

Subduction and rift processes: Their effects on mantle heterogeneities and magmatism at the Antarctic Peninsula and surrounding mid-ocean ridges

by

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Dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in the Department of Earth, Environmental and Planetary Sciences
at Brown University

Providence, Rhode Island

May, 2024

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EPIGRAPH

For the less even as for the greater there is some deed that he may accomplish but once only; and
in that deed his heart shall rest.

—J. R. R. Tolkien, *The Silmarillion*

ACKNOWLEDGEMENTS

I am not exaggerating when I say these past years working towards this degree have been some of the most painful, unpleasant, and difficult in my life. I have encountered some of the greatest losses, heartbreaks, conflicts, and challenges that I hope I will face, and yet scattered throughout these arduous years are some of my hardest laughs and strongest emotional recoveries. I have learned a lot in my time at Brown, but among the greatest lessons was that there will never be anything more important to me than the people who helped me reach those high points. You are collectively my family, and whether you know how you have inspired my success and perseverance or not, I love you, and I thank you.

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INTRODUCTION

Decades of studying the Earth's mantle have revealed that it has experienced a long and complex history of differentiation, mixing, melt extraction, and recycling of surface material (e.g., Hofmann, 1988; Stolper and Newman, 1994; McDonough and Sun, 1995). Many of these processes are ongoing today, although their effects on the structure, composition, and evolution of the mantle are debated and challenging to deconvolve. One of the most significant of these processes is subduction, which has long been invoked to explain the origins of Earth's heterogeneous mantle and the continental crust (Hofmann and White, 1982; Zindler and Hart, 1986; Hofmann, 1988; Workman et al., 2004). The injection of fluids, sediments, crust, and lithospheric mantle into the convecting mantle at subduction zones is expected to have substantial and long-term geochemical impacts on the mantle. Yet, we still struggle to quantify many of these impacts. Geophysical observations provide critical constraints on the physical structure of subduction zones today but offer little insight into mantle composition and evolution on a geologic timescale. Direct sampling of the upper mantle is not possible, so melts derived from the upper mantle remain our best means to understand subduction's influence on mantle geochemistry and evolution.

The South Shetland subduction zone in the northern Antarctic Peninsula is the site of abundant and well-sampled magmatism with the ideal characteristics to investigate many outstanding subduction-related questions. The majority of lavas from the region are basaltic, indicating that they have not undergone extreme differentiation or assimilation. Furthermore, the overlying is relatively thin compared to most subduction zones, which largely occur in continental environments. Thus, melts have less opportunity to be affected by shallow level secondary processes upon ascent. Many of the samples are also submarine and glassy, allowing

us to measure the volatile contents of melts from the region, which have important controls on mantle melting and magma crystallization, especially at subduction zones. Furthermore, the diversity of their geochemistry indicates the presence of a heterogeneous mantle that has been variably affected by subduction processes (Fretzdorff et al., 2004). This paired with comprehensive melt sampling both along-trench and across-trench allows us to evaluate broad spatial variations in the extent to which recycled sediments and fluids permeate the upper mantle. The geochemical diversity of these lavas is also key to identifying the major compositional mantle endmembers of the region, both today and in the past. Most lavas from the back-arc region erupted within the last ~6 Myr, offering a near-present glimpse into the region's mantle (e.g., Barker, 1982; Kristjánsson et al., 2005; Pańczyk and Nawrocki, 2011). By contrast, lavas from the volcanic front have been age dated and range from 140 Ma to the present, allowing us to assess the mantle's geochemical evolution with time. Finally, two mid-ocean ridges neighbor the subduction zone, providing essential “baseline” compositions for a present-day local upper mantle that has not been affected by subduction processes. This is critical in quantifying the extent to which subduction has modified the region's mantle.

Since the Paleozoic formation of Gondwana, the region that today makes up the Antarctic Peninsula has been dominated by subduction processes (Nelson and Cottle, 2019). At the time, West Antarctica composed a substantial portion of the paleo-Pacific margin of Gondwana, and even as the supercontinent began to separate near the end of the Mesozoic, the Phoenix Plate continued subducting beneath the peninsula at what was becoming the South Shetland subduction zone (Barker, 1982; Dalziel et al., 2013; Eagles and Jokat, 2014). The modern Bransfield Strait back-arc had not yet formed, and the volcanic front extended along much more of the peninsula than what remains of it today as the South Shetland Islands. As South America

continued to separate from West Antarctica through the end of the Mesozoic and early Cenozoic, the Drake Passage opened in the area between, initiating a second, smaller eastward-dipping subduction zone known as the Ancestral South Sandwich subduction zone (predecessor to the modern South Sandwich subduction zone) and early spreading of the West Scotia Ridge (Eagles, 2010; Maldonado et al., 2014). Spreading at the ridge, paired with the rapid eastern migration of the Ancestral South Sandwich Arc, produced a broad loop of predominantly submarine ridges and troughs north of the Antarctic Peninsula known today as the Scotia Arc (not to be confused with a volcanic arc), consisting of the Scotia and Sandwich Plates (Eagles, 2010; Maldonado et al., 2014). Over this same period, the Phoenix Plate continued to subduct beneath the Antarctic Plate, bringing the Phoenix mid-ocean ridge at its western boundary closer to the trench. By 50 Ma, the southernmost segment of the Phoenix Ridge had reached the trench, marking the first of a series of ridge-trench collisions that lasted until ~4 Ma (Barker 1982; Hole et al., 1995; Hole, 2021). As the trailing half of each segment remained fixed at the trench, its corresponding half continued to subduct, producing a broadening window in the mantle beneath the region where there was no slab (Hole, 1990; Hole et al., 1991; Hole et al., 1995; Guenthner et al., 2010; Hole, 2021). Today, this slab window extends northwards along the peninsula up to the Hero Fracture Zone, where the surviving portion of the Phoenix Plate remains. There are three segments of the Phoenix Ridge that failed to reach the trench, and this is likely due to concurrent slowdown of both spreading at the ridge and convergence at the subduction margin, on account of this series of collisions (Livermore et al., 2000; Haase et al., 2011). It is debated whether the South Shetland subduction zone remains active today, but seismic evidence suggests that subduction continues, although extremely slowly (Jordan et al., 2020; Leat and Riley, 2021a and 2021b). Following the final ridge-trench collision ~4 Ma, the Phoenix Slab likely steepened to its present

angle of $\sim 70^\circ$ (Park et al., 2012; An et al., 2015). The limits of the Bransfield Strait back-arc roughly coincide with the modern extent of the trench, suggesting that the strait opened through lithospheric thinning in response to this roll-back within the past ~ 4 Myr (e.g., Barker, 1982; Haase and Beier, 2021). This recent thinning may also explain why the modern volcanic front, the South Shetland Islands, is offset to the northwest from the main peninsula. As subduction slowed to nearly a halt following the final ridge-trench collision, geochemically unique, “post-subduction” alkaline lavas began erupting broadly along the Peninsula. This coincidence has led many workers to hypothesize that the magmatism was triggered by the combined slowdown of subduction and inflow of fresh sub-slab asthenosphere through the wide slab window (e.g., Hole et al., 1993; Hole et al., 1995). Today, the modern South Shetland subduction zone consists of the South Shetland Islands volcanic front and a series of back-arc extensional features at progressive distances from the trench: The Bransfield Strait, the Prince Gustav Rift, and the Larsen Rift. Melts from these areas, along with the neighboring Phoenix and West Scotia Ridges allow us to better understand the geochemical history and evolution of the region.

Many workers have struggled to explain the geochemical diversity of magmas erupted across a relatively short space and time in the Antarctic Peninsula. Within the past ~ 6 Myr, mid-ocean ridge basalts ranging from N-MORB to E-MORB, arc-like lavas with signs of widely variable subduction modification, and alkali basalts with no clear evidence of subduction influence, have all erupted throughout the region. Much this geochemical diversity correlates spatially, adding an additional facet of complexity to this problem. Equally complicated is the northeastward progression of magmatism occurring from 140 to 30 Ma along the South Shetland Islands volcanic front, which also appears to correspond to a transition in melt geochemistry (Haase et al., 2012; Leat and Riley, 2021b). The diversity of melts from the region suggests a

geochemically complex mantle, the origins of which have inspired numerous hypotheses – variable fluxing of the mantle wedge, changes to the flux composition with time, melting of metasomatized veins within the lithospheric mantle, melting of the slab itself, melting of upwelling sub-slab asthenosphere, and even the presence of a plume. (e.g., Hart et al., 1995; Fretzdorff et al., 2004; Haase et al., 2012; Hole, 2021).

Additionally problematic is the lack of volatile data for the region, despite many previous studies invoking them to support the aforementioned hypotheses. Volatiles in magmatic systems have significant impacts on the extent of mantle melting, melt composition, and magma differentiation (Stolper and Newman, 1994; Asimow and Langmuir, 2003; Katz et al., 2003). Additionally, measured volatile contents provide key insights into the sources and histories of their host melts. For instance, H₂O and CO₂ contents can be used to model melt saturation pressures –useful measures of magma storage depths in the crust and indicators of whether samples were collected in-situ (Stolper and Newman, 1994; Dixon and Stolper, 1995; Wieser et al., 2022). We can also use H₂O and Cl to identify the effects of hydrothermal alteration and assimilation of hydrothermally altered crust on melt compositions (e.g., Shimizu et al., 2016). Furthermore, variations in fO_2 may be inferred from S contents (e.g., Hughes et al., 2023). It is also expected that the volatile contents of various mantle reservoirs will differ, and this difference should be expressed in the volatile contents of their melts (Peslier et al., 2017). Particularly in a subduction zone, where there is a heavy supply of fluids from the downgoing slab, the lack of volatile data is a significant omission.

Another complication is that many of the “post-subduction” alkali basalts from across the Antarctic Peninsula may have actually erupted before subduction slowed to its present speed (Hole, 2021). Prior workers suggested these melts formed from upwelling asthenosphere through

the widening slab window to the southwest (e.g., Hole et al., 1995; Barker and Austin, 1998). However, there is no clear progression of magmatism associated with the propagation of the slab window over time (Hole, 2021). These basalts are geochemically unique, with enriched trace element and isotope compositions showing no clear signs of subduction influence, despite erupting in conjunction with arc-like lavas across the back-arc of a region with a 150 Myr history of subduction (Fretzdorff et al., 2004; Košler et al., 2009; Leat and Riley, 2021b). Furthermore, alkaline melts with nearly identical isotope compositions have been recovered across the subduction margin at the Phoenix Ridge, demonstrating that the source of these alkali basalts is more widespread than previously thought (Choe et al., 2007; Choi et al., 2008). There remain a great number of uncertainties surrounding these lavas, and their origins continue to lack a satisfying explanation.

These are the main outstanding problems that I aim to address in the three chapters of this thesis using a combination of geochemical and numerical tools. The data collected for this thesis significantly expand the geochemical dataset for lavas in the region, improving our resolution into their compositional differences and the mantle sources and processes they represent.

Chapter 1, referred to subsequently as Anderson et al. (2023), presents new major and trace element contents for a suite of over 100 glassy submarine lavas from the Bransfield Strait back-arc, the Phoenix Ridge, and the West Scotia Ridge. Additionally, this chapter reports radiogenic isotope data (Sr, Nd, Hf, and Pb) on select lavas from this suite and new trace element and Pb isotope data for sediments from atop the Phoenix Plate today. Results from this chapter indicate a recent, large-scale eastward flow of mantle from the Pacific into the regions beneath the Antarctic Peninsula and West Scotia Ridge. Geochemical similarities between melts from the East Pacific Rise, the Phoenix Ridge, and the West Scotia Ridge support that Pacific MORB

mantle has flowed into the Drake Passage and Scotia Sea. Furthermore, spatial correlations with geochemistry along the length of the Bransfield Strait back-arc reveal that this eastward flow of MORB mantle also extended into the mantle wedge of the South Shetland subduction zone – lavas at the edges of the back-arc have compositions similar to MORB from the Phoenix Ridge, whereas lavas near the center of the back-arc show the strongest geochemical signs of subduction influence. This suggests that sub-slab asthenosphere is flowing toroidally around the edges of the slab, diluting the effects of subduction processes on the borders of the mantle wedge, and focusing the most subduction-modified portions of the mantle wedge toward its center.

Assuming that the mantle wedge represents mixtures of Phoenix Ridge-like depleted MORB mantle and a subduction component comprised of fluids and sediments, Monte Carlo simulations suggest Bransfield Strait back-arc lavas represent 0-3% addition of a subduction component with a fluid/sediment ratio of ~ 1 to the Phoenix Ridge upper mantle. By comparison, our modeling suggests South Shetland Islands volcanic front lavas represent $\sim 3\%$ addition of a subduction component with a fluid/sediment ratio ranging from ~ 0.18 -4 to a slightly more depleted MORB mantle. This range in fluid/sediment ratios corresponds to a spatiotemporal progression of volcanism at the volcanic front from the southwest (40–140 Ma) to the northeast (30–60 Ma), and it suggests that as this pulse of magmatism migrated to the northeast, the composition of the subduction component became increasingly fluid-dominant.

Chapter 2, hereafter referred to as Anderson et al. (2024), presents the first ever volatile element (CO_2 , H_2O , Cl, F, S) data for Antarctic Peninsula lavas, collected on the same suite of ~ 100 submarine glassy lavas. Having identified the geochemistry and distribution of the major mantle components in the northern Antarctic Peninsula in Anderson et al. (2023), we attempt to characterize their volatile compositions. The results reveal that increasing trace element and

isotope enrichment in Phoenix Ridge lavas corresponds to increasing volatile enrichment, which, combined with published lava ages and ridge spreading rates, suggest that as spreading slowed, less abundant but more fertile, volatile-rich enriched MORB mantle preferentially melted and increasingly dominated the compositions of the lavas. In the back-arc, increasing subduction signal corresponds to increasing volatile enrichment, and this relationship follows the same spatial expression as discussed in Chapter 1. Areas near the edges of the strait, which are in the most direct contact with toroidally inflowing sub-slab asthenosphere have the most MORB-like volatile compositions. A few lavas from the back-arc have strong subduction signals in their trace element compositions but have comparatively low volatile contents. Based on their distinct trace element compositions and isotopic similarities to the abundant alkaline magmas found across the Antarctic Peninsula, we speculate that these lavas represent flux melting of residual enriched mantle that remained following recent alkaline magmatism east of the Bransfield Strait, which was subsequently dragged beneath the back-arc via corner flow and fluxed. We also use the new volatile data reported in this chapter to estimate mantle potential temperatures beneath the Phoenix Ridge and Bransfield Strait, and the results agree well with global ranges for mid-ocean ridges and subduction zones, respectively. Also presented in this chapter are new major, trace, and volatile element data and radiogenic isotope ratios for a set of lavas from the W7 segment of the West Scotia Ridge that show strong signs of subduction influence. Newly revealed geochemical similarities between W7 lavas and those of the South Sandwich Arc suggest they sample a mantle component left behind by the arc as it migrated eastwards over the past ~30 Myr.

Chapter 3, subsequently referred to as Anderson et al. (*in prep*), focuses on the seemingly ubiquitous Cenozoic alkaline magmatism spanning the length of the Antarctic Peninsula,

historically considered to be “post subduction.” Major and trace element data collected on a combination of whole rock and glass samples are reported for 10 lavas from James Ross Island and 32 lavas from the Seal Nunataks. In addition, radiogenic isotope data were collected on 23 select lavas from each location. These lavas are uniquely alkaline, with trace element and isotope compositions markedly distinct from other ridge- and subduction-derived melts of the region, and lavas of comparable geochemistry have been collected broadly across the peninsula at the Phoenix Ridge, the Bransfield Strait, James Ross Island, the Seal Nunataks, and Alexander Island. We suggest that these lavas were produced during recent detachment of the lithospheric mantle, which was metasomatized within the past ~100 Myr by a combination of E-MORB and arc melts generated during West Antarctica’s long history of rifting and subduction. We apply a simple model to simulate metasomatism in support of this hypothesis, and we demonstrate how our interpretation can more broadly explain the widespread Cenozoic alkaline magmatism that has occurred across the West Antarctic continent (i.e., Peter I Island, the Jones Mountains, Mount Early, and Sheridan Bluff) and even southern Patagonia.

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CHAPTER 1

Tracing mantle components and the effect of subduction processes beneath the northern Antarctic Peninsula

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Published in *Geochimica et Cosmochimica Acta* (2023) 343, 234-249

Abstract

Understanding subduction processes is critical in assessing the long-term evolution of the upper mantle and continental crust. We present new geochemical data on glassy submarine lavas from the Bransfield Strait, the Phoenix and the West Scotia ridges, and previously unpublished data of marine sediments from atop the Phoenix Plate. We combined new and published geochemical data from across the northern sector of the Antarctic Peninsula to unravel both large-scale mantle composition and flow across the region. The geochemistry of Phoenix and West Scotia ridge basalts supports the hypothesis that both ridges are underlain by Pacific MORB mantle, brought into the region through the eastward expansion of the Scotia Plate. Comparisons among lavas from the Phoenix/West Scotia ridges, the South Shetland Islands volcanic arc, and the Bransfield Strait/Prince Gustav Rift back-arc region reveal that the Pacific upper mantle flowed into the mantle wedge and was subsequently modified by subduction processes. The compositions of Bransfield Strait lavas range from strongly subduction-influenced near the strait's center to akin to Phoenix Ridge MORB toward the strait's edges. This suggests that the Phoenix MORB mantle has flowed around the slab edges into the mantle wedge, diluting the subduction signal and focusing the subduction-modified mantle towards the center of the strait. Monte Carlo simulations indicate that mixing of Phoenix MORB mantle with 0 to 3% subduction component having a fluid/sediment ratio of ~ 1 can explain the compositional range in the Bransfield Strait. Furthermore, our modeling suggests the presence of a more depleted Phoenix MORB mantle beneath the South Shetland Islands modified by the addition of $\sim 3\%$ subduction component with a fluid/sediment ratio ranging from ~ 0.18 to 4. The increase in fluid/sediment ratios in the South Shetland Island lavas corresponds to a spatiotemporal progression of volcanism from the southwest (40-140 Ma) to the northeast (30-60 Ma). Finally, we have identified a set of lavas with

unique trace element and isotope compositions typical of alkaline volcanism found across other parts of the Antarctic Peninsula. Surprisingly, we find occurrences of these lavas on both sides of the South Shetland Trench, suggesting the presence of a distinct enriched source in the upper mantle throughout the region.

1. Introduction

Assessing the long-term evolution of Earth's upper mantle and continental crust hinges on our understanding subduction processes. However, there is no way to quantify these effects without being able to first infer the composition of the mantle wedge unaffected by subduction, an issue that has led previous researchers to work in back-arc basins further from the trench (e.g., Stolper and Newman, 1994; Pearce et al., 2005; Langmuir et al., 2006). Back-arc regions are characterized by much lower subduction fluxes, inhibiting the formation of large magma chambers associated with MASH (melting, assimilation, storage, homogenization) processes (Hildreth and Moorbath, 1988) typical of volcanic front regions and limiting the overwhelming subduction effects that would obscure the geochemical signals inherent to the mantle wedge itself.

Most studied arcs and back-arc basins are either in continental environments or located far from mid-ocean ridges. However, this is not the case for the South Shetland subduction zone in the northern Antarctic Peninsula. There, we can utilize lavas from the South Shetland Islands volcanic front, the Bransfield Strait and Prince Gustav Rift back-arc extensional features, and the neighboring Phoenix mid-ocean ridge to assess the influences of subduction processes on the upper mantle (Fig. 1.1). The relatively young ages (~6 Ma) of most of these lavas offer a near-current glimpse into the mantle beneath the region. Furthermore, the basalts from the Phoenix Ridge provide a geochemical endmember that we can use as a “background” mantle composition

unaffected by subduction processes. Comparing the geochemical compositions of the lavas along a transect from the Phoenix Ridge to the Prince Gustav Rift not only allows us to identify different mantle endmembers in the region but also to assess variations in the effect of subduction flux on the upper mantle with increasing distance from the South Shetland Trench.

Here we present new major and trace element contents, and radiogenic isotope data (Sr, Nd, Hf, and Pb) on selected submarine lavas from the Bransfield Strait, Phoenix Ridge, and two samples from the nearby West Scotia Ridge, as well as unpublished trace element and Pb isotope data from sediment core GC05-DP02, collected atop the Phoenix Plate near the trench (Fig. 1.1). We combine the new data with those already published for lavas from the South Shetland Islands to evaluate the mantle composition and the effect of subduction processes across the northern Antarctic Peninsula.

2. Geologic Background

Our region of study represents a transect across the northern Antarctic Peninsula that extends from the Phoenix mid-ocean ridge through the South Shetland subduction zone, consisting of a volcanic front and a series of back-arc regions (Fig. 1.1). Additionally, somewhat north of the transect lies the West Scotia mid-ocean ridge, which we use as an auxiliary point of comparison in this study.

2.1 The South Shetland Subduction Zone

The southeastward subduction of the Phoenix Plate beneath the Antarctic Plate has been ongoing along the Antarctic Peninsula since the Mesozoic, and seismic evidence supports that subduction continues, though slowly, in the present (Larter et al., 2002; Robertson Maurice et al.,

2003; Jordan et al., 2020; Leat and Riley, 2021a and 2021b). Today, the South Shetland Trench marks the modern subduction margin, and southeast of the trench, the South Shetland Islands form the modern volcanic front (Fig. 1.1). Published ages indicate the South Shetland Islands experienced a prolonged episode of volcanism that initiated in the southwest ~140 Ma and progressed northeastwards before ceasing ~30 Ma (Pankhurst and Smellie, 1983; Haase et al., 2012; Leat and Riley 2021a). We divide the samples based on age and location between older (~40-140 Ma) southwestern lavas and younger (~30-60 Ma) northeastern lavas (Leat and Riley, 2021a). Additionally, there are isolated instances of Quaternary volcanism on Livingston Island, Penguin Island, and King George Island (Fig. 1.1b).

The South Shetland subduction zone is also characterized by a series of back-arc extensional features, positioned at varying distances from the trench: The Bransfield Strait, Prince Gustav Rift, and Larsen Rift (Fig. 1.1b). Our primary focus is on the Bransfield Strait, which is situated nearest to the trench and is one of the most volcanically active areas in the Antarctic Peninsula today. The boundaries of the strait lie roughly parallel to what remains of the South Shetland Trench today, which reached its present extent ~4 Ma (Barker, 1982; Fig. 1.1). For this reason, lavas from the Bransfield Strait are expected to have erupted over the past ~4 Ma (e.g., Barker 1982; Haase and Beier, 2021). There is no universally agreed upon explanation for how the Bransfield Strait formed. Some workers have suggested that roll-back of the subducting Phoenix Plate produced extension of the overlying lithosphere, generating the back-arc (Keller et al., 2002; Leat et al., 2021). Indeed, 3-D P- and S-wave seismic velocity models reveal a high-velocity slab at a dip angle of ~70° up to 300 km depth, possible evidence that the slab had steepened in the past (Park et al., 2012; An et al., 2015). In contrast, others have proposed that the westward propagation of the nearby South Scotia Ridge fault has progressively opened the strait

from the northeast via trans-tension (Grácia et al., 1996; Barker and Austin, 1998; Fretzdorff et al., 2004). Whatever the cause of the Bransfield Strait's inception, its well-sampled, recent magmatism offers an opportunity to study the mantle beneath the northern Antarctic Peninsula today.

2.2 The Phoenix and West Scotia Ridges

The modern Phoenix Ridge consists of three extremely slow or possibly extinct spreading segments: P1, P2, and P3, which lie northwest of the Antarctic Peninsula (Fig. 1.1). These segments are what remain of an extensive mid-ocean ridge system that was gradually consumed during a series of collisions from ~50 to ~4 Ma between segments of the ridge and the South Shetland Trench, which lie oblique to one another (Barker 1982; Hole et al., 1994; Hole, 2021). During this time, a slab window opened from southwest to northeast as the trailing half of each collided ridge segment remained locked at the trench, forming a passive margin while the down-going half continued to subduct (Hole, 1990; Hole et al., 1991; Hole et al., 1994; Guenthner et al., 2010; Hole, 2021). Spreading rates in the Phoenix Ridge began decreasing significantly until extreme slowdown or possibly extinction by 3.3 Ma (Livermore et al., 2000; Haase et al., 2011). During this period of slowdown, magmatic productivity also began to wane, though there is evidence that mantle upwelling and melting continued until more recently, as published age dates for samples collected along and near the ridge axis range to as young as 1 Ma (Choe et al., 2005; Choi et al., 2008; Haase et al., 2011).

While not the intended subject of our study, the West Scotia Ridge offers a helpful point of comparison for our work. The ridge lies to the north of the Antarctic Peninsula and began spreading ~26-30 Ma as the Scotia Plate opened towards the east (Barker 2001; Eagles, 2010;

Dalziel et al., 2013; Maldonado et al., 2014; Fig. 1.1). Spreading at the West Scotia Ridge persisted until ~6 Ma (Eagles et al., 2005; Maldonado et al., 2014; Eagles and Jokat, 2014).

3. Materials and Methods

For each sample, three to five chips of the freshest available, least crystalline, naturally-quenched submarine volcanic glass were mounted in indium and polished using diamond grit paste down to 1 μm . Multiple chips were used per sample to characterize natural variation and determine the reproducibility of the measurement. All major and trace element data were collected on the same glass chips. Corresponding isotope analyses were made on a selection of 22 samples. Only nine of those samples had sufficient glass to measure isotopes, and whole rock powders were used for the other thirteen samples. The locations of each sample dredge are listed in Supplementary Table 1.S1 and shown in Figure 1.1.

The 25 Phoenix Ridge glass samples analyzed in this study were dredged from the P3 segment and a small spreading segment between P2 and P3 during the 2001 HYDROARC (SO-155) cruise by the FS *Sonne* (Fig. 1.1b).

The 75 Bransfield Strait samples used in this study were also collected during the SO-155 cruise, in addition to cruises NBP93-1 and NBP99-4 of the RVIB *Nathaniel B. Palmer* and one sample from a 1986 “Deep Freeze” cruise by U.S. Coast Guard icebreaker *Glacier* (Fig. 1.1b). One Bransfield sample powder, 04DR-13, was analyzed only for isotopes in this study; its major and trace element data come from XRF and ICP-MS analyses presented in Fretzdorff et al. (2004).

Additionally, our two samples from the W5 segment of the West Scotia Ridge were dredged during British Antarctic Survey cruise JR77 (March 2004) on RRS *James Clark Ross* (Fig. 1.1a).

