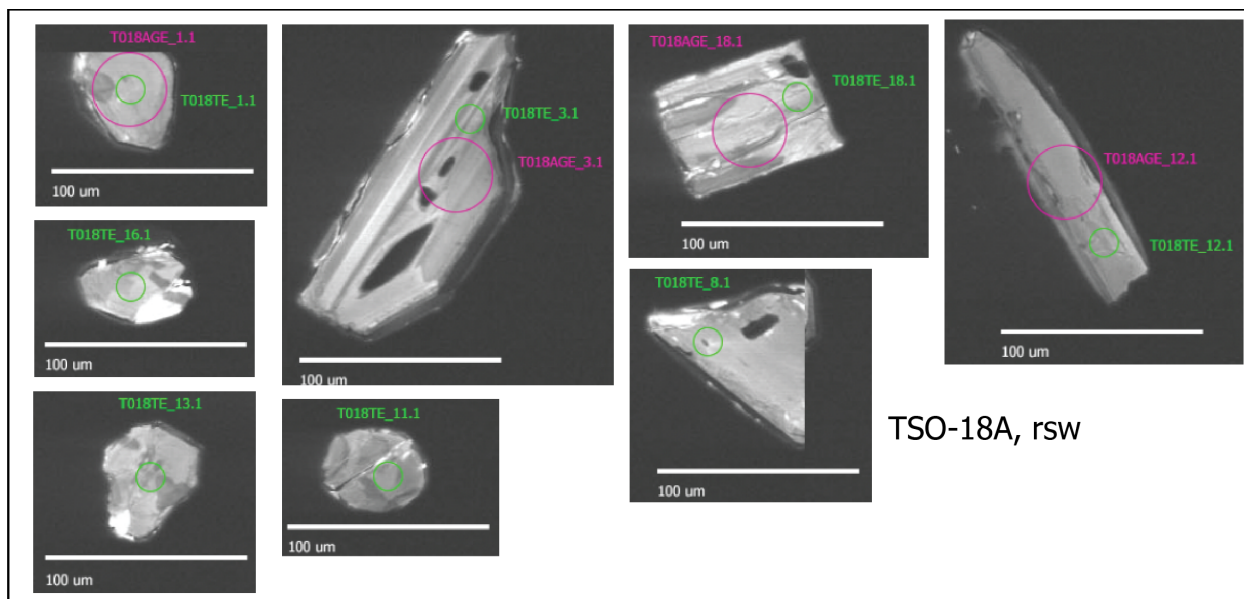


Figure A2: Compiled cathodoluminescence images of polished interior zircon crystals used in this study. Scale bar indicates 100 μm . Bright pink text and circle indicate U-Th age beam location. Bright green text and circle indicate trace element beam location.

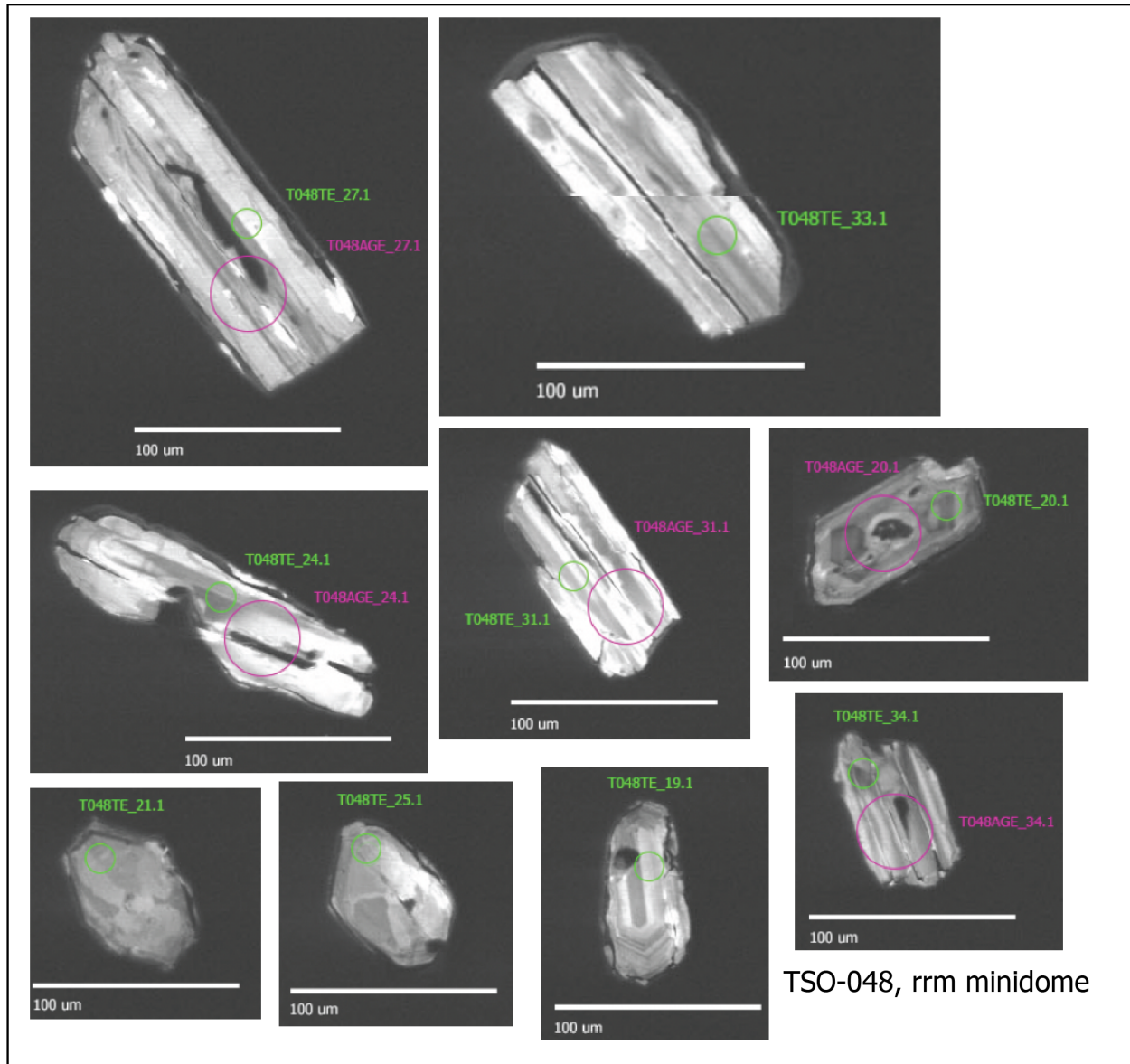


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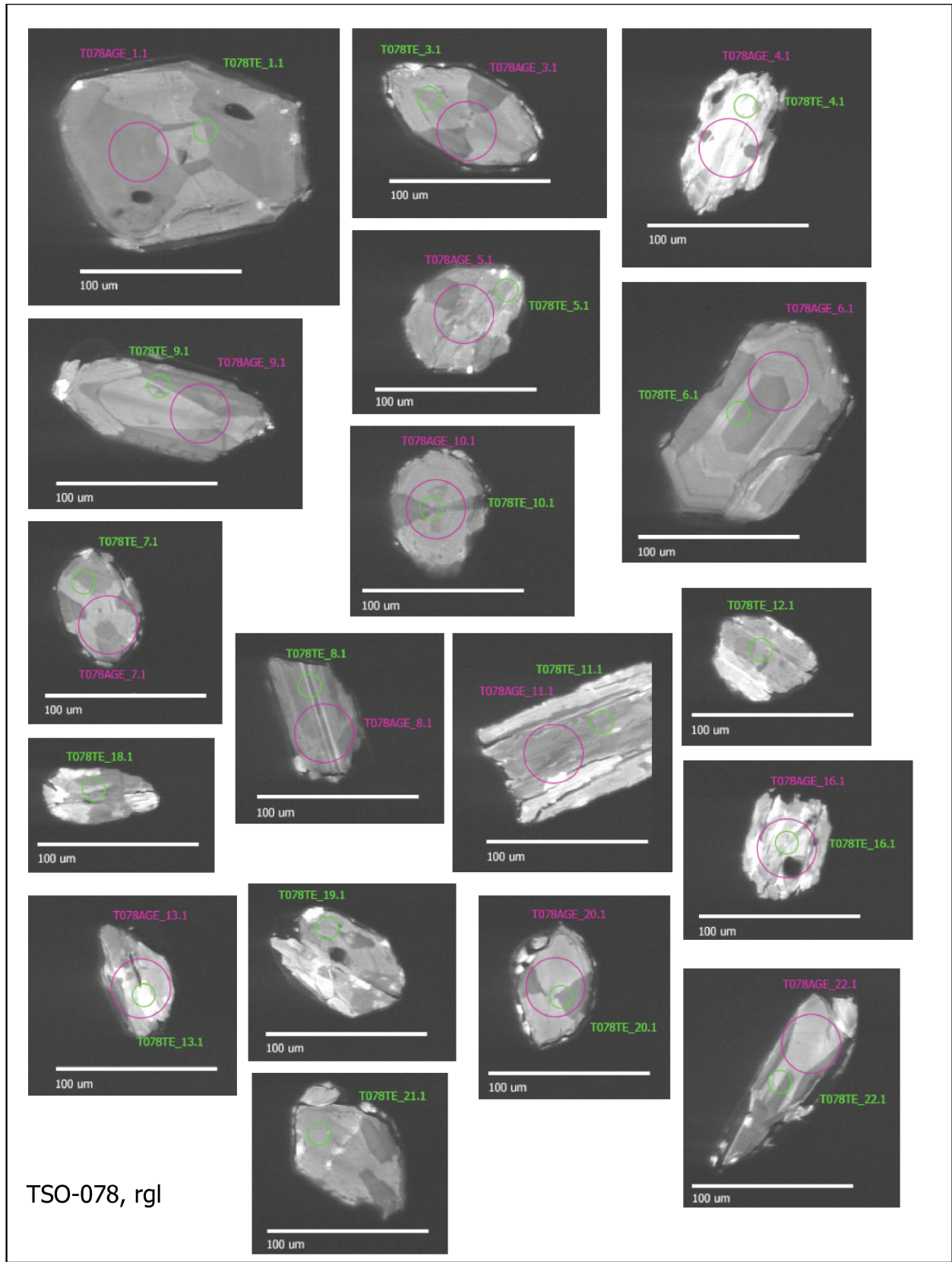


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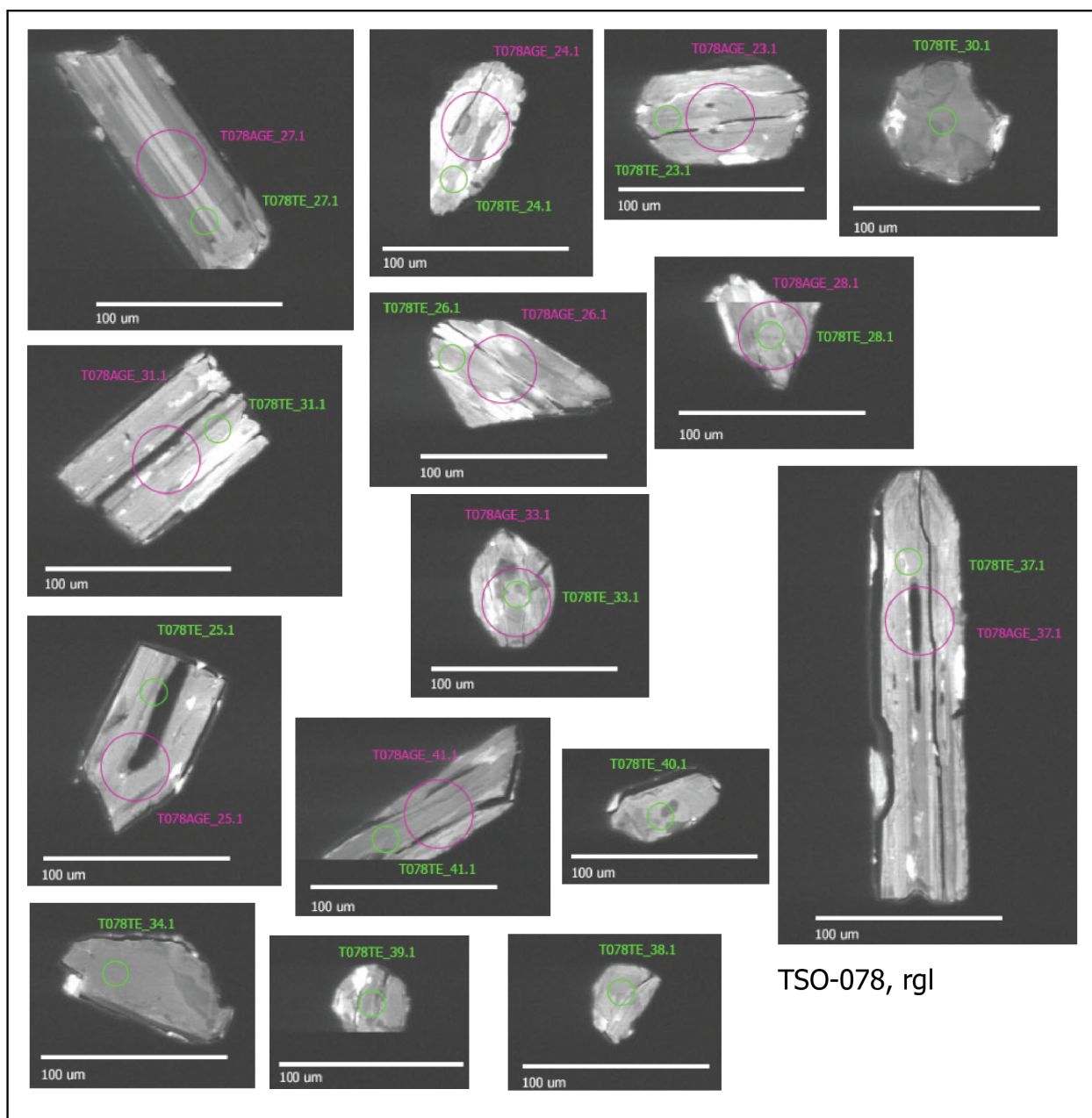


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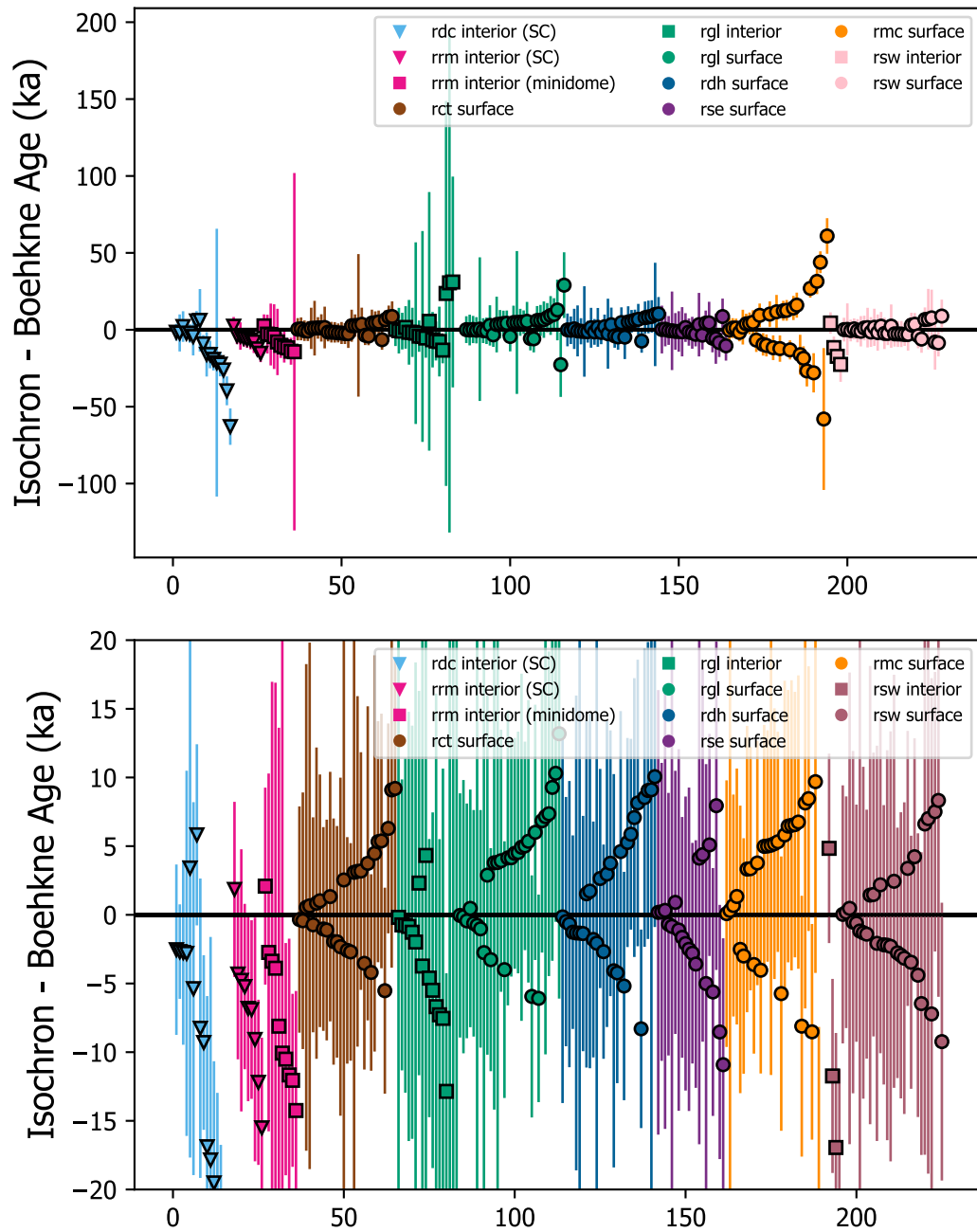


Figure A3: The difference between isochron zircon model age and Boehnke et al. (2016) model age. Melt compositions for the isochron zircon model utilize whole rock U and Th values analyzed on split from the zircon sample. See Table S4 for these values. Uncertainty plotted is the variance of the combined uncertainties for each crystal from all methods. We do not calculate the difference if either method found the zircon date or positive date error to be in secular equilibrium or undefinable. Geologic unit abbreviations—Rhyolite of Devils Chain (rdc), Rhyolite of Rock Mesa (rrm), Rhyolite of South Sister Climbers Trail (rct), Rhyolite of Green Lakes (rgl), Rhyolite of Devils Hill (rdh), Rhyolite of southeast Lewis Glacier (rse), Rhyolite of Mesa Creek (rmc), Rhyolite southwest of Lewis Glacier (rsw).

Title	Unit	Sample ID	Domain	¹⁴ C or ⁴⁰ Ar/ ³⁹ Ar Date (ka)	Zircon Weighted Mean (ka)
Rhyolite of Devils Chain	rdc	08DH-15, 08DH-19	interior	2.00 ± 0.2	
Rhyolite of Rock Mesa	rrm	08DH-21	interior	2.15 ± 0.15	33.57 ± 2.74
Rhyolite of Rock Mesa	rrm minidome	TSO-048	interior	2.15 ± 0.15	26.74 ± 4.47
Rhyolite of South Sister Climbers Trail	ret	TSO-090A	surface	24.0 ± 5.40	31.39 ± 2.09
Rhyolite of Green Lakes	rgl	TSO-078	interior	31.9 ± 0.70	43.03 ± 4.24
Rhyolite of Green Lakes	rgl	TSO-083	surface	31.9 ± 0.70	29.42 ± 2.16
Rhyolite of Devils Hill	rdh	TSO-091	surface	34.8 ± 1.50	33.81 ± 2.20
Rhyolite of southeast Lewis Glacier	rse	TSO-085	surface	35.0 ± 2.7	36.80 ± 2.85
Rhyolite of Mesa Creek	rnc	TSO-086	surface	47.39 ± 9.70	31.54 ± 2.07
Rhyolite southwest of Lewis Glacier	rsw	TSO-18A	interior	51.39 ± 9.70	32.00 ± 5.26
Rhyolite southwest of Lewis Glacier	rsw	TSO-087	surface	51.39 ± 9.70	39.14 ± 2.43

Figure A4: Unit name, sample abbreviations, and zircon crystal domain analyzed. ¹⁴C dating method use for rdc and rrm, ⁴⁰Ar/³⁹Ar at the 1σ level for the rest. Comparison of eruption age and calculated zircon weighted mean.