The major element analyses of our glasses were performed on the Brown University Cameca SX-100 electron microprobe. The operating conditions of the instrument consisted of 15 kV voltage, 10 nA current and either a 10 μm diameter (for fully glassy chips) or a 5 μm (partially crystallized or vesiculated chips) spot size defocused beam, calibrated against a number of natural glasses and natural and synthetic minerals. Counting times were 40 s for on peak, and half that time for backgrounds, for all elements except Na (peak, 20 s) and K (peak, 30 s). Reproducibility of the three to five chips for each individual sample was calculated, then averaged across all samples. The average reproducibility (2σ SE) for each oxide is as follows: $<0.5\%$ for SiO_2 , $<1\%$ for MgO , CaO , Al_2O_3 , and FeO_T , $<2\%$ for TiO_2 , $\sim 3\%$ for Na_2O , $<5\%$ for K_2O , $<11\%$ for P_2O_5 , and $<17\%$ for MnO . For many partially crystallized or vesiculated Bransfield Strait samples, some of these values are higher. USGS Columbia River basalt BCR-2G and USGS KN18B rhyolite glasses were used as secondary standards. The reproducibility of these standards is $<<1\%$ (2σ SE) for all elements over three analytical sessions. For most elements, our analyses deviate $<5\%$ from the values reported for Bransfield Strait and Phoenix Ridge glass chips of the same samples in Fretzdorff et al. (2004) and Haase et al. (2011).

Trace element concentrations of glasses were determined by 193 nm wavelength excimer Analyte G2 laser ablation system coupled to a Thermo Scientific X-Series II quadrupole ICP-MS at Brown University. The ICP-MS was tuned to optimize the signal on La using NIST 612 glass with a 65 μm spot and 2 $\mu\text{m/s}$ scan speed on a line. During tuning, ThO/Th was monitored and kept below 1% to minimize the oxide production, and the Th/U ratio was kept close to 1, the value of NIST 612, to minimize fractionation. Samples were analyzed with a 150 μm spot with 10 Hz repetition rate with a laser frequency of 3.78 J/cm^2 at 50% energy level. For some partially crystallized or vesiculated chips, the spot size was reduced to 85 μm . Each analysis consisted of

30 s of gas background followed by 20 s of ablation. USGS glass standards (BHVO2-G, BIR1-G, and BCR2-G) were used as calibration standards and their preferred concentrations are taken from the GeoRem database. ^{43}Ca was used as an internal standard to normalize the raw counts, which were then reduced to concentrations using a VBA-based Excel macro developed by J. Sparks, Boston University. Again, reproducibility of the three to five chips per sample was calculated, then averaged across all samples. The average reproducibility (2σ SE) obtained is better than 8% for the majority of elements. We see slight differences in K, P, and Ti data between microprobe and ICP-MS analyses, however, these offsets are not big enough to affect our interpretations.

Isotope ratios were measured on whole-rock powders or were otherwise determined using hand-picked glass chips. For the powders, about 1 g of sample was leached with 6N double distilled HCl for 1 hour at 100 °C and then rinsed with 18 M Ω water three times. During each rinsing step, samples were centrifuged to ensure the complete removal of any residual acid. Glasses were leached with cold 2.5N HCl for 30 minutes. About 100 mg of powder and glass was dissolved in a double distilled HF(3):HNO₃(1) mixture.

Ion exchange chromatography for Sr, Nd, Hf and Pb isotope analyses were performed in the PicoTrace clean lab at Brown University. All clean lab chemistry was done with double distilled acid and 18 M Ω Milli-Q water. Sr, Nd, Hf and Pb were extracted from the matrix of the same dissolved rock solution. Pb was separated first from the matrix using AG1-X8 (100-200 mesh, BIO-RAD) resin and then Hf using Ln resin (Eichrom). The remaining matrix was passed through TRU-spec resin (Eichrom) to separate Rb-Sr from REE. The Rb-Sr fraction was then passed through Sr-spec resin (Eichrom) to get a clean Sr fraction and REE fraction was passed through Ln resin (Eichrom) to get a clean Nd fraction.

Sr, Nd, Hf, and Pb isotopic compositions were measured on a Thermo Scientific Neptune Plus MC-ICP-MS at the Mass Spectrometer Analytical Facility, Brown University. Sr, Nd, Hf, and Pb were introduced in the plasma using a PFA nebulizer with a flow rate of ~50 $\mu\text{l}/\text{min}$ coupled to an APEX-IR introduction system. The mass spectrometer was equipped with an H-skimmer cone and H-sampler cone. The baseline measurement was taken at -0.5 amu for all interested masses. $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ were corrected for instrumental mass fractionation using an $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$, $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ and $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ respectively with an exponential law. The sample Pb solution was spiked with NBS SRM-997 Tl standard prior to analysis with a Pb/Tl ratio of ~4 to correct for the mass fractionation using an exponential law with a $^{203}\text{Tl}/^{205}\text{Tl} = 0.418922$. $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, and $^{176}\text{Hf}/^{177}\text{Hf}$ of samples are reported relative to NBS SRM-987 $^{87}\text{Sr}/^{86}\text{Sr} = 0.71024$, JNd-i Nd standard $^{143}\text{Nd}/^{144}\text{Nd} = 0.512115$ and JMC-475 Hf standard $^{176}\text{Hf}/^{177}\text{Hf} = 0.282160$, respectively. $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ are reported relative to the NBS 981 standard $^{206}\text{Pb}/^{204}\text{Pb} = 16.9356$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.4891$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.7006$ (Todt et al., 1996). The external precision on the ratios over the course of two years is 30 ppm for Sr (2σ) and Nd (2σ), 40 ppm for Hf (2σ) and 80 ppm (2σ) for Pb. The Sr and Pb blanks were < 50 pg, and Nd and Hf blanks were < 30 pg. The USGS reference material BHVO-1 was processed during the sample preparation and measured as a secondary standard with the same instrument set up. Its Sr, Nd, Hf and Pb isotope ratios are reported in Supplementary Table 1.S2 and are in agreement with the range of ratios reported in the GeoRem database.

Pb isotope analyses of the GC05-DP02 sediment core samples, including chemical separation and measurement on the Isoprobe-T VG54-30 multi-collector TIMS, were performed at the Korea Basic Science Institute (KBSI). For every ~15 cm length of the core, about 50 mg of powder was dissolved in a HF+HClO₄ (10:1) and HNO₃ mixture for 24 hours at 120 °C. Pb was

extracted by anion column chemistry (Dowex AG1-X8, #100-200, Cl-form) using HBr media and loaded on Re filaments with silica gel and H₃PO₄. Isotope ratios were measured in static mode by a multi-collector TIMS equipped with nine faraday cups and a Daly system. Data obtained have been checked by running Pb standards of known isotopic compositions immediately prior to sample runs and measuring ratios across temperatures ranging from 1100 °C to 1200 °C. Replicate analyses of NBS 981 gave $^{206}\text{Pb}/^{204}\text{Pb} = 16.903 \pm 0.005$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.445 \pm 0.005$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.525 \pm 0.070$ (n=30, 2 σ SE). The data are reported relative to the NBS 981 standard using the same values listed above for our lavas. Total procedural blank levels were < 300 pg. See Lee et al. (2005) for details on how the trace element data for the GC05-DP02 samples were collected.

4. Results

We separate our glass samples into groups based on tectonic setting and influence from subduction processes (Table 1). We quantify subduction influence using ratios of fluid-mobile large ion lithophile elements (LILE; e.g., Cs, Rb, Ba, K) to fluid-immobile high field strength elements (HFSE; e.g., Nb, Ta, Hf, Ti) (e.g., Kogiso et al., 1997; Kessel et al., 2005; Rustioni et al., 2021). These ratios are hereafter referred to as “subduction signal.” We have identified four main compositional groups in our data as follows. 1) *MORB* from the Phoenix and West Scotia ridges, which have no subduction signals and compositions consistent with published MORB (e.g., Workman and Hart, 2005; Stracke, 2012; Shimizu et al., 2016; Mallick et al., 2019). 2) *Strong Arc lavas* from the Bransfield Strait with the strongest subduction signals. 3) *Weak Arc lavas* from the Bransfield Strait with weak subduction signals; we note that the cutoff between the Weak and Strong Arc groups is arbitrary, since these lavas form a compositional continuum between Strong

Arc lavas and MORB. The distinction allows us to more easily visualize differences in the degree of subduction influence throughout the Bransfield Strait. 4) Rare alkaline lavas from the Bransfield Strait carrying no clear subduction signals, with compositions analogous to alkaline lavas from across the region, which we collectively refer to as the *Antarctic Peninsula Alkaline Volcanic group (APAV)* (e.g., Hole, 1990; Košler et al., 2009; Hole, 2021; Panter et al., 2022; Table 1). We find that APAV-type lavas are present on both sides of the South Shetland Trench, occurring at the Phoenix Ridge (Choe et al., 2007; Choi et al., 2008), the Bransfield Strait (Fretzdorff et al., 2004), and James Ross Island (Košler et al., 2009). Here, we report data for our Bransfield Strait APAV samples, but we do not speculate on their genesis, as it is the focus of our ongoing research.

Isotope ratios of one highly differentiated Strong Arc sample, 03DR-7 (MgO = 0.53 wt. %), were measured to test the potential effect of assimilation-fractional crystallization processes on the compositions of these lavas. This sample shares a similar range in isotope ratios to high-MgO Strong Arc samples. This is also the case for differentiated samples from Fretzdorff et al. (2004). This suggests that their major element and incompatible trace element compositions are mainly controlled by crystal fractionation rather than crustal contamination. Although all Bransfield Strait data are presented in Figures 1.2 and 1.3 and Supplementary Table 1.S1, data in all other figures are filtered for samples with MgO > 3.0 wt. %.

Fretzdorff et al. (2004) identified a set of lavas in the Bransfield Strait with similar incompatible trace element and isotope compositions to those from the South Shetland Islands, which they named the Gibbs group. These lavas were thought to represent melts from an extinct and since-collapsed portion of the volcanic front. However, we do not consider Gibbs group lavas in this study since nearly all of them have MgO contents < 3.0 wt. % and were noted to be more weathered than other lavas from the Bransfield Strait.

4.1 Major Elements

Our samples cover a range of compositions and alkalinity (Figs. 1.2 and 1.3). We evaluate alkalinity using the boundary between alkaline and subalkaline compositions defined by MacDonald and Katsura (1964; Fig. 1.3). We quantify vertical deviations from this boundary in total alkali versus silica diagrams as Δ alkalinity, and the equation we use to calculate Δ alkalinity is shown in Figure 1.3a. The MORB data extend between basalt and trachybasalt, and the most alkaline MORB have very high concentrations of Na_2O , TiO_2 , K_2O , and P_2O_5 (Fig. 1.2). APAV lavas, which range between basalt, trachybasalt, and basanite, are also very enriched in these oxides, but in contrast to the alkaline MORB, they range to low SiO_2 and CaO contents (Fig. 1.2-1.3). Although Phoenix Ridge APAV lavas have major and trace element contents similar to our alkaline MORB, as we show below, their isotopic compositions indicate a distinct mantle source that justifies their grouping as APAV. Strong and Weak Arc lavas extend between basalt and rhyolite, though after filtering for $\text{MgO} > 3.0$ wt. %, most samples evaluated are basalts and basaltic andesites. Decreasing subduction signal correlates with higher Δ alkalinity, and the most alkaline, least subduction-modified Bransfield Strait lavas were collected at the NE and SW edges of the strait. In contrast to our alkaline MORB and APAV lavas, Strong Arc lavas have the lowest concentrations of Na_2O , TiO_2 , and P_2O_5 and the highest concentrations of SiO_2 at comparable MgO contents (Fig. 1.2). Weak Arc lavas have largely intermediate major element compositions between the Strong Arc and MORB samples. Published South Shetland Island samples have major element compositions that overlap with those of the Bransfield Strait Strong Arc lavas; however, South Shetland Island lavas range to higher Al_2O_3 and CaO and lower Na_2O , TiO_2 , K_2O , and P_2O_5 . These differences may be produced by plagioclase accumulation in the South Shetland Island

whole rock analyses, which we are comparing to Bransfield Strait glass analyses. Moreover, there is no clear separation within the South Shetland Island major element data based on location or age, though the Quaternary lavas are generally more primitive (Fig. 1.2).

4.2 Trace Elements

MORB from both the Phoenix and West Scotia ridges have very similar primitive mantle normalized incompatible trace element patterns, sharing negative anomalies in K and Pb typical of MORB. These lavas range in their levels of trace element enrichment, extending between N-MORB and E-MORB, and they have relatively flat HREE patterns (Fig. 1.4). A few of the most alkaline enriched MORB may have slightly negative HREE patterns, indicative of garnet in their source residues, but this is unclear.

Together, Weak and Strong Arc lavas form a geochemical continuum between MORB and the strongly subduction-modified South Shetland Island lavas (Fig. 1.4 and 1.5). Strong Arc lavas have strong subduction signals, and their trace element patterns are characterized by strongly negative Nb and Ta anomalies, very strong positive Pb and Sr anomalies, and overall enrichments in LILE. Weak Arc lavas have moderate to low subduction signals in their trace element patterns, possessing small but noticeable negative anomalies in Nb and Ta and positive anomalies in Pb. Both groups have flat HREE patterns.

APAV lavas have unique, though less easily defined trace element patterns. Their overall trace element concentrations are similar to our enriched MORB samples at a similar range in MgO, though they generally have smoother, less distinct positive anomalies in Nb and Ta, weak or no negative K anomalies, and somewhat steeper HREE patterns (Fig. 1.4).

4.3 Isotopes

The isotope data correspond well with the major and trace element differences between our compositional groups, and each group occupies a unique field in isotope space (Fig. 1.6). For instance, both increasing Δ alkalinity and trace element enrichment correlate with isotopic enrichment in our MORB (Fig. 1.7). Notably, it can be seen in Figure 1.7 that with increasing Δ alkalinity, $^{143}\text{Nd}/^{144}\text{Nd}$ does not continue decreasing but instead ultimately flattens. This variation in Δ alkalinity at a fixed $^{143}\text{Nd}/^{144}\text{Nd}$ may represent a variation in degree of melting from a common source. Additionally, our MORB data form tight linear trends in isotope space that correspond well with published Pacific MORB, suggesting a relationship that will be explored further below (Supplementary Fig. 1.S1).

As is observed with the trace element contents of the Weak and Strong Arc lavas, their isotopic compositions extend between MORB and an arc endmember with radiogenic Sr and Pb, unradiogenic Nd, and intermediate $^{176}\text{Hf}/^{177}\text{Hf}$. Interestingly, the range in $^{206}\text{Pb}/^{204}\text{Pb}$ is remarkably narrow for these samples, especially given their ranges in all other isotope ratios (Fig. 1.6). Unsurprisingly, increasing subduction signal is matched by high $^{87}\text{Sr}/^{86}\text{Sr}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$, along with low $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{176}\text{Hf}/^{177}\text{Hf}$.

There are spatial/temporal differences in the isotope ratios of South Shetland data. The ~40-140 Ma, southwestern lavas have higher radiogenic Sr, lower radiogenic Nd, and higher $\Delta 8/4$ (as defined in Hart, 1984) when compared to the ~30-60 Ma, northeastern lavas. This will be important when we consider how subduction signal varies based on influences from fluids and sediments. Quaternary South Shetland lavas are isotopically similar to Strong Arc lavas, suggesting they share similar sources. Many of the Quaternary South Shetland lavas outcrop at the

boundary between the Bransfield Strait and the South Shetland Islands, supporting this relationship.

Despite somewhat similar trace element patterns to enriched MORB, APAV samples have higher $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ but lower $^{143}\text{Nd}/^{144}\text{Nd}$ at similar $^{206}\text{Pb}/^{204}\text{Pb}$ ratios. APAV lavas seem to define trends in isotope space between two endmember components: one similar to our most enriched MORB and the other similar to our Strong Arc lavas. This is less clear in $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$, and we do not have sufficient Hf isotope data for this group, though our two APAV samples have the least radiogenic Hf of all lavas in this study, extending to an even more enriched endmember than our enriched MORB.

5. Discussion

5.1 The Antarctic Peninsula Alkaline Volcanic Group (APAV)

The APAV lavas are a unique set of samples, with particularly low CaO contents and distinct trace element patterns and isotope ratios from the other groups in this study. Alkaline lavas from both sides of the South Shetland Trench share similar levels of trace element enrichment and similar primitive mantle normalized trace element patterns (Fig. 1.4 and 1.5). These melts also occupy the same fields in isotope space, covering similar ranges in Sr, Nd, and Pb, and they consistently define trends between enriched MORB and subduction endmembers (Fig. 1.6). Alkali basalts of similar geochemical affinities have also been found further southwest along the peninsula at the Seal Nunataks and Alexander Island, along with deeper into the continent at Mount Early and Sheridan Bluff, suggesting their source is not exclusive to the northern portion of the Antarctic Peninsula (e.g., Hole, 1990; Hole et al., 1993; Hole et al., 1994; Hole, 2021; Panter et al., 2022). Furthermore, a few Strong Arc samples seem to carry the isotopic signal of APAV

lavas, despite retaining strong subduction signals in their trace element patterns (Fig. 1.6e). Similarly, rare samples from Livingston Island in the South Shetland Islands (Haase et al., 2012) have particularly high $^{206}\text{Pb}/^{204}\text{Pb}$ compared to other South Shetland Island samples (Fig. 1.6a-d). It is possible that these lavas may have been influenced by the APAV source. Speculating on the origins of the APAV source is beyond the objective of this study, but we intend to focus on this in a future paper.

5.2 Degree of Melting and Source Variations

The spectrum of enrichment, both in trace element and isotope ratios, suggests that variable amounts of mixing between depleted and enriched MORB endmembers produced the geochemical range in our MORB lavas. This would suggest that the upper mantle beneath both the Phoenix and West Scotia ridges is heterogeneous, consistent with the findings of previous studies (e.g., Choe et al, 2007; Choi et al., 2008; Haase et al., 2011). Correlations between isotopes and published ^{40}Ar - ^{39}Ar ages (Lee et al, 2003; Choi et al., 2008; Haase et al., 2011) for Phoenix Ridge lavas show that the enriched mantle component was increasingly sampled at the ridge as spreading slowed. During slowdown, melt productivity also decreased, as evidenced by increasing Δ alkalinity with decreasing eruption age, indicating that over its lifetime the ridge produced increasingly low degree melts. Together, these pieces of information would suggest that the upper mantle beneath the ridge is mostly trace element and isotopically depleted, interspersed with enriched pockets that were overwhelmed at higher degrees of melting. As spreading rates decreased, a growing lithospheric lid began encroaching on the melting zone, severely limiting the extent to which the less fusible depleted mantle could melt. Thus, the more fertile (and more fusible) enriched portions of the mantle progressively dominated the compositions of erupted lavas, which were further

enriched in incompatible trace elements by low degree partial melting. In fact, it seems that many of our most enriched lavas are nearing the isotopic composition of the pure enriched solid source, since several samples show a wide range in Δ alkalinity with no corresponding changes in isotope ratios (Fig. 1.7). This would suggest that those particular samples represent variations in degrees of melting of the same source.

Source variations appear to control the degree of melting of Bransfield Strait lavas as well. The compositional range of Bransfield Strait lavas reflects the increasing effect of subduction processes on their compositions. Strong Arc lavas carrying the most intense subduction signals show evidence of having melted to the greatest extents, likely on account of high volatile fluxing from the subducting slab. At a fixed MgO content, Bransfield Strait lavas with the highest subduction signals have the lowest concentrations of “incompatible” major element oxides, including Na₂O, TiO₂, and P₂O₅ (Fig. 1.2). The only exception is K₂O, for which many Strong Arc lavas have intermediate concentrations. However, K is fluid-mobile and is observed to be elevated in arc and back-arc lavas, apparently outpacing the effect of higher degree melting in Strong Arc samples (e.g., Stolper and Newman, 1994). We see this in their trace element patterns as well, where they often have positive K anomalies (Fig. 1.4). Strong Arc lavas also have some of the highest SiO₂ contents at a fixed MgO content, which may in part be caused by high volatile fluxing, in addition to lower average melting pressures. In contrast, Weak Arc lavas deviate only slightly, if at all, from our most depleted MORB in their major element compositions, suggesting a relationship between the Phoenix Ridge upper mantle and regions of the mantle wedge that have only been weakly affected by subduction processes (Fig. 1.2). Weak Arc lavas also generally have higher Δ alkalinity values at the same range in MgO than Strong Arc lavas, a further indication

that increasing subduction influence corresponds to greater extents of melting in the back-arc (Fig. 1.3).

5.3 The Movement and Distribution of Pacific MORB Mantle

A remarkable feature of Phoenix and West Scotia ridge basalts is their geochemical similarity. Although there are only two samples from the West Scotia Ridge, they nearly always fall within the range of Phoenix Ridge lavas in isotope plots. Furthermore, their major element compositions are extremely similar, and their trace element patterns share many of the same relative enrichments and depletions in various elements. These data suggest that the upper mantle beneath the Phoenix Ridge is compositionally alike to that beneath the West Scotia Ridge.

Furthermore, there are strong isotopic similarities between our Phoenix-West Scotia MORB data and compiled global Pacific MORB data, which both differ isotopically from Atlantic MORB data (Stracke, 2012; Shimizu et al., 2016; Mallick et al., 2019; Supplementary Fig. 1.S1). This indicates that the Phoenix and West Scotia ridges are underlain by Pacific upper mantle today. It seems that within the past 30 Myr, the Pacific upper mantle has flowed beneath the Drake Passage and the Scotia Plate, consistent with the conclusions of Pearce et al. (2001) (Fig. 1.1). Our findings agree with tectonic reconstructions, which suggest the Scotia Plate opened eastwards over time, allowing for Pacific upper mantle to flow to the east as South America and the Antarctic Peninsula separated (e.g., Dalziel et al., 2013).

Our data also reveal a clear relationship between Phoenix Ridge MORB and our Bransfield Strait samples. Weak Arc lavas largely overlap with and extend along the same trends defined by our most depleted MORB lavas in major element vs MgO plots (Fig. 1.2). In trace element ratio plots, Bransfield Strait samples form an array of increasing subduction signal that extends directly

from MORB (Fig. 1.5). The same can be seen with isotopes, where the Bransfield Weak Arc lavas overlap with depleted MORB (Fig. 1.6). In other words, the least subduction-modified Bransfield Strait samples are geochemically alike to our MORB. Thus, the mantle wedge beneath the Bransfield Strait is compositionally the same as the upper mantle beneath the Phoenix Ridge, though it has been variably modified by subduction processes, producing the range of Weak and Strong Arc lavas. The widening slab window southwest of the Hero Fracture Zone likely provided an opening through which sub-slab asthenosphere could enter the mantle wedge, following a toroidal flow pattern (Fig. 1.1 and 1.8). Experimental studies of mantle flow at subduction zones with slab windows support this hypothesis (e.g., MacDougall et al., 2014; Kincaid and Griffiths, 2003; Kincaid and Griffiths, 2004). Sub-slab asthenosphere may have an additional path into the mantle wedge via return flow around the northeast edge of the Phoenix slab at the Shackleton Fracture Zone (Fig. 1.1 and 1.8).

This flow of sub-slab asthenosphere into the mantle wedge may be controlling the spatial trends in geochemistry observed along the Bransfield Strait. The data show a gradual along-axis increase in subduction signal beginning around 58.3°W, followed by a sharper decrease in subduction signal at around 56.0°W (Fig. 1.9a and 1.9b). This skewed parabolic pattern is observed with isotopes and numerous LILE/HFSE ratios and was also noted by Fretzdorff et al. (2004). Strong Arc samples with the lowest Δ alkalinity values and strongest subduction signals occur at the center of the Bransfield Strait, whereas samples with the highest Δ alkalinity values and weakest subduction signals occur at the edges (Fig. 1.9c). The proposed transport of sub-slab asthenosphere could bring Phoenix MORB mantle beneath the edges of the Bransfield Strait, where we observe melts with the strongest geochemical similarities to Phoenix Ridge MORB. Here, a direct supply of fresh asthenosphere along the edges of the slab would dilute the effects of

subduction processes and potentially focus the subduction-modified mantle towards the center of the mantle wedge, following toroidal mantle flow patterns (e.g., MacDougall et al., 2014). This fresh MORB mantle at the edges would also be carrying fewer volatiles, lowering the degree of melting, which would largely be by decompression rather than flux melting.

As was discussed, the most alkaline samples occur at both edges of the Bransfield Strait (Fig. 1.9c). This is inconsistent with the hypothesis that the back-arc opened via trans-tension, initiated by the westward propagation of the South Scotia Ridge fault. If this were the case, the strait would be widest to the east where it approaches the fault, and thus, lavas there would be produced by the highest degrees of melting and have the lowest Δ alkalinity values (Fig. 1.1). However, Figure 1.9c clearly shows this is not the case. In contrast, we find that the lowest Δ alkalinity values and strongest subduction signals roughly coincide with where the Bransfield Strait reaches its widest point near its center (e.g., Grácia et al., 1996; Galindo-Zaldívar et al., 2004), which would be more consistent with a pull-apart structure produced by the oblique subduction of the Phoenix Plate, relative to the South Shetland Trench (e.g., Tikoff and Teyssier, 1992).

The spatial pattern across the Bransfield Strait is asymmetric, which could be the result of a number of factors. Because the Phoenix Ridge is advancing obliquely towards the trench, the age of the Phoenix Plate at the subduction margin increases from southwest to northeast (Larter and Barker, 1991). This increase in age may result in a difference in the slab pull force along the trench, supported by somewhat faster estimated convergence rates in the northeast, according to the latest reported finite rotation pole (Eagles 2004). Whether this increase in age may also result in a greater slab dip to the northeast is possible but unknown. These along-slab differences may be causing

variations in the strength of the subduction signal across the Bransfield Strait, in combination with return flow around the slab edge in the northeast and through the slab window in the southwest.

Interestingly, though the Phoenix Ridge upper mantle is heterogeneous, all Bransfield Strait lavas extend from the same depleted MORB composition in isotope space (Fig. 1.6). If the heterogeneities in the Phoenix Ridge upper mantle survived transport to beneath the Bransfield Strait, perhaps the degree of melting was large enough to mostly overwhelm the isotopic signal of the enriched MORB source. Alternatively, the more fusible enriched MORB source could have been preferentially depleted in incompatible trace elements from progressive melting beneath the mid-ocean ridge prior to arriving beneath the Bransfield Strait, allowing its enriched isotopic signal to be easily overwhelmed during melting in the back-arc.

We observe a similar pattern in South Shetland Island isotope data, which also extend between MORB and a subduction endmember (Fig. 1.6). However, these lavas project back towards an even more depleted MORB composition than Bransfield Strait lavas (Fig. 1.6). Again, this difference could be controlled by degree of melting. Greater subduction fluxes at the volcanic front would result in greater extents of melting—greater even than in the Bransfield Strait. On the other hand, this could indicate the mantle was depleted prior to arriving beneath the volcanic front via corner flow, likely while passing and partially melting beneath the back-arc.

5.4 The Origin of the Subduction Signal in the Bransfield Strait

As discussed, Bransfield Strait and South Shetland Island lavas form an array of increasing subduction influence, corresponding to greater extents of melting (e.g., lower “incompatible” major element concentrations; lower Δ alkalinity values), more arc-like trace element patterns (negative anomalies in Nb, Ta, and Ti; positive anomalies in K, Pb, and Sr; high concentrations of

Cs, Rb, Ba, Th, and U), and increasing contributions from a subduction component in their isotopic compositions (Fig. 1.2-1.6).

It is unlikely that these signals are the products of crustal or shallow sediment assimilation in the Bransfield Strait. Differentiated sample 03DR-7 (MgO = 0.53 wt. %) shares a similar range in isotope ratios to high-MgO Strong Arc samples (Supplementary Table 1.S1). Furthermore, neither subduction signal nor isotopic composition correlate with MgO, suggesting that the geochemistry of our lavas is not the product of crustal assimilation during magma differentiation. The crust in the Bransfield Strait is only ~8.5-12.5 km thick along its volcanic axis, minimizing the amount of crust the lavas could travel through and interact with (Christeson et al., 2003; Catalán et al., 2013). There is also geophysical evidence that the Bransfield Strait crust is at least partially oceanic, which would not produce the mentioned trace element anomalies observed in our lavas (Catalán et al., 2013). We also compared our lava compositions to sediment data from within the Bransfield Strait reported by Lee et al. (2005), and we find no evidence of shallow level sediment assimilation either.

Instead, it seems that the subduction signals of our lavas come from slab-derived fluids and subducted sediment melts. High concentrations of fluid-mobile LILE elements, relative to fluid-immobile HFSE support the presence of slab fluid in the source of these lavas. Enrichments in Th suggest that sediment melts also make up a substantial portion of the subduction component in these lavas (Johnson and Plank, 2000; Plank 2005; Fig. 1.5). The influence of sediments is also evident in the isotope ratios of our lavas (Fig. 1.6). Bransfield Strait and South Shetland Island lavas trend towards the data for sediment core GC05-DP02, a six-meter, mostly terrigenous core collected near the trench on the subducting Phoenix Plate. Data come from Lee et al. (2012), in conjunction with new data we report in Supplementary Table 1.S3.

The proportions of slab fluids and sediments in the source of these lavas vary between the Bransfield Strait and South Shetland Islands. In the Bransfield Strait, lavas form tight correlations in Th/La vs Ba/Nb that suggest a fairly consistent fluid/sediment ratio (Fig. 1.5b). By contrast, the South Shetland Island data show a spread that suggests high variability in their fluid/sediment ratios. This can also be seen in Figure 1.10, where the oldest, southwestern lavas roughly trend towards the compositions of our Phoenix Plate sediments, but the youngest, northeastern lavas extend to much higher Ba/Nb values and project towards the isotopic compositions of Phoenix Ridge MORB. This trend in the northeastern lava data suggests that they have largely been affected by fluids derived from subducted, hydrothermally altered Phoenix MORB, carrying strong LILE/HFSE ratios and MORB-like isotope compositions, as proposed by Haase et al. (2012). Thus, it seems that at the volcanic front, there was a temporospatial progression from a sediment-dominated subduction component ~140 Ma to a fluid-dominated subduction component by ~30 Ma. Despite variations in the fluid/sediment ratios across these groups, all Bransfield Strait and South Shetland Island lavas, including those erupted in the Quaternary, extend towards the same sediment isotope compositions (Fig. 1.6 and 1.10). This suggests that at least since the Cretaceous, the compositions of the subducted sediments have not changed substantially.

5.5 Monte Carlo simulations of fluid-sediment addition to the mantle wedge

We test the effects of both sediment and fluid inputs on our lavas with a model that generates mixtures of representative fluid, sediment, and depleted MORB mantle (DMM) endmember compositions. The model uses Monte Carlo techniques to randomly pick compositions of fluids and sediments from distributions described below. The compositions were then mixed with DMM, and then this process was repeated a total of 7500 times. The model was run twice

with different sets of parameters, once to fit the Bransfield Strait data and once to fit the South Shetland Island data (Fig. 1.11 and 1.12). Details of the model parameters are listed in Supplementary Table 1.S4.

Fluid endmember compositions were calculated by multiplying fluid-eclogite K_D values at 6 GPa from Rustioni et al. (2021) by the incompatible trace element contents of the hydrothermally altered oceanic crust Super Composite from Staudigel et al. (1996). A Pb concentration was not reported for the Super Composite, so the value was taken from the Kelley et al. (2003) Super Composite instead. The Rustioni et al. (2021) K_D values are strongly dependent on the Cl content of the fluid. We allowed fluid Cl contents to range between 5 and 6 wt. %, which captures the range in Ba/Nb observed in the data for the lavas (~10-300) without adding unrealistic amounts of fluid to the mantle. This range in Cl content was kept the same for both the Bransfield Strait and South Shetland models, since without better constraints we assume the same slab fluid is fluxing the mantle in both cases. There is no way to know how accurate the K_D values we are using are, as the Rustioni et al. (2021) experiments were run at 700-800 °C and our fluid Cl content is not well constrained. However, the results of our simulations match the trends in our data well and support reasonable conclusions about the mantle wedge beneath the volcanic front and back-arc, as will be discussed below. We fit a uniform distribution to the calculated fluid compositions across the range of Cl contents. The model then independently selected a random fluid endmember composition from this distribution for each mixture. Isotope ratios for each fluid composition were kept constant. The Nd isotope ratio of the fluid was estimated using a concentration weighted average of PR3 Phoenix Ridge samples from Choe et al. (2007) and Choi et al. (2008). The Sr isotope ratio was estimated to be somewhat higher than the concentration weighted average value of 0.70269 from the PR3 samples —around 0.70300 instead. We see good reason for this value to

be slightly higher (e.g., Staudigel et al., 1996), likely on account of some minor influence from seawater. The PR3 lavas have no Pb concentration data to weight the average with, so a simple average of the Pb isotopes was used. We chose to use the PR3 data because the lavas are elevated in Cs, Rb, and K compared to the most depleted Phoenix Ridge MORB samples from this study and Haase et al. (2010) —strong evidence of hydrothermal alteration. These samples should therefore be geochemically akin to hydrothermally altered oceanic crust on the subducting Phoenix slab.

Data for the sediment core GC05-DP02 were used to constrain the sediment endmember compositions of the model. We fit a multivariate normal distribution to the data for all incompatible trace elements and isotope ratios at once. This is advantageous because our randomly generated sediment compositions retained correlations inherent to the original sediment data, and it allowed our model to test intermediate compositions we have no data for. The model then independently selected a random sediment endmember composition from this distribution for each mixture.

The composition of DMM was allowed to vary based on an imposed range in $^{206}\text{Pb}/^{204}\text{Pb}$. Both $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ were calculated using the NHRL equation from Hart (1984). Strontium and Nd isotope ratios were fit using linear regressions of Pacific and Phoenix Ridge MORB data from Supplementary Table 1.S5. DMM trace element concentrations are from Workman and Hart (2005). We used an average DMM trace element composition for the Bransfield Strait; however, in the South Shetland Islands, we used a depleted DMM composition to simulate a more depleted mantle beneath the volcanic front. The model then uniformly and independently selected at random the generated DMM compositions for each simulated mixture. As discussed, Bransfield Strait lavas appear to source an upper mantle composition that is more enriched in trace elements and isotopes than the South Shetland Island lavas. Thus, the DMM

compositional range used to model Bransfield Strait data has higher incompatible trace element concentrations and is more isotopically enriched than the DMM range used to model the South Shetland Island data (see Sup. Table 5 for detailed information).

We imposed limits on the proportions of each endmember allowed to mix to produce our results. This process can be considered as a binary mixture of a single sediment-fluid component, hereafter referred to as the subduction component, being added in variable amounts to DMM within the mantle wedge. After allowing the amount of fluid in the subduction component to range from 0 to 100% and the amount of subduction component addition to the mantle to range from 0 to 6%, we used the model results to constrain the approximate proportion of fluid in the subduction component and the total amount of subduction component added to DMM. This exercise was repeated individually for the Bransfield Strait, southwestern South Shetland Island lavas, and northeastern South Shetland Island lavas. Bransfield Strait data reflect a fairly constant proportion of fluid in their subduction component, about 50%, across all samples, as evidenced by their tight correlations in Figures 1.5b and 1.10. Variations in composition in the Bransfield Strait lavas are thus controlled by the amount of this subduction component added to DMM, ranging from 0 to 3%. By contrast, all South Shetland Island data can be matched well with a fixed 3% addition of subduction component to DMM. Variations in composition in the South Shetland Islands are therefore mostly controlled by variable proportions of fluid in the subduction component—about 15-50% for southwestern lavas and 50-80% for northeastern lavas (Fig. 1.11 and 1.12). Thus, our model results support that older, southwestern lavas are largely influenced by a predominantly sediment-derived subduction component, while younger, northeastern lavas are more heavily influenced by slab fluids derived from dehydration of the subducted hydrothermally altered

oceanic crust. These findings again suggest that there was a strong temporal shift in the composition of the subduction component between ~140 Ma and 30 Ma.

The Bransfield Strait and South Shetland Island data roughly form perpendicular trends in Figures 1.10 and 1.11, supporting that Bransfield Strait data reflect variations in the amount of subduction component mixed with DMM, while South Shetland Island data instead reflect differences in fluid/sediment ratios and a relatively uniform amount of subduction component added to a more depleted mantle wedge. It is reasonable that the mantle beneath the South Shetland Islands would be somewhat more isotopically and trace element depleted, since it would likely have already partially melted beneath the back-arc before continuing on towards the volcanic front via corner flow. This difference in mantle enrichment between the Bransfield Strait and South Shetland Islands is clear in Figure 1.6 and is supported by the results presented in Figures 1.11 and 1.12.

Because the isotopic compositions of the slab fluids and DMM are similar, each being estimated from MORB data, the ternary mixing trends generally “collapse” in isotope-isotope plots (e.g., Fig. 1.12a and 1.12b). The effect of the fluids is most strongly expressed in plots with incompatible trace element ratios, where the difference between the fluid, sediment, and mantle endmembers is more easily distinguishable (Fig. 1.11). This may partly explain why many studies of the region have been able to reasonably reproduce isotope trends using simple binary mixing models (Keller et al., 1991; Keller et al., 2002; Fretzdorff et al., 2004). The results of our Monte Carlo simulations reveal that oceanic crust-derived fluids are an additionally important component of this system, synthesizing the variability in incompatible trace element and isotope data of South Shetland Island and Bransfield Strait lavas.

6. Conclusions

We have identified several mantle sources contributing to the compositions of melts across the northern Antarctic Peninsula, including at the Phoenix and West Scotia ridges. This study revealed a number of newfound geochemical relationships between different areas in the region. The Phoenix and West Scotia ridges appear to be underlain by the same Pacific MORB mantle, with enriched portions interspersed within more depleted regions. This mantle was brought into the region from the Pacific through the eastward expansion of the Scotia Plate. Our data confirm that slowdown of Phoenix Ridge spreading and a decrease in melt productivity led to the increased sourcing of the enriched mantle and a decrease in the extent of melting with decreasing age of eruption. This Pacific MORB mantle seems to have been transported into the mantle wedge beneath the Bransfield Strait via return flow around the slab edges and through the slab window. Lavas with the weakest subduction signals occur at the edges of the Bransfield Strait, areas in more direct contact with inflowing Phoenix Ridge MORB mantle, which has passed around the slab's edges via toroidal flow. The asymmetry of this spatial geochemical pattern along the Bransfield Strait may reflect the opening of the slab window to the southwest and differences in slab age and slab dip along the trench. The results of our Monte Carlo simulations suggest that Bransfield Strait lavas were generated by ~0 to 3% addition of a subduction component with a fixed fluid/sediment ratio of ~1. Additionally, the results suggest that South Shetland Island lavas were generated by ~3% addition of a subduction component with fluid/sediment ratios ranging between ~0.18 and 4. Older, southwestern lavas (40-140 Ma) are largely influenced by sediment, whereas younger, northeastern lavas (30-60 Ma) are mostly dominated by fluid derived from the dehydration of hydrothermally altered Phoenix crust during subduction. These same model results also support that the mantle wedge beneath the Bransfield Strait is somewhat more enriched in incompatible

trace elements and isotopes than that beneath the South Shetland Islands, likely on account of progressive melting and depletion during corner flow. Additionally, we have recognized an enriched source with unique trace element and isotope compositions typical of Antarctic Peninsula alkaline volcanism, including beneath the Phoenix Ridge. This suggests the presence of a distinct enriched source in the upper mantle throughout this region.

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Figures

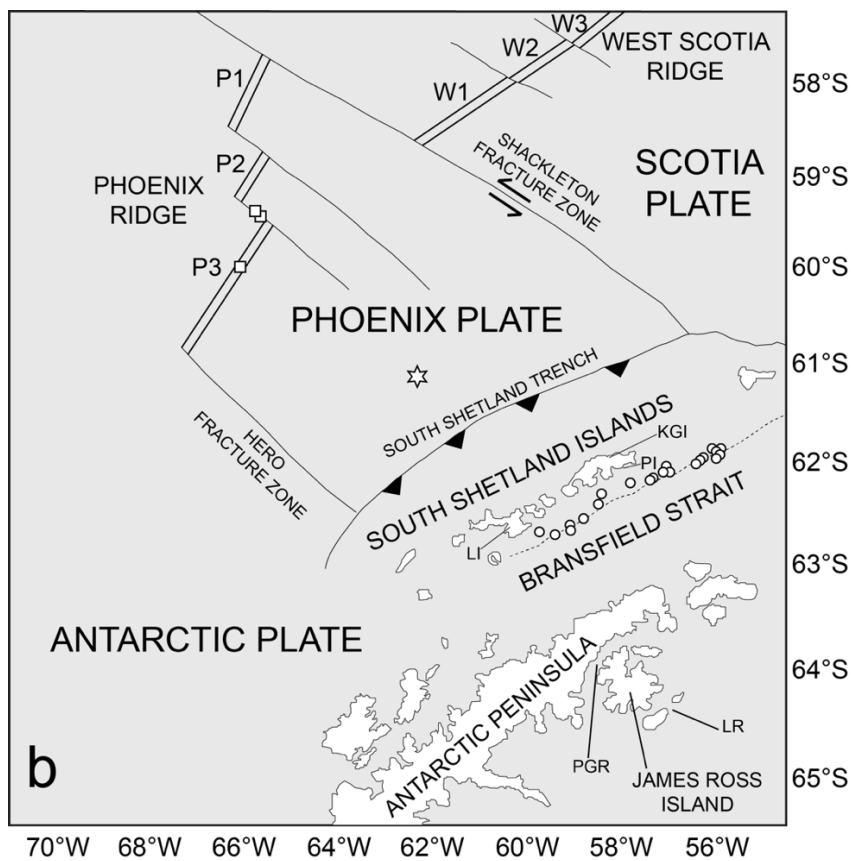
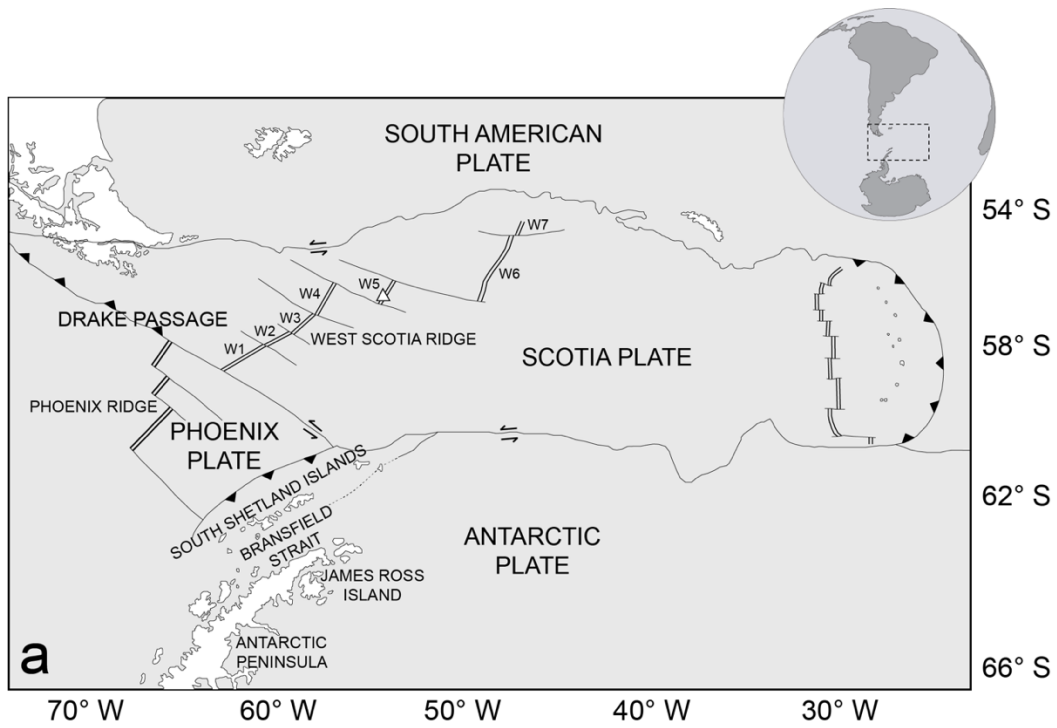


Figure 1.1: a) Map of the greater Antarctic Peninsula region showing the configuration of the South American, Phoenix, Antarctic, and Scotia Plates, along with the Phoenix Ridge (segments P1-P3), West Scotia Ridge (segments W1-W7), South Shetland Islands, Bransfield Strait, Antarctic Peninsula, and James Ross Island. The dredge location for West Scotia Ridge samples is marked by an open triangle. b) Map of the northern Antarctic Peninsula, showing the locations of the Bransfield Strait, King George Island (KGI), Livingston Island (LI), Penguin Island (PI), the Prince Gustav Rift (PGR), and the Larsen Rift (LR). Dredge locations are marked by open circles in the Bransfield Strait and open squares in the Phoenix Ridge. The sampling location of sediment core GC05-DP02 is marked with an open star.

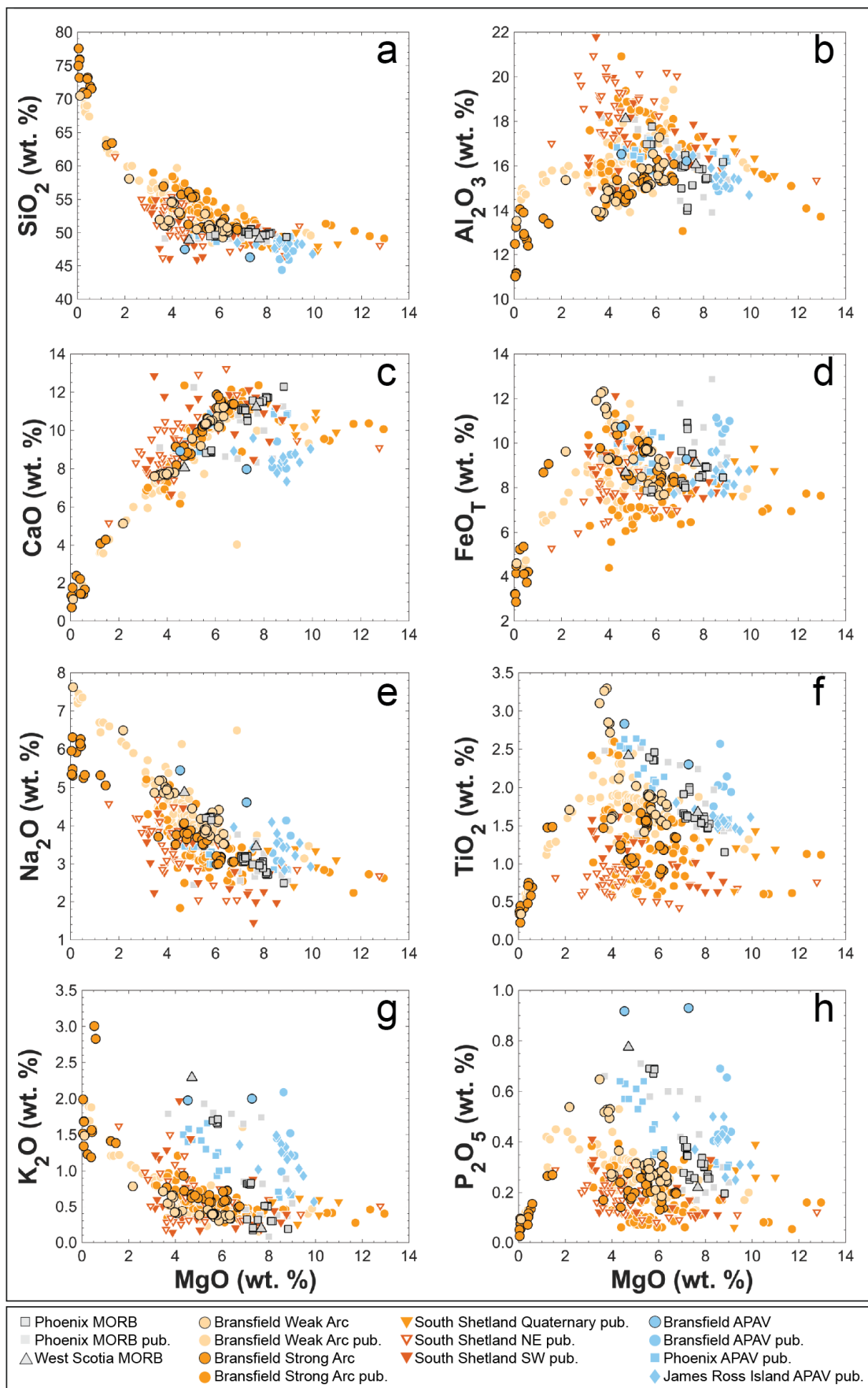


Figure 1.2: Variations in major element concentrations vs MgO. Gray squares and triangles represent Phoenix and West Scotia Ridge *MORB* samples. Blue circles represent Bransfield Strait *Weak Arc* (light blue) and *Strong Arc* (dark blue) samples. Inverted blue triangles represent Quaternary (light blue), 30-60 Ma northeastern (dark blue with white spots), and 40-140 Ma southwestern lavas from the South Shetland Islands. Pink circles, squares, and diamonds represent *APAV* lavas from the Bransfield Strait, Phoenix Ridge, and James Ross Island, respectively. All black bordered markers are data from this study, whereas borderless markers are published data from the Phoenix Ridge (Haase et al., 2011; Choe et al., 2007; Choi et al., 2008), the South Shetland Islands (Haase et al., 2012), the Bransfield Strait (Baker et al., 1975; Weaver et al., 1979; Keller et al., 1992; Keller and Fisk, 1992; Keller et al., 2002; Fretzdorff et al., 2004; Kraus et al., 2013; Martí et al., 2013), and James Ross Island (Košler et al., 2009).

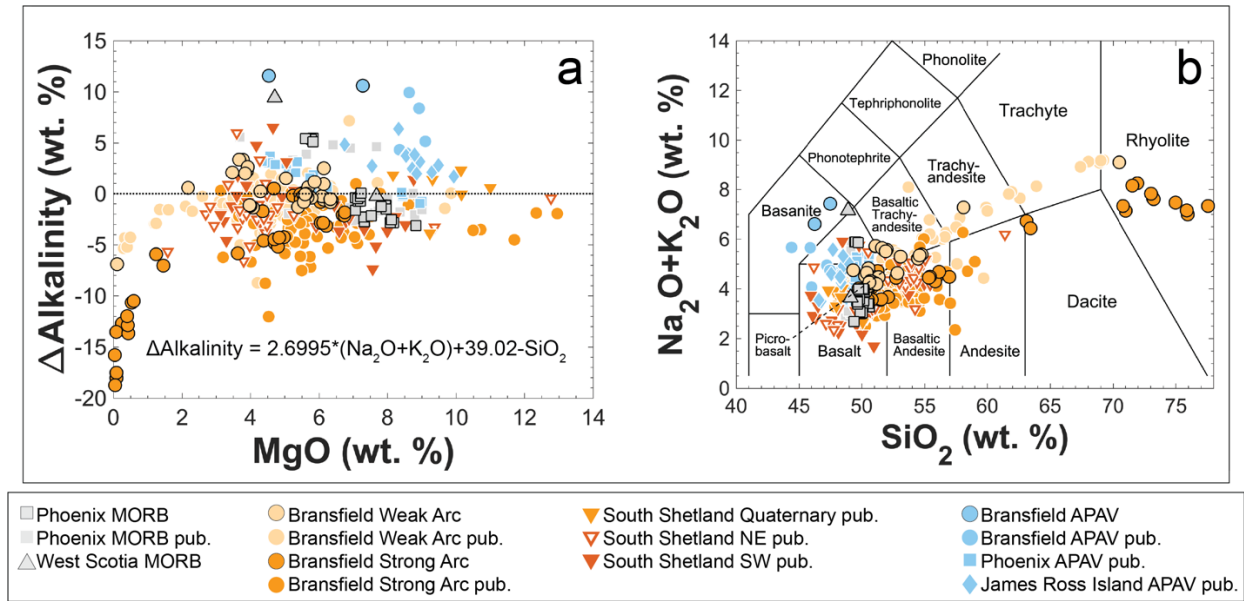


Figure 1.3: a) Δ alkalinity vs MgO. Δ alkalinity is calculated as the vertical deviation from the alkaline-subalkaline compositional boundary from MacDonald and Katsura (1964). b) Total alkalis vs silica (TAS) diagram showing the compositions of lavas from each of the areas. Dashed line represents the alkaline-subalkaline boundary from MacDonald and Katsura (1964). The equation for Δ alkalinity is shown in Figure 1.3a.