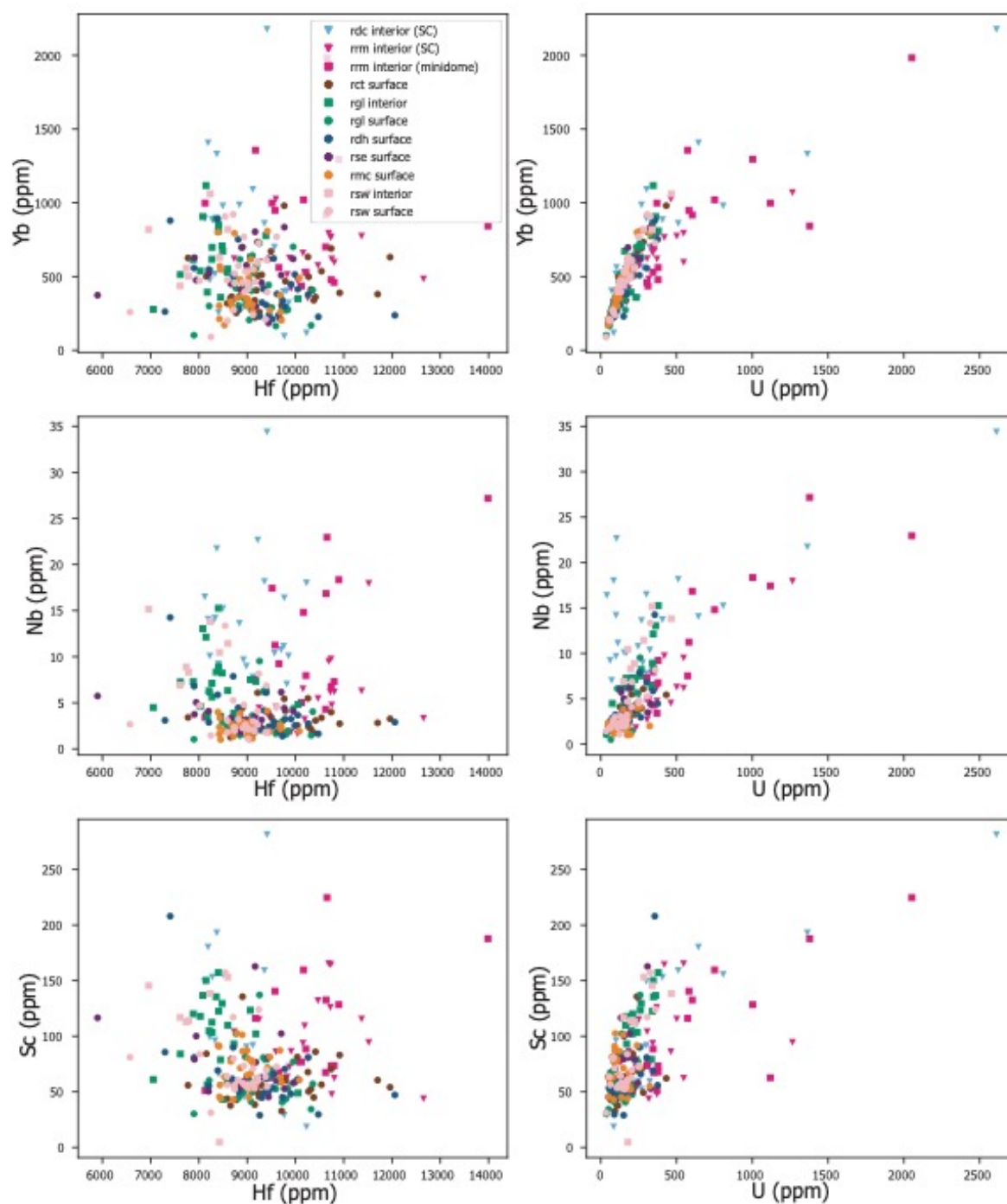


Figure A5: Trace element variation figures. Geologic unit abbreviations—Rhyolite of Devils Chain (rdc), Rhyolite of Rock Mesa (rm), Rhyolite of South Sister Climbers Trail (rct), Rhyolite of Green Lakes (rgl), Rhyolite of Devils Hill (rdh), Rhyolite of southeast Lewis Glacier (rse), Rhyolite of Mesa Creek (rmc), Rhyolite southwest of Lewis Glacier (rsw).

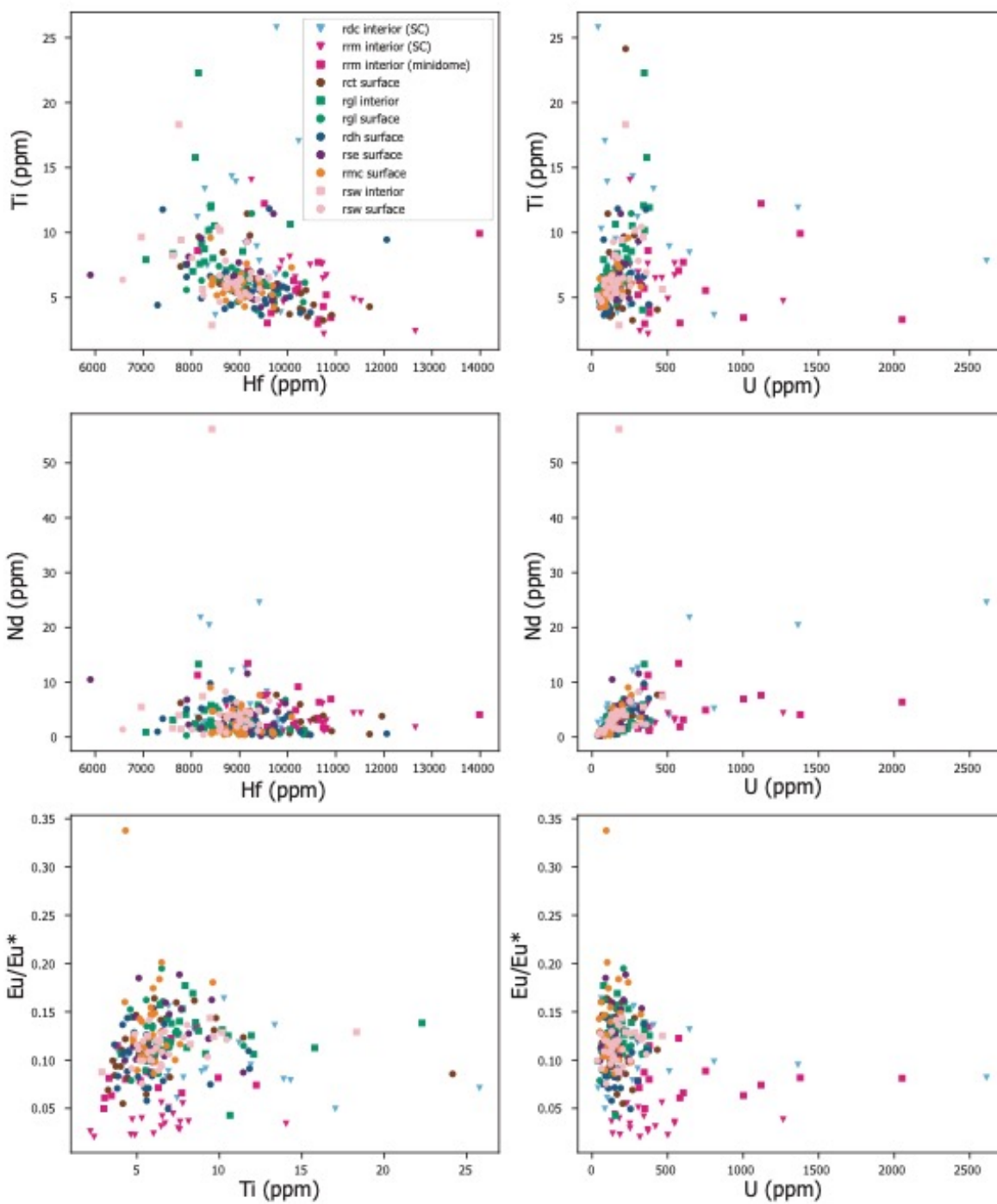


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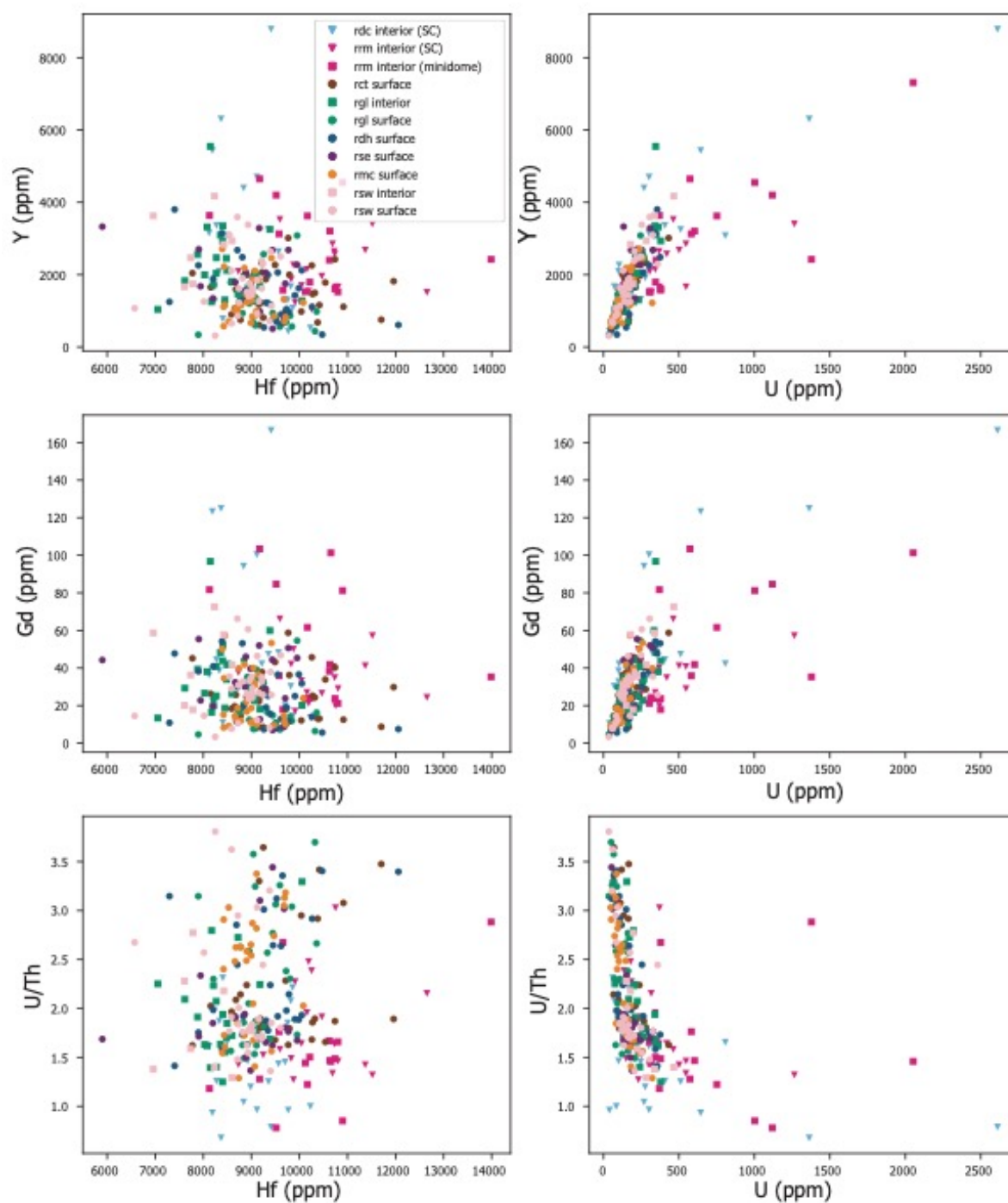


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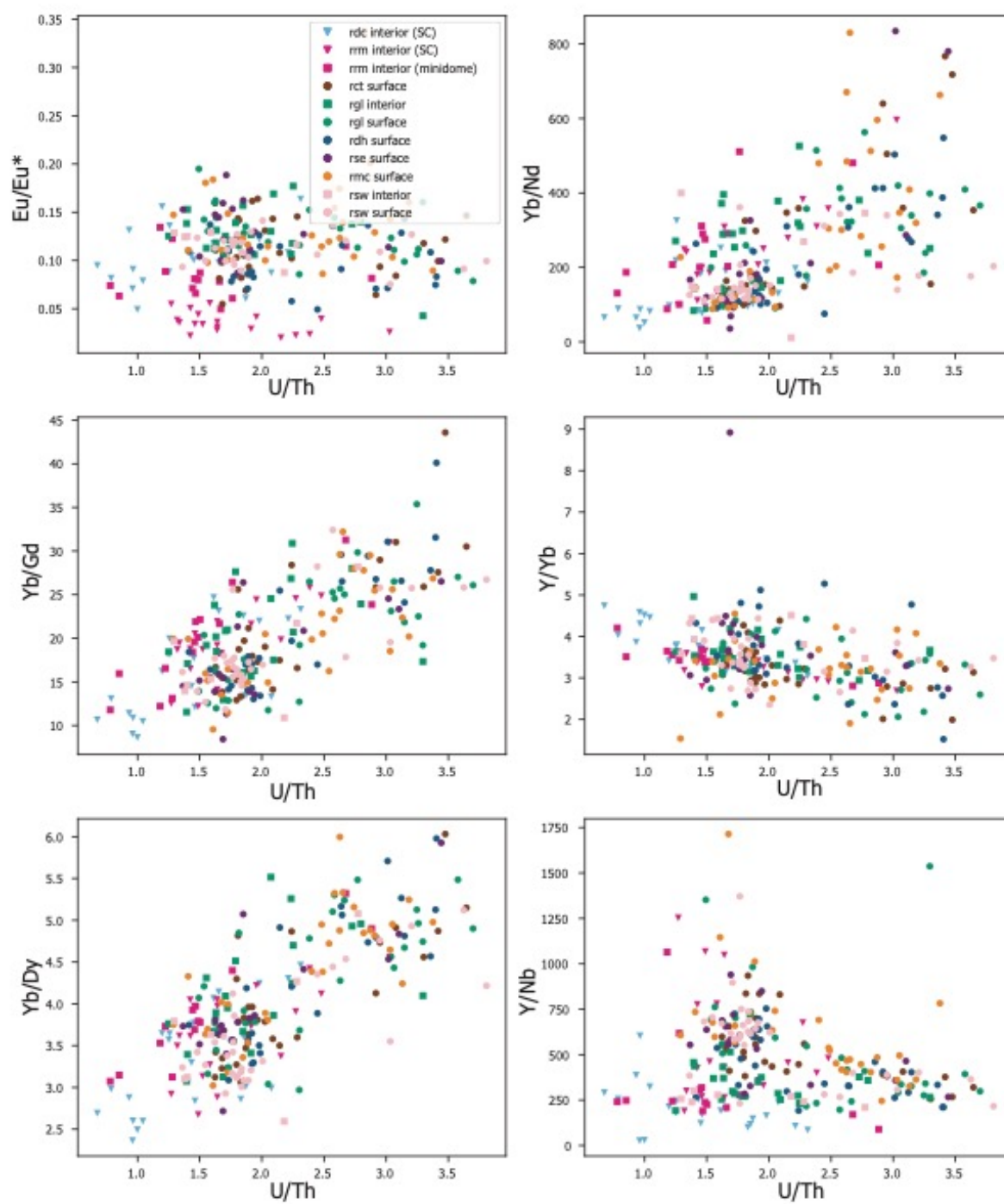


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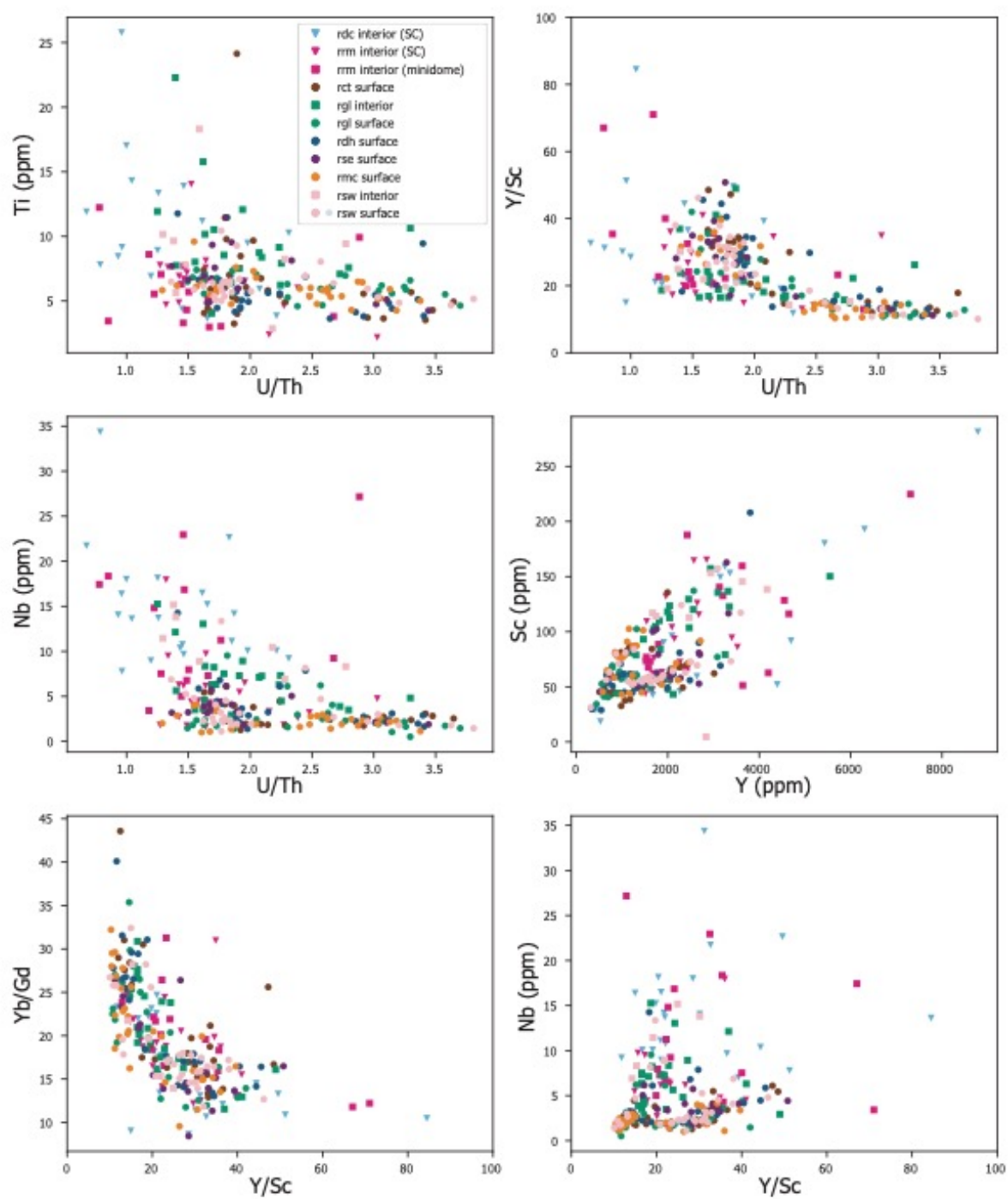


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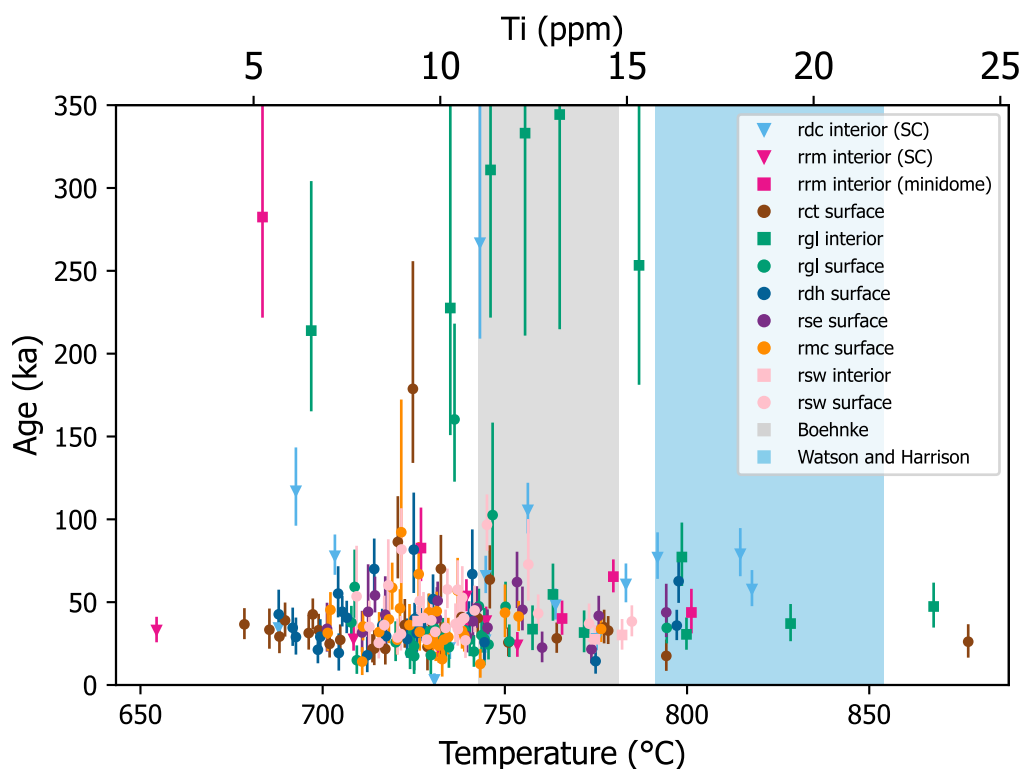


Figure A6: Ti-in-zircon crystallization ages calculated via Ferry & Watson (2007) for ^{48}Ti using $a\text{SiO}_2 = 1$ and $a\text{TiO}_2 = 0.7$. Gray box highlights the range of temperatures at which the melt has reached zircon saturation state as calculated by (Boehnke et al., 2016). Blue box highlights the range of temperatures at which the melt has reached zircon saturation state as calculated by (Watson & Harrison, 1983). Given that more Ti-in-zircon temperatures suggest a lower temperature range, we believe the model of Boehnke et al. (2016) fits this system better. Geologic unit abbreviations—Rhyolite of Devils Chain (rdc), Rhyolite of Rock Mesa (rrm), Rhyolite of South Sister Climbers Trail (rct), Rhyolite of Green Lakes (rgl), Rhyolite of Devils Hill (rdh), Rhyolite of southeast Lewis Glacier (rse), Rhyolite of Mesa Creek (rmc), Rhyolite southwest of Lewis Glacier (rsw).