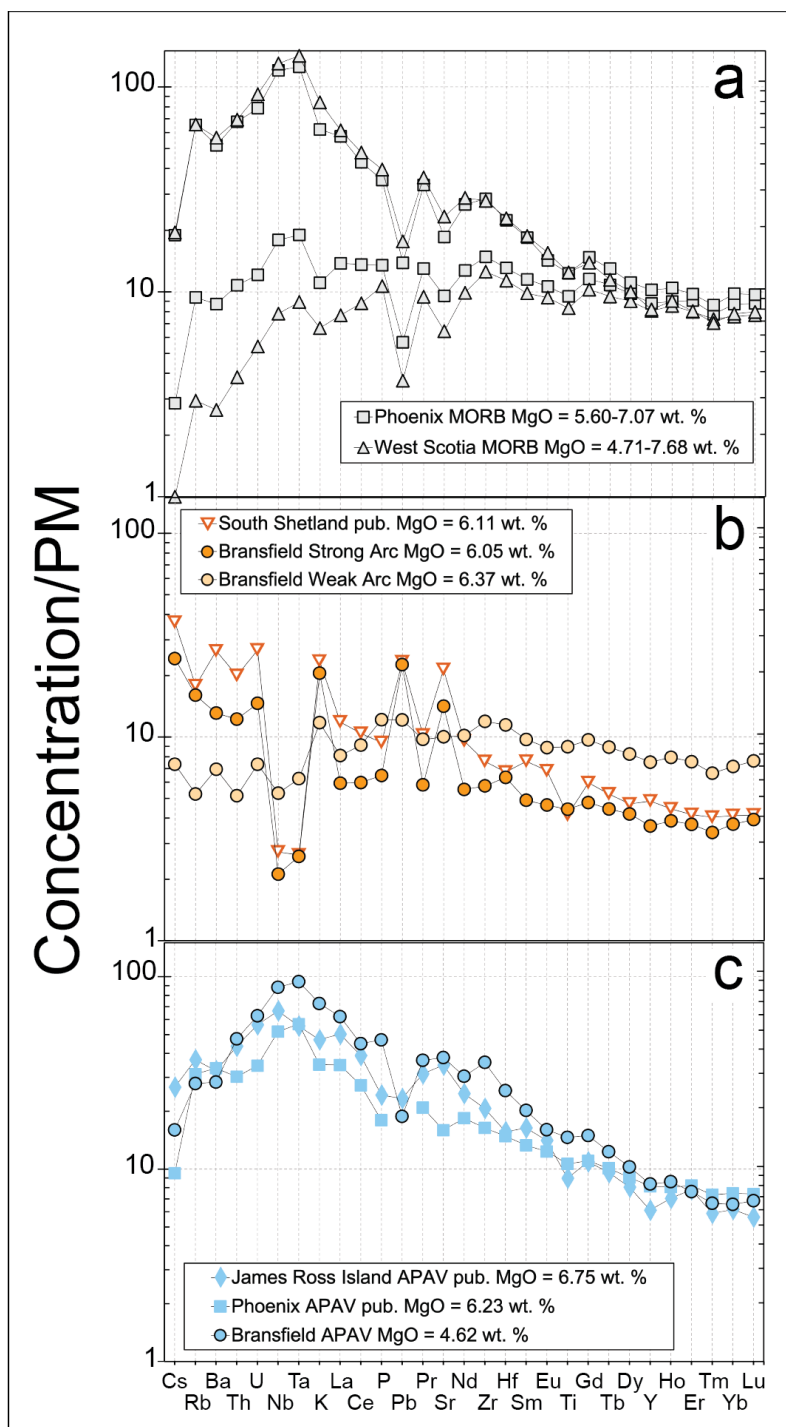


Figure 1.4: Primitive mantle normalized trace element diagram of representative a) Phoenix Ridge and West Scotia Ridge MORB, b) Bransfield Strait Weak Arc and Strong Arc and South Shetland Island lavas, c) Bransfield Strait, James Ross Island, and Phoenix Ridge APAV samples. Primitive mantle composition is from McDonough and Sun (1995).

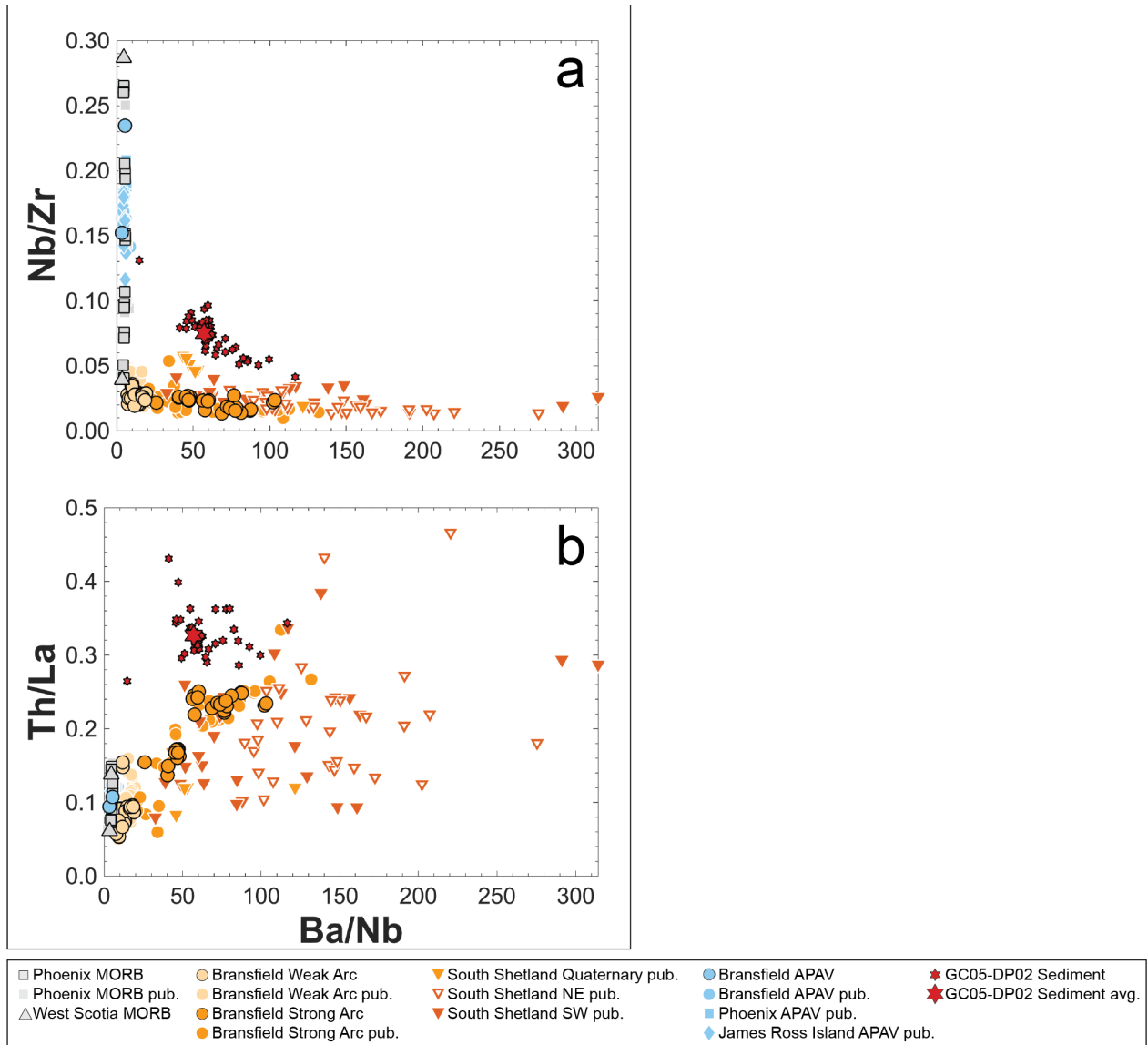


Figure 1.5: New and published a) Nb/Zr and b) Th/La vs Ba/Nb of the lavas in this study. Also plotted are compositions for all measured intervals of sediment core GC05-DP02 from the Phoenix Plate (Lee et al., 2012; this study). Lava data in this figure and all subsequent figures are filtered for MgO > 3.0 wt. %.

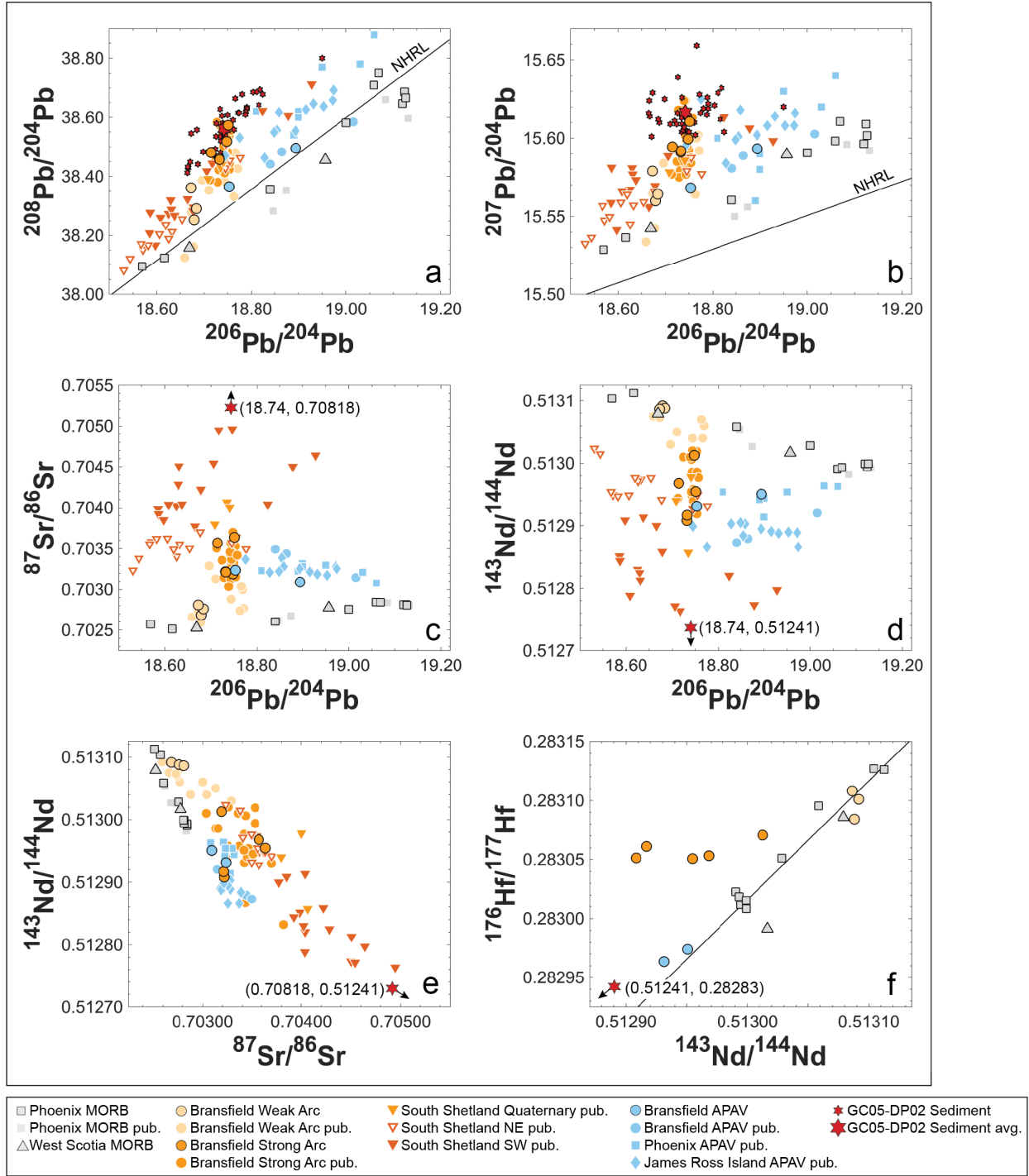


Figure 1.6: a) $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$. Solid black line is the Northern Hemisphere Reference Line from Hart (1984). b) $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$. c) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$. d) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$. e) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$. f) $^{176}\text{Hf}/^{177}\text{Hf}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$. $^{176}\text{Hf}/^{177}\text{Hf}$ for the sediment comes from the subducted oceanic sediment composition of Chauvel et al. (2008). Solid black line is a regression line of Phoenix and West Scotia ridge MORB ($R^2 = 0.89$), which coincides well with published Pacific MORB data (see Supplementary Fig. 1.S1).

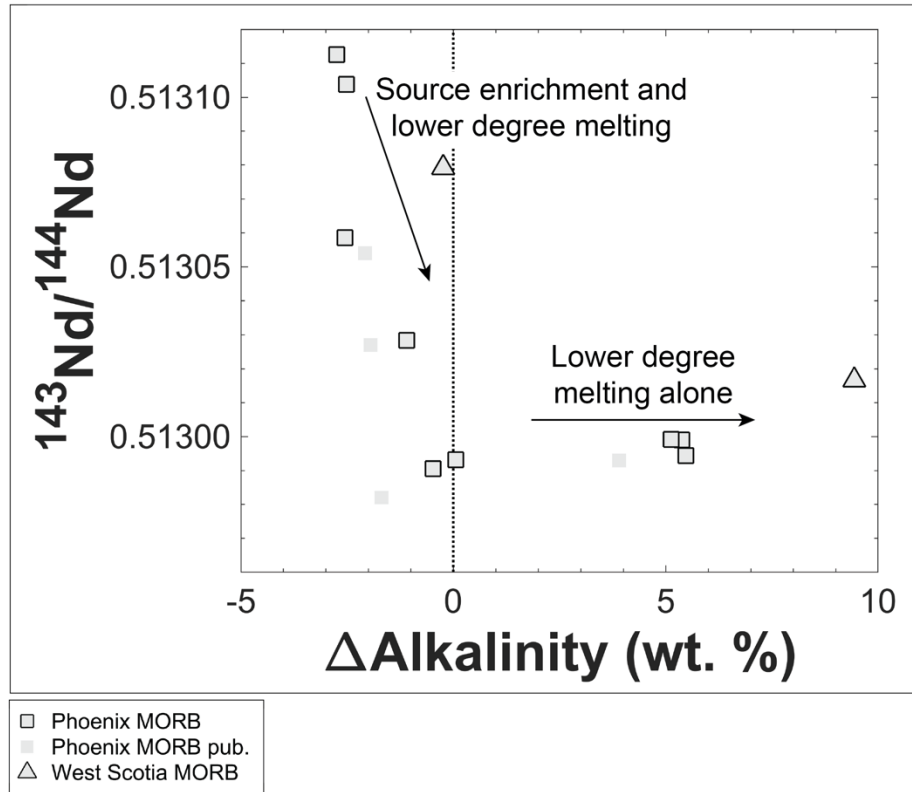


Figure 1.7: $^{143}\text{Nd}/^{144}\text{Nd}$ vs Δ alkalinity for new and published Phoenix and West Scotia Ridge data. Arrows show the general difference in the effect of variations in degree of melting alone, versus the combined effect of variations in degree of melting and source composition, together.

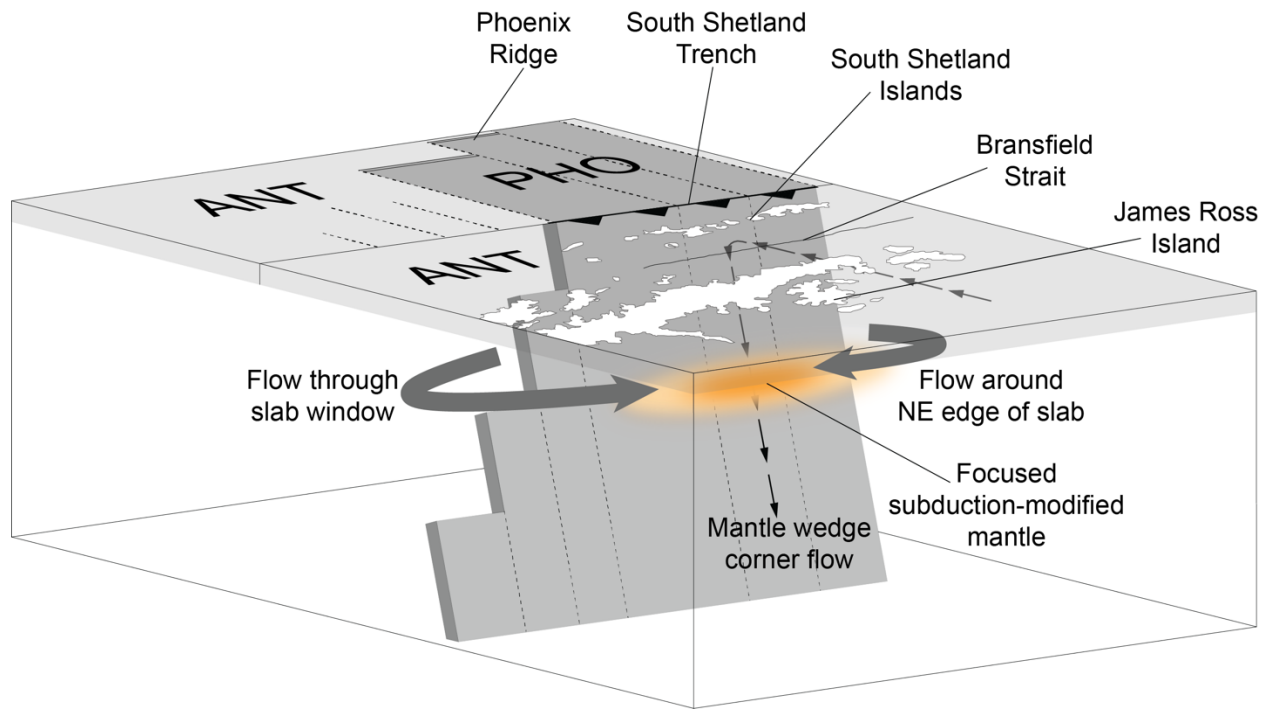


Figure 1.8: 3D schematic diagram of the northern Antarctic Peninsula showing the Phoenix Plate (PHO) subducting beneath the Antarctic Plate (ANT). Toroidal return flow of sub-slab asthenosphere into the mantle wedge is depicted with large arrows around the edges of the slab. The shaded blue field represents the area beneath the Bransfield Strait where subduction-modified mantle has been focused by the return flow of sub-slab asthenosphere. Corner flow in the mantle wedge is represented by smaller arrows.

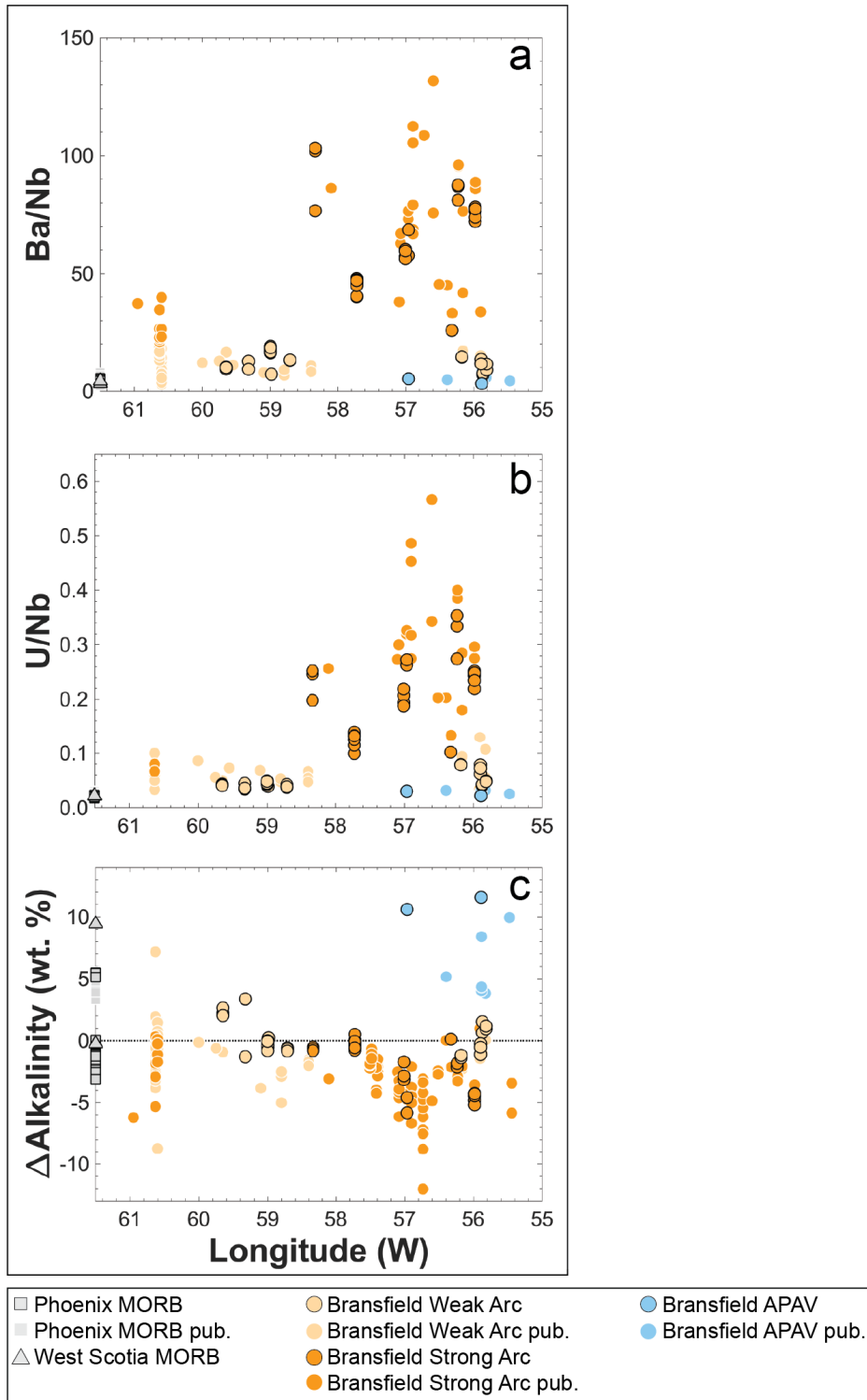


Figure 1.9: a) Ba/Nb, b) U/Nb, and c) Δ alkalinity vs longitude along the Bransfield Strait. Phoenix and West Scotia Ridge MORB data are plotted on the vertical axis for reference.

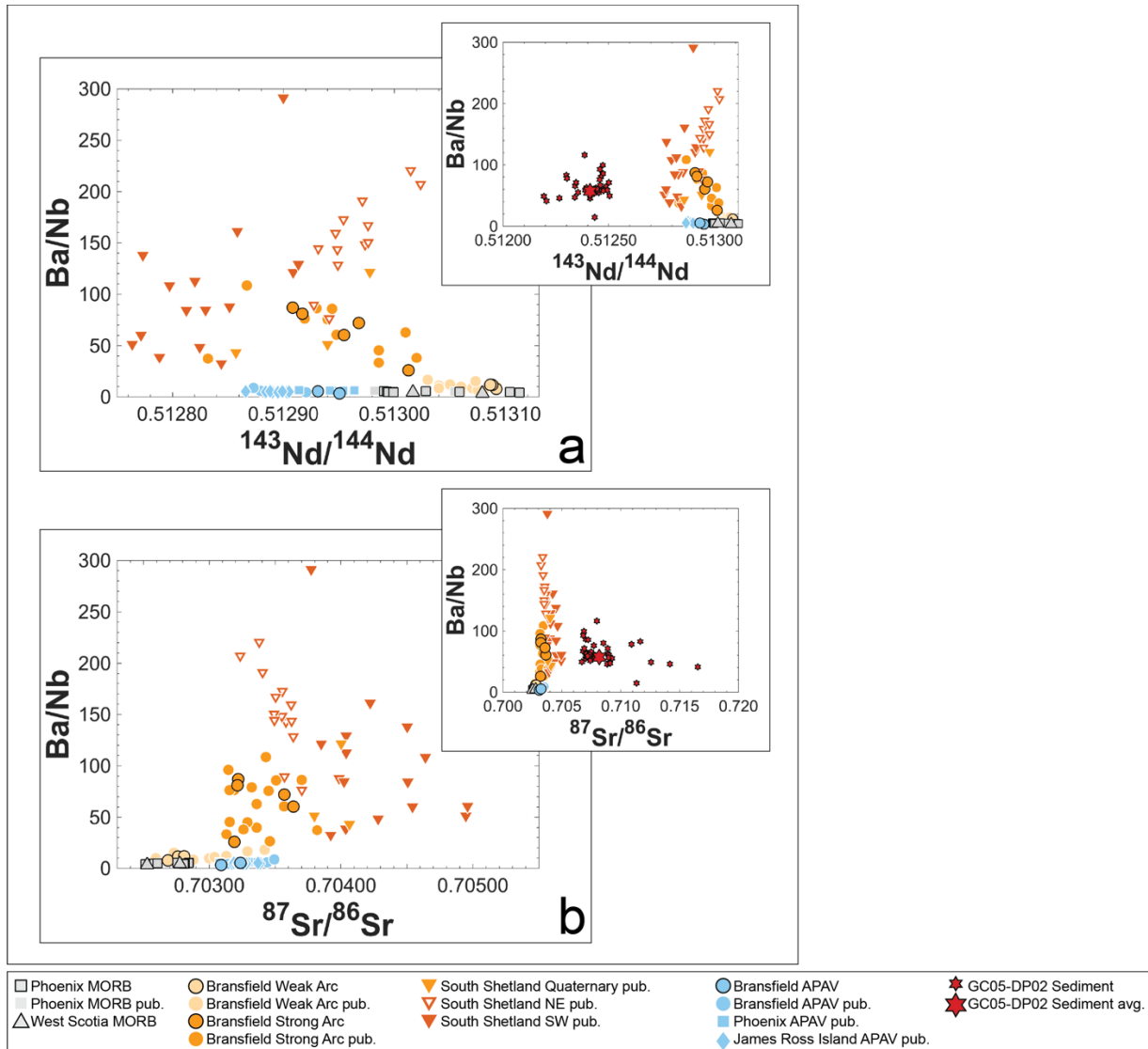


Figure 1.10: a) Ba/Nb vs $^{143}\text{Nd}/^{144}\text{Nd}$ and b) Ba/Nb vs $^{87}\text{Sr}/^{86}\text{Sr}$. Insets are expanded views of each plot that include all GC05-DP02 sediment core data and their weighted average. See text for discussion.

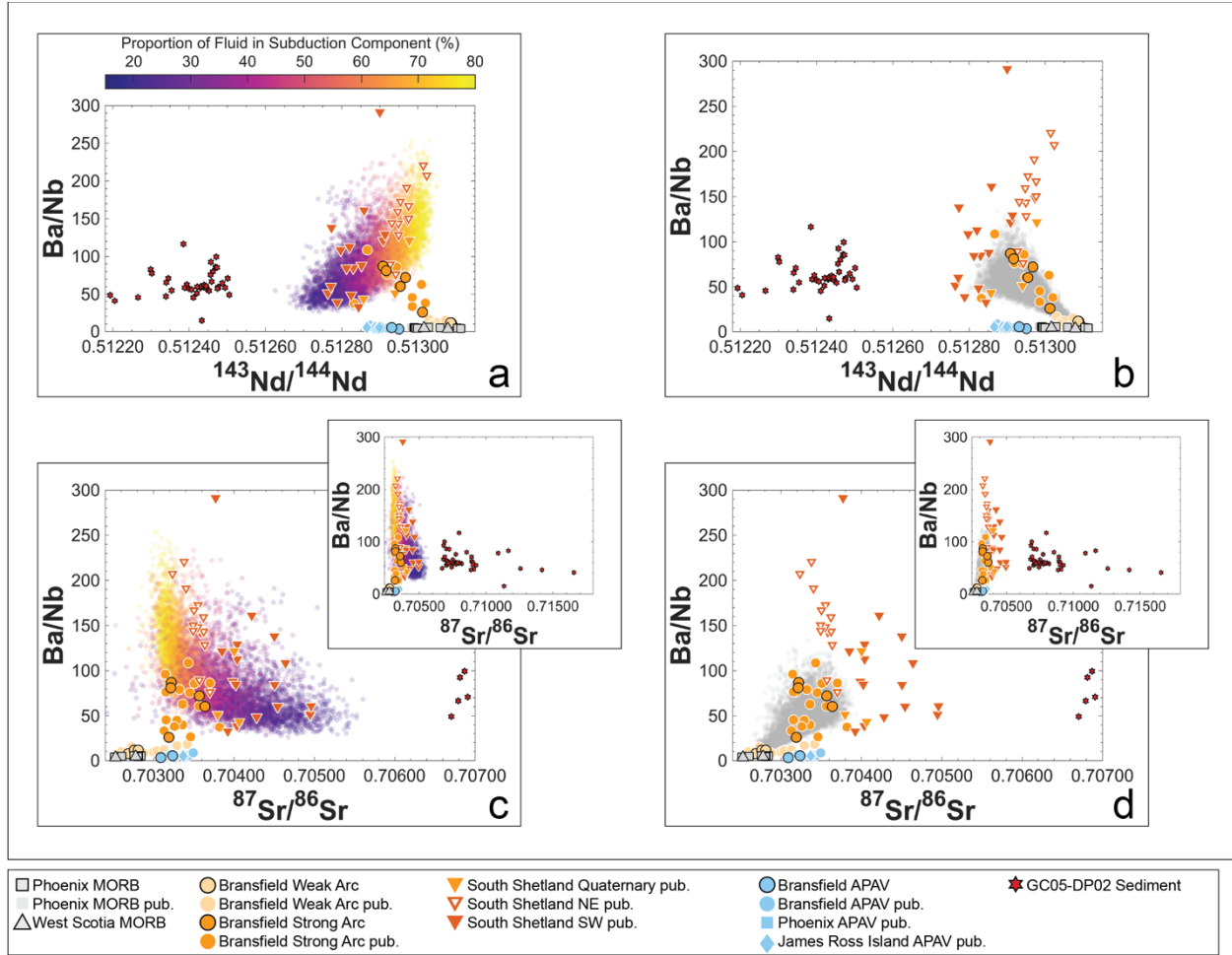


Figure 1.11: a-b) Ba/Nb vs $^{143}\text{Nd}/^{144}\text{Nd}$ showing results of Monte Carlo simulations for the South Shetland Islands and Bransfield Strait, respectively. The color gradient in the South Shetland Island results represents the proportion of fluid in the subduction component added to DMM. No color gradient is applied for the Bransfield Strait model since the fluid/sediment ratio in the subduction component is fixed. Point density reflects the likelihood that a mixture of a specific composition is produced, given the constraints of the model. c-d) Ba/Nb vs $^{87}\text{Sr}/^{86}\text{Sr}$ showing results of Monte Carlo simulations for the South Shetland Islands and Bransfield Strait, respectively. Parameters for each model run are listed in Supplementary Table 1.S4. See text for discussion.

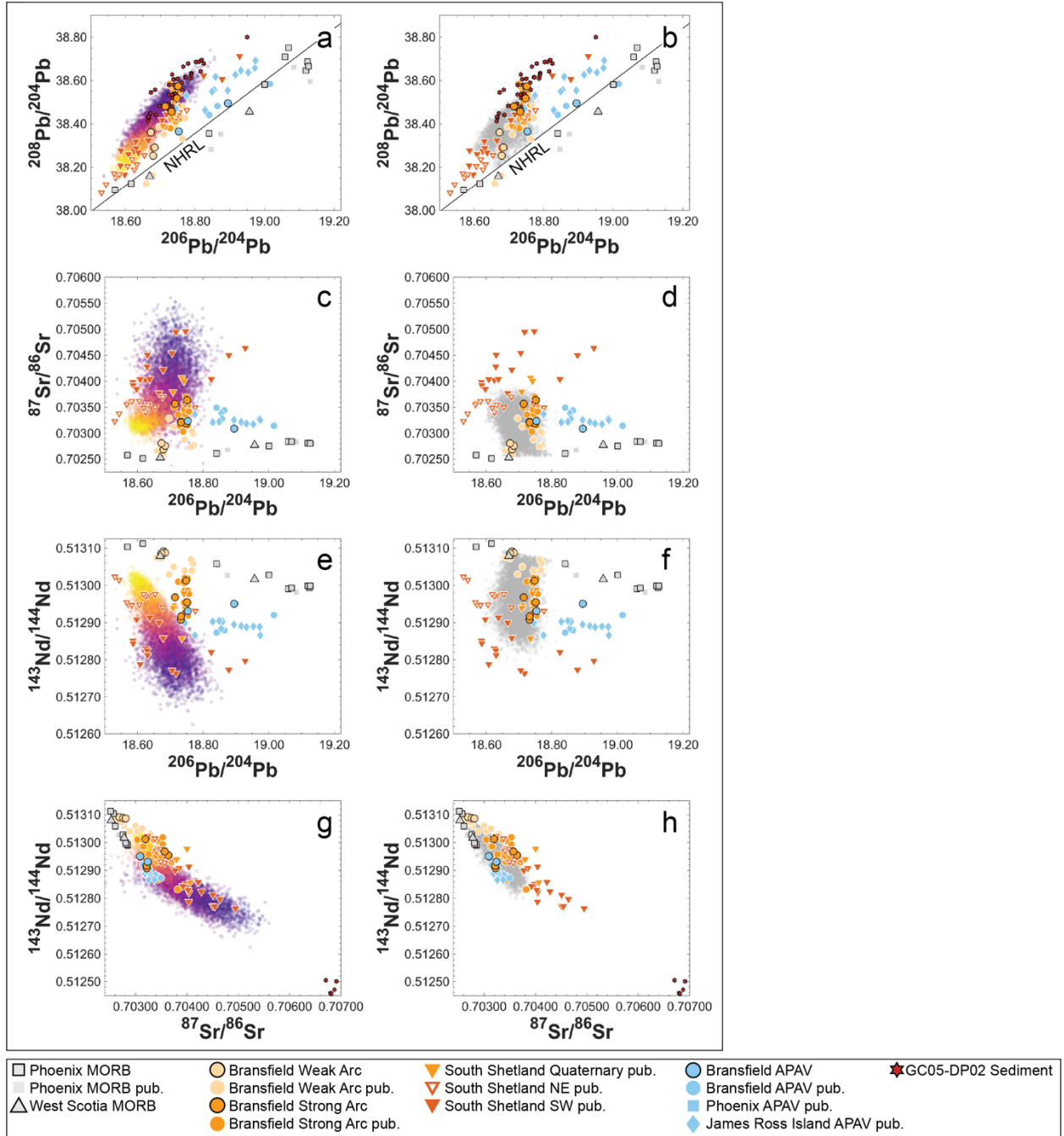
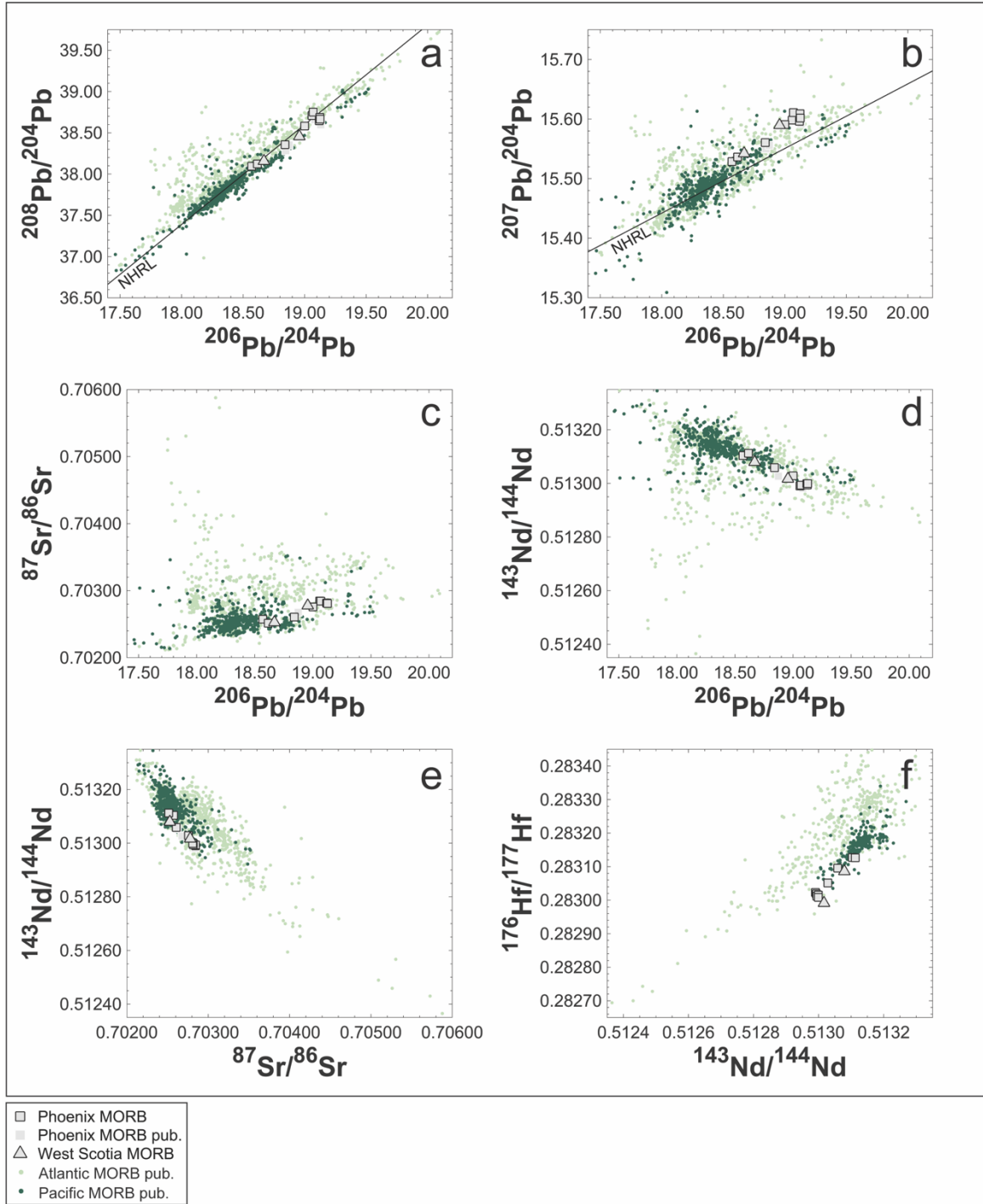


Figure 1.12: a-b) $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, c-d) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, e-f) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, and g-h) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$ showing results of Monte Carlo simulations for the South Shetland Islands and Bransfield Strait, respectively. Color schemes and point density are as in Figure 1.9. Parameters for each model run are listed in Supplementary Table 1.S4. See text for discussion.



Supplementary Figure 1.S1: (a) $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$. (b) $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$. Solid black line in (a) and (b) is the NHRL from Hart (1984). (c) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$. (d) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$. (e) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$. (f) $^{176}\text{Hf}/^{177}\text{Hf}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$. Light and dark circles are Atlantic MORB and Pacific MORB data, respectively, compiled from Stracke (2012), Shimizu et al. (2016), and Mallick et al. (2019). Symbols for Phoenix Ridge and West Scotia Ridge lavas are as in all other figures.

Tables

Table 1.1: Master key of the main magmatic features of the northern Antarctic Peninsula, their tectonic settings, the various geochemical groupings of their lavas, the ages of the lavas, and the symbols we use in our figures to represent them.

	Phoenix Ridge		West Scotia Ridge	South Shetland Islands			Bransfield Strait			James Ross Island
Setting	mid-ocean ridge		mid-ocean ridge	volcanic front			back-arc basin			back-arc basin
Grouping	MORB	APAV	MORB	Quaternary	Young NE	Old SW	Weak Arc	Strong Arc	APAV	APAV
Age (Myr)	1-6 ^a	1-6 ^a	~6 ^b	<1 ^c	30-60 ^d	40-140 ^d	<4 ^e	<4 ^e	<4 ^e	4-6 ^f
Symbol										

^aHaase et al. (2011)

^bRiley et al. (2019)

^cBarker (1982)

^dHaase et al. (2012)

^eLeat and Riley (2021a)

^fKošler et al. (2009)

Supplementary Table 1.S1: New major and trace element concentrations and isotope compositions for lavas of this study

Sample	Group	CIPW Norm.	Latitude (S)	Longitude (W)	Depth (m)	SiO ₂ (wt. %)	TiO ₂ (wt. %)	Al ₂ O ₃ (wt. %)	FeO (wt. %)	MnO (wt. %)	MgO (wt. %)	CaO (wt. %)	Na ₂ O (wt. %)	K ₂ O (wt. %)	P ₂ O ₅ (wt. %)	Total
02DR-1	BS Strong Arc	Qz	-62.12	-57.01	1289	52.09	0.92	15.32	8.35	0.16	6.20	11.58	3.09	0.39	0.14	98.32
02DR-14	BS Strong Arc	Hy	-62.12	-57.01	1289	51.49	0.87	16.29	7.90	0.17	6.05	11.83	2.99	0.37	0.13	98.32
02DR-2	BS Strong Arc	Hy	-62.12	-57.01	1289	51.55	0.93	15.72	8.16	0.15	6.12	11.78	3.00	0.59	0.16	98.14
02DR-3	BS Strong Arc	Qz	-62.12	-57.01	1289	52.72	1.25	15.37	10.39	0.18	4.35	9.15	3.51	0.93	0.24	98.07
03DR-7	BS Strong Arc	Qz	-62.12	-56.89	545	71.94	0.58	12.67	3.73	0.06	0.53	1.42	5.25	3.01	0.13	99.31
03DR-9	BS Strong Arc	Qz	-62.12	-56.89	545	71.54	0.69	12.41	4.22	0.08	0.59	1.66	5.33	2.83	0.16	99.49
04DR-10	BS Strong Arc	Qz	-62.06	-56.96	703	63.43	1.49	13.42	9.07	0.19	1.45	4.29	5.06	1.39	0.27	100.05
04DR-11	BS Strong Arc	Qz	-62.06	-56.96	703	63.11	1.48	13.65	8.69	0.19	1.24	4.09	5.32	1.41	0.27	99.43
04DR-13	BS Enriched Alkali	Ne	-62.06	-56.96	703											
04DR-3	BS Strong Arc	Qz	-62.06	-56.96	703	55.73	1.19	14.65	9.21	0.15	4.38	8.18	3.76	0.72	0.14	98.11
04DR-7	BS Strong Arc	Qz	-62.06	-56.96	703	56.95	1.47	13.74	9.78	0.18	3.63	7.67	3.71	0.77	0.17	98.07
07GTV-4	BS Strong Arc	Qz	-62.19	-57.28	1050	73.19	0.23	13.27	2.86	0.07	0.08	1.75	6.31	1.34	0.10	99.17
15DR-1	BS Strong Arc	Hy	-62.04	-56.33	1834	49.75	1.76	15.34	10.06	0.16	5.65	10.62	3.62	0.40	0.20	97.56
16DR-2	BS Strong Arc	Hy	-62.00	-56.24	2125	50.47	1.35	16.08	8.26	0.15	6.75	11.39	3.06	0.51	0.20	98.21
16DR-4	BS Strong Arc	Hy	-62.00	-56.24	2125	50.69	1.35	15.48	8.42	0.16	6.68	11.38	3.06	0.49	0.20	97.92
16DR-5	BS Strong Arc	Hy	-62.00	-56.24	2125	50.79	1.34	15.34	8.49	0.15	6.74	11.35	3.06	0.50	0.20	97.96
17DR-2	BS Weak Arc	Qz	-61.97	-56.18	2332	54.46	1.63	14.92	9.34	0.20	4.07	7.83	4.81	0.40	0.27	97.94
17DR-9	BS Weak Arc	Qz	-61.97	-56.18	2332	54.73	1.61	14.88	9.28	0.19	4.00	7.67	4.97	0.42	0.26	98.01
18DR-10	BS Strong Arc	Qz	-61.88	-55.98	1421	55.33	1.08	14.70	8.57	0.19	4.84	8.84	3.79	0.66	0.18	98.17
18DR-2	BS Strong Arc	Qz	-61.88	-55.98	1421	55.93	1.06	14.39	8.60	0.16	4.70	8.65	3.80	0.67	0.19	98.15
18DR-7	BS Strong Arc	Qz	-61.88	-55.98	1421	55.82	0.99	14.64	8.60	0.17	4.80	8.70	3.65	0.65	0.17	98.19
18DR-8	BS Strong Arc	Qz	-61.88	-55.98	1421	56.13	1.05	14.50	8.54	0.18	4.70	8.67	4.06	0.63	0.21	98.67
18DR-9	BS Strong Arc	Qz	-61.88	-55.98	1421	55.41	1.02	14.75	8.33	0.16	4.97	8.77	3.88	0.62	0.20	98.11
25DR-2	BS Weak Arc	Ne	-61.89	-55.82	2135	50.25	1.56	17.29	7.66	0.14	6.13	10.19	4.15	0.37	0.29	98.01
25DR-3	BS Weak Arc	Ne	-61.89	-55.82	2135	50.40	1.64	16.55	8.03	0.15	5.87	10.52	4.35	0.30	0.21	98.01
25DR-4	BS Weak Arc	Ne	-61.89	-55.82	2135	49.32	1.91	15.93	8.95	0.17	6.13	10.29	4.41	0.34	0.35	97.80
26DR-1	BS Enriched Alkali	Ne	-61.93	-55.89	1775	47.49	2.83	16.54	10.72	0.17	4.53	8.91	5.45	1.98	0.92	99.53
27DR-1	BS Weak Arc	Hy	-61.96	-55.87	1800	50.53	2.02	15.49	9.28	0.17	5.03	9.57	4.45	0.38	0.32	97.22
27DR-5	BS Weak Arc	Ne	-61.96	-55.87	1800	50.70	1.71	15.87	8.16	0.16	5.68	10.59	4.21	0.35	0.28	97.71
28DR-1	BS Weak Arc	Hy	-61.99	-55.90	1850	50.78	1.51	16.13	7.70	0.15	6.33	10.74	3.78	0.38	0.27	97.76
28DR-3	BS Weak Arc	Hy	-61.99	-55.90	1850	51.34	1.57	15.57	7.89	0.14	6.07	10.73	4.09	0.38	0.24	98.05
28DR-9	BS Strong Arc	Qz	-62.18	-57.24	1335	54.86	1.59	14.88	9.34	0.22	3.97	7.75	4.93	0.52	0.27	97.99
38DR-4	BS Strong Arc	Qz	-62.18	-57.24	1335	73.23	0.76	12.86	4.14	0.15	0.43	1.42	6.08	1.54	0.12	100.69
38DR-6	BS Strong Arc	Qz	-62.18	-57.24	1335	73.03	0.71	12.96	4.12	0.13	0.42	1.43	6.27	1.57	0.10	100.71
40DR-5	BS Strong Arc	Qz	-62.19	-57.28	1063	70.79	0.48	13.91	5.36	0.17	0.40	2.20	6.15	1.19	0.07	100.71
D15A	BS Strong Arc	Hy	-62.23	-57.73	1572	50.73	1.56	15.36	9.74	0.20	5.48	10.27	3.53	0.58	0.26	97.69
D15B	BS Strong Arc	Hy	-62.23	-57.73	1572	50.77	1.48	15.31	9.59	0.18	5.49	10.25	3.69	0.55	0.20	97.49
D15E	BS Strong Arc	Hy	-62.23	-57.73	1572	50.94	1.61	15.28	9.78	0.20	5.44	10.18	3.67	0.59	0.26	97.96
D15F	BS Strong Arc	Hy	-62.23	-57.73	1572	50.79	1.52	15.39	9.68	0.21	5.91	10.27	3.80	0.32	0.27	97.98
D15G	BS Strong Arc	Hy	-62.23	-57.73	1572	51.25	1.73	14.95	10.81	0.25	4.68	9.15	4.04	0.68	0.28	97.82
D15I	BS Strong Arc	Hy	-62.23	-57.73	1572	50.82	1.57	15.56	9.67	0.20	5.50	10.22	3.50	0.59	0.24	97.85
D15J	BS Strong Arc	Hy	-62.23	-57.73	1572	50.88	1.57	15.37	9.91	0.18	5.44	10.16	3.76	0.58	0.29	98.14
D15K	BS Strong Arc	Hy	-62.23	-57.73	1572	50.85	1.67	15.30	10.10	0.19	5.24	9.88	3.69	0.62	0.26	97.78
D15L	BS Strong Arc	Hy	-62.23	-57.73	1572	50.85	1.54	15.48	9.68	0.18	5.53	10.26	3.68	0.56	0.27	98.01
D15M	BS Strong Arc	Hy	-62.23	-57.73	1572	50.69	1.55	15.42	9.91	0.18	5.45	9.94	3.64	0.67	0.29	97.72
D15N	BS Strong Arc	Hy	-62.23	-57.73	1572	50.63	1.56	15.27	9.65	0.16	5.46	10.20	3.52	0.56	0.23	97.25
D16A	BS Strong Arc	Hy	-62.34	-58.34	1733	50.09	1.18	15.95	8.55	0.15	6.22	11.48	3.19	0.73	0.31	97.84
D16B	BS Strong Arc	Hy	-62.34	-58.34	1733	50.18	1.18	16.06	8.45	0.16	6.21	11.50	3.17	0.72	0.28	97.90
D16D	BS Strong Arc	Hy	-62.34	-58.34	1733	50.41	1.24	15.87	8.77	0.16	6.04	11.18	3.21	0.71	0.28	97.86
D17B	BS Strong Arc	Qz	-62.19	-57.27	1109	75.93	0.34	11.18	4.15	0.13	0.09	1.16	5.31	1.69	0.05	100.03
D17C	BS Strong Arc	Qz	-62.19	-57.27	1109	71.00	0.42	14.06	5.24	0.17	0.24	2.37	5.92	1.23	0.08	100.73
D18C	BS Strong Arc	Qz	-62.19	-57.27	1070	75.86	0.45	11.13	4.50	0.12	0.09	1.21	5.48	1.68	0.07	100.58
D18D	BS Strong Arc	Qz	-62.19	-57.27	1070	74.97	0.37	12.50	3.22	0.09	0.04	1.32	5.96	1.52	0.05	100.02
D18E	BS Strong Arc	Qz	-62.19	-57.27	1070	77.56	0.34	11.02	3.20	0.09	0.05	0.71	5.35	1.99	0.03	100.33
D19A	BS Weak Arc	Hy	-62.58	-58.71	1343	50.24	1.82	15.45	9.30	0.18	6.13	11.18	3.65	0.33	0.19	98.56
D19B	BS Weak Arc	Hy	-62.58	-58.71	1343	50.07	1.75	15.33	9.02	0.17	6.37	11.24	3.52	0.33	0.24	98.02
D19E	BS Weak Arc	Hy	-62.58	-58.71	1343	50.28	1.78	15.39	9.19	0.17	6.33	11.23	3.53	0.33	0.25	98.47
D20A	BS Weak Arc	Qz	-62.74	-59.32	1139	52.82	1.42	15.90	8.50	0.18	5.39	9.19	4.18	0.46	0.31	98.33
D20B	BS Weak Arc	Hy	-62.74	-59.32	1139	51.09	3.29	13.90	12.32	0.27	3.78	7.74	5.18	0.53	0.53	98.63
D20C	BS Weak Arc	Hy	-62.74	-59.32	1139	51.10	3.26	13.93	12.25	0.27	3.67	7.63	5.18	0.55	0.52	98.36
D21A	BS Weak Arc	Qz	-62.71	-59.65	1073	51.97	3.10	13.97	11.91	0.25	3.47	7.60	4.86	0.72	0.65	98.49
D21B	BS Weak Arc	Hy	-62.71	-59.65	1073	51.78	2.84	14.54	11.62	0.23	3.90	7.69	4.90	0.66	0.49	98.65
D21C	BS Weak Arc	Hy	-62.71	-59.65	1073	51.60	2.72	15.00	11.30	0.20	3.92	7.75	5.01	0.63	0.53	98.65
D21D	BS Weak Arc	Hy	-62.71	-59.65	1073	51.89	2.85	14.55	11.55	0.22	3.84	7.71	4.86	0.65	0.52	98.66
D22A	BS Weak Arc	Hy	-62.65	-59.00	1088	50.79	1.91	15.02	9.78	0.19	5.55	10.29	3.90	0.39	0.30	98.11
D22B	BS Weak Arc	Hy	-62.65	-59.00	1088	50.79	1.89	15.12	9.65	0.20	5.60	10.36	3.77	0.39	0.27	98.04
D22C	BS Weak Arc	Hy	-62.65	-59.00	1088	50.68	1.88	15.13	9.65	0.20	5.63	10.37	3.88	0.39	0.28	98.10
D22D	BS Weak Arc	Hy	-62.65	-59.00	1088	51.04	1.88	15.07	9.71	0.20	5.56	10.27	3.84	0.39	0.31	98.27
D22E	BS Weak Arc	Qz	-62.65	-59.00	1088	70.49	0.34	13.54	4.61	0.14	0.11	1.14	7.62	1.49	0.09	99.57
D23A	BS Weak Arc	Hy	-62.65	-59.00	1072	50.52	1.86	15.17	9.62	0.21	5.78	10.49	3.73	0.38	0.27	98.03
D23B	BS Weak Arc	Hy	-62.65	-59.00	1072	50.75	1.89	15.12	9.72	0.19	5.66	10.36	3.83	0.39	0.32	98.23
D23C	BS Weak Arc	Hy	-62.65	-59.00	1072	50.66	1.91	15.05	9.74	0.22	5.62	10.32	3.92	0.39	0.26	98.10
D24A	BS Weak Arc	Hy	-62.65	-59.00	1030	51.17	1.88	15.05	9.73	0.18	5.55	10.33	3.81	0.39	0.32	98.41
D24B	BS Weak Arc	Hy	-62.65	-59.00	1030	50.59	1.89	15.02	9.70	0.21	5.59	10.36	3.88	0.39	0.29	97.92
D2J	BS Weak Arc	Qz	-62.44	-58.41		58.09	1.71	15.36	9.63	0.22	2.18	5.14	6.49	0.79	0.54	100.14
DF86.32	BS Weak Arc	Qz	-62.69	-58.99	1226	53.08	2.12	14.41	10.73	0.24	4.29	7.80	4.8			