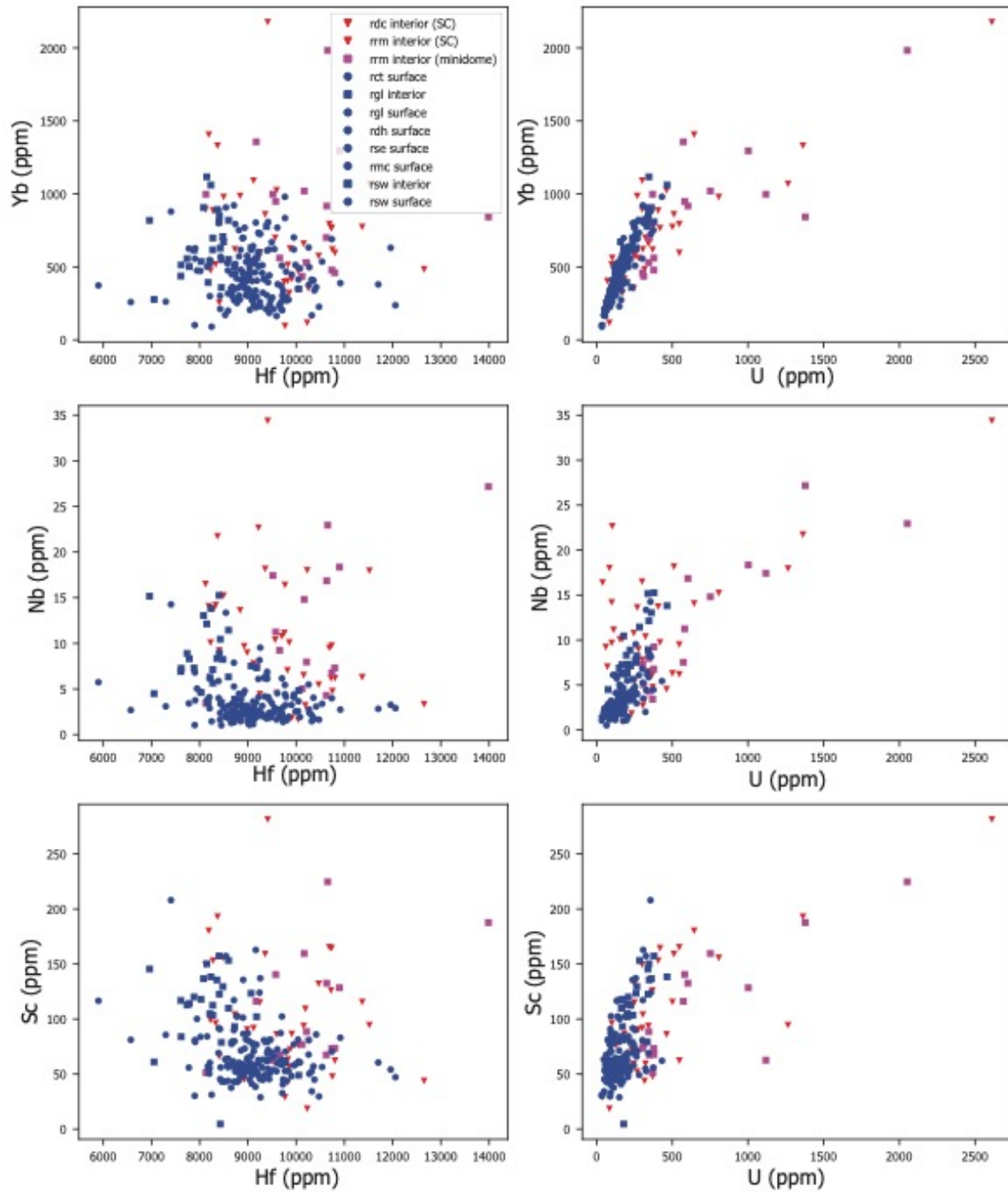


Figure A7: Trace element variation diagrams symbolized by eruptive epoch. Main rdc and rrm Holocene is red, rrm minidome is magenta, Pleistocene is blue. Geologic unit abbreviations—Rhyolite of Devils Chain (rdc), Rhyolite of Rock Mesa (rrm), Rhyolite of South Sister Climbers Trail (rct), Rhyolite of Green Lakes (rgl), Rhyolite of Devils Hill (rdh), Rhyolite of southeast Lewis Glacier (rse), Rhyolite of Mesa Creek (rmc), Rhyolite southwest of Lewis Glacier (rsw).

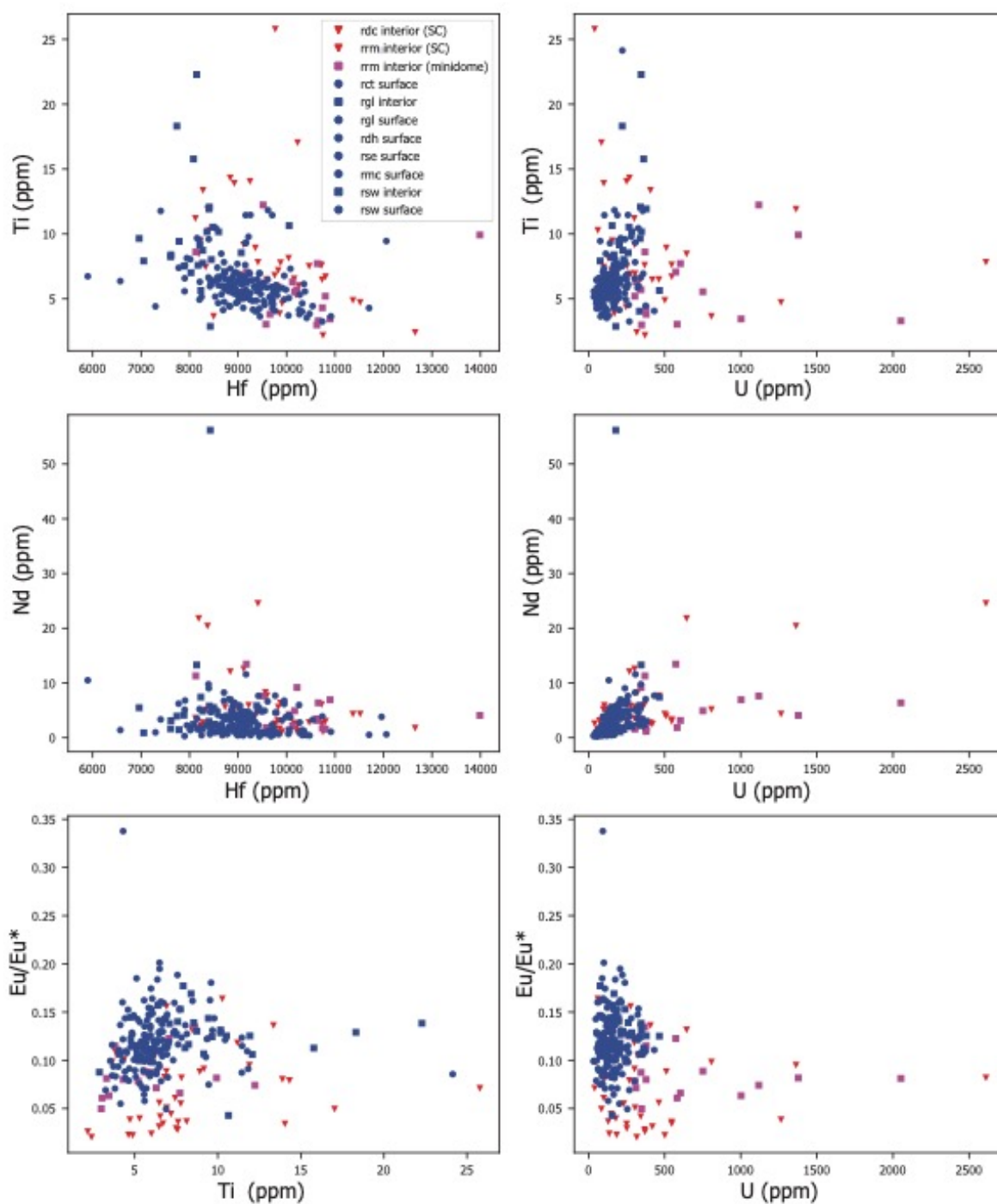


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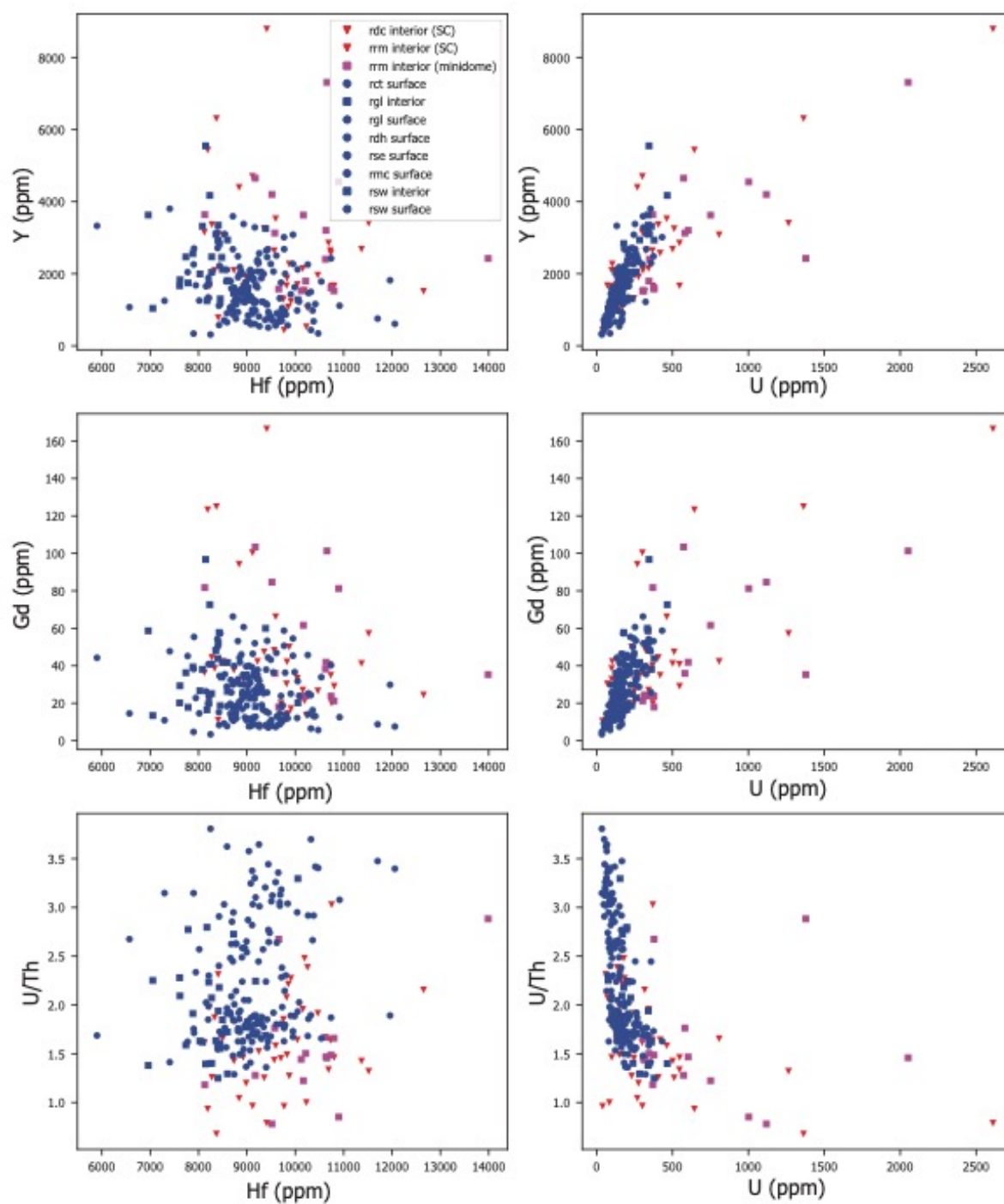


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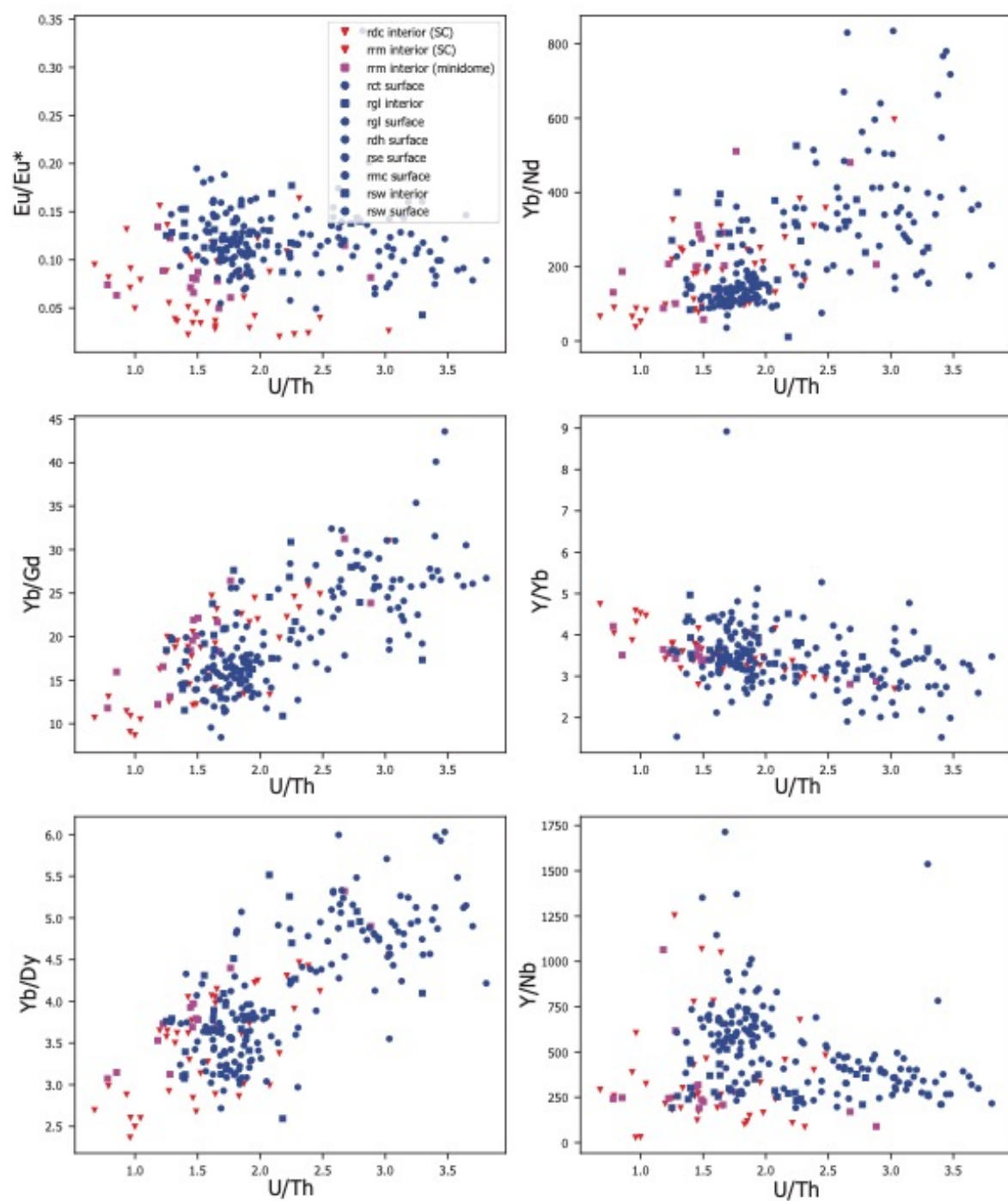


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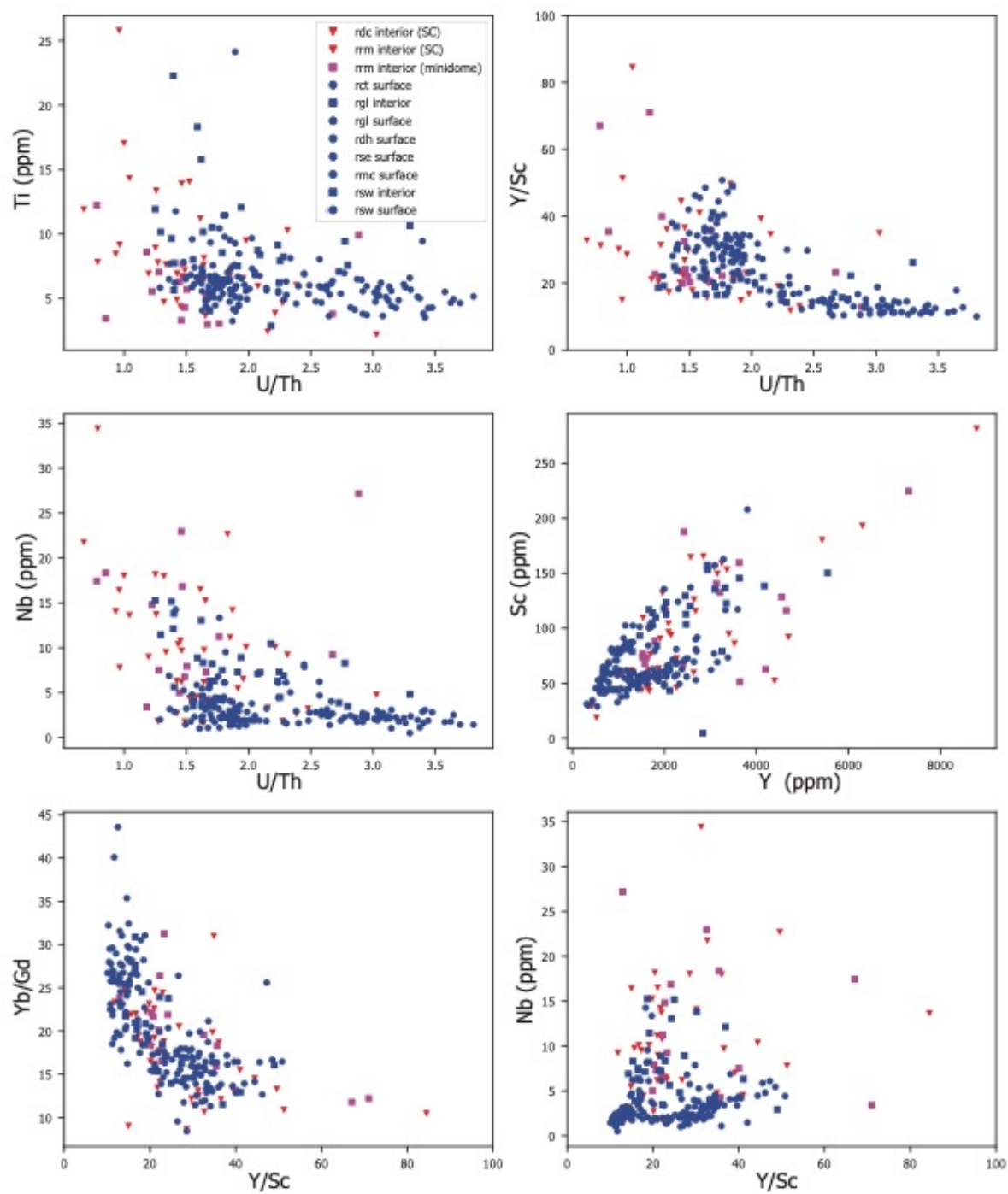


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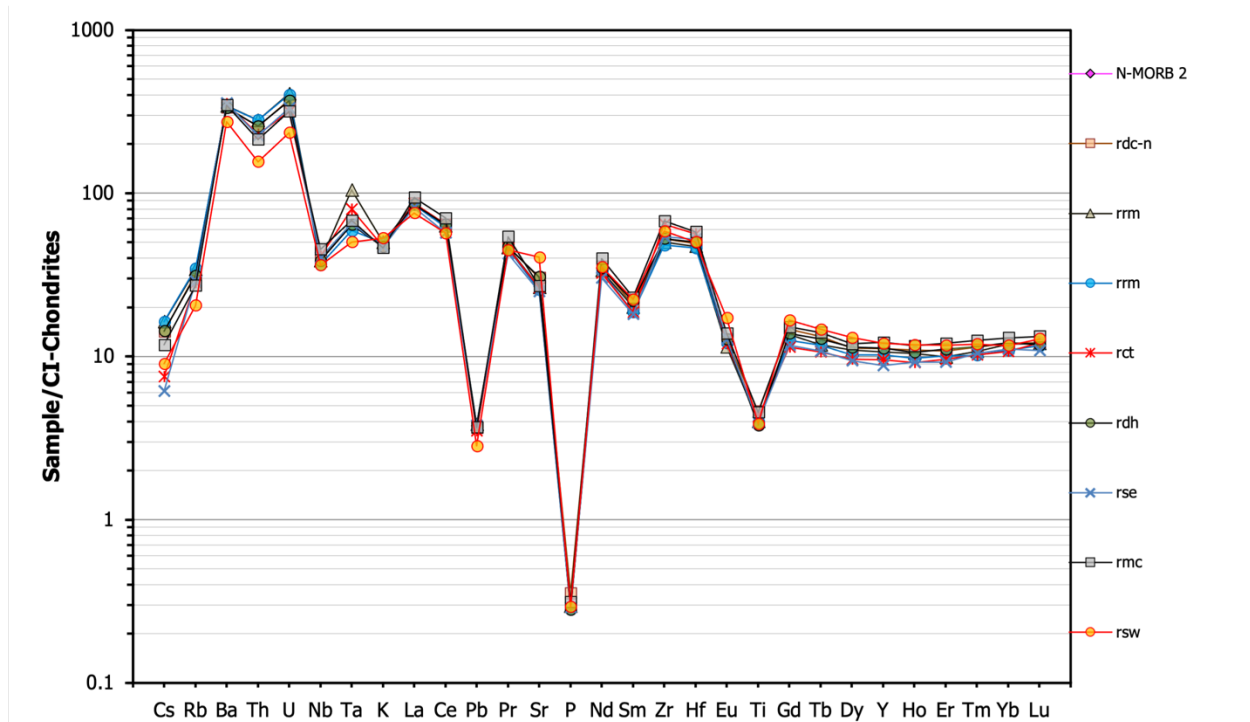


Figure A8: Chondrite-normalized whole rock compositions (McDonough and Sun, 1995). Concave up feature in the HREE is suggestive of the presence of amphibole in the system. Geologic unit abbreviations—Rhyolite of Devils Chain (rdc), Rhyolite of Rock Mesa (rrm), Rhyolite of South Sister Climbers Trail (rct), Rhyolite of Green Lakes (rgl), Rhyolite of Devils Hill (rdh), Rhyolite of southeast Lewis Glacier (rse), Rhyolite of Mesa Creek (rmc), Rhyolite southwest of Lewis Glacier (rsw).