Supplementary Table 1.S1 (continued)

Cs (ppm)	Rb (ppm)	Ba (ppm)	Th (ppm)	U (ppm)	Nb (ppm)	Ta (ppm)	⁸⁷ Rb (ppm)	La (ppm)	Ce (ppm)	¹⁴⁷ Sm (ppm)	Pb (ppm)	Pr (ppm)	Sr (ppm)	Nd (ppm)	Zr (ppm)	Hf (ppm)	Sm (ppm)	Eu (ppm)	¹⁵² Eu (ppm)	Gd (ppm)	Tb (ppm)
0.63	12.26	107.15	1.33	0.36	1.87	0.14	2761.43	5.42	12.54	434.23	4.31	1.87	232.50	8.89	84.79	2.57	2.53	0.89	4704.77	3.64	0.59
0.49	9.25	83.36	0.94	0.29	1.38	0.09	1523.08	3.75	9.76	328.31	3.25	1.44	271.49	6.74	58.85	1.75	1.94	0.70	4052.09	2.54	0.43
0.65	12.39	100.53	1.20	0.34	1.79	0.13	2697.87	4.99	11.40	436.45	4.00	1.71	213.21	8.44	76.66	2.27	2.45	0.85	3835.78	3.34	0.56
0.59	8.16	69.49	0.80	0.26	1.17	0.08	1917.91	3.29	8.21	289.21	3.00	1.20	188.18	5.69	51.06	1.48	1.64	0.58	3366.57	2.17	0.37
3.04	89.75	358.63	9.55	2.65	6.22	0.40	27061.51	16.86	43.61	557.83	10.60	5.73	51.00	24.84	142.03	5.59	6.48	0.89	4915.29	7.78	1.30
2.27	84.17	343.02	9.44	3.41	5.39	0.41	25007.60	18.80	50.26	696.07	10.47	6.73	55.75	29.04	383.70	11.60	12.65	1.02	4136.21	9.36	1.56
0.89	16.28	107.74	1.43	0.50	1.99	0.14	5921.47	5.92	15.41	611.03	4.46	2.47	183.41	12.49	126.12	3.62	3.80	1.20	5953.46	5.15	0.84
0.75	13.95	98.89	1.31	0.45	1.65	0.13	2905.76	5.47	13.76	479.41	4.13	2.22	201.54	11.28	115.27	3.51	3.63	1.16	3899.93	4.88	0.79
0.80	14.80	92.03	1.06	0.42	1.59	0.11	2964.04	4.83	13.14	530.63	4.02	2.02	277.10	10.33	100.60	2.71	3.31	1.10	6793.01	4.17	0.68
0.58	8.74	63.95	0.75	0.25	0.93	0.08	2063.12	3.27	8.32	311.37	2.70	1.38	259.42	7.33	69.47	2.22	2.41	0.87	3963.23	3.12	0.54
0.96	21.79	132.70	3.04	0.98	5.79	0.37	6063.20	13.91	37.73	369.52	6.05	5.54	74.17	26.23	373.55	8.90	7.49	1.44	2164.20	9.66	1.62
0.39	9.21	59.81	0.86	0.24	2.33	0.18	1950.76	5.53	13.92	632.85	2.29	2.28	226.11	11.43	107.43	2.88	3.43	1.35	8480.68	4.62	0.77
0.28	10.97	125.75	2.89	0.43	1.55	0.12	3361.96	11.79	26.13	632.85	2.86	3.79	309.00	16.86	111.99	2.83	4.10	1.24	7701.54	4.43	0.66
0.31	10.91	139.70	2.99	0.54	1.61	0.12	1979.78	11.99	29.90	625.10	2.31	4.09	391.68	17.77	103.59	2.91	4.01	1.34	5943.81	4.37	0.67
0.28	11.95	146.21	3.02	0.59	1.67	0.12	1910.55	12.16	31.78	683.34	2.40	4.30	383.24	18.22	102.42	2.93	4.19	1.35	5821.70	4.26	0.69
0.37	7.37	61.26	0.75	0.34	4.26	0.32	1774.30	8.26	26.23	1045.25	2.68	4.20	150.68	21.38	205.15	5.58	6.56	2.38	7990.41	8.63	1.46
0.40	7.60	64.25	0.81	0.35	4.42	0.33	1868.38	8.65	26.98	1029.70	2.73	4.43	151.57	22.55	220.03	6.04	6.98	2.44	8249.33	9.37	1.55
0.34	9.03	82.66	0.94	0.25	1.07	0.07	1639.47	3.97	9.21	363.71	1.73	1.39	174.43	6.82	68.95	1.85	1.97	0.70	3176.51	2.62	0.42
0.48	9.12	84.14	0.90	0.26	1.17	0.07	2036.42	3.81	9.36	355.43	1.77	1.36	221.61	6.32	62.66	1.68	1.77	0.64	3356.34	2.42	0.38
0.34	8.66	83.90	0.84	0.27	1.10	0.07	2114.22	3.75	9.28	358.07	1.81	1.34	218.30	6.44	61.82	1.74	1.87	0.64	3354.54	2.39	0.40
0.38	8.61	81.14	0.83	0.26	1.04	0.06	2184.37	3.61	8.96	338.02	1.77	1.28	221.77	6.05	59.07	1.64	1.79	0.64	3342.63	2.22	0.37
0.80	11.74	100.43	1.09	0.34	1.36	0.08	2437.72	4.67	11.56	443.04	2.29	1.63	226.35	7.91	78.46	2.11	2.27	0.80	4243.42	2.91	0.49
0.17	3.56	38.52	0.51	0.21	4.28	0.30	1452.34	6.69	19.91	910.11	1.26	3.05	248.41	14.85	170.52	3.92	4.17	1.45	7789.75	5.28	0.87
0.12	2.95	33.23	0.34	0.14	2.88	0.20	1521.87	5.14	15.09	709.23	1.06	2.48	247.97	12.29	149.36	3.29	3.76	1.35	9934.08	4.90	0.80
0.08	2.69	27.18	0.45	0.20	5.29	0.36	1894.70	8.26	25.06	1246.06	1.27	3.84	261.48	18.46	218.07	4.71	5.32	1.83	11369.28	6.84	1.13
0.32	15.94	178.62	3.58	1.20	54.51	3.28	18151.79	37.97	71.33	3680.73	2.70	8.88	719.83	36.18	358.38	6.93	7.86	2.37	17600.66	7.84	1.18
0.00	3.53	36.75	0.43	0.21	4.84	0.32	2121.73	7.42	21.51	1101.83	1.43	3.30	255.49	16.28	192.86	4.11	4.80	1.65	11231.32	6.04	1.00
0.12	3.41	33.37	0.43	0.20	4.84	0.32	1931.35	6.79	20.14	990.08	1.22	3.12	266.90	15.24	173.82	3.72	4.33	1.47	9498.41	5.51	0.91
0.26	5.18	46.60	1.00	0.29	4.02	0.27	1411.19	6.48	17.24	800.16	1.29	2.60	247.13	12.54	144.19	3.21	3.69	1.25	8970.14	4.69	0.76
0.30	5.56	49.15	1.01	0.33	4.17	0.29	2063.66	6.79	18.09	889.83	1.60	2.72	264.27	13.01	149.16	3.42	3.68	1.34	8799.93	4.77	0.83
0.38	7.08	57.48	0.70	0.26	4.26	0.30	2277.77	7.97	24.58	1062.58	2.36	3.98	153.79	20.13	210.92	5.18	6.21	2.23	9378.93	8.58	1.43
0.64	15.07	123.88	2.62	0.61	3.78	0.27	3113.68	12.42	29.61	433.07	3.84	4.33	86.93	20.00	248.39	6.11	5.18	1.19	2091.48	6.80	1.10
0.95	17.61	135.45	2.82	0.76	4.28	0.30	3564.55	13.13	33.75	471.74	4.53	4.82	83.38	21.82	261.60	6.31	5.64	1.25	2369.66	7.26	1.18
0.98	20.70	147.32	3.60	0.97	5.99	0.45	5110.36	16.39	41.72	331.95	5.78	6.49	99.76	30.51	454.62	11.52	8.73	1.81	2396.25	11.71	2.03
0.48	11.71	95.79	0.79	0.24	2.38	0.11	2946.90	5.77	13.72	640.13	3.12	2.11	227.17	10.10	93.32	1.94	3.00	1.02	8410.76	3.55	0.57
0.60	13.10	115.14	1.16	0.33	2.47	0.16	3195.93	6.94	16.70	872.90	4.39	2.70	250.63	13.30	103.65	2.75	3.82	1.32	8930.19	4.95	0.77
0.60	12.85	107.71	1.00	0.31	2.66	0.14	2656.36	6.66	16.49	916.54	3.76	2.47	276.31	12.28	102.11	2.34	3.54	1.19	9379.69	4.31	0.68
0.80	11.83	102.90	0.94	0.30	2.15	0.13	1909.26	5.78	15.07	774.70	4.72	2.32	323.55	11.11	81.60	2.10	3.23	1.12	8166.03	3.76	0.61
0.60	14.03	120.10	1.24	0.35	2.53	0.16	3818.52	7.20	17.83	982.01	4.49	2.86	261.79	13.95	103.37	2.67	4.04	1.37	9589.46	4.98	0.80
0.63	13.55	113.16	1.03	0.34	2.43	0.14	2767.04	6.42	17.15	872.90	4.24	2.57	317.60	12.44	90.33	2.35	3.56	1.26	9149.95	4.23	0.69
0.59	12.88	117.30	1.24	0.33	2.49	0.16	3694.00	7.24	17.10	872.90	4.24	2.77	240.34	14.06	107.47	2.89	4.13	1.38	9439.63	4.93	0.81
0.57	12.72	115.62	1.21	0.33	2.51	0.16	2656.36	7.00	17.28	872.90	4.30	2.77	233.89	13.74	102.08	2.72	4.01	1.34	9649.40	4.78	0.77
0.59	12.71	112.34	1.17	0.31	2.47	0.17	2863.89	6.83	16.73	916.54	4.18	2.66	269.85	13.18	100.59	2.59	3.80	1.31	9409.66	4.67	0.74
0.52	13.00	114.85	1.11	0.32	2.55	0.14	1992.27	6.63	17.32	851.08	4.31	2.57	280.81	13.20	97.62	2.29	3.58	1.23	9070.03	4.35	0.68
0.63	10.95	101.56	1.02	0.29	2.16	0.14	2794.71	6.06	14.63	763.79	3.68	2.30	256.59	11.51	90.78	2.32	3.31	1.16	8131.06	4.09	0.65
0.41	16.93	220.74	2.75	0.53	2.16	0.14	3126.76	11.88	26.08	807.43	3.71	3.49	320.59	14.96	98.83	2.52	3.44	1.08	6053.35	3.76	0.59
0.45	17.38	233.25	2.86	0.57	2.26	0.13	3154.43	12.22	27.99	807.43	4.12	3.67	312.58	15.24	95.77	2.48	3.56	1.14	5873.55	3.70	0.58
0.42	16.35	205.34	2.46	0.53	2.68	0.16	3071.42	11.10	24.67	771.06	3.63	3.30	314.30	14.15	98.43	2.53	3.36	1.11	6253.13	3.71	0.58
0.56	12.40	97.62	2.46	0.67	3.43	0.23	4122.89	9.99	25.87	174.58	3.88	4.08	44.10	18.96	271.30	6.61	5.33	1.01	1258.62	6.84	1.10
1.02	24.68	178.88	4.16	1.00	6.34	0.44	5589.42	19.61	51.85	283.69	5.72	8.20	93.72	34.15	521.11	11.99	10.36	2.06	2487.27	14.56	2.34
0.73	16.89	113.41	2.84	0.80	4.15	0.29	6889.93	12.14	32.20	207.31	4.95	4.82	51.42	22.50	305.83	7.81	6.26	1.28	1633.21	8.21	1.38
0.91	21.32	147.39	3.66	1.03	5.21	0.37	8771.52	15.48	41.14	283.69	6.09	6.21	72.93	29.00	399.07	9.99	8.07	1.72	2127.66	10.43	1.79
0.30	6.89	56.19	1.32	0.32	1.73	0.13	1535.71	5.80	14.15	87.29	1.94	2.18	36.02	10.35	150.01	3.65	3.00	0.73	659.28	3.87	0.65
0.22	3.40	47.29	0.39	0.14	3.61	0.23	1743.24	5.16	15.45	741.96	1.81	2.49	201.14	12.20	121.68	3.00	3.81	1.35	10353.62	5.09	0.84
0.15	3.08	44.60	0.40	0.15	3.41	0.23	1743.24	5.10	14.82	785.61	1.76	2.40	192.83	12.29	121.01	3.14	3.83	1.33	10068.94	5.10	0.86
0.21	3.05	44.67	0.39	0																	

Supplementary Table 1.S1 (continued)

Dy (ppm)	Y (ppm)	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Li (ppm)	Sc (ppm)	Cr (ppm)	Co (ppm)	Ni (ppm)	Cu (ppm)	V (ppm)	Cd (ppm)	Material for Isotopes	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	¹⁷⁶ Hf/ ¹⁷⁷ Hf	²⁰⁶ Pb/ ²⁰³ Pb	²⁰⁷ Pb/ ²⁰³ Pb	²⁰⁸ Pb/ ²⁰³ Pb
4.02	22.52	0.81	2.27	0.34	2.34	0.34	7.33	40.58	38.82	31.10	46.20	95.24	233.11	0.06	glass	0.703638	0.512955	0.283051	18.751	15.611	38.573
2.77	15.44	0.57	1.60	0.23	1.61	0.26	5.69	32.16	50.89	26.53	44.15	75.60	132.89	0.06							
3.55	20.35	0.76	2.07	0.29	2.07	0.33	6.23	37.64	34.20	27.78	27.71	88.64	159.67	0.10							
2.32	13.38	0.49	1.38	0.19	1.36	0.22	4.64	27.94	55.92	20.77	30.02	59.46	116.05	0.06							
8.11	49.83	1.64	4.70	0.65	4.48	0.68	16.32	14.02	0.62	5.03	0.29	29.58	23.96	0.11	powder	0.703464	0.512950	0.283056	18.740	15.608	38.551
9.95	55.47	2.05	5.96	0.87	6.00	0.99	23.79	14.03	0.65	5.97	0.38	31.61	36.98	0.11							
5.34	30.64	1.11	3.12	0.45	3.08	0.50	9.29	21.22	0.34	14.46	0.71	52.73	61.77	0.03							
5.16	27.78	1.08	3.00	0.42	2.92	0.48	8.01	18.53	0.43	11.51	0.45	42.11	54.91	0.07							
4.39	25.54	0.93	2.63	0.36	2.51	0.38	10.37	36.37	22.55	29.71	13.85	120.54	260.80	0.11	powder	0.703238	0.512931	0.282964	18.753	15.568	38.365
3.47	19.14	0.74	1.98	0.27	1.98	0.33	5.59	25.78	14.66	16.62	5.41	98.80	161.73	0.05							
10.42	67.00	2.28	6.77	0.95	6.74	1.09	19.05	10.99	0.52	0.82	0.00	4.45	0.24	0.18							
5.06	28.31	1.08	2.93	0.40	2.65	0.44	6.22	43.41	86.84	33.23	25.09	80.46	229.52	0.11							
4.17	22.93	0.84	2.24	0.32	2.07	0.34	6.23	35.89	143.58	29.28	36.58	69.42	168.40	0.09	powder	0.703191	0.513013	0.283071	18.748	15.599	38.518
4.11	20.89	0.80	2.22	0.31	2.14	0.32	4.74	30.50	129.60	29.31	32.68	69.68	228.25	0.08							
4.09	20.69	0.82	2.22	0.30	2.15	0.34	4.74	30.63	130.76	30.93	36.19	74.25	242.54	0.10	glass	0.703220	0.512908	0.283051	18.732	15.592	38.461
9.60	50.48	1.96	5.47	0.78	5.45	0.87	9.43	25.94	29.26	24.64	19.46	36.87	211.87	0.20							
10.25	53.80	2.11	5.95	0.84	5.82	0.93	9.86	26.34	24.91	24.19	18.69	37.84	212.58	0.22	powder	0.703570	0.512968	0.283053	18.714	15.594	38.481
2.74	15.72	0.56	1.59	0.23	1.64	0.25	5.68	23.45	9.55	15.34	13.66	63.51	120.93	0.06							
2.41	14.18	0.50	1.47	0.20	1.31	0.23	6.84	20.28	10.14	15.01	6.59	73.39	163.67	0.06							
2.45	14.15	0.52	1.42	0.21	1.52	0.24	6.79	20.81	18.16	15.90	8.86	72.49	163.42	0.06							
2.38	13.31	0.47	1.37	0.20	1.38	0.21	6.42	19.09	11.00	14.88	7.21	68.79	153.08	0.05	glass	0.702740	0.513095	0.283106	18.652	15.552	38.291
3.05	17.73	0.64	1.81	0.25	1.74	0.27	7.80	25.89	38.35	18.99	13.59	93.86	211.04	0.37							
5.54	30.72	1.17	3.24	0.47	3.23	0.53	5.55	31.21	123.13	26.38	40.71	60.07	139.89	0.09							
5.10	29.36	1.08	2.99	0.42	2.88	0.46	7.03	37.59	136.01	27.62	33.07	68.34	155.71	0.04							
6.80	39.63	1.46	4.16	0.57	3.99	0.65	7.54	35.10	168.07	33.09	49.67	57.83	255.05	0.15	powder	0.703091	0.512951	0.282974	18.894	15.593	38.495
6.71	34.92	1.24	3.25	0.44	2.82	0.45	9.90	28.64	78.90	28.93	25.84	60.79	145.65	0.02							
6.47	35.44	1.32	3.59	0.49	3.53	0.53	8.41	31.75	22.56	28.22	15.09	76.64	247.34	0.15	powder	0.702685	0.513092	0.283101	18.679	15.560	38.253
5.72	32.62	1.14	3.25	0.43	3.07	0.51	7.31	36.70	150.17	29.21	30.83	65.52	239.27	0.13							
4.86	27.79	1.01	2.81	0.40	2.80	0.44	6.87	37.15	139.96	26.79	31.68	73.24	174.91	0.03	powder	0.702810	0.513086	0.283108	18.673	15.579	38.361
5.11	28.69	1.04	2.95	0.41	2.89	0.44	6.86	37.35	142.95	27.49	30.11	78.06	226.72	0.11							
8.86	51.33	1.85	5.32	0.73	5.39	0.84	10.64	26.90	27.04	24.99	19.86	39.07	205.41	0.20							
7.23	44.69	1.50	4.56	0.65	4.69	0.75	11.02	6.37	0.48	1.49	0.00	1.03	3.13	0.13							
7.50	46.47	1.60	4.81	0.68	4.86	0.79	12.00	7.60	0.44	1.91	0.00	1.31	4.22	0.10	powder	0.702514	0.513113	0.283126	18.616	15.536	38.123
13.42	82.36	2.79	8.39	1.18	8.54	1.43	13.71	13.10	0.53	1.02	0.06	6.69	0.06	0.17							
3.52	24.36	0.73	2.01	0.29	1.88	0.29	7.89	42.24	43.63	32.59	0.00	132.35	302.51	0.09							
4.86	28.48	1.01	2.69	0.38	2.72	0.41	7.98	41.44	42.37	27.46	22.28	132.51	281.52	0.12							
4.24	26.77	0.88	2.40	0.34	2.26	0.34	8.91	39.62	36.54	28.68	21.76	136.67	357.37	0.11	glass	0.702740	0.513095	0.283106	18.652	15.552	38.197
3.75	22.11	0.78	2.15	0.31	2.03	0.32	7.92	33.48	39.65	25.35	19.61	116.97	312.32	0.11							
4.85	28.52	1.00	2.83	0.38	2.70	0.42	9.01	39.41	14.61	26.90	11.10	156.04	351.50	0.10							
4.19	24.31	0.84	2.37	0.33	2.24	0.35	8.94	36.69	40.80	30.29	32.26	134.01	397.82	0.13							
5.02	29.31	1.03	2.92	0.42	2.79	0.45	8.08	41.68	39.27	29.19	27.43	132.69	283.66	0.10	powder	0.702514	0.513113	0.283126	18.616	15.536	38.123
4.80	27.61	0.98	2.77	0.38	2.75	0.43	8.07	40.08	41.54	26.69	20.05	131.06	287.85	0.11							
4.75	27.44	0.94	2.67	0.38	2.62	0.39	8.73	40.62	43.31	28.74	24.84	138.46	309.65	0.10							
4.50	25.96	0.92	2.39	0.34	2.29	0.37	8.21	40.08	41.38	29.86	23.53	140.56	371.30	0.10							
4.06	24.70	0.87	2.35	0.34	2.19	0.37	7.57	34.59	37.71	24.04	19.12	112.71	249.04	0.09	glass	0.702573	0.513104	0.283127	18.569	15.529	38.095
3.57	20.53	0.73	2.02	0.28	2.00	0.31	6.57	33.63	110.15	25.46	28.77	102.60	176.59	0.10							
3.70	20.09	0.73	2.05	0.28	1.97	0.31	6.37	36.06	170.47	25.77	31.34	104.79	197.45	0.12							
3.62	20.77	0.72	2.01	0.28	1.95	0.32	7.07	33.77	129.98	25.52	27.82	104.53	177.19	0.10							
7.73	47.29	1.52	4.76	0.65	5.02	0.76	11.01	8.32	0.20	0.58	0.00	10.49	0.05	0.11	powder	0.702514	0.513113	0.283126	18.616	15.536	38.123
14.85	89.64	3.16	8.62	1.24	8.34	1.37	18.29	15.12	0.27	1.17	0.00	20.93	0.04	0.20							
9.05	53.79	1.93	5.65	0.83	5.83	0.96	13.62	9.26	0.22	0.71	0.02	10.19	0.04	0.13							
11.81	71.53	2.49	7.33	1.07	7.59	1.26	17.52	11.78	0.29	1.14	0.00	11.63	0.07	0.16							
4.32	26.81	0.91	2.72	0.40	2.76	0.44	5.51	4.10	0.15	0.24	0.00	2.91	0.02	0.05	powder	0.702815	0.512994	0.283015	19.124	15.609	38.687
5.39	31.19	1.08	3.11	0.41	3.02	0.47	7.95	40.57	59.75	31.63	29.08	101.17	258.28	0.11							
5.40	31.44	1.15	3.22	0.44	3.07	0.50	7.36	40.61	80.09	34.21	52.54	92.27	211.80	0.10							
5.42	32.35	1.12	3.21	0.46	3.06	0.49	7.82	39.53	72.17	31.64	34.23	95.36	218.63	0.10							
7.53	43.57	1.60	4.53	0.66	4.56	0.70	9.05	34.23	99.32	26.16	30.13	56.51	162.76	0.15	powder	0.702808	0.512999	0.283008	19.126	15.602	38.666
11.80	68.81	2.41	6.85	0.94	6.61	1.04	15.25	34.89	1.25	26.78	3.64	38.17	278.38	0.16							
11.13	65.42	2.34	6.64	0.94	6.35	0.99	14.43	33.90	4.68	26.55	4.53	37.91	293.95	0.16							
7.25	41.43	1.50	4.14	0.56	3.87	0.60	12.08	26.52	1.36	23.82	2.51	24.80	223.13	0.16							
7.50	43.75	1.53	4.27	0.59	4.05	0.62	11.28	27.63	1.69	23.48	2.32	25.06	199.83	0.12	powder	0.702885	0.512999	0.283015	19.119	15.596	38.647
8.24	47.59	1.70	4.76	0.67	4.31	0.68	12.68	31.26	1.57	26.10	2.62	26.17	223.87	0.15							
7.21	41.92	1.47	4.20	0.58	3.73	0.62	11.19	26.76	1.29	22.25	2.20	22.48	192.09	0.13							
5.42	29.97	1.20	3.11	0.47	3.08	0.51	8.84	32.37	79.59	24.05	18.25	64.82	201.21	0.11							
7.04	40.47	1.43	4.11	0.59	3.90	0.62	11.04	41.44	106.01	38.75	0.00	85.51	239.34	0.14	glass	0.702846	0.512991	0.283023	19.059	15.598	38.709
6.86	39.24	1.39	3.97	0.56	3.81	0.59	9.81	40.28	94.83	28.56	21.80	80.03	229.06	0.13							
6.30	36.72	1.29	3.56	0.49	3.56	0.53	7.90	36.07	69.52	22.38	15.98	62.70	186.03	0.10							
26.87	172.49	5.91	18.01	2.69	18.91	3.12	47.39	8.58	0.61	0.64	0.11	11.60	0.30	0.34							
6.83	39.95	1.42	4.06	0.56	3.83	0.59	9.40	41.51	113.02	28.86	22.87	83.15	223.89	0.16	powder	0.702815	0.512994	0.283015	19.124	15.609	

Supplementary Table 1.S2: Average major and trace element concentrations and isotope compositions for secondary standards used for lava data

Standard	SiO ₂ (wt. %)	TiO ₂ (wt. %)	Al ₂ O ₃ (wt. %)	FeO _T (wt. %)	MnO (wt. %)	MgO (wt. %)	CaO (wt. %)
BCR2 n=35	54.31	2.31	13.53	12.44	0.20	3.62	7.22
KN18 n=9	74.41	0.17	10.45	3.59	0.07	0.00	0.12
BCR-2G n=32	--	--	--	--	--	--	--
BIR-1G n=32	--	--	--	--	--	--	--
BHVO-2 n=32	--	--	--	--	--	--	--
BHVO-1 n=2	--	--	--	--	--	--	--

Supplementary table 1.S2 (continued)

Na ₂ O (wt. %)	K ₂ O (wt. %)	P ₂ O ₅ (wt. %)	Total	Cs (ppm)	Rb (ppm)	Ba (ppm)	Th (ppm)
3.30	1.77	0.37	99.05	--	--	--	--
5.85	4.40	0.01	99.06	--	--	--	--
--	--	--	--	1.19	52.50	669.55	6.27
--	--	--	--	0.10	9.91	127.31	1.25
--	--	--	--	0.01	0.21	6.37	0.03
--	--	--	--	--	--	--	--