APPENDIX B

SUPPLEMENTAL MATERIAL FOR CHAPTER 3

```

BASE_X (INTEGER):
200
BASE_Y (INTEGER):
200
BASE_Z (INTEGER):
200
WIDTH (REAL,METERS):
45000.
HEIGHT (REAL,METERS):
45000.
ZWIDTH (REAL,METERS):
45000.
FREQUENCY (INTEGER) Average number of timesteps between intrusions
5
DELTATIME (REAL, YEARS):
1000.
Timesteps (INTEGER):
130
FREQUENCY OF WRITEOUT (INTEGER):
5
RANDOM SEED (NEGATIVE INTEGER):
-9
BASE CRUST (REAL, METERS):
44000.
Gradient (degrees/meter):
-.050
SILL THICKNESS (real, meters - pixels= SILL_THICKNESS/(HEIGHT/BASE_Y) )
ideally want to be at least 3 DY or bigger:
1000.0
SILL LENGTH (real, randomized, meters - pixels= SILL LENGTH/(WIDTH/BASE_X) ):
5000.0
PLUTONS, BASEMENT (bottom, REAL METERS)
44000.0
SUBVOLCANIC PLUTONS (bottom, REAL METERS)
30000.0
METAVOLCANICS, PLUTONS (bottom, REAL METERS)
12000.0
NEO-VOLCANICS, UPPER CRUST
4000.0
INJECT WIDTH X (REAL, METERS - region at base of crust where magma intrudes)
14000.0
INJECT WIDTH Z (REAL, METERS - region at base of crust where magma intrudes)
20000.0
TECTONIC RATE (REAL,METERS/year)
0.0
TECTONIC REGION (meters)
30000.0
DIKE WIDTH (real, meters - pixels in dike= DIKE_WIDTH/(WIDTH/BASE_X) )
500.0
MAX INJECT HEIGHT (distance from surface were magma is excluded)

```

```

0.0
SEDIMENTATION WIDTH (REAL, METERS region at to crust that volcanics are
added)
5000.0
ERUPTIVE FLUX (REAL, meters/yr) Ignore this for the present eruption code
0.0
Critical melt fraction for dike propagation and eruptive melt
0.4
Focus Factor (larger than 1, this is an area ratio of melt that is
concentrated from a projected area on the Moho)
1.0
FLAG for calculating initial mush (integer) -- Set to 1 for mush calculation
0
Intrusion distance from western boundary, in m
17500.0
Intrusion width EW, in m
10000.0
Intrusion depth, in m
15000.0
Intrusion thickness, in m
14000.0
Intrusion distance from southern boundary, in m
17500.0
!Intrusion NS Width, in m
10000.0
Initial Mush Temperature (C)
1000.0
Switch for intrusion only in to mush area (using flux parameters listed
above) (1 == TRUE)
1
Flag for temperature control (otherwise start with initial geotherm)
(1==TRUE)
0
Flag for fully or partially constant values or fully 'random_run',
(1==TRUE==random_run)
1
Timestep after which the run becomes random (if bigger than timesteps fully
constant)
0
Frequency for checking for eruption condition (put 1 to check every timestep)
6
Minimum Eruption Volume (m^3) [needs to be resolvable
2*SILL_THICKNESS*SILL_WIDTH^2 or bigger; otherwise will cause the run to
hang]
40000000.
Effusive (1) or Explosive (2) eruptions?
2
How frequently to check for extraction from lower crust (put 1 to check every
timestep, should in general be less that the diking frequency)
50000
What part of the crust is available for eruption? This is height measured
above Moho in meters.
29000.
Timestep to start high resolution recording (set to an arbitrarily high value
to deactivate):
1000

```

Timestep to stop high resolution recording (must be bigger than start):
1200
Frequency (in timesteps) to writeout at high resolution. These will be
denoted by ' _HF'
10

Figure B1: Example input file to run the magma dynamics code for R021, explosive mafic focused magma body. Currently set to run on the University of Oregon Talapas high-performance computing cluster.

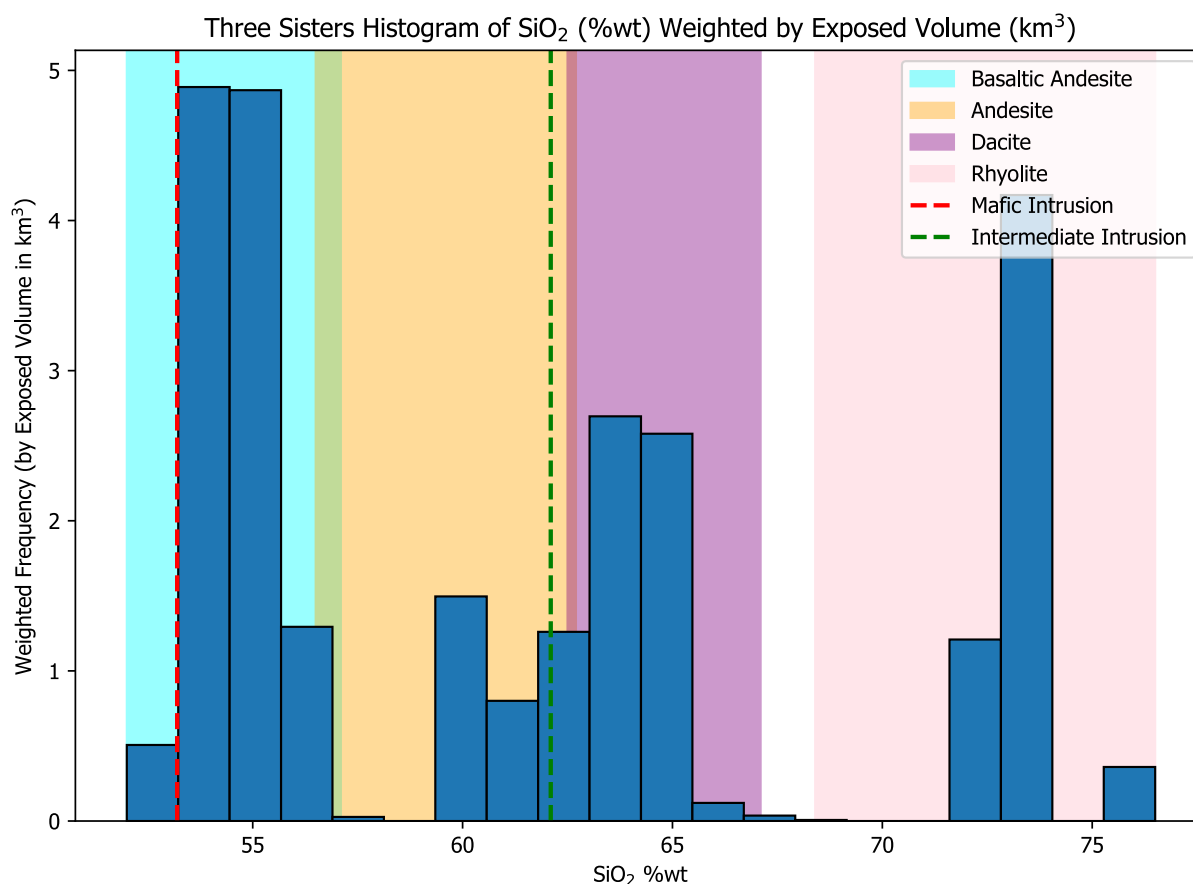


Figure B2: Histogram of the SiO₂ %wt composition of lavas erupted from the Three Sisters, weighted by eruptive volume (exposed, km³). Background boxes show the SiO₂ %wt for the different lava types. Dashed lines show the modeled intrusions SiO₂ %wt: red for the mafic intrusion and green for the intermediate intrusion. Data from (Fierstein et al., 2011; Hildreth et al., 2012; Calvert et al., 2018).

Eruption Style	Input Composition	Focusing Style	Realization Number	Flux Value	Avg Timestep Between Intrusions	Depth (km)
Effusive	Felsic	Focused	R082		5	6
Effusive	Felsic	Focused	R083		5	15
Effusive	Felsic	Focused	R081		10	6
Effusive	Felsic	Focused	R087		10	15
Effusive	Felsic	Focused	R080		15	6
Effusive	Felsic	Focused	R084		20	15
Effusive	Felsic	Focused	R085		20	6
Effusive	Felsic	Focused	R086		20	15
Effusive	Felsic	Focused	R088		30	6
Effusive	Felsic	Focused	R089		30	15
Effusive	Felsic	Distributed	R079		5	6
Effusive	Felsic	Distributed	R090		5	15
Effusive	Felsic	Distributed	R078		10	6
Effusive	Felsic	Distributed	R091		10	15
Effusive	Felsic	Distributed	R077		15	6
Effusive	Felsic	Distributed	R092		20	15
Effusive	Felsic	Distributed	R093		20	6
Effusive	Felsic	Distributed	R094		20	15
Effusive	Felsic	Distributed	R095		30	6
Effusive	Felsic	Distributed	R096		30	15
Effusive	Intermediate	Focused	R079		5	6
Effusive	Intermediate	Focused	R097		5	15
Effusive	Intermediate	Focused	R069		10	6
Effusive	Intermediate	Focused	R101		10	15
Effusive	Intermediate	Focused	R068		15	6
Effusive	Intermediate	Focused	R098		20	15
Effusive	Intermediate	Focused	R099		20	15
Effusive	Intermediate	Focused	R100		20	6
Effusive	Intermediate	Focused	R102		30	6
Effusive	Intermediate	Focused	R103		30	15
Effusive	Intermediate	Distributed	R067		5	6
Effusive	Intermediate	Distributed	R104		5	15
Effusive	Intermediate	Distributed	R066		10	6
Effusive	Intermediate	Distributed	R108		10	15
Effusive	Intermediate	Distributed	R065		15	6
Effusive	Intermediate	Distributed	R105		20	6
Effusive	Intermediate	Distributed	R106		20	15
Effusive	Intermediate	Distributed	R107		20	15
Effusive	Intermediate	Distributed	R109		30	6
Effusive	Intermediate	Distributed	R110		30	15

Figure B3: Major variables set for each of the magma dynamics realizations. Eruption style, input composition, realization number, flux value (used to set the intrusion timing before upgraded to average number of timesteps), average number of timesteps between magmatic intrusions, and depth (km). Blue realization numbers are the best fit in the end (match two eruptive episodes), while orange realization numbers are the good fits (match one eruptive episode), given eruption volume modeling.

Eruption Style	Input Composition	Focusing Style	Realization Number	Flux Value	Avg Timestep Between Intrusions	Depth (km)
Explosive	Felsic	Focused	R076		5	6
Explosive	Felsic	Focused	R075		10	6
Explosive	Felsic	Focused	R074		15	6
Explosive	Felsic	Focused	R111		20	6
Explosive	Felsic	Focused	R052		20	15
Explosive	Felsic	Focused	R050		30	6
Explosive	Felsic	Focused	R051		30	15
Explosive	Felsic	Focused	R012	4		6
Explosive	Felsic	Focused	R013	4		15
Explosive	Felsic	Focused	R014	3		15
Explosive	Felsic	Distributed	R073		5	6
Explosive	Felsic	Distributed	R072		10	6
Explosive	Felsic	Distributed	R071		15	6
Explosive	Felsic	Distributed	R112		15	15
Explosive	Felsic	Distributed	R049		20	6
Explosive	Felsic	Distributed	R053		20	15
Explosive	Felsic	Distributed	R113		30	6
Explosive	Felsic	Distributed	R114		30	15
Explosive	Felsic	Distributed	R011	3		6
Explosive	Felsic	Distributed	R015	3		15
Explosive	Intermediate	Focused	R021		5	15
Explosive	Intermediate	Focused	R024		5	15
Explosive	Intermediate	Focused	R027		5	15
Explosive	Intermediate	Focused	R028		5	15
Explosive	Intermediate	Focused	R064		5	6
Explosive	Intermediate	Focused	R022		6	15
Explosive	Intermediate	Focused	R025		6	15
Explosive	Intermediate	Focused	R063		10	6
Explosive	Intermediate	Focused	R026		10	15
Explosive	Intermediate	Focused	R023		10	15
Explosive	Intermediate	Focused	R062		15	6
Explosive	Intermediate	Focused	R030		20	15
Explosive	Intermediate	Focused	R029		20	15
Explosive	Intermediate	Focused	R031		20	15
Explosive	Intermediate	Focused	R042		20	15
Explosive	Intermediate	Focused	R034		30	15
Explosive	Intermediate	Focused	R035		30	15
Explosive	Intermediate	Focused	R040		30	6
Explosive	Intermediate	Focused	R041		30	15
Explosive	Intermediate	Distributed	R061		5	6
Explosive	Intermediate	Distributed	R060		10	6
Explosive	Intermediate	Distributed	R117		10	15
Explosive	Intermediate	Distributed	R059		15	6
Explosive	Intermediate	Distributed	R039		20	6
Explosive	Intermediate	Distributed	R043		20	15
Explosive	Intermediate	Distributed	R115		30	6
Explosive	Intermediate	Distributed	R116		30	15
Explosive	Intermediate	Distributed	R001	3		6

Figure B3 continued

Eruption Style	Input Compositon	Focusing Style	Realization Number	Flux Value	Avg Timestep Between Intrusions	Depth (km)
Plutonic	Felsic	Focused	R127		30	6
Plutonic	Felsic	Focused	R055	3		6
Plutonic	Felsic	Focused	R057	3		15
Plutonic	Felsic	Focused	R070	8		6
Plutonic	Felsic	Focused	R072	8		15
Plutonic	Felsic	Distributed	R124		5	6
Plutonic	Felsic	Distributed	R126		5	15
Plutonic	Felsic	Distributed	R125		10	15
Plutonic	Felsic	Distributed	R122		30	15
Plutonic	Felsic	Distributed	R123		30	6
Plutonic	Intermediate	Focused	R120		30	6
Plutonic	Intermediate	Focused	R121		30	15
Plutonic	Intermediate	Focused	R021	3		15
Plutonic	Intermediate	Focused	R034	8		6
Plutonic	Intermediate	Focused	R036	8		15
Plutonic	Intermediate	Distributed	R118		30	6
Plutonic	Intermediate	Distributed	R119		30	15
Plutonic	Intermediate	Distributed	R003	3		15
Plutonic	Intermediate	Distributed	R016	8		6
Plutonic	Intermediate	Distributed	R018	8		15

Figure B3 continued

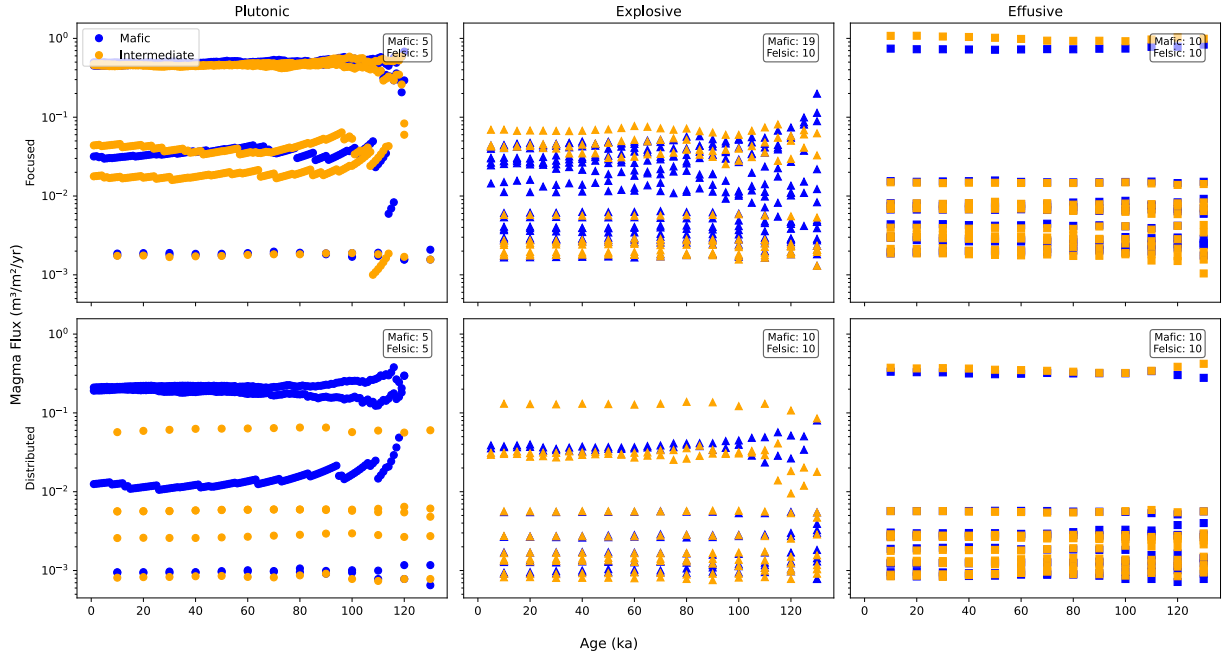


Figure B4: Plot displaying the magma flux into the system through time for the parameter space tested. The first column is the plutonic realizations, the second is the explosive eruption realizations, and the third is the effusive eruption realizations. The first row shows the focused style of magmatic intrusions, while the second row shows the distributed style. Magmatic flux is plotted on a log scale. Mafic magmatic intrusions are plotted in blue, while intermediate magmatic intrusions are plotted in orange.