Supplementary table 1.S2 (continued)

U (ppm)	Nb (ppm)	Ta (ppm)	K (ppm)	La (ppm)	Ce (ppm)	P (ppm)	Pb (ppm)
--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--
1.77	13.82	0.85	15384.98	25.24	54.32	29.58	1548.72
0.43	19.65	1.23	3003.00	15.23	38.34	24.73	1155.91
0.02	0.57	0.04	132.97	0.61	1.96	2.45	84.73
--	--	--	--	--	--	--	--

Supplementary table 1.S2 (continued)

Pr (ppm)	Sr (ppm)	Nd (ppm)	Zr (ppm)	Hf (ppm)	Sm (ppm)	Eu (ppm)	Ti (ppm)
--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--
10.90	7.05	341.11	207.74	5.31	6.75	1.98	13521.64
1.73	5.46	395.51	185.70	4.60	6.14	2.06	15862.21
3.48	0.39	93.55	15.88	0.62	1.14	0.53	5616.06
--	--	--	--	--	--	--	--

Supplementary table 1.S2 (continued)

Gd (ppm)	Tb (ppm)	Dy (ppm)	Y (ppm)	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)
--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--
7.31	1.13	6.78	37.67	1.36	3.75	0.52	3.59
6.49	0.98	5.46	26.62	1.01	2.52	0.32	2.05
2.10	0.39	2.70	16.28	0.60	1.73	0.25	1.76
--	--	--	--	--	--	--	--

Supplementary table 1.S2 (continued)

Lu (ppm)	Li (ppm)	Sc (ppm)	Cr (ppm)	Co (ppm)	Ni (ppm)	Cu (ppm)	V (ppm)
--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--
0.56	9.96	32.38	14.77	36.03	10.50	17.64	392.32
0.30	4.89	30.40	264.37	42.46	104.82	126.45	290.03
0.27	3.22	41.87	389.70	50.40	152.96	120.88	276.53
--	--	--	--	--	--	--	--

Supplementary table 1.S2 (continued)

Cd (ppm)	Material for isotopes	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	¹⁷⁶ Hf/ ¹⁷⁷ Hf	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb
--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--
0.16	--	--	--	--	--	--	--
0.08	--	--	--	--	--	--	--
0.09	--	--	--	--	--	--	--
--	powder	0.703484	0.512987	0.283099	18.682	15.561	38.320

Supplementary Table 1.S3: New trace element concentrations and Pb isotope compositions for sediment core GC05-DP02

Depth below seafloor (cm)	Latitude (S)	Longitude (W)	Depth (m)	Cs (ppm)	Rb (ppm)	Pb (ppm)	Sr (ppm)	Hf (ppm)	Li (ppm)
1	-61.05	-62.64	3503	4.81	88.09	7.72	197.26	3.79	19.26
10	-61.05	-62.64	3503	4.58	77.63	10.10	212.85	3.28	16.28
20	-61.05	-62.64	3503	3.89	70.44	9.31	271.01	2.92	13.86
25	-61.05	-62.64	3503	3.68	65.60	9.43	289.31	2.77	18.50
45	-61.05	-62.64	3503	3.73	49.27	8.05	224.10	3.46	12.29
50	-61.05	-62.64	3503	4.27	67.87	7.48	250.50	3.48	13.36
60	-61.05	-62.64	3503	4.33	66.42	7.57	247.23	3.31	15.19
70	-61.05	-62.64	3503	4.23	64.01	10.31	240.50	3.04	15.94
80	-61.05	-62.64	3503	5.98	80.79	13.03	139.83	3.79	15.39
95	-61.05	-62.64	3503	6.80	107.27	10.84	156.77	3.65	27.00
105	-61.05	-62.64	3503	6.53	74.84	13.68	120.39	4.77	14.66
120	-61.05	-62.64	3503	6.07	105.73	10.10	133.91	6.36	20.45
140	-61.05	-62.64	3503	5.67	67.03	9.26	206.81	3.51	18.02
160	-61.05	-62.64	3503	4.40	64.19	9.00	243.11	3.15	14.32
180	-61.05	-62.64	3503	4.33	65.19	12.68	283.58	2.86	15.38
195	-61.05	-62.64	3503	4.81	68.15	13.09	229.70	3.14	13.49
205	-61.05	-62.64	3503	4.95	65.74	9.33	188.78	3.03	13.83
215	-61.05	-62.64	3503	4.73	66.05	10.32	203.44	3.64	11.78
230	-61.05	-62.64	3503	5.24	72.77	9.26	236.16	2.94	19.66
250	-61.05	-62.64	3503	5.81	75.47	9.56	229.08	3.05	20.20
260	-61.05	-62.64	3503	5.89	78.50	10.05	213.78	3.47	18.04
280	-61.05	-62.64	3503	7.27	107.52	10.48	167.75	3.47	20.59
300	-61.05	-62.64	3503	7.69	112.38	11.14	171.52	3.54	27.47
320	-61.05	-62.64	3503	6.36	80.30	14.61	177.74	3.37	18.43
340	-61.05	-62.64	3503	5.55	75.37	12.27	227.74	3.25	18.33
350	-61.05	-62.64	3503	4.66	64.55	9.96	245.29	2.51	14.39
370	-61.05	-62.64	3503	4.52	62.41	8.98	247.89	2.95	13.75
385	-61.05	-62.64	3503	5.55	62.09	8.65	166.90	3.59	15.39
395	-61.05	-62.64	3503	6.48	82.35	18.04	192.25	3.12	22.42
405	-61.05	-62.64	3503	5.59	72.91	10.42	226.30	3.23	18.26
420	-61.05	-62.64	3503	6.66	83.02	10.47	186.21	3.79	19.47
440	-61.05	-62.64	3503	4.14	56.89	8.00	234.90	2.83	13.37
460	-61.05	-62.64	3503	4.90	68.24	9.94	241.54	2.98	18.51
480	-61.05	-62.64	3503	5.07	62.78	9.42	244.34	3.22	17.43
500	-61.05	-62.64	3503	5.40	64.28	10.46	216.40	3.35	16.74
520	-61.05	-62.64	3503	5.19	66.39	9.52	238.40	3.25	18.93
540	-61.05	-62.64	3503	4.73	56.47	9.35	244.57	3.23	14.22
560	-61.05	-62.64	3503	5.04	61.69	10.52	234.48	3.34	14.49
575	-61.05	-62.64	3503	5.33	71.93	9.92	236.31	2.87	22.24
590	-61.05	-62.64	3503	6.51	78.36	9.16	189.06	3.54	19.61

Supplementary Table 1.S3 (continued)

Cr (ppm)	Co (ppm)	Ni (ppm)	Cu (ppm)	V (ppm)	Ga (ppm)	Cd (ppm)	Sb (ppm)	Zn (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb
15.29	6.92	13.06	13.96	127.34	31.85	0.03	0.52	50.59	18.742	15.605	38.539
74.37	6.58	12.29	11.91	118.56	30.91	0.03	0.44	44.87	18.698	15.625	38.483
53.23	6.48	11.27	9.85	97.32	30.24	0.04	0.25	41.35	18.735	15.609	38.480
495.67	9.42	16.58	13.20	131.67	30.11	0.04	0.35	60.55	18.766	15.659	38.664
90.20	5.91	10.14	11.30	100.78	26.31	0.03	0.41	37.00	18.772	15.628	38.615
270.36	6.26	10.42	11.67	106.15	28.73	0.03	0.40	39.24	18.825	15.604	38.678
51.19	7.06	12.24	13.28	109.81	28.89	0.03	0.37	46.06	18.816	15.612	38.642
146.20	7.54	14.07	18.96	92.79	28.13	0.04	0.30	53.67	18.687	15.610	38.441
205.49	4.88	11.54	11.73	97.30	31.12	0.03	0.54	41.08	18.673	15.629	38.545
234.02	8.53	19.25	17.43	125.71	33.43	0.02	0.48	67.62	18.734	15.604	38.628
213.67	3.55	7.91	7.61	91.98	33.13	0.02	0.58	31.77	18.685	15.612	38.557
23.47	5.59	11.77	10.95	98.33	31.49	0.03	0.51	60.07	18.950	15.620	38.800
379.57	7.19	14.60	12.42	126.74	32.54	0.03	2.46	47.18	18.803	15.621	38.685
235.95	7.42	13.50	12.23	116.56	28.16	0.02	0.46	48.20	18.774	15.616	38.615
61.63	8.14	15.44	29.59	125.59	30.10	0.09	0.48	56.17	18.671	15.601	38.449
119.03	6.54	12.68	15.08	120.21	29.42	0.03	0.56	44.43	18.667	15.614	38.429
253.78	5.79	11.18	13.22	110.75	27.03	0.03	0.59	39.99	18.726	15.639	38.579
61.74	4.92	9.34	11.13	98.34	26.93	0.03	0.51	33.55	18.735	15.626	38.520
56.25	8.40	15.56	16.19	119.78	29.52	0.03	0.41	54.89	18.719	15.611	38.473
126.80	8.25	16.00	17.35	120.89	30.04	0.03	0.36	56.01	18.790	15.619	38.634
309.96	7.57	15.59	20.65	118.19	30.92	0.03	0.47	54.95	18.750	15.604	38.608
101.30	6.71	16.17	16.40	120.72	32.52	0.02	0.54	56.00	18.738	15.605	38.605
31.94	8.55	19.43	18.37	128.43	34.81	0.04	0.67	63.87	18.740	15.607	38.580
20.95	6.50	14.91	13.49	120.38	29.54	0.03	0.95	46.47	18.665	15.616	38.412
34.25	7.17	14.38	15.47	114.39	29.82	0.04	0.50	47.73	18.723	15.609	38.492
152.35	6.77	12.47	11.62	112.79	27.57	0.02	0.47	39.65	18.744	15.614	38.522
1.07	6.92	12.64	14.15	115.51	28.55	0.03	0.49	41.41	18.790	15.622	38.629
21.73	5.90	11.86	13.00	111.21	28.61	0.03	0.45	37.44	18.780	15.619	38.678
7.42	8.69	16.72	17.29	122.49	30.93	0.02	0.82	56.68	18.666	15.624	38.432
115.73	6.75	12.81	14.44	112.99	29.91	0.03	0.49	43.45	18.788	15.626	38.619
177.82	7.24	14.99	19.41	127.39	31.28	0.03	1.72	51.69	18.710	15.609	38.484
136.82	7.12	12.45	11.47	102.89	26.32	0.03	0.40	40.50	18.787	15.615	38.609
263.04	8.51	15.79	15.74	116.22	29.84	0.02	0.38	51.85	18.745	15.613	38.567
38.61	8.66	16.72	23.32	126.18	29.61	0.05	0.37	54.05	18.745	15.616	38.539
470.45	7.62	14.05	21.11	115.86	30.02	0.02	0.35	50.02	18.734	15.613	38.535
105.04	8.74	15.96	22.77	125.80	30.39	0.03	0.38	56.84	18.763	15.602	38.558
184.42	7.45	12.91	15.79	115.90	28.86	0.03	0.35	43.40	18.761	15.610	38.590
237.69	6.64	12.78	16.71	121.95	29.62	0.04	0.40	43.72	18.725	15.616	38.535
118.09	8.71	16.36	14.70	121.51	31.27	0.02	0.62	54.22	18.811	15.629	38.686
130.19	6.17	12.96	13.34	116.43	30.98	0.02	0.66	45.75	18.819	15.632	38.694

Supplementary Table 1.S4: Parameters for Monte Carlo simulations of ternary mixing between sediment, fluid, and mantle

	Bransfield Strait	South Shetland Islands
DMM Trace Element Source	Avg. DMM, Workman and Hart (2005)	D-DMM, Workman and Hart (2005)
DMM $^{206}\text{Pb}/^{204}\text{Pb}$ Range	18.65-18.80	18.4-18.5
DMM $^{207}\text{Pb}/^{204}\text{Pb}$ Range ^a	15.51-15.53	15.49-15.50
DMM $^{208}\text{Pb}/^{204}\text{Pb}$ Range ^a	38.17-38.36	37.87-37.99
DMM $^{87}\text{Sr}/^{86}\text{Sr}$ Range ^b	0.70255-0.70257	0.70253-0.70254
DMM $^{143}\text{Nd}/^{144}\text{Nd}$ range ^b	0.51307-0.51309	0.51312-0.51314
Fluid $^{206}\text{Pb}/^{204}\text{Pb}$ ^c	18.53	18.53
Fluid $^{207}\text{Pb}/^{204}\text{Pb}$ ^c	15.53	15.53
Fluid $^{208}\text{Pb}/^{204}\text{Pb}$ ^c	38.03	38.03
Fluid $^{87}\text{Sr}/^{86}\text{Sr}$ ^d	0.70300	0.70300
Fluid $^{143}\text{Nd}/^{144}\text{Nd}$ ^e	0.51311	0.51311
Composition of Altered Oceanic Crust ^f	Staudigel et al. (1996) Super Composite	Staudigel et al. (1996) Super Composite
Fluid Pressure (GPa)	6	6
Fluid Cl Contents (wt. %)	5-6	5-6
Sediment Source ^g	GC05-DP02	GC05-DP02
Proportion of Fluid in Subduction Component (%)	50	15-80
Addition of Subduction Component to DMM (%)	0-3	3

^aCalculated from the listed range in $^{206}\text{Pb}/^{204}\text{Pb}$ using the NHRL equation from Hart (1984).

^bFit to the $^{206}\text{Pb}/^{204}\text{Pb}$ range using linear regressions of MORB data from Supplementary Table 1.S5. The DMM endmember for each simulated mixture was randomly, independently, and uniformly selected from the defined compositional range.

^cPb isotope ratios for the fluid are an average of PR3 lava ratios from Choe et al. (2007) and Choi et al. (2008). There are no reported Pb concentration data for these samples, so calculated ratios are not concentration weighted.

^dThe Sr isotope ratio of the fluid was estimated to be somewhat higher than the concentration weighted average value of 0.70269 from the PR3 samples of Choe et al. (2007) and Choi et al. (2008). We see good reason for the Sr isotope ratio to be slightly higher (e.g., Staudigel et al., 1996), likely on account of some minor influence from seawater.

^eConcentration weighted average of Nd isotope ratios of PR3 samples from Choe et al. (2007) and Choi et al. (2008).

^fFluid compositions were calculated by multiplying trace element concentrations of Altered Oceanic Crust by the fluid-eclogite KD values from Rustioni et al. (2021) at the listed fluid pressures and Cl contents. Pb concentration data were not reported in Rustioni et al. (1996), so values from the Kelley et al. (2003) Super Composite were used instead. The Fluid endmember for each simulated mixture was randomly, independently, and uniformly selected from this defined compositional range.

^gThe sediment endmember for each simulated mixture was randomly and independently selected from a multivariate normal distribution generated from the ITE and isotope composition of all intervals of sediment core GC05-DP02.

Supplementary Table 1.S5: MORB data used to generate a range of DMM isotope compositions for Monte Carlo simulations

Sample	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
R8-8 ^a	0.702484	0.513131	18.504	15.499	37.879
R80-1 ^a	0.702529	--	18.400	15.489	37.903
R96-24 ^a	0.702551	0.513143	18.340	15.485	37.841
R102-1 ^a	0.702530	0.513143	18.351	15.495	37.818
53DR-2 ^b	0.702514	0.513113	18.616	15.536	38.123
53DR-20 ^b	0.702573	0.513104	18.569	15.529	38.095
56DR-8HY ^b	0.702606	0.513059	18.841	15.560	38.356
DR190 ^b	0.702527	0.513079	18.669	15.542	38.158
^a Shimizu et al. (2016)					
^b This study					

CHAPTER 2

Source variations in volatile contents of Bransfield Strait back-arc and Phoenix/West Scotia mid-ocean ridge lavas, northern Antarctic Peninsula

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Published in *Chemical Geology* (2024) 646, 1-18

Abstract

We present the first volatile contents (H_2O , CO_2 , Cl, F, S) of young (< 6 Ma) submarine basaltic glasses from the Phoenix and West Scotia mid-ocean ridges and the Bransfield Strait back-arc of the South Shetland subduction zone in the Antarctic Peninsula.

The volatile contents of the MORB glasses correspond well with those of published Pacific MORB and reflect covariations in source enrichment and extent of melting. Our results support the hypothesis that decreasing spreading rates at the Phoenix Ridge resulted in preferential melting of less abundant enriched MORB mantle, due to its greater fertility and higher volatile contents, relative to the more abundant depleted MORB mantle.

The volatile contents of the Bransfield Strait back-arc glasses correlate with other geochemical indicators of subduction processes and reveal an along-axis spatial distribution consistent with a toroidal inflow of sub-slab asthenosphere around the edges of the subducting plate into the mantle wedge. This inflow should be considered when assessing spatial and geochemical variability at subduction zones, particularly those with slab windows and tears.

A small group of Bransfield Strait samples have volatile contents that do not correlate with other geochemical signals of subduction influence. We speculate that these samples reflect flux melting of residual enriched mantle brought beneath the Bransfield Strait via corner flow following recent alkaline magmatism in the far eastern regions of the Antarctic Peninsula. Our new data on lavas from the W7 segment of the West Scotia Ridge reveal their source was significantly affected by subduction processes. Unexpectedly, these lavas have $\text{CO}_2\text{-H}_2\text{O}$ pressures of vapor saturation that suggest they were collected in-situ and erupted relatively recently (~ 6 Ma), at odds with previous interpretations of their origins. We suggest they originated from a subduction-modified mantle (lithosphere or asthenosphere) left behind by the eastward-migrating South Sandwich

subduction zone sometime over the past ~30 Myr. These lavas demonstrate the long-lasting effects of subduction processes on the upper mantle and their potential to influence melt compositions even in non-subduction environments today.

We use the compositions of lavas from the Phoenix Ridge and Bransfield Strait to estimate mantle potential temperatures; our results agree well with global estimates for mid-ocean ridges and subduction zones, respectively.

1. Introduction

Volatiles have strong effects on mantle melting and magma crystallization, especially at subduction zones where there is a heavy supply of fluids from the subducting slab (e.g., Stolper and Newman, 1994; Wallace, 2005). Along-slab variations in fluid flux have been used to explain spatial trends in the geochemistry of arc and back-arc lavas at subduction zones across the world, but often these studies are not supplemented with volatile data (e.g., Pearce et al., 2005; Barry et al., 2006; Haase et al., 2012). Submarine glasses from along the length of the Bransfield Strait, a back-arc of the South Shetland subduction zone in the northern Antarctic Peninsula, are ideal samples to investigate trench-parallel variations in fluid flux. Their major and trace element contents and radiogenic isotope compositions indicate significant along-trench differences in the extent of slab-derived material fluxing the mantle wedge (e.g., Fretzdorff et al., 2004; Anderson et al., 2023). The abundant glassy rinds from basalts erupted at 1-2 km depth below the sea surface make excellent targets to measure volatile concentrations (Stolper and Newman, 1994; Dixon and Stolper, 1995; Shimizu et al., 2016). Furthermore, we have the advantage of using geochemically well-characterized basalts from the nearby Phoenix and West Scotia mid-ocean ridges to infer a local “background” mantle composition unaffected by subduction processes. Here we present the first volatile measurements (H_2O , CO_2 , Cl, F, S) of submarine glasses from the Bransfield Strait,

Phoenix Ridge, and West Scotia Ridge to assess the volatile contents of mantle sources beneath the ridges and the trench-parallel variability in the slab flux throughout the South Shetland subduction zone mantle wedge.

2. Geologic Background

2.1 The South Shetland Subduction Zone

Since the Mesozoic, ongoing subduction of the Phoenix Plate beneath the Antarctic Plate has shaped the geologic history of the Antarctic Peninsula (Fig. 2.1). This subduction zone is characterized by the South Shetland Islands volcanic front and a series of back-arc extensional features at progressive distances from the trench: The Bransfield Strait, the Prince Gustav Rift, and the Larsen Rift. Our study is centered on the Bransfield Strait, where recent submarine volcanism offers a unique opportunity to study the effects of subduction processes on the mantle of the northern Antarctic Peninsula. The limits of the Bransfield Strait roughly coincide with the modern extent of the trench, leading many workers to suggest that the strait opened through lithospheric thinning in response to roll-back of the subducting Phoenix slab in recent (<4 Ma) times (e.g., Barker, 1982; Haase and Beier, 2021). Today, seismic evidence suggests that the South Shetland subduction zone remains active, though subduction is proceeding quite slowly (Jordan et al., 2020; Leat and Riley, 2021a and 2021b).

2.2 The Phoenix and West Scotia Ridges

Neighboring the South Shetland subduction zone are the Phoenix and West Scotia mid-ocean ridges (Fig. 2.1). The lavas from these areas are important points of comparison for our study since they sample a portion of the upper mantle that has not been modified by subduction

processes, with the exception of lavas from the West Scotia Ridge segment W7. The three segments of the Phoenix Ridge are what remain today of an extensive mid-ocean ridge system that was progressively consumed during a series of collisions with the trench from ~50-4 Ma (Barker, 1982; Hole et al., 1994; Hole, 2021). The oblique angle between the trench and ridge segments resulted in the formation of a slab window beneath the Antarctic Peninsula from southwest to northeast, as the trailing half of each segment remained locked at the trench while the leading half continued to subduct (Hole, 1990; Guenthner et al., 2010; Hole, 2021). Spreading rates at the ridge decreased significantly until extreme slowdown by 3.3 Ma, though published ages for samples collected along and near the ridge axis range to as young as 1 Ma (Livermore et al., 2000; Choe et al., 2005; Choi et al., 2008; Haase et al., 2011).

Spreading at the West Scotia Ridge initiated ~30 Ma, resulting in the eastward opening of the Drake Passage and formation of the Central Scotia Plate (predecessor to today's Scotia Plate), north of the Antarctic Peninsula (Eagles, 2010; Maldonado et al., 2014; Fig. 2.1). The seven segments of the West Scotia Ridge continued spreading until extinction ~6 Ma (Eagles et al., 2005; Maldonado et al., 2014).

3. Materials and Methods

For each sample, three to five hand-picked chips of the freshest available, naturally-quenched submarine volcanic glass were mounted in indium and polished using diamond grit paste down to 1 μm . Additionally, a small subset of olivine phenocrysts from six samples were mounted, polished, and analyzed for their major element and V concentrations to estimate $\text{Fe}^{3+}/\text{Fe}_T$ following the approach of Kelley and Cottrell (2012). Multiple glass chips and olivine separates were used per sample to characterize natural variation of the sample and determine the reproducibility of the

measurement. Wherever possible, measurements were made on the glass encompassing the olivine separates, though not all olivine grains were directly in contact with analyzable glass.

All new data are reported in Supplementary Tables 2.S1-2.S3 and through Mendeley Data at <https://doi.org/10.17632/stz3xzt98n.1>. The major and trace element concentrations and isotope ratios of most lavas used in this study were previously reported by Anderson et al. (2023). However, we re-collected major element and V concentrations for several samples with glass in contact with the olivine separates, which we used to estimate their $\text{Fe}^{3+}/\text{Fe}_T$ (Kelley and Cottrell, 2012). In addition, we present new data for six lavas from the W7 segment of the West Scotia Ridge analyzed during the same analytical sessions as the data reported in Anderson et al. (2023) but never published. These six samples were dredged during the British Antarctic Survey cruise JR16003 (November 2016-January 2017) on RRS *James Clark Ross*, and the dredge locations for all samples are listed in Supplementary Table 2.S2 and shown in Figure 2.1. We also report new isotope ratios for three Bransfield Strait lavas with previously published major and trace element data from Anderson et al. (2023). Their material was provided by the Polar Rock Repository (PRR), Byrd Polar and Climate Research Center (BPCRC), Ohio State University. Finally, we report data for one basaltic sample from the Seal Nunataks, R3723.7 (collected by the British Antarctic Survey; Fig. 2.1), which we use for the model in Supplementary Figure 2.S1. Major and trace element contents were measured on whole rock powder at the Peter Hooper GeoAnalytical Lab at Washington State University (see lab for details on long term precision and standards: <https://environment.wsu.edu/facilities/geoanalytical-lab>). A detailed description of how all major and trace element and isotope analyses were conducted is provided in Anderson et al., (2023), and we present abbreviated methods below.

Volatile element (H_2O , CO_2 , Cl, F, and S) analyses were performed using the Cameca 6F ion probe at the Carnegie Institution for Science. Each glass chip was analyzed using a 10–15 nA current, 10 μm diameter Cs^+ primary beam scanned over a 20 μm diameter raster area using a manual diaphragm to avoid surface contamination. Data come from a 3 μm circle within this area. Spots were pre-sputtered for 180 s prior to 210 s count times. See Hauri et al. (2002) for further details on analytical techniques and standards. Reproducibility of the three to five chips for each individual sample was calculated, then averaged across all samples. For the Phoenix and West Scotia Ridge glasses, the average reproducibility (2σ SE) is $< 5\%$ for all volatiles except CO_2 and Cl, which are $< 8\%$. For Bransfield Strait glasses, the average reproducibility (2σ SE) is $< 8\%$ for all volatiles except CO_2 , which is $\sim 24\%$ on account of extremely low concentrations. Average root mean square errors on our volatile calibration curves were $< 5\%$ for Cl, $< 6\%$ for F, $< 9\%$ for CO_2 , and $< 10\%$ for S and H_2O .

Major element analyses for the glasses and olivine separates were performed on the Brown University Cameca SX-100 electron microprobe. The operating conditions of the instrument consisted of 15 kV voltage, 10 nA current and either a 10 μm (glass) or a 1 μm (olivine) diameter spot size. Reproducibility of repeated analyses per sample was calculated, then averaged across all samples. For the glasses, the average reproducibility (2σ SE) for each oxide is $< 0.5\%$ for SiO_2 , $< 1\%$ for Al_2O_3 and FeO_T , $< 1.6\%$ for MgO and CaO , $< 2.8\%$ for TiO_2 and Na_2O , $< 5.5\%$ for K_2O , $< 10.5\%$ for P_2O_5 , and $< 14.5\%$ for MnO , consistent with values reported in Anderson et al. (2023). For the olivine, the average reproducibility (2σ SE) is, $< 0.5\%$ for SiO_2 and MgO , 1.75 % for FeO , and $< 10.5\%$ for MnO . To ensure the olivine was in equilibrium with its surrounding glass, we calculated molar Mg# for each grain, as $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$, and then we compared that value to the Mg# of olivine that would be in equilibrium with the glass using an olivine-melt Fe^{2+}/Mg K_D of

0.3 (Roeder and Emslie, 1970). The reproducibility of secondary standards USGS BCR-2G and San Carlos Fo90 olivine is <1 % (2σ SE) for all major elements except MnO (5.4 %).