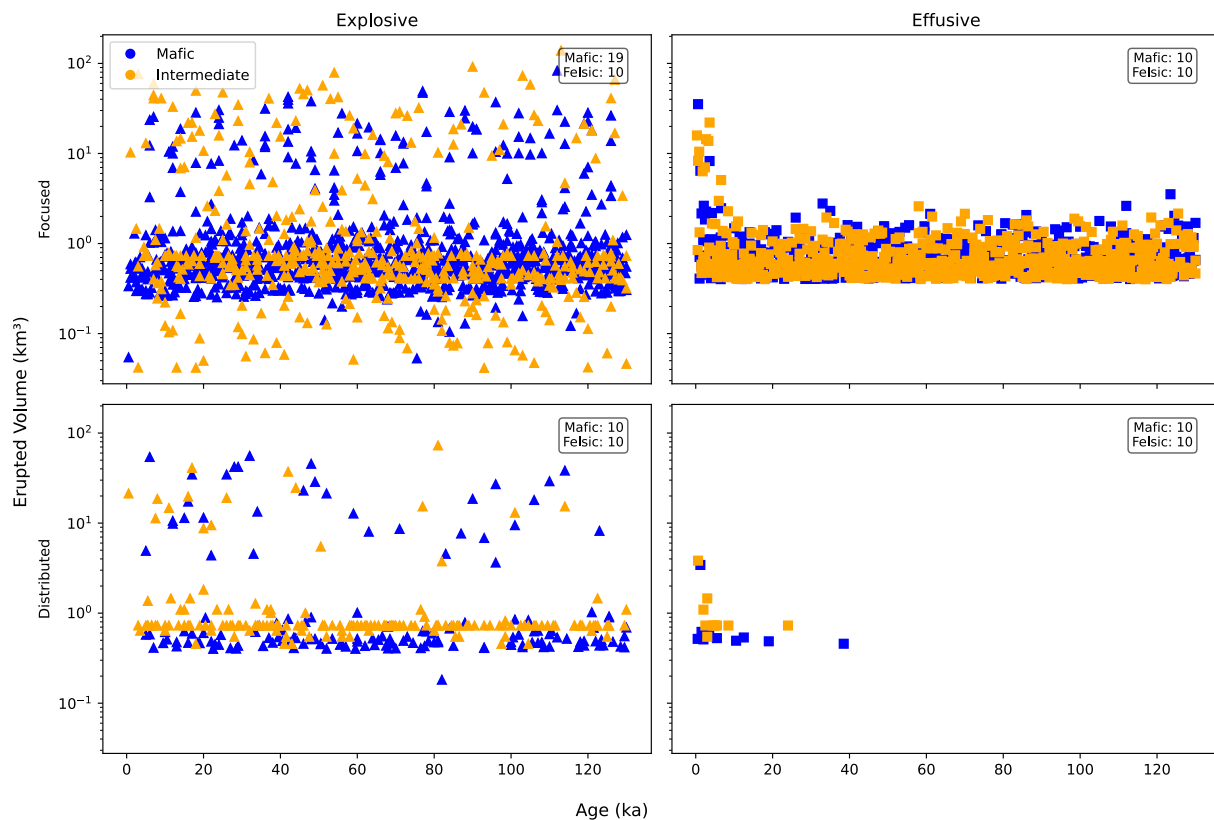
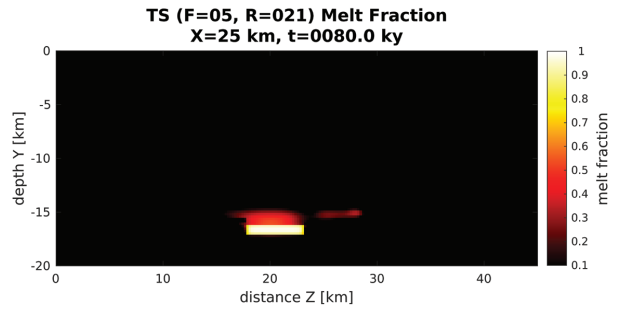
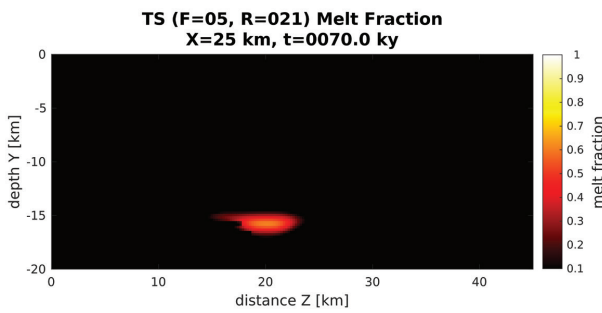
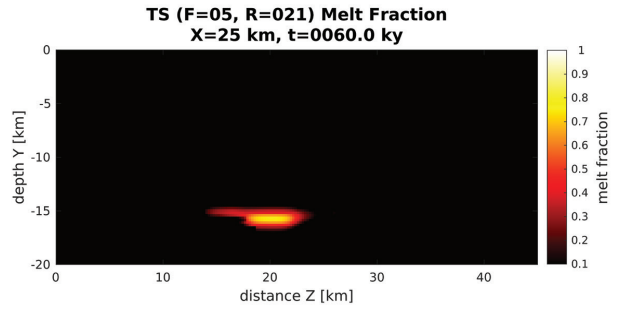
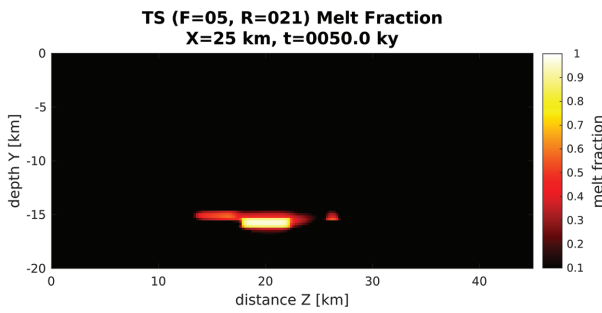
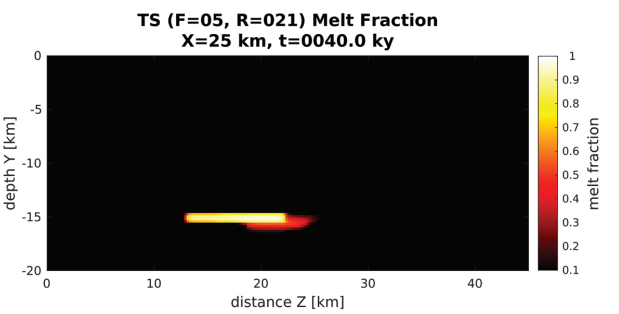
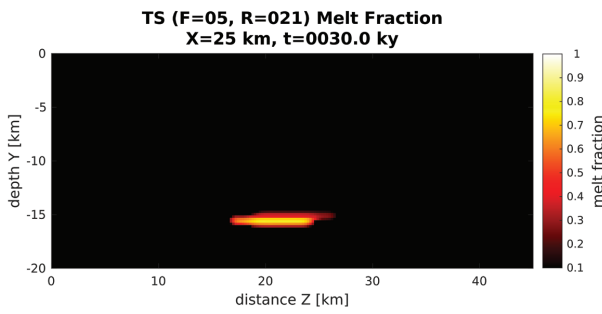
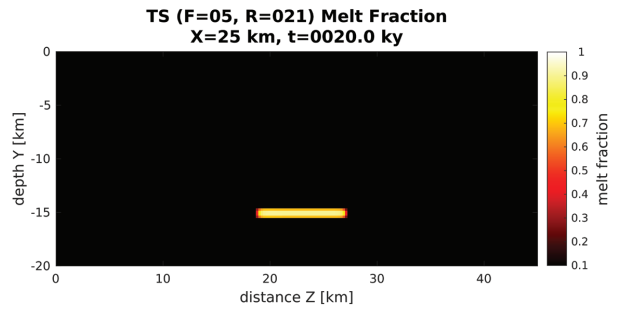
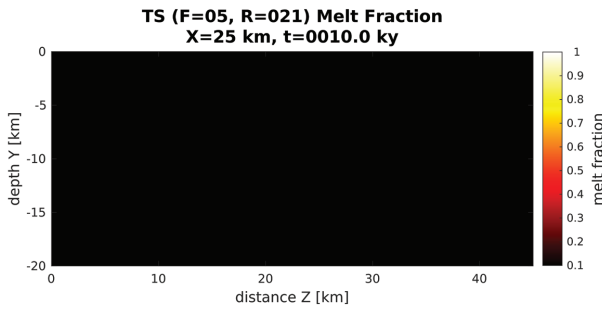


Figure B5: Plot displaying the erupted volumes of magma through time for the parameter space tested. The first column is the explosive eruption realizations, and the second is the effusive eruption realizations. The first row shows the focused style of magmatic intrusions, while the second row shows the distributed style. Erupted volume is plotted on a log scale. Mafic magmatic intrusions are plotted in blue, while intermediate magmatic intrusions are plotted in orange.



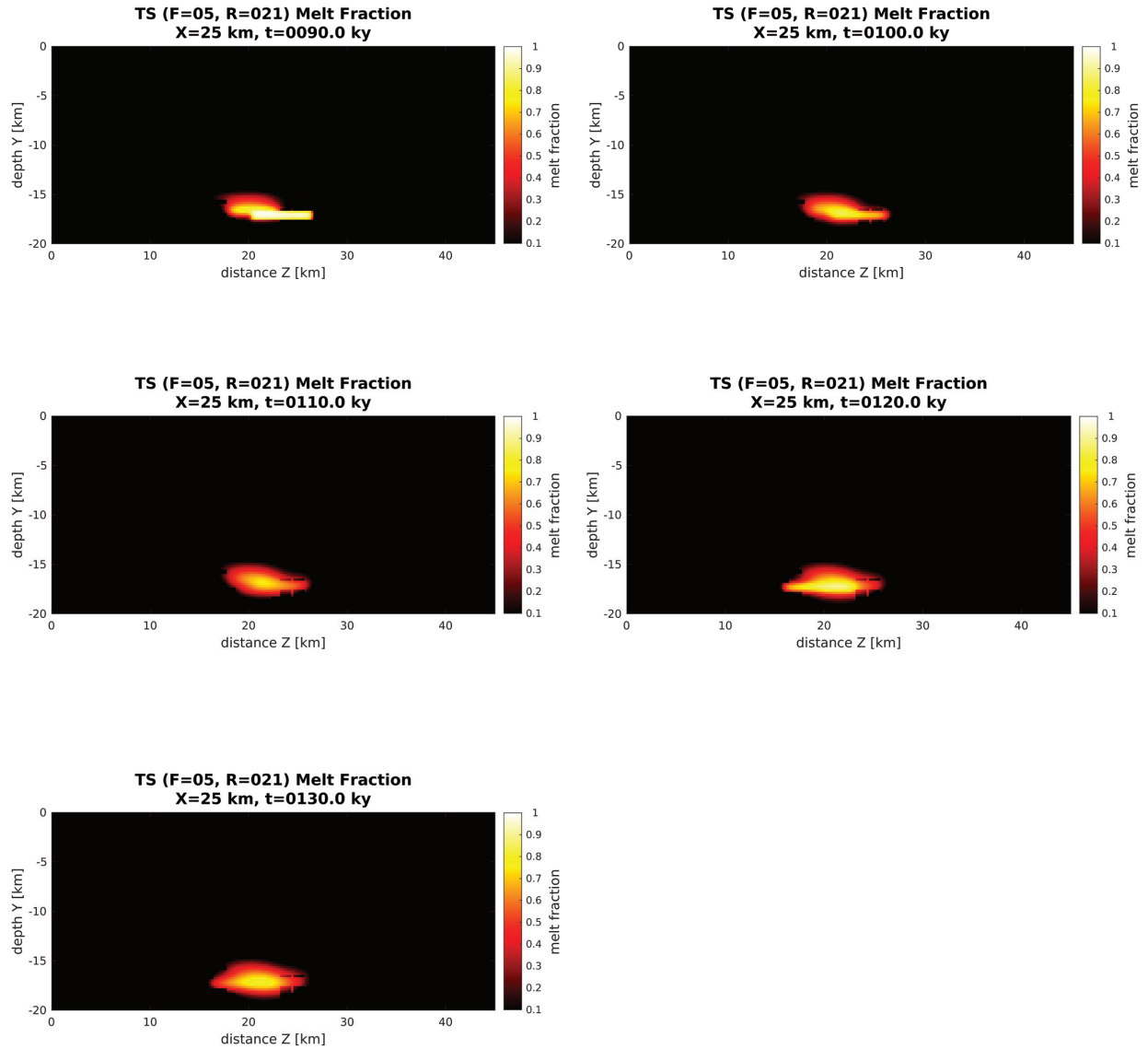


Figure B6: Timeseries of example R021. Here, we see the melt fraction evolution from the start of the magma dynamics model (i.e., at 10 ky, the model has run for 10 ka, and the Three Sisters age would be 120 ka). Timestep $t = 130$ ky corresponds to the modern-day signal, displaying how the magmatic system has been built up over the simulation, and is the timestep with which we compare to the modern-day Bouguer gravity anomaly.

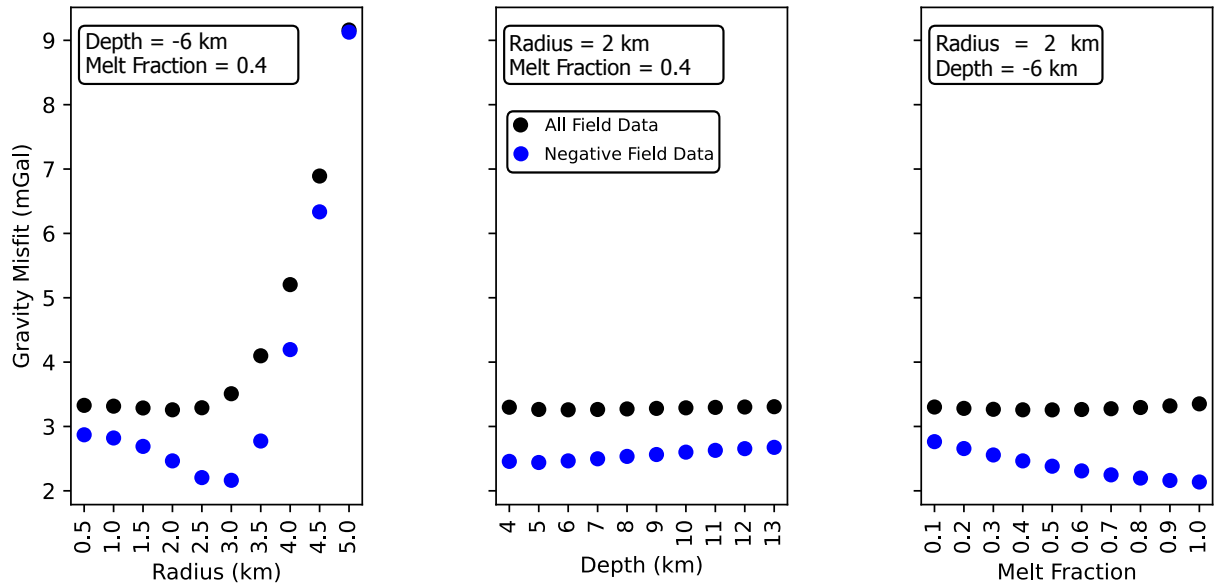


Figure B7: Spherical sensitivity test of the forward gravity model. A spherical body varying with the depth, melt fraction, and radius size. Black circles represent the gravity misfit between the simulated gravity anomaly and the modern-day Bouguer gravity anomaly at the Three Sisters, considering all field data points. Blue circles represent the gravity misfit, but with removing the positive field gravity measurements to better focus on the gravity misfit represented by negative gravity anomalies.

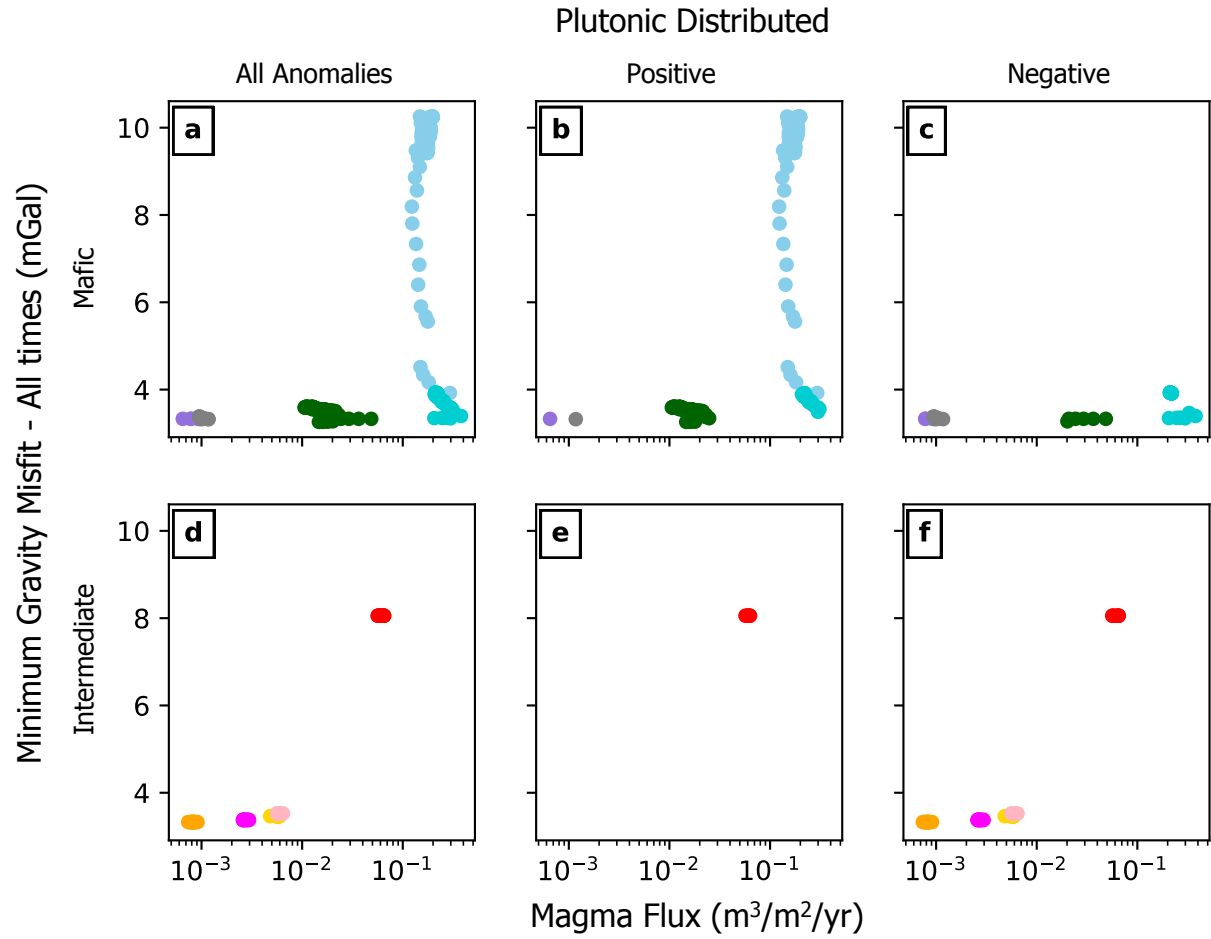


Figure B8: Results for the plutonic style with distributed magmatic intrusions. Plot showing the magma flux at each timestep compared to the gravity misfit for each timestep. Note that the gravity misfit compares all timesteps to the modern gravity survey. Panels a-c are for the mafic magma flux, while panels d-f are for the intermediate magma flux. Panels a and d show all gravity anomalies, panels b and e show the on-average positive gravity anomalies, while panels c and f show the on-average negative gravity anomalies. Each color represents a different realization.

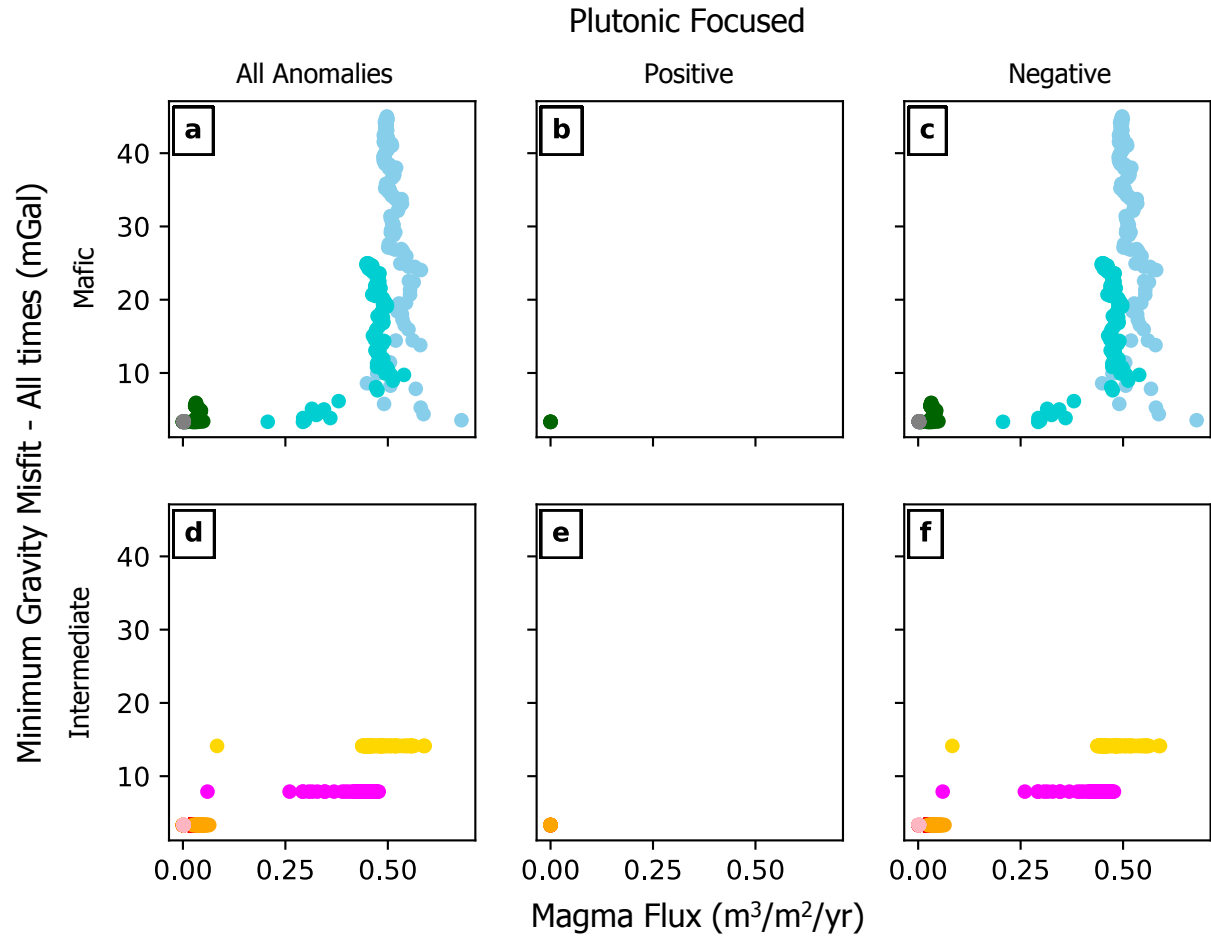


Figure B9: Results for the plutonic style with focused magmatic intrusions. Plot showing the magma flux at each timestep compared to the gravity misfit for each timestep. Note that the gravity misfit compares all timesteps to the modern gravity survey. Panels a-c are for the mafic magma flux, while panels d-f are for the intermediate magma flux. Panels a and d show all gravity anomalies, panels b and e show the on-average positive gravity anomalies, while panels c and f show the on-average negative gravity anomalies. Each color represents a different realization.

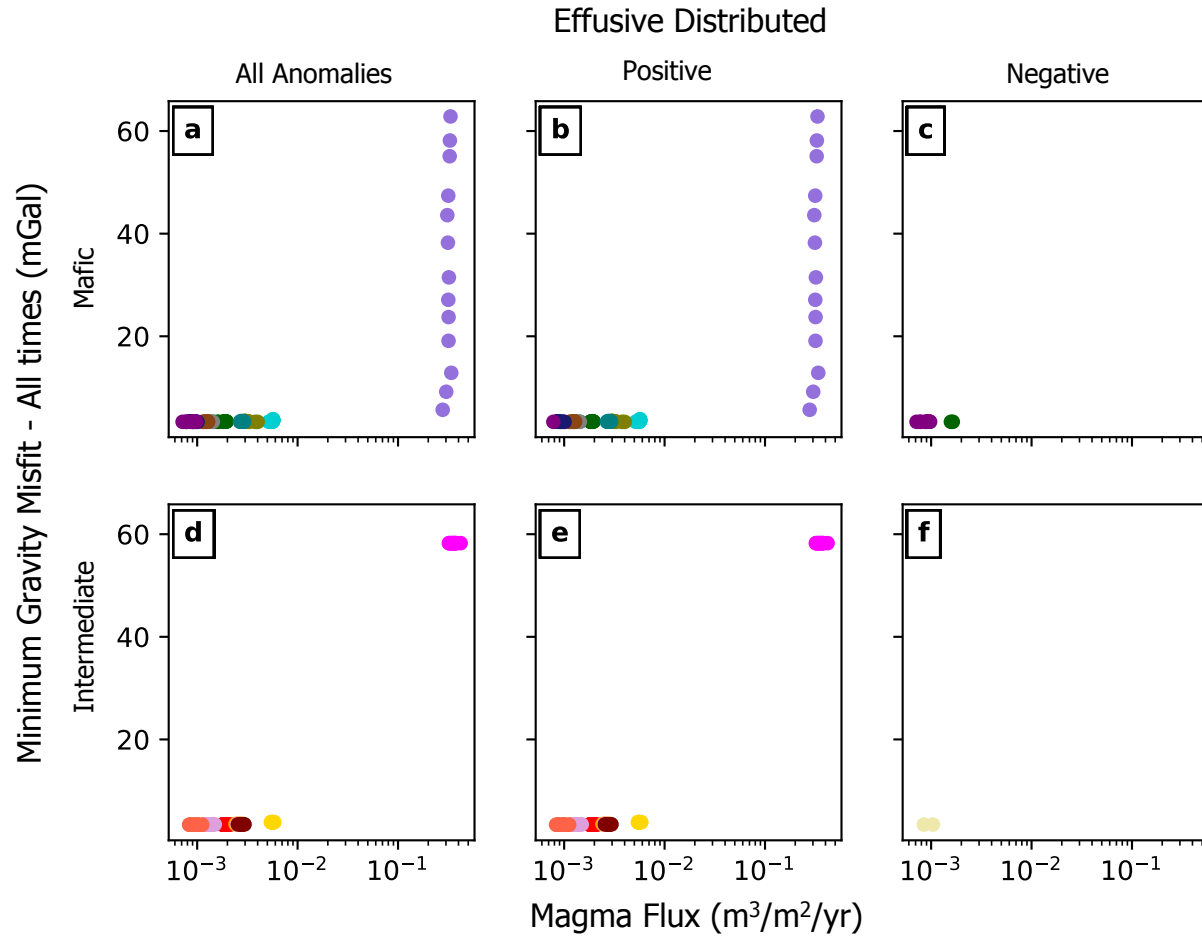


Figure B10: Results for the effusive style eruptions with distributed magmatic intrusions. Plot showing the magma flux at each timestep compared to the gravity misfit for each timestep. Note that the gravity misfit compares all timesteps to the modern gravity survey. Panels a-c are for the mafic magma flux, while panels d-f are for the intermediate magma flux. Panels a and d show all gravity anomalies, panels b and e show the on-average positive gravity anomalies, while panels c and f show the on-average negative gravity anomalies. Each color represents a different realization.

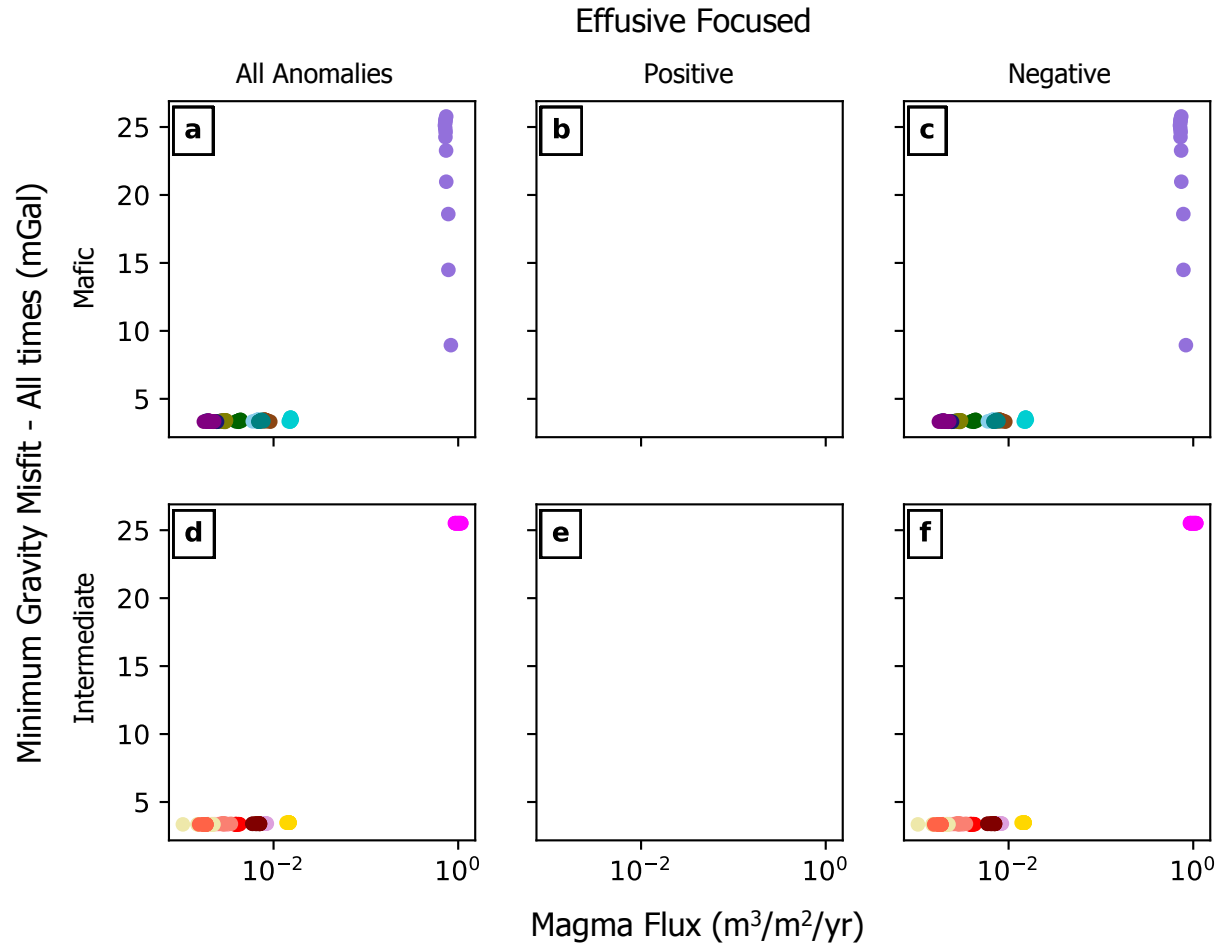


Figure B11: Results for the effusive eruption style with focused magmatic intrusions. Plot showing the magma flux at each timestep compared to the gravity misfit for each timestep. Note that the gravity misfit compares all timesteps to the modern gravity survey. Panels a-c are for the mafic magma flux, while panels d-f are for the intermediate magma flux. Panels a and d show all gravity anomalies, panels b and e show the on-average positive gravity anomalies, while panels c and f show the on-average negative gravity anomalies. Each color represents a different realization.

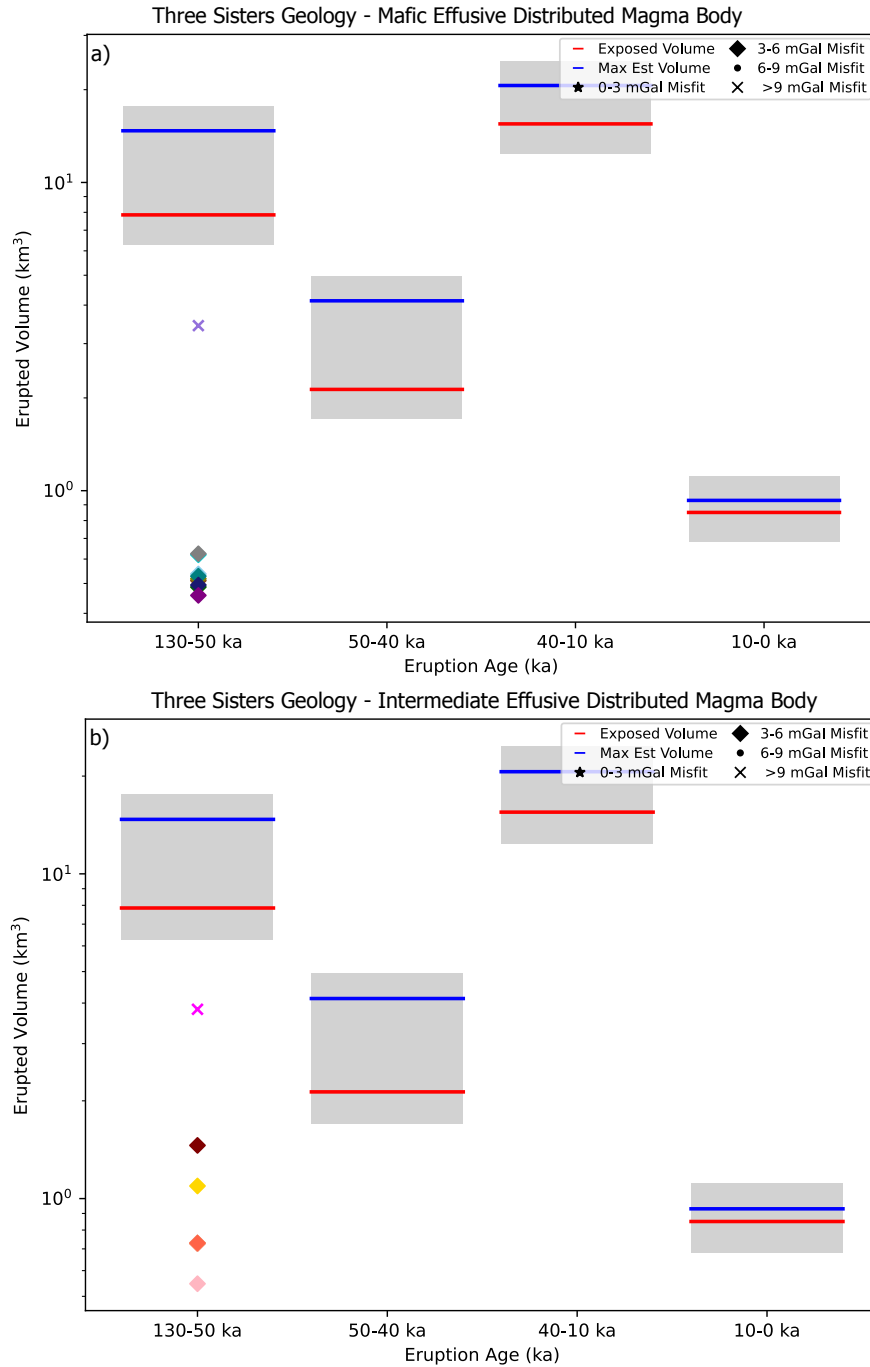


Figure B12: Eruptive volume results for the effusive eruptions with distributed magmatic intrusions. Red horizontal line represents the mapped eruptive volumes, blue horizontal line represents the maximum estimated eruptive volumes, and gray square shows the 20% misfit of these volumes. 130-50 ka represents North Sister eruptions, 50-40 ka Middle Sister, 40-10 ka coeval Middle Sister and South Sister, 10-0 ka the Holocene eruptions. a) Mafic realizations. b) Intermediate realizations.

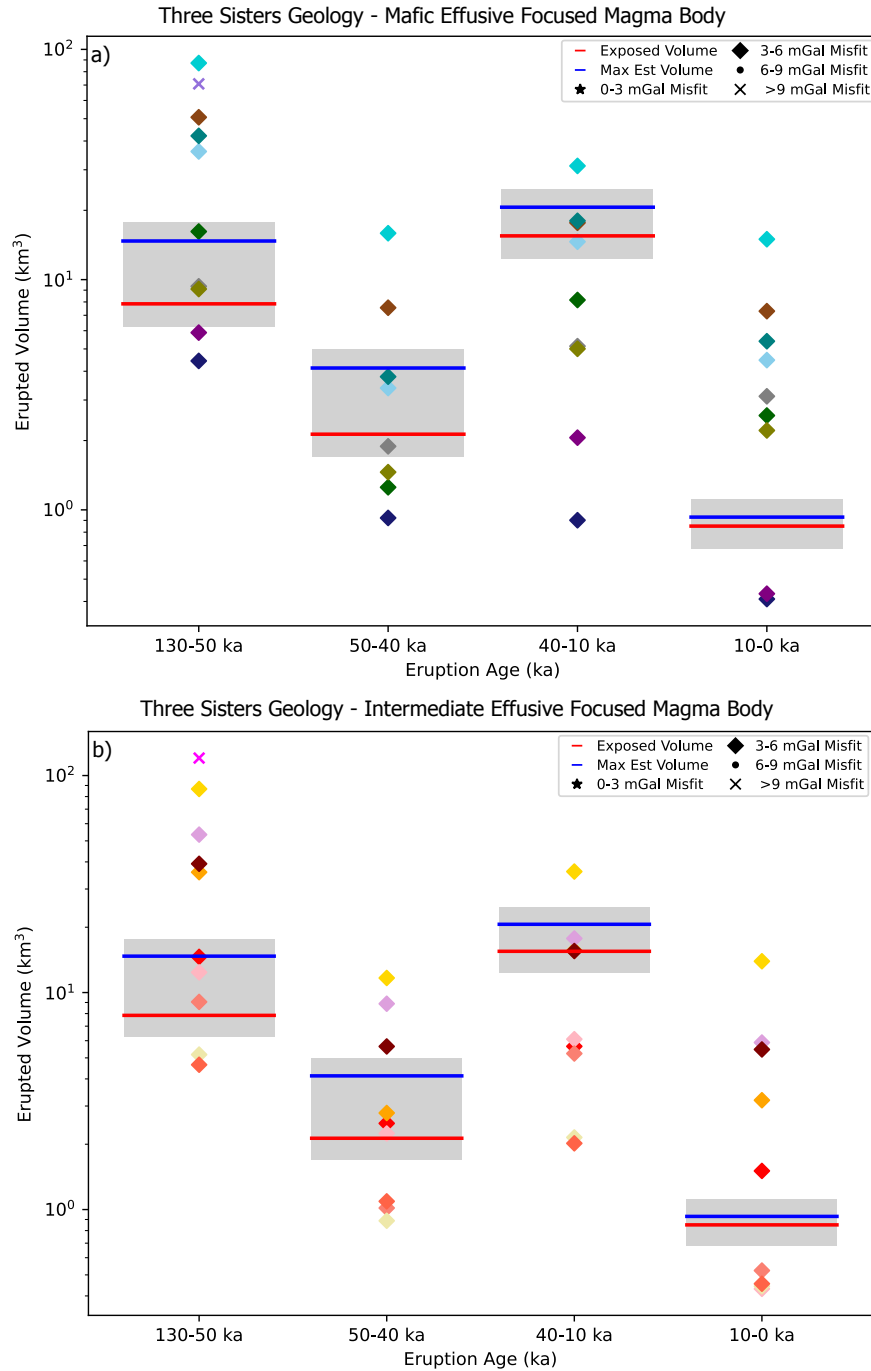


Figure B13: Eruptive volume results for the effusive eruptions with focused magmatic intrusions. Red horizontal line represents the mapped eruptive volumes, blue horizontal line represents the maximum estimated eruptive volumes, and gray square shows the 20% misfit of these volumes. 130-50 ka represents North Sister eruptions, 50-40 ka Middle Sister, 40-10 ka coeval Middle Sister and South Sister, 10-0 ka the Holocene eruptions. a) Mafic realizations. b) Intermediate realizations.

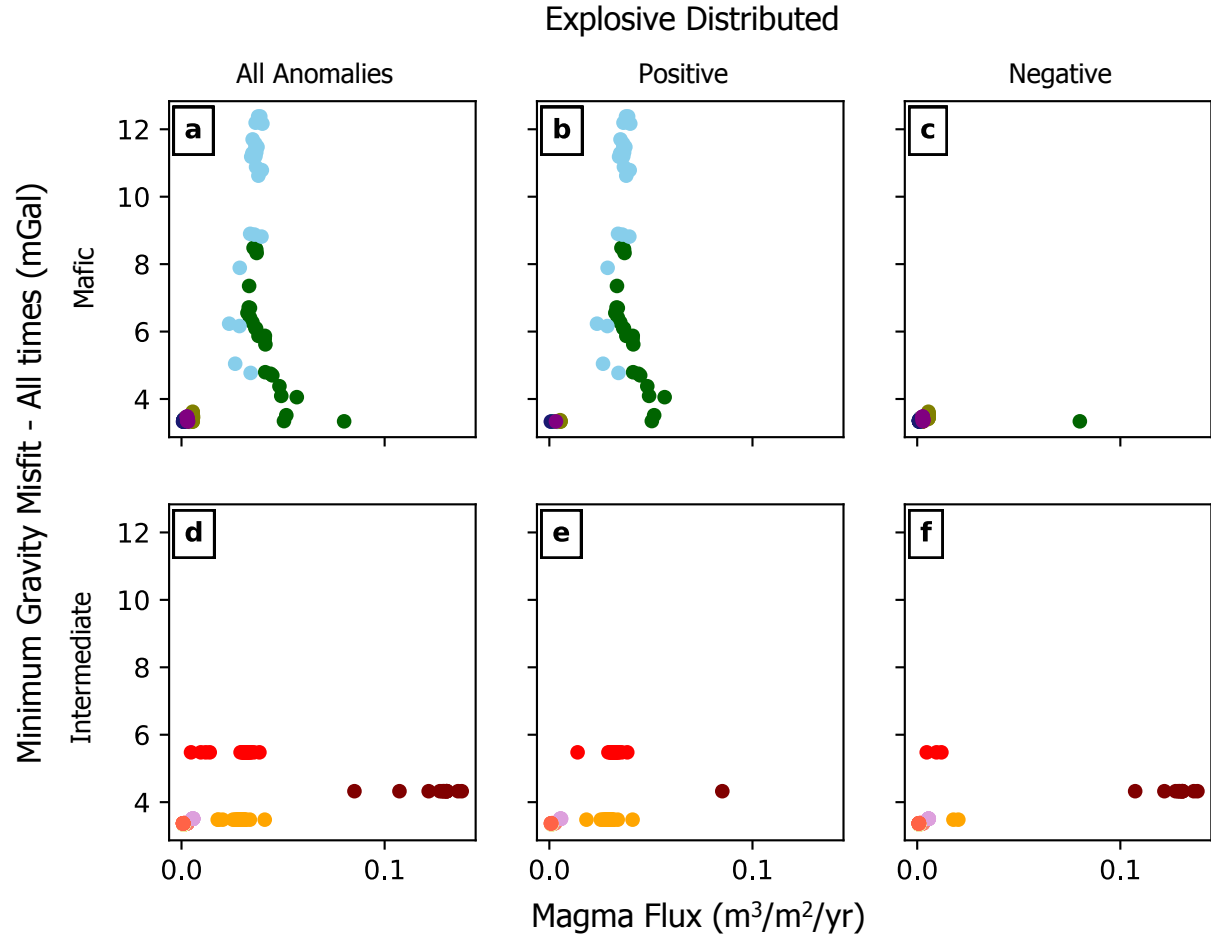


Figure B14: Results for the explosive eruption style with distributed magmatic intrusions. Plot showing the magma flux at each timestep compared to the gravity misfit for each timestep. Note that the gravity misfit compares all timesteps to the modern gravity survey. Panels a-c are for the mafic magma flux, while panels d-f are for the intermediate magma flux. Panels a and d show all gravity anomalies, panels b and e show the on-average positive gravity anomalies, while panels c and f show the on-average negative gravity anomalies. Each color represents a different realization.

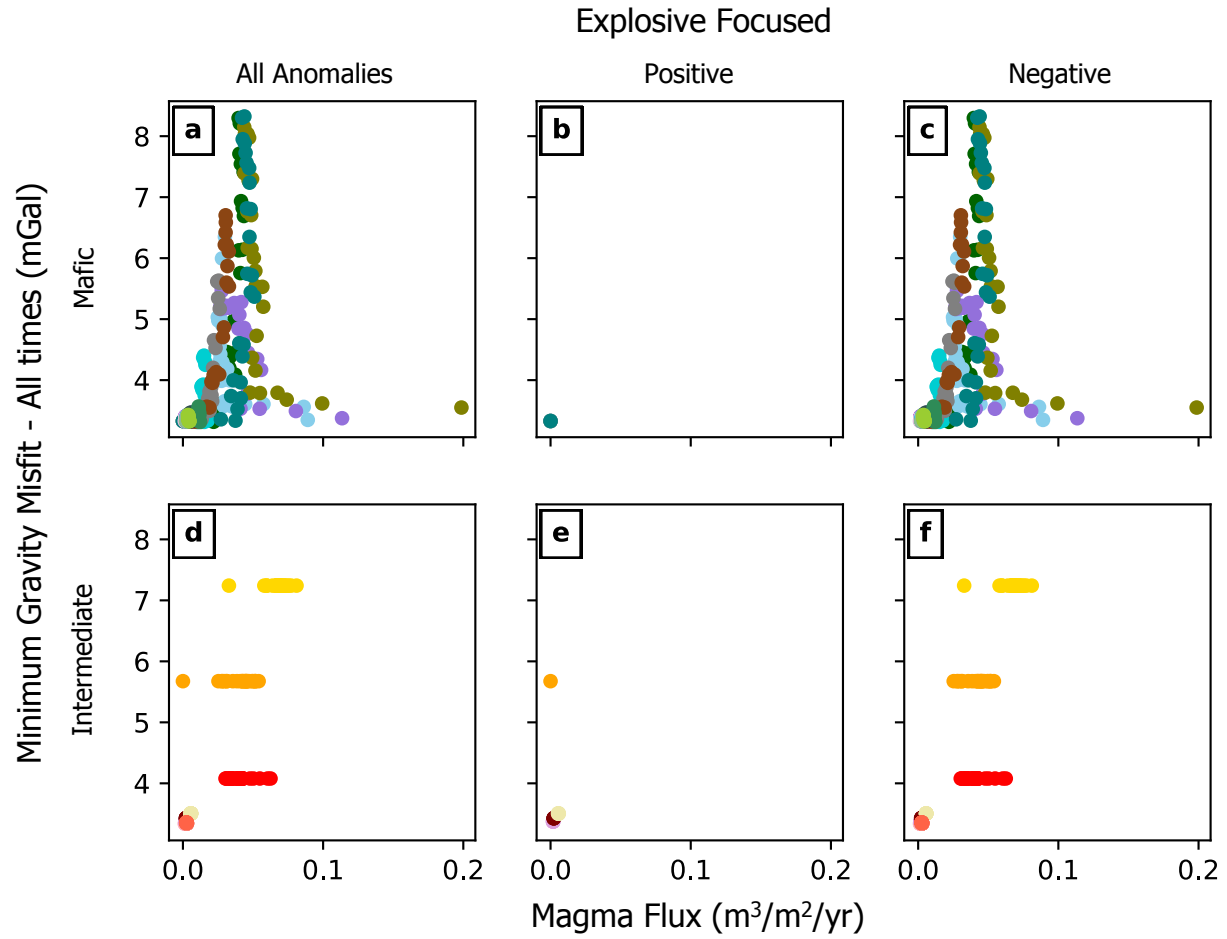


Figure B15: Results for the explosive eruption style with focused magmatic intrusions. Plot showing the magma flux at each timestep compared to the gravity misfit for each timestep. Note that the gravity misfit compares all timesteps to the modern gravity survey. Panels a-c are for the mafic magma flux, while panels d-f are for the intermediate magma flux. Panels a and d show all gravity anomalies, panels b and e show the on-average positive gravity anomalies, while panels c and f show the on-average negative gravity anomalies. Each color represents a different realization.

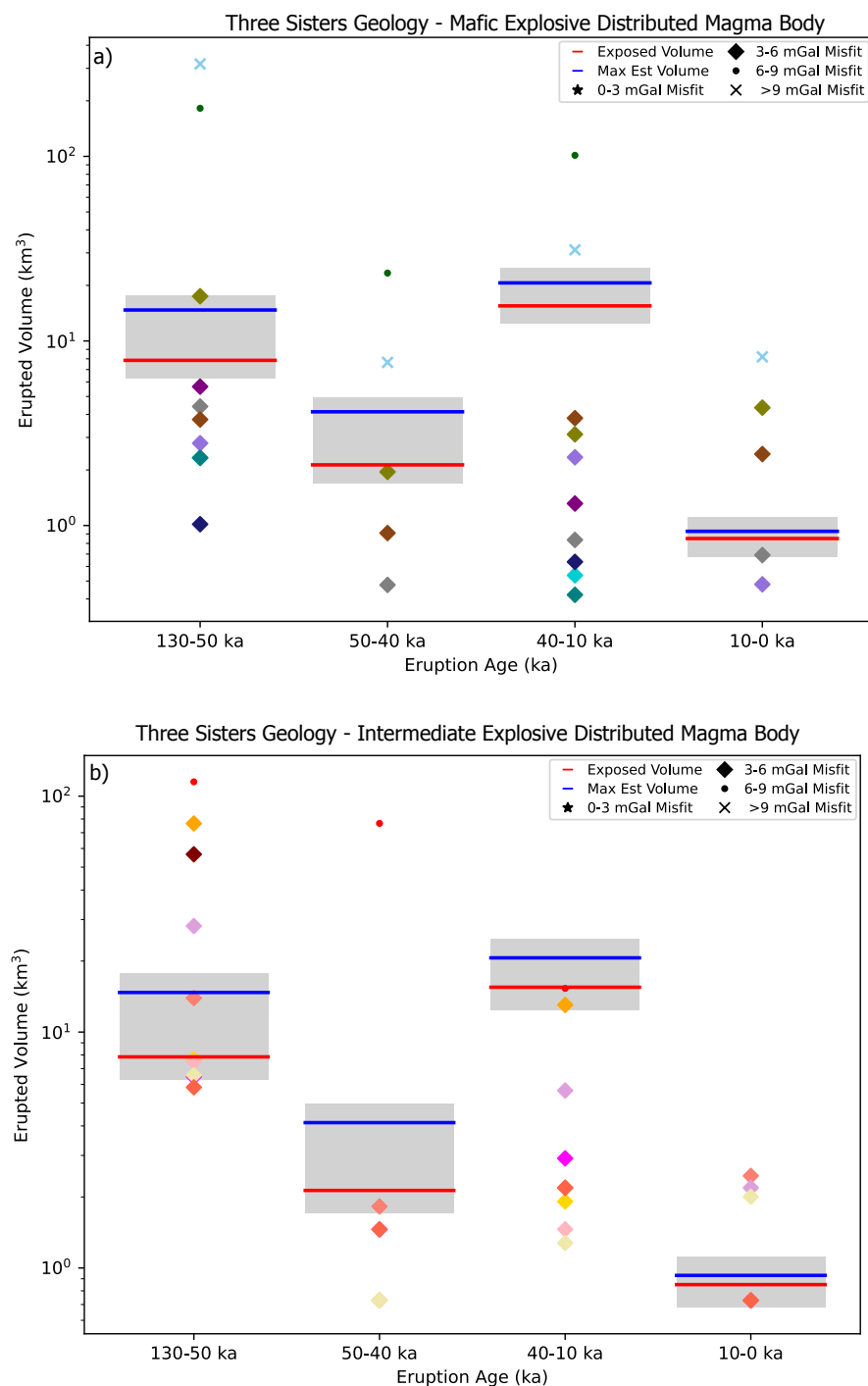


Figure B16: Eruptive volume results for the explosive eruptions with distributed magmatic intrusions. Red horizontal line represents the mapped eruptive volumes, blue horizontal line represents the maximum estimated eruptive volumes, and gray square shows the 20% misfit of these volumes. 130-50 ka represents North Sister eruptions, 50-40 ka Middle Sister, 40-10 ka coeval Middle Sister and South Sister, 10-0 ka the Holocene eruptions. a) Mafic realizations. b) Intermediate realizations.

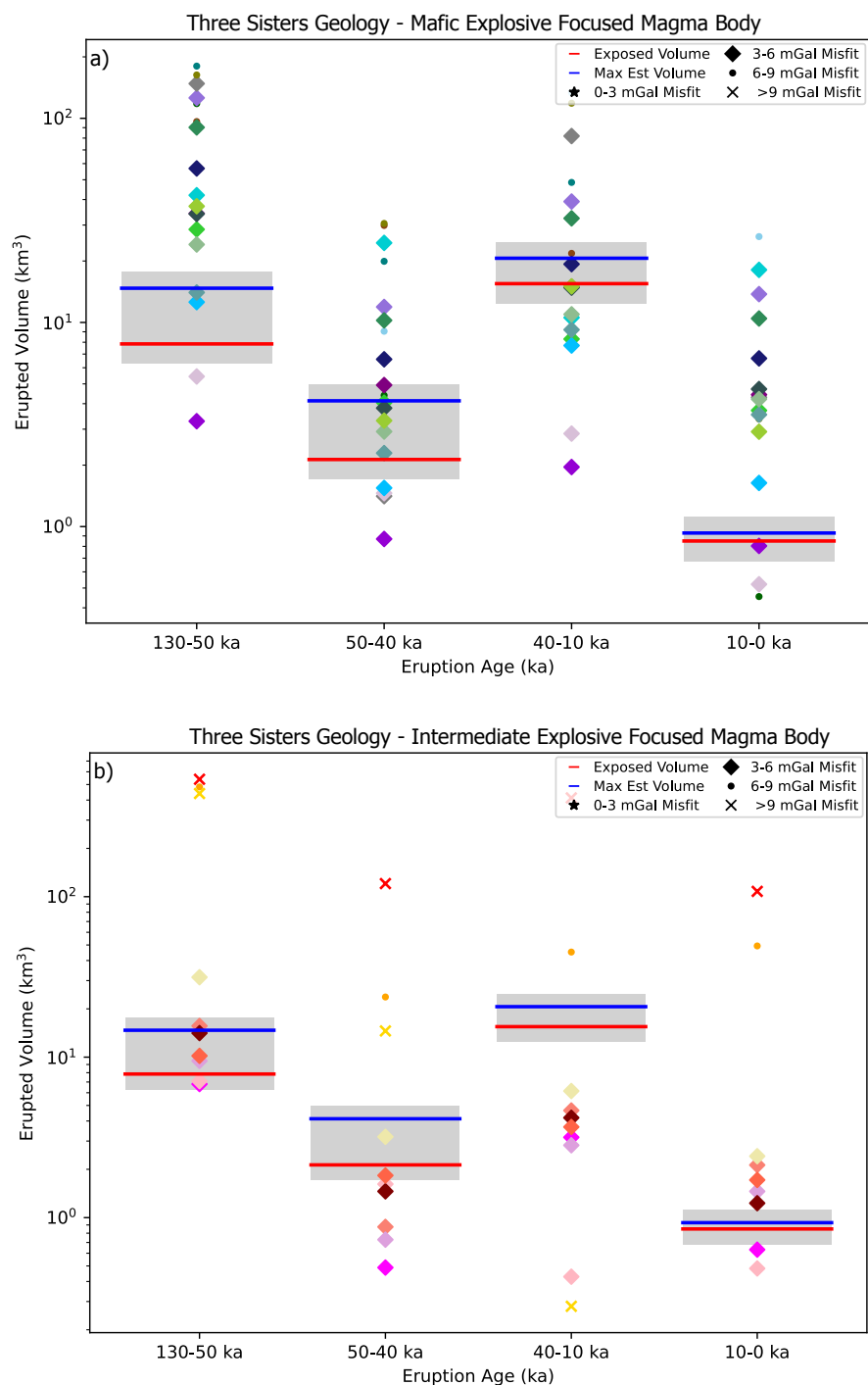


Figure B17: Eruptive volume results for the explosive eruptions with focused magmatic intrusions. Red horizontal line represents the mapped eruptive volumes, blue horizontal line represents the maximum estimated eruptive volumes, and gray square shows the 20% misfit of these volumes. 130-50 ka represents North Sister eruptions, 50-40 ka Middle Sister, 40-10 ka coeval Middle Sister and South Sister, 10-0 ka the Holocene eruptions. a) Mafic realizations. b) Intermediate realizations.

Variables Explored	Two Matches	One and Two Matches	One Match
number of realizations	17	40	23
mafic	9	19	10
intermediate	8	21	13
focused	12	30	18
distributed	5	10	5
explosive	11	28	17
effusive	6	12	6
6 km	10	21	11
15 km	7	19	12
5 flux	2	3	1
10 flux	5	8	3
15 flux	2	5	3
20 flux	6	14	8
30 flux	1	7	6
NS	10	20	10
MS	14	27	3
Active	7	14	7
Holocene	3	6	3
NS + MS	7	7	X
NS + Active	0	0	X
NS + Holo	3	3	X
MS + Active	7	7	X
MS + Holo	0	0	X
Active + Holo	0	0	X

Figure B18: Counts of the good fit (one or two eruptive episodes matched) and best fit (two eruptive episodes matched) realizations to demonstrate which varying parameters fit the most realizations. Flux values count the average number of timesteps between magmatic intrusions (i.e., 5 flux has more intrusions than 30 flux). The “Active” eruptive episode refers to the coeval eruptions of Middle and South Sister.

Layer Depth (km) or Intrusion	Minimum Density (kg/m ³)	Maximum Density (kg/m ³)
0 – 4	2,404	2,707
4 – 12	2,555	2,922
12 – 30	2,574	2,932
30 – 44	2,583	3,061
Intermediate	2,459	2,819
Mafic	2,541	3,020

Figure B19: Density ranges for each of the four crustal layers and the two intrusion compositions. The density for each of the layers and compositions is calculated based on depth and melt fraction, creating the range of values.

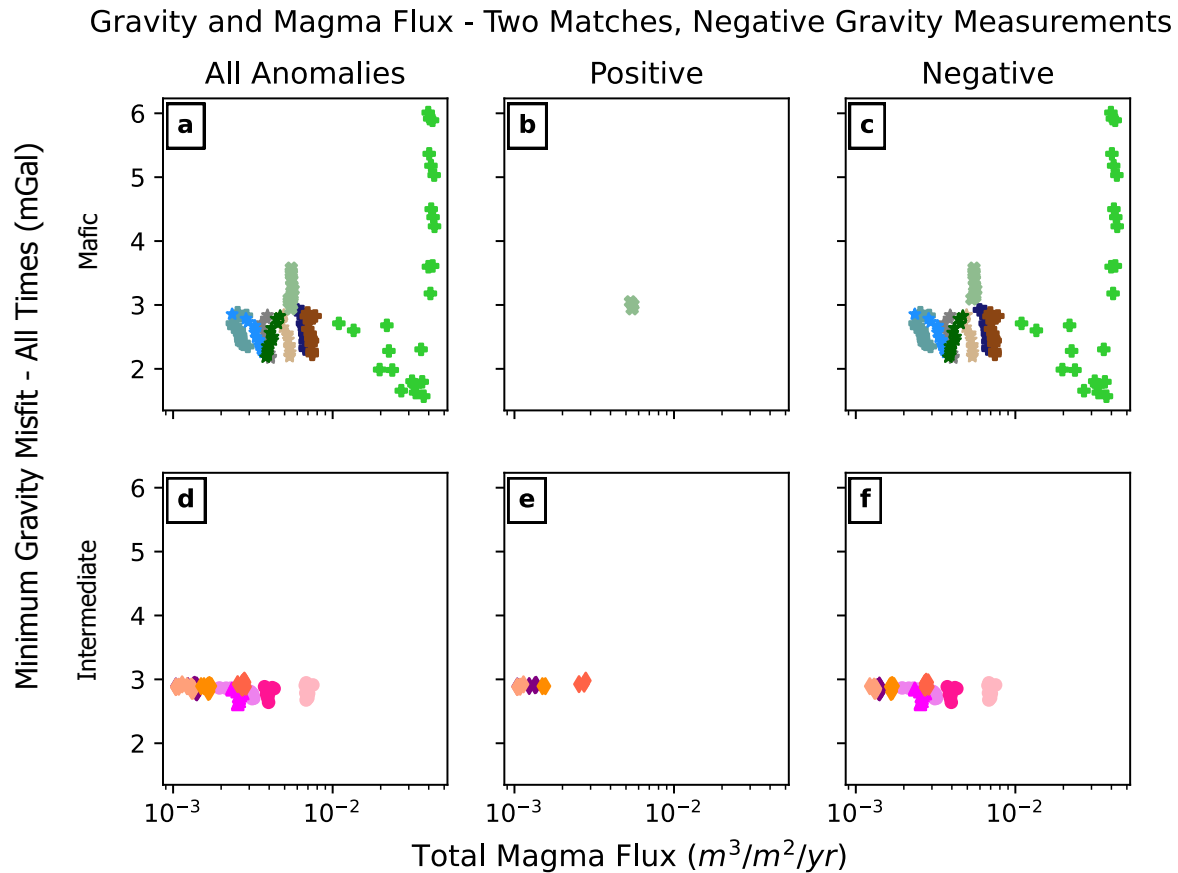


Figure B20: Gravity results for the 17 realizations that fit two modeled eruptive volume within the Three Sisters eruptive episodes when only considering the negative gravity anomaly field data. Colors throughout a-g represent a single realization and match those represented in Figure 7. By removing the positive gravity field data, the misfit calculation only considers the simulation space and the negative gravity field data, removing the model bias of the background crust 2.89 mGal misfit from flooding the calculation.

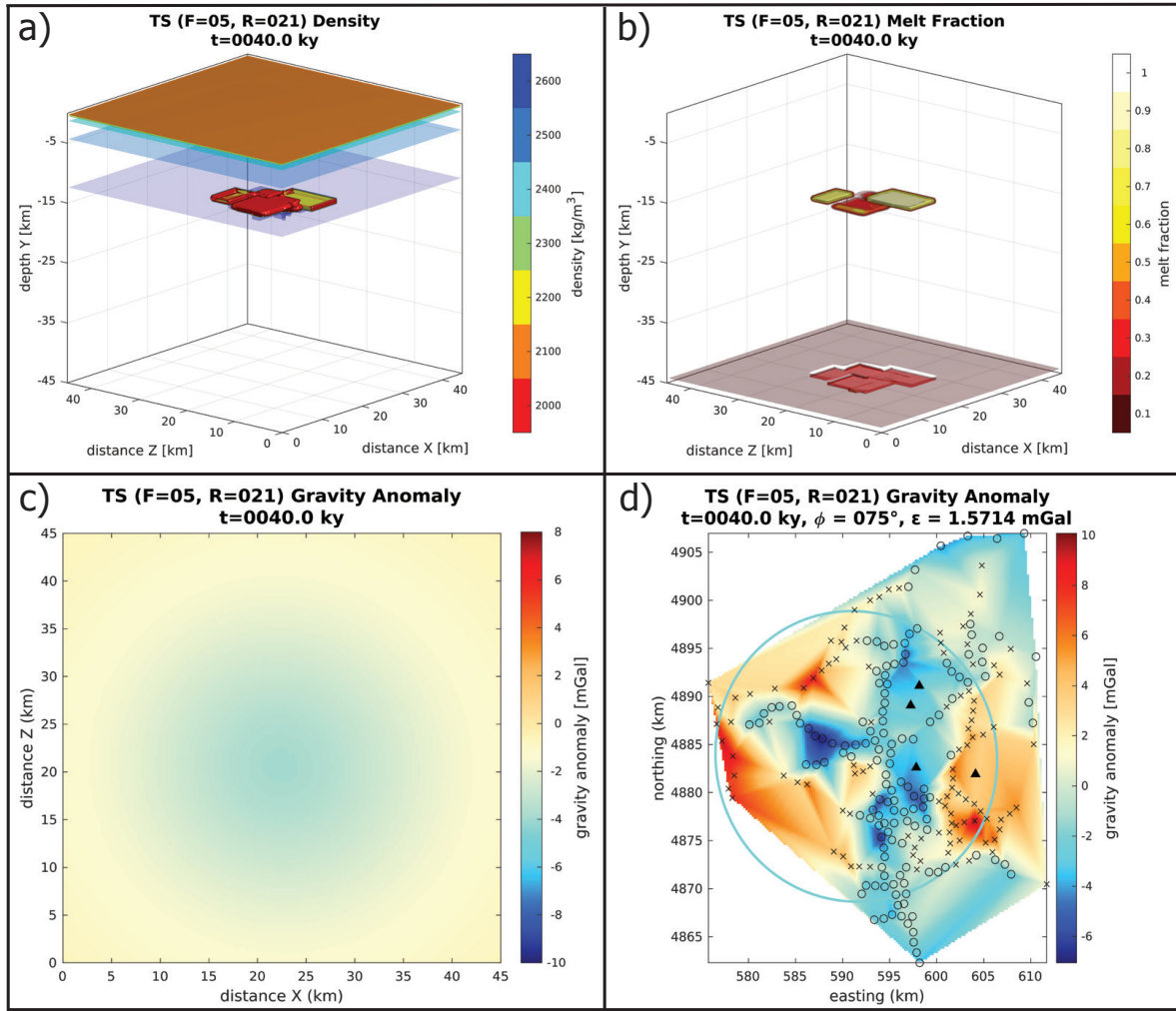


Figure B21: Snapshots of the magma dynamics outputs and forward gravity model for the lowest gravity anomaly timestep with removing the positive field gravity measurements. a) Density of the mafic intrusions. b) Melt fraction of the intrusions. There is 221.9 km³ of melt fraction > 0.005, 207.76 km³ of melt fraction > 0.1, 112.45 km³ of melt fraction > 0.4, 63.53 km³ of melt fraction > 0.6, and 0.07 km³ of melt fraction > 0.99. c) Simulated surface gravity anomaly based on the magmatic simulation. d) Comparison between the simulated and measured gravity anomalies. Circles denote field measurements used in the evaluation, Xs denote field measurements not used in the evaluation as they record positive gravity anomalies.

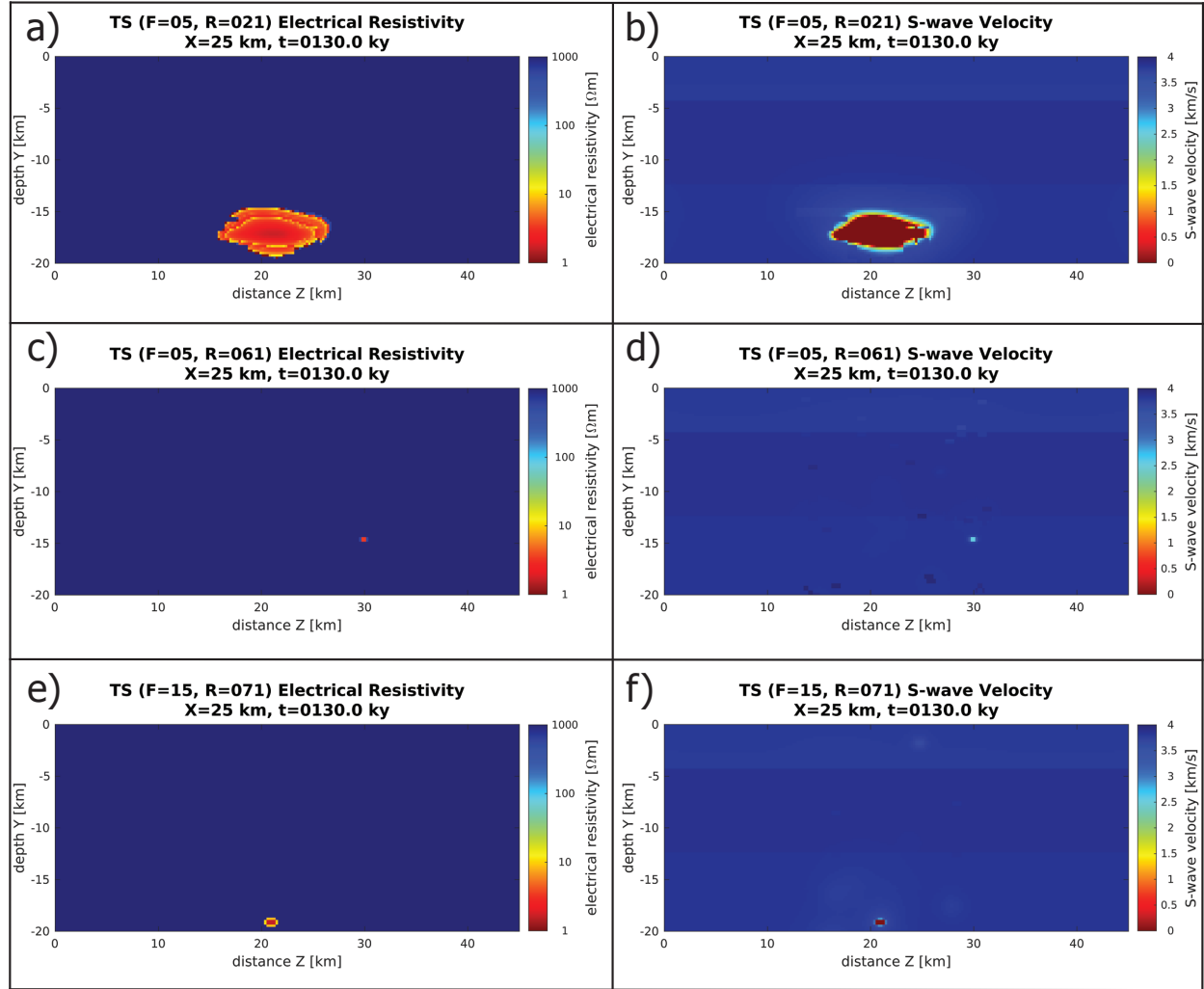


Figure B22: Example realization of electrical resistivity (a, c, e) and S-wave velocity (b, d, f) outputs based on the magmatic simulation. R021 represents the most built-up magma body of the best fit realizations. R061 and R071 are representative of most of the best fit simulations, with very few and very small anomalies where there are small pockets of melt.

APPENDIX C **SUPPLEMENTAL MATERIAL FOR CHAPTER 4**

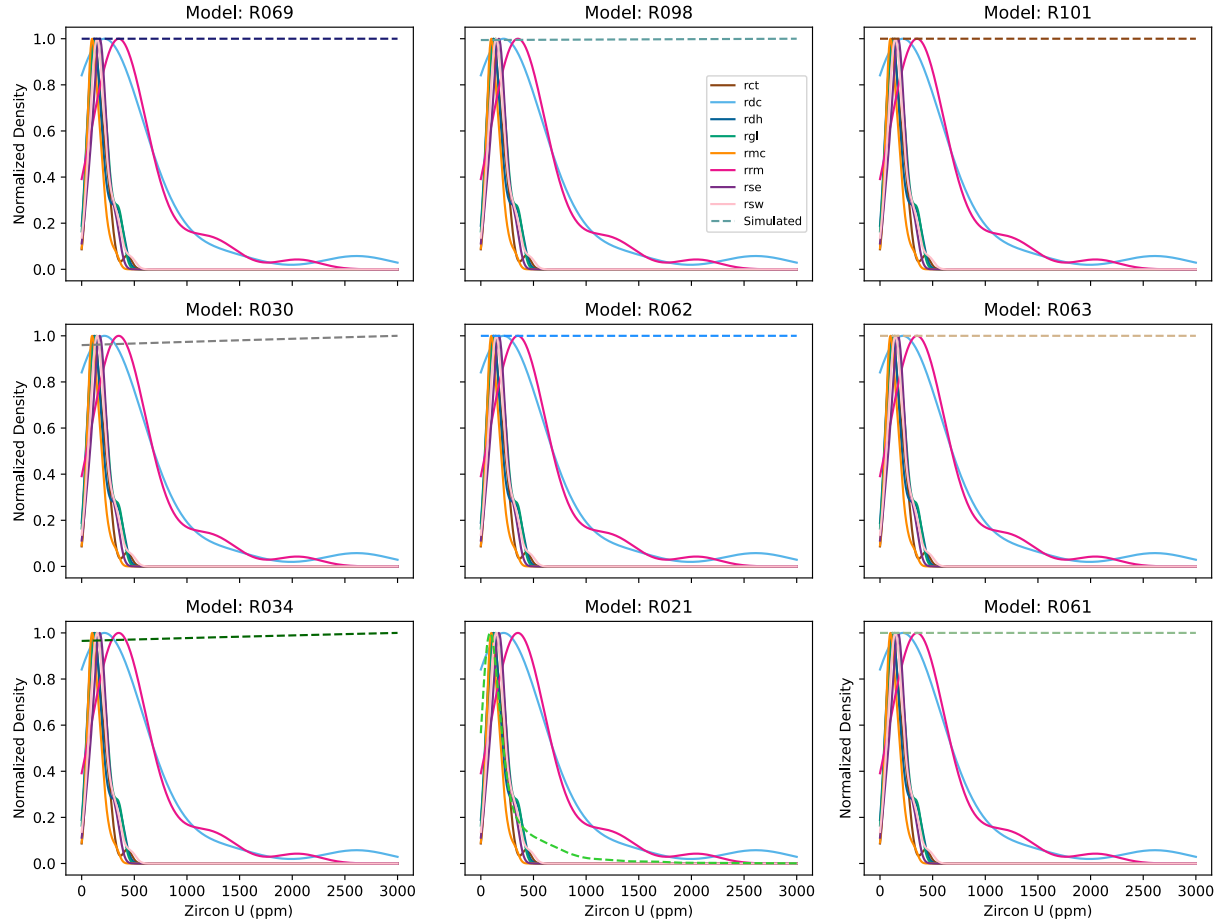


Figure C1: U ppm data for South Sister zircons and for mafic model realizations. Normalized probability density functions of the zircon population U data by unit from Dechert et al. (2024) in solid lines. Dashed line shows the U data for each model realization. The first eight realizations are formed by focused intrusions, and the final realization is formed by distributed intrusions.

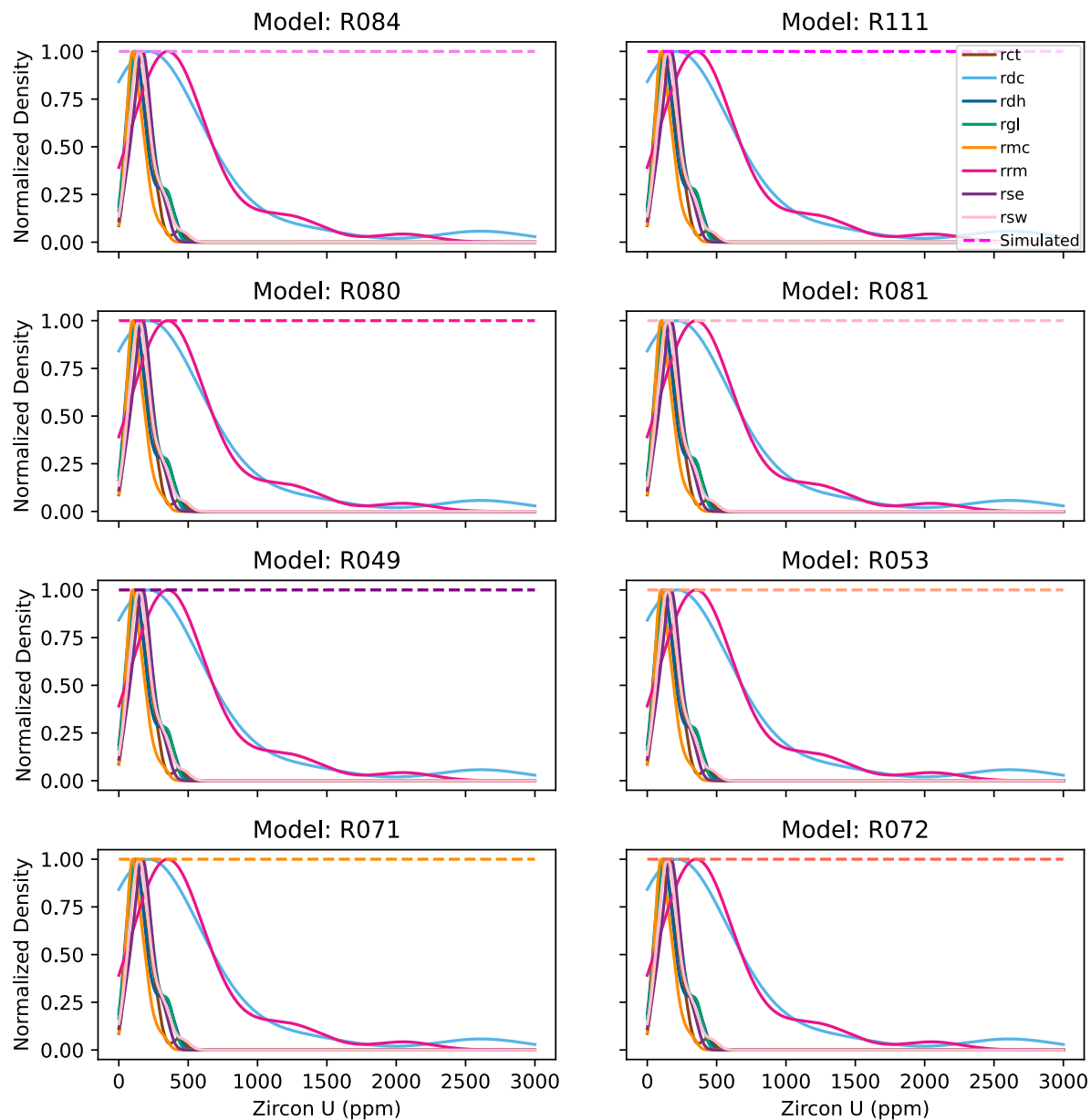


Figure C2: U ppm data for South Sister zircons and for intermediate model realizations. Normalized probability density functions of the zircon population U data by unit from Dechert et al. (2024) in solid lines. Dashed line shows the U data for each model realization. The first four realizations are formed by focused intrusions, and the final four realizations are formed by distributed intrusions.

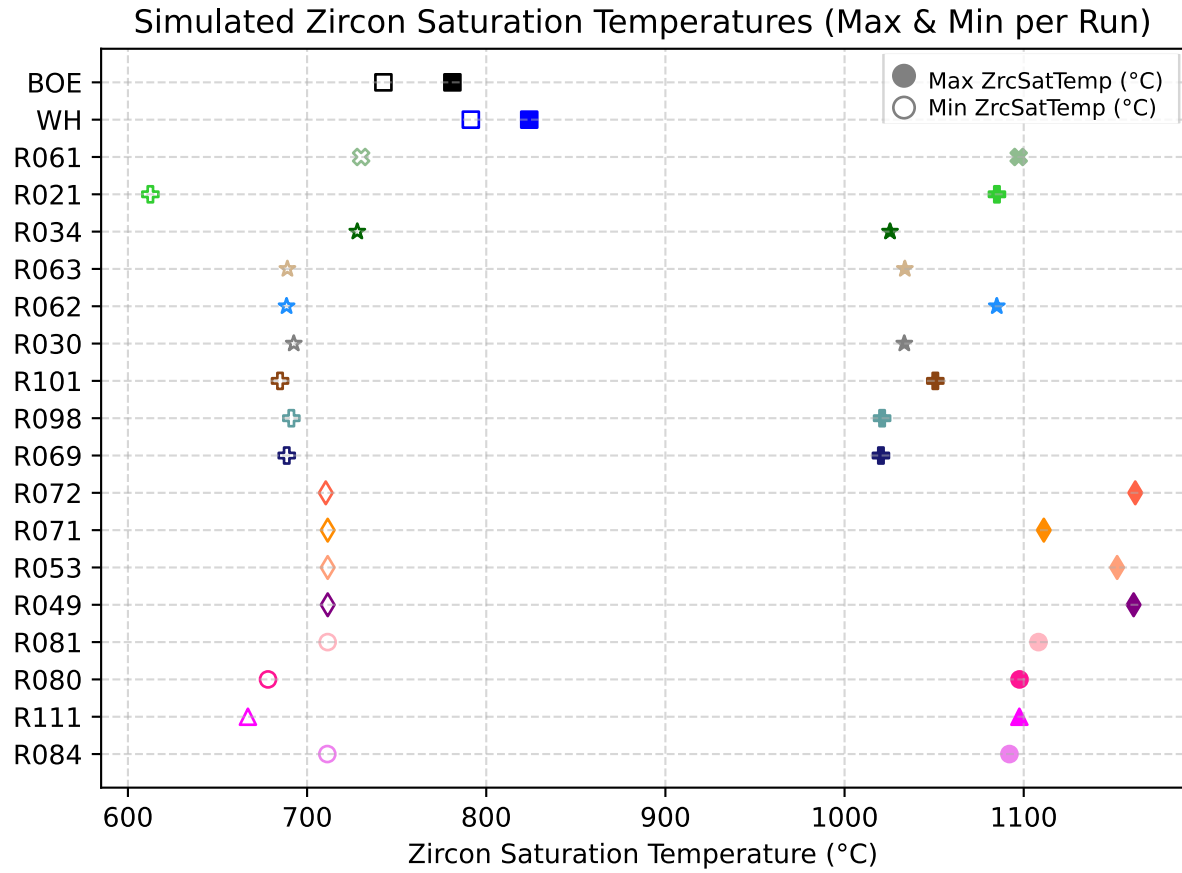


Figure C3: Zircon saturation temperatures calculated for each realization and for the zircons of Dechert et al. (2024). Filled symbols show the maximum, and open symbols show the minimum calculation. Realization zircon saturation temperatures calculated via Watson and Harrison (1983) for magma above 0.6 melt fraction. Symbology for the realizations: triangles denote explosive, intermediate, focused intrusions; diamonds denote explosive, intermediate, distributed intrusions; stars denote explosive, mafic, focused intrusions; Xs denote explosive, mafic, distributed intrusions; circles denote effusive, intermediate, focused intrusions; pluses denote effusive, mafic, focused intrusions. Squares denote natural sample calculations via Watson and Harrison (1983) as well as Boehne et al. (2013), which is the preferred method of Dechert et al. (2024) given the Ti-in-zircon temperature calculations for the units.

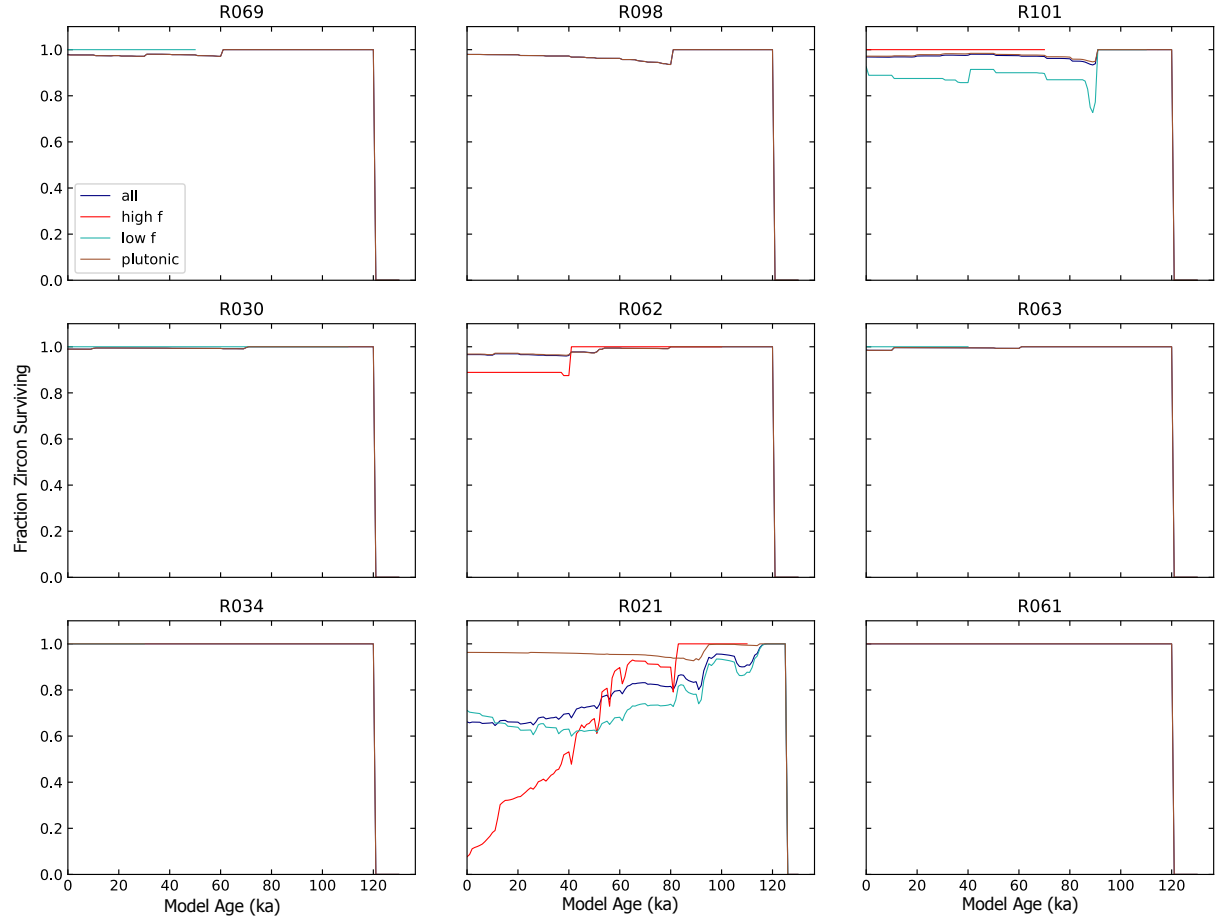


Figure C4: Zircon survivability for the mafic model realizations. Blue denotes all magma greater than 0.05 melt fraction, red denotes all magma greater than 0.6 melt fraction, teal denotes between 0.05-0.6 melt fraction, and brown shows the solidified magma. The first eight realizations are formed by focused intrusions, and the final realization is formed by distributed intrusions.

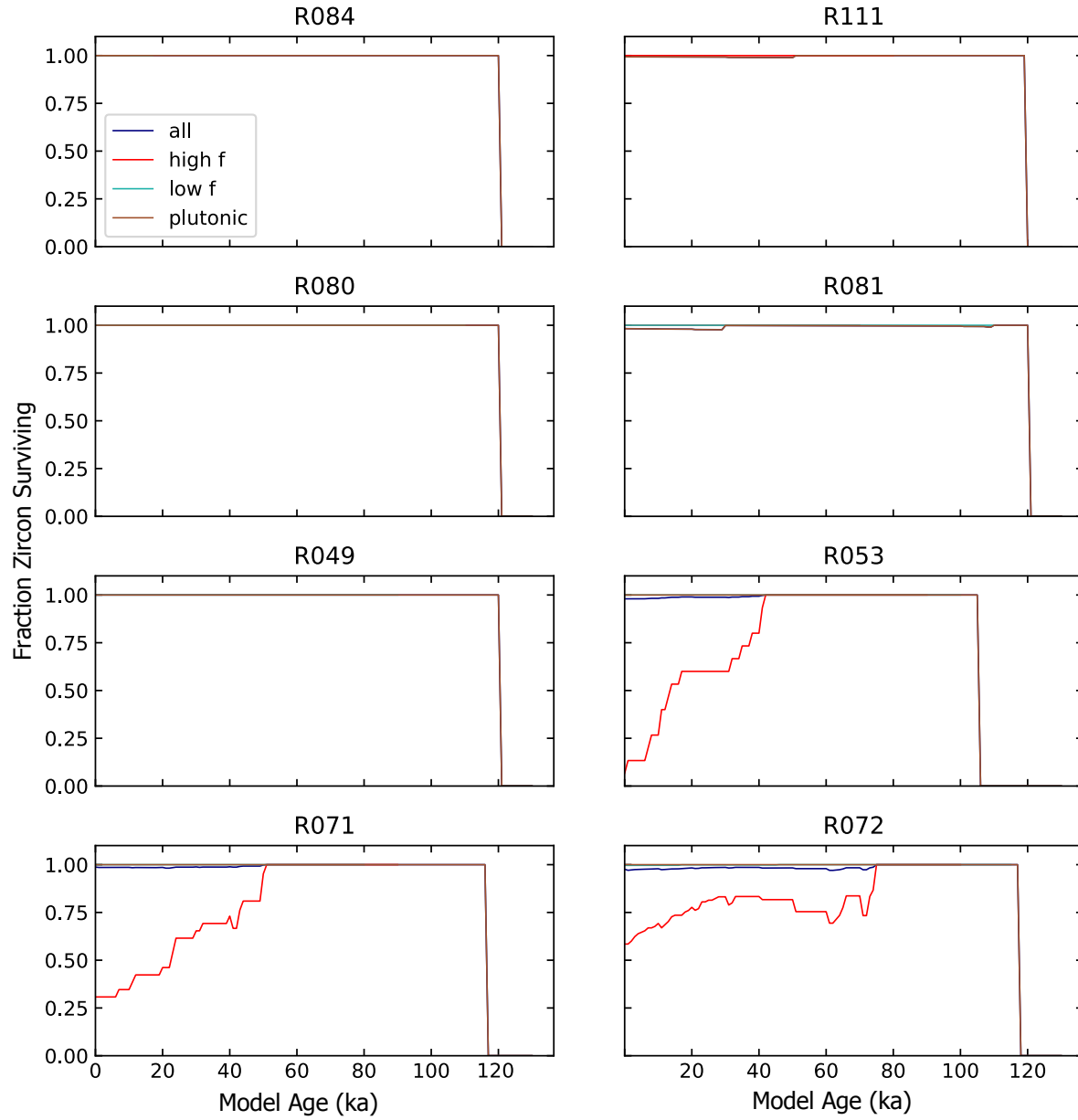


Figure C5: Zircon survivability for the intermediate model realizations. Blue denotes all magma greater than 0.05 melt fraction, red denotes all magma greater than 0.6 melt fraction, teal denotes between 0.05-0.6 melt fraction, and brown shows the solidified magma. The first four realizations are formed by focused intrusions, and the final four realizations are formed by distributed intrusions.

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