Trace element concentrations of glasses and V contents of olivine separates were determined by 193 nm wavelength excimer Analyte G2 laser ablation system coupled to a Thermo Scientific X-Series II quadrupole ICP-MS at Brown University. Olivine separates were analyzed using a 150 μm spot with a 20 Hz repetition rate and a laser frequency of 3.78 J/cm² at 50 % energy level. Glass chips were analyzed using a 150 μm spot and 10 Hz repetition rate, though for some partially crystallized or vesiculated samples, the spot size was reduced to 85 μm . The average reproducibility (2σ SE) obtained for the glass samples is better than 8 %, consistent with values reported in Anderson et al. (2023).

The new isotope data reported here were collected on hand-picked glass chips that were leached with cold 2.5N HCl for 30 min, dissolved in a mixture of HF(3):HNO₃(1), and then processed through ion exchange chromatography. Sr, Nd, Hf, and Pb isotopic compositions were measured on a Thermo Scientific Neptune Plus MC-ICP-MS at the Mass Spectrometer Analytical Facility, Brown University. To account for instrumental mass fractionation, we applied corrections using $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$, $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ and $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ and an exponential law. Sample Pb solutions were spiked with NBS SRM-997 Tl standard prior to analysis with a Pb/Tl ratio of ~ 4 to correct for mass fractionation using an exponential law and $^{203}\text{Tl}/^{205}\text{Tl} = 0.418922$. Sr, Nd, and Hf isotope ratios are reported relative to NBS SRM-987 $^{87}\text{Sr}/^{86}\text{Sr} = 0.71024$, JNd-i $^{143}\text{Nd}/^{144}\text{Nd} = 0.512115$, and JMC-475 $^{176}\text{Hf}/^{177}\text{Hf} = 0.282160$, respectively. Pb isotope ratios are reported relative to the NBS 981 $^{206}\text{Pb}/^{204}\text{Pb} = 16.9356$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.4891$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.7006$ (Todt et al., 1996). The external precision on the ratios over the course of two years is 30

ppm for Sr (2σ) and Nd (2σ), 40 ppm for Hf (2σ) and 80 ppm (2σ) for Pb. All blanks were < 50 pg.

4. Results

We report new volatile data for a suite of lavas that were previously analyzed for major and trace element contents, and isotope ratios (Anderson et al., 2023). Additionally, we report new major element, trace element, and radiogenic isotope compositions for a set of West Scotia Ridge lavas from the northernmost W7 segment. The lavas in this study extend in composition from basaltic to rhyolitic and range from tholeiitic to slightly alkalic, though there are a few instances of trachybasalts and basanites (Fig. 2.2). Isotope data on the most differentiated samples from the Bransfield Strait overlap with the range of more primitive lavas from the same area, suggesting that crustal assimilation is not controlling their compositions (Anderson et al., 2023). However, to avoid the effects of accessory mineral crystallization on the volatile/refractory incompatible trace element ratios used in this study, we do not consider data for any sample more differentiated than basaltic andesite when assessing source variations in volatile contents. All data and results are presented in Figure 2.2 and Supplementary Table 2.S2, but in all other figures the data are filtered for $\text{SiO}_2 < 57.0$ wt. %.

We separate the samples into four groups based on tectonic setting, source enrichment, and extent of subduction influence (Fig. 2.3). We assess the effects of subduction using ratios of fluid-mobile large ion lithophile elements (LILE; e.g., Cs, Rb, Ba, K) to fluid-immobile high field strength elements (HFSE; e.g., Nb, Ta) (e.g., Rustioni et al., 2021). These ratios are hereafter referred to as “subduction signal.” We also include Th/La, since increases in this ratio indicate sediment input into the source of arc and back-arc lavas (Johnson and Plank, 2000; Plank, 2005).

Surprisingly, subduction signals have been reported in lavas from the W7 segment of the West Scotia Ridge, and our new data corroborate that these melts have been affected by a subduction-like source (Riley et al., 2019; Fig. 2.3c-d). We add these new West Scotia Ridge lavas to the appropriate compositional groups, described below, according to the strengths of their subduction signals.

The four main compositional groups, which come from Anderson et al. (2023), are defined as follows. 1) *MORB* from the Phoenix and West Scotia ridges, which have compositions consistent with published Pacific MORB (Haase et al., 2011; Stracke, 2012; Anderson et al., 2023). This group forms a compositional range from normal MORB (N-MORB, $0.06 < \text{Th/La} < 0.11$, after Shimizu et al., 2016) to enriched MORB (E-MORB, $\text{Th/La} > 0.11$). 2) *Weak Arc lavas* from the Bransfield Strait and West Scotia Ridge, which have weak subduction signals (Fretzdorff et al., 2004; Riley et al., 2019; Anderson et al., 2023). 3) *Strong Arc lavas* from the Bransfield Strait and West Scotia Ridge, which have the strongest subduction signals (Fretzdorff et al., 2004; Riley et al., 2019; Anderson et al., 2023). We note that the cutoff between Weak and Strong Arc is arbitrary —lavas of both groups form a spectrum of increasing subduction signal that extends from MORB. 4) *Antarctic Peninsula Alkaline Volcanic lavas (APAV)*, which are seemingly ubiquitous alkaline lavas found across the region that carry no clear subduction signals (e.g., Hole, 1990; Košler et al., 2009; Hole, 2021; Panter et al., 2022; Anderson et al., 2023). We were only able to retrieve glass and measure the volatile contents of one APAV submarine sample from the Bransfield Strait.

The samples show wide variations in volatile contents; in Figure 2.4 we compare them to concentrations of refractory elements of similar incompatibility during mantle melting. In most cases, the MORB and arc-like lavas define their own respective fields and slopes in these plots.

Volatile contents roughly correlate with incompatible trace element enrichment in the MORB samples. The most trace element enriched MORB have the highest concentrations of H₂O, Cl, and F and the lowest concentrations of CO₂ and S (Fig. 2.4-2.5). In the Bransfield Strait, Strong Arc lavas range to lower F and S than Weak Arc lavas, whereas the ranges in H₂O, CO₂, and Cl contents overlap between the two groups. Furthermore, nearly all Bransfield Strait lavas have extremely low CO₂ contents, suggesting loss during magma degassing. Separations between West Scotia Weak and Strong Arc lavas are clearer than for the Bransfield Strait. West Scotia Strong Arc lavas range to greater abundances of H₂O, Cl, and F and lower concentrations of CO₂ and S than Weak Arc lavas. Notably, West Scotia Ridge Weak Arc lavas largely have volatile concentrations within the range of N-MORB. The APAV sample has exceptionally low concentrations of H₂O and CO₂ and relatively low Cl, F, and S contents compared to E-MORB samples from the Phoenix and West Scotia ridges.

5. Discussion

5.1 The Effect of Shallow Level Processes on Volatile Contents

Past work has shown that the bulk partition coefficients of volatile elements are similar to certain refractory incompatible trace elements during mantle melting: H₂O-Ce, CO₂-Ba, Cl-K-Nb-Ba, F-Nd-P, S-Dy (e.g., Michael and Cornell, 1998; Danyushevsky et al., 2000; Saal et al., 2002; Rosenthal et al., 2015; Shimizu et al., 2016). By closely comparing variations in absolute volatile concentrations, ratios of volatile to refractory incompatible trace elements, and experimentally derived thermodynamic models, we can account for the effects of shallow level processes (e.g., crystal fractionation, magma degassing, contamination, assimilation of hydrothermally altered crust, sulfide saturation, etc.) and assess source variations in volatile abundance.

5.1.1 Crystal Fractionation

Though we report data for andesites and rhyolites, they cannot be used reliably to assess source composition. This is due to the potential effects of late-stage crystallization of accessory minerals on the volatile/refractory trace element ratios of the glasses, making the ratios unreliable source indicators. Additionally, ratios of volatile elements themselves can be influenced by this differentiation process. For instance, Cl/F ratios, commonly used to distinguish between MORB and subduction influenced compositions can be modified by apatite fractionation during late stage crystallization. Thus, we do not consider these samples when assessing source variations in the upcoming discussion.

5.1.2 Degassing

A growing number of studies have shown the significant control that melt composition, exsolved gas composition, pressure, fO_2 , etc. have on the solubility of volatiles and the extent to which degassing governs melt volatile composition, even at submarine pressures (e.g., Dixon, 1997; Straub and Layne, 2003; Wallace, 2005; Edmonds et al., 2009; Plank et al., 2013; Ghiorso and Gualda, 2015; Thomas and Wood, 2021; Hughes et al., 2022; Wieser et al., 2022; Ding et al., 2023). Thus, it is necessary to assess the effects of degassing on the volatile compositions of the lavas. Using the compositions of the lavas in this study and the MagmaSat model of Ghiorso and Gualda (2015), we calculated pressures of CO_2 - H_2O saturation (P_{sat}). We then compared these pressures to the approximate pressures of sample collection, P_{coll} , to assess whether the samples were CO_2 - H_2O saturated at their collection depths (Fig. 2.6). In nearly all cases, the lavas fall along the 1:1 line, indicating that they were saturated at their collection depths (i.e., they were likely

collected in-situ) and experienced some degree of CO₂-H₂O degassing. A few samples from the Bransfield Strait are CO₂-H₂O supersaturated, with P_{sat} values above the 1:1 line. These samples must have ascended from within the crust so quickly that they failed to re-equilibrate prior to erupting. On average, this supersaturation corresponds to crustal depths of ~270 m, assuming a crustal density of 2800 kg/m³, though one extreme sample's overpressure corresponds to a depth of ~750 m within the crust. The APAV lava is the only CO₂-H₂O undersaturated sample in this study. Though it was collected at 178 bars of water pressure, its extremely low CO₂-H₂O contents yield a P_{sat} of 0 bars, suggesting either that its source is extremely CO₂-H₂O depleted (unlikely) or the lava significantly degassed and erupted at subaerial pressures and was subsequently transported to its collection depth.

The CO₂-H₂O of most Phoenix and West Scotia Ridge MORB overlap with the range for published Pacific MORB glasses, reflecting degassing and melt equilibration with a CO₂-dominant vapor phase (Fig. 2.5a). The alkaline E-MORB samples (H₂O > 1.0 wt. %) have somewhat lower H₂O contents for a given Ce content than the Pacific E-MORB, and they have exceptionally low H₂O/Ce, which may indicate they degassed slightly more H₂O than the tholeiitic E-MORB (Fig. 2.4a and Fig. 2.7a). Yet, their F contents, which should not degas substantially at submarine pressures, correlate strongly with H₂O and fall within range of Pacific MORB, suggesting this degassing has only minimally affected their H₂O contents (Edmonds et al., 2009; Fig. 2.5c).

Lavas from the Bransfield Strait have extremely low CO₂ and span a wide range of H₂O contents, suggesting that they have significantly degassed and equilibrated with an H₂O-dominant vapor phase (Fig. 2.5a). Degassing of this H₂O-rich vapor phase likely resulted in some H₂O loss in these samples (e.g., Wallace, 2005; Plank et al., 2013). However, positive correlations between H₂O and F contents (Fig. 2.5c), as well as between H₂O/Ce and subduction signal (e.g., Th/La and

Ba/Nb; Fig. 2.7a and Fig. 2.8, respectively) suggest that despite H₂O degassing, the H₂O/Ce ratios of the Bransfield Strait lavas still reflect compositional differences in their sources (i.e., extent of subduction influence).

5.1.3 Contamination with Hydrothermally Altered Material

Assimilation of hydrothermally altered crust and seawater-derived brines will elevate the Cl contents of a lava, making Cl a useful tool to assess contamination in MORB (e.g., Michael and Cornell, 1998; Shimizu et al., 2016). It is more difficult to assess these effects in subduction-derived melts, which are fluxed with significant amounts of Cl. However, since we intend to compare the Cl contents between the MORB and arc-like samples, we use Cl/Nb instead of Cl/K or Cl/Ba, since slab-derived fluids will elevate arc-like lavas in Cl, K, and Ba.

The MORB samples in this study show no signs of assimilation of hydrothermally altered crust in their Cl/Nb ratios. Compared to our MORB data, the Pacific MORB glasses from Shimizu et al. (2016) extend to higher Cl for a given Nb and higher Cl/Nb at similar values of Th/La, indicating Cl addition through assimilation of hydrothermally altered crust or brines. In contrast, the MORB samples of this study form a tight, shallow positive correlation (Fig. 2.4c, 2.5b, and 2.7b). Prior work suggested that decreasing spreading rates at the Phoenix Ridge resulted in progressively lower degree melts sampling increasingly trace element and isotope enriched sources (Haase et al., 2011; Anderson et al., 2023). The steady increase in Cl/Nb in the MORB samples with increasing Th/La is consistent with this shift to lower extents of melting and greater source enrichment, rather than contamination. Our data suggest that Cl/Nb ratios of uncontaminated N-MORB and E-MORB are roughly < 15 and 20, respectively. The Pacific MORB data from Shimizu et al. (2016) are filtered on this basis in all figures except Figures 2.4, 2.5, and 2.7b, where we are

not considering differences in the volatile contents of their sources. For the arc-like lavas, high Cl/Nb ratios correlate with stronger subduction signals. The positive correlation between Cl/Nb and Th/La reflects a high Cl input from slab fluids that corresponds well with increasing sediment flux (as indicated by Th/La). This increase in Cl/Nb could be controlled by assimilation of hydrothermally altered crust. At a given range in Th/La, many of the arc-like lavas show slight variations in Cl/Nb, which could be caused by some assimilation of hydrothermally altered crust or brine. However, these lavas display no clear changes in trace element or isotope ratios with decreasing MgO, suggesting assimilation is not the main control on their compositions.

5.1.4 Sulfide Saturation and Sulfur Degassing

We calculated the sulfur content at sulfide saturation (SCSS) using the model of Smythe et al. (2017), which we then compared to the measured S concentrations of the lavas (Fig. 2.9). The SCSS of a melt depends heavily on pressure, temperature, melt composition, and fO_2 (Smythe et al., 2017., Nash et al., 2019; O'Neill, 2021). We broadly assume MORB melt near the conditions of the fayalite-magnetite-quartz (FMQ) oxygen buffer (Lee et al., 2005; O'Neill et al., 2018), but this may not be the case for the subduction-influenced lavas (Lee et al., 2005; Kelley and Cottrell, 2012; Plank and Forsyth, 2016). For this reason, we estimated the fO_2 of the subduction-influenced lavas using the partitioning of V between olivine and melt after Canil (2002). The data collected for this model are presented in Supplementary Table 2.S3. The fO_2 values were then converted to proportions of Fe^{3+} relative to total Fe (Fe^{3+}/Fe_T) using the model of Kress and Carmichael (1991). This conversion was done using pre-eruptive temperatures (using the thermometer of Wallace and Carmichael, 1992, calibrated using olivine-diopside-silica multiple saturation experiments and correcting for the effect of H_2O using Médard and Grove, 2008) at 0.1 GPa. Although we did not

measure V in the MORB and APAV samples, we used the values presented in Kelley and Cottrell (2012) for the East Pacific Rise. Our values for $\text{Fe}^{3+}/\text{Fe}_T$ at pre-eruptive conditions were ~ 0.17 for MORB and APAV, ~ 0.20 for arc-like West Scotia Ridge lavas, and ~ 0.25 for Bransfield Strait lavas. We combined these $f\text{O}_2$ estimates with the calculated pre-eruptive temperatures at 0.1 GPa to calculate SCSS for each sample.

The results of the model reveal that all samples from the Phoenix and West Scotia ridges are within error of sulfide saturation. As a result, any signal of source composition in the S contents of these lavas has likely been overprinted by sulfide saturation. Figure 2.9 shows that the E-MORB require lower S to saturate than the N-MORB, on account of differences in melt chemistry, which may explain their lower absolute S contents (Fig. 2.4e, 2.5d, and 2.9). This also explains why a subset of alkaline E-MORB (seen in Fig. 2.2) have particularly low S/Dy (Fig. 2.7e and 2.10). While their S contents are within range of other E-MORB, their Dy contents are elevated due to their lower extents of melting (Fig. 2.4e).

The $f\text{O}_2$ of the arc-like samples seems to be the dominant variable controlling their S contents. Despite their strong subduction signals, arc-like samples from the West Scotia Ridge are sulfide saturated and have lower $f\text{O}_2$ compared to the Bransfield Strait lavas, which have high $f\text{O}_2$ and are sulfide undersaturated. Despite their strong subduction signals, the West Scotia arc-like lavas have S/Dy ratios consistent with those of MORB, whereas the S/Dy ratios of the Bransfield Strait lavas roughly correlate negatively with subduction signal (Fig. 2.7e). This negative correlation suggests either the slab flux producing the subduction signal has low S/Dy or the melts have lost S during degassing. However, the S contents of arc magma sources are expected to be higher than those of the MORB mantle; therefore, S loss through degassing is a more viable explanation (De Hoog et al., 2001; Wallace, 2005; Taracsák et al., 2023). This S loss was likely

spurred by high H₂O contents and higher fO_2 (e.g., Liu et al., 2007; Wallace and Edmonds, 2011; Hughes et al., 2022; Ding et al., 2023). The negative correlation between S/Dy and H₂O/Ce for the Bransfield Strait lavas in Figure 2.10 supports this hypothesis. The effect of fO_2 on sulfide saturation and sulfur degassing in the West Scotia arc-like lavas can also be seen in Figure 2.10, since the melts have similar values of S/Dy to those of MORB despite wide ranges in H₂O/Ce and strong subduction signals. The results of the SCSS model suggest that any signal of source variation in the S contents of the lavas has been overprinted by either sulfide saturation or degassing, so we will not consider S source contents any further.

5.2 Source Variations in Volatile Contents

Having assessed the effects of secondary processes on the geochemistry of the lavas, we can assess variations in the volatile contents of their mantle sources. The H₂O, CO₂, and S of the lavas have likely degassed to some extent and have, for the latter, additionally been affected by sulfide saturation. However, as indicated before, H₂O degassing did not completely erase the initial H₂O/Ce source signals of the lavas, and thus, H₂O/Ce may still be informative of source composition. Only the APAV sample degassed so extensively that its H₂O/Ce bears no source signal. Furthermore, secondary processes have not affected the Cl and F contents of the lavas, even for the extremely degassed APAV lava (Fig. 2.4, 2.5, and 2.7).

Figure 2.11 demonstrates the strong relationship between Th/La and source composition. In the following discussion, we use Th/La as a proxy for source composition, which allows us to consider the source volatile contents of samples that do not have isotope data. Increasing Th/La in the MORB samples corresponds to greater isotopic source enrichment, whereas increasing Th/La in the arc-like lavas reflects greater subduction influence.

5.2.1 Source Variations in Volatile Contents of Phoenix and West Scotia Ridge MORB

Differences in volatile/refractory incompatible trace element ratios correspond well with source variations for the MORB samples (Fig. 2.7). The most trace element and isotope enriched MORB have the lowest $\text{H}_2\text{O}/\text{Ce}$ and CO_2/Ba and the highest Cl/Nb and F/Nd . The lower CO_2/Ba ratios in the E-MORB are jointly controlled by higher Ba concentrations and CO_2 degassing at similar pressures to the N-MORB samples (Fig. 2.6). The MORB samples follow a shallow negative correlation in $\text{H}_2\text{O}/\text{Ce}$ with increasing Th/La and appear to define mixtures of melts from a depleted MORB mantle (D-DMM) and a low- $\text{H}_2\text{O}/\text{Ce}$ enriched MORB mantle (E-DMM) (Fig. 2.7a). This was similarly observed in East Pacific Rise MORB by Shimizu et al. (2016), with many lavas varying little in $\text{H}_2\text{O}/\text{Ce}$ across broad ranges in Th/La . There are two possibilities to explain the low- $\text{H}_2\text{O}/\text{Ce}$ in E-MORB: They either melted from E-DMM with intrinsically low $\text{H}_2\text{O}/\text{Ce}$ (e.g., Dixon et al., 2002), or they melted from E-DMM with high initial $\text{H}_2\text{O}/\text{Ce}$ that subsequently experienced solid state H_2O diffusive loss to the surrounding depleted mantle as proposed by Shimizu et al. (2016). Either way, Phoenix and West Scotia Ridge E-MORB seem to represent melting from an $\text{H}_2\text{O}/\text{Ce}$ -depleted E-DMM, resulting in the shallow trend observed in Figure 2.7a.

Despite this $\text{H}_2\text{O}/\text{Ce}$ depletion, our estimate for the H_2O concentration of Phoenix Ridge E-DMM is still slightly higher than that of DMM. For the most depleted N-MORB (average $\text{H}_2\text{O}/\text{Ce} = 187 \pm 15$ 2σ SD), we assume a DMM Ce concentration of 0.55 from Workman and Hart (2005), which yields a DMM H_2O concentration of 103 ± 8 ppm. Because the alkaline E-MORB samples may have degassed some H_2O , we only consider tholeiitic E-MORB (average $\text{H}_2\text{O}/\text{Ce} = 175 \pm 14$ 2σ SD) in our E-DMM estimate. We assume an E-DMM Ce concentration of 0.726 from Workman and Hart (2005), resulting in an E-DMM H_2O concentration of 127 ± 10 ppm.

Furthermore, Cl/Nb and F/Nd correlate positively with source enrichment, and the MORB data from this study overlap with the Pacific MORB lavas from Shimizu et al. (2016). The slight offset in our data to slightly lower H₂O/Ce, Cl/Nb, and F/Nd at a given Th/La suggest our samples define a lower bound for Pacific MORB (Fig. 2.7). The data indicate that for the Phoenix and West Scotia ridges, the E-MORB source is more enriched in H₂O, Cl, and F than the N-MORB source, in agreement with what Shimizu et al. (2016) found for East Pacific Rise MORB. These findings support that the most enriched MORB, generated as spreading rates at the Phoenix Ridge decreased, were preferentially formed due to higher volatile contents and greater fertility of the E-MORB source (e.g., Choi et al., 2008; Haase et al., 2011).

5.2.2 Source Variations in Bransfield Strait Volatile Contents

Bransfield Strait lavas show variations in volatile/refractory incompatible trace element ratios that correspond well with varying amounts of subduction input to their mantle sources. Positive correlations in H₂O/Ce, Cl/Nb, and F/Nd vs Th/La support that increasing slab flux produces greater volatile enrichment (Fig. 2.7).

Furthermore, previous work has shown that Bransfield Strait lavas follow a gradual along-axis increase in subduction signal from SW to NE beginning at about 59 °W until reaching about 56 °W, where the signal sharply decreases (Fretzdorff et al., 2004; Anderson et al., 2023). Our volatile data reveal that this spatial compositional trend is also present in volatile/refractory incompatible trace element ratios (Fig. 2.12). Lavas with the highest H₂O/Ce, Cl/Nb, and F/Nd are roughly found near the central-NE region of the back-arc, where the mantle wedge is expected to carry the strongest signs of subduction influence (Anderson et al., 2023). This makes sense because greater subduction influence should raise the volatile contents of the mantle, spurring high extents

of melting and lowering the concentrations of similarly incompatible refractory elements. Indeed, Anderson et al. (2023) found that Bransfield Strait lavas bearing the strongest subduction signals melted to the greatest extents, an unsurprising effect of increased subduction influence. Interestingly, S/Dy forms the reverse trend, with the highest values occurring near the ends of the strait in the least subduction-modified lavas (Fig. 2.12d). This again is likely a function of the effect of fO_2 (increasing with increased slab flux) and H_2O degassing, which vary along the length of the Bransfield Strait —the areas where S/Dy is lowest correspond to the areas where H_2O/Ce is highest (Figs. 2.10 and 2.12).

The observed spatial geochemical trend along the Bransfield Strait is likely tied to the area's complex mantle dynamics. The Phoenix Ridge upper mantle has likely passed into the mantle wedge via toroidal flow around the edges of the Phoenix slab as the subduction angle has steepened through time, diluting the effects of subduction processes at the ends of the strait and forcing the most subduction-modified portions of the mantle wedge to the center (Anderson et al., 2023). This is why lavas that occur at the ends of the strait, areas that are in more direct contact with fresh inflowing sub-slab MORB mantle, have the weakest subduction signals and lowest volatile/refractory incompatible trace element ratios (Fig. 2.12). Our findings suggest that inflowing sub-slab asthenosphere into the mantle wedge may strongly influence spatial and compositional variations in back-arc basalts, especially in subduction zones with slab windows and tears.

A subset of Strong Arc lavas from the Bransfield Strait back-arc range to low H_2O/Ce and F/Nd and high S/Dy at high Th/La, deviating from the trends defined by other Bransfield Strait samples (Fig. 2.7, highlighted in pink). However, their range in volatile contents overlaps with that of other Strong Arc lavas at comparable MgO contents and Th/La ratios (Fig. 2.4-2.5). Thus, their

distinct H₂O/Ce, F/Nd, and S/Dy ratios must, in part, be affected by their elevated Ce and Nd and lower Dy concentrations. This can be seen clearly when comparing their primitive mantle-normalized incompatible trace element patterns to those of other Strong Arc lavas at similar MgO and H₂O contents (Fig. 2.13). Their relative depletions in Nb, Ta, Ti, and mid to heavy rare earth elements (REE) suggest that their mantle source was depleted in incompatible refractory trace elements before being affected by subduction processes (Fig. 2.13). In spite of this, these lavas have some of the most enriched isotope compositions in the Bransfield Strait, suggesting that recent melting of an isotopically enriched source produced this trace element depletion (Fig. 2.14). Their isotope compositions also suggest a connection to the enriched APAV lavas ubiquitously present throughout the Antarctic Peninsula (Fig. 2.14; e.g., Hole et al., 1990; Košler et al., 2009). We speculate that residual mantle from recent APAV melt generation beneath the Prince Gustav Rift region behind the Bransfield Strait has been dragged beneath the Bransfield Strait via corner flow and fluxed with subducted sediments and fluids, producing low degree melts ($\leq 3\%$ melting) with elevated incompatible trace element concentrations (e.g., Ce and Nd) and steep REE slopes (which may also indicate the presence of residual garnet in their source). Using the simple model presented in Supplementary Figure 2.S1, we show that this process could explain the compositions of these Strong Arc lavas from the Bransfield Strait. Although by no means is this the only possible explanation for their origins, this is a reasonable model to explain their trace element, volatile element, and radiogenic isotope compositions.

With only one sample, we cannot infer much about the volatile composition of the APAV source. However, despite the significant loss of H₂O, CO₂, and S to degassing, the APAV lava appears to have retained its Cl and F. It is at least clear that the Cl/Nb and F/Nd of this single

sample are very close to those of MORB, suggesting its source may at least have similar Cl/Nb and F/Nd to DMM (Fig. 2.7).

5.2.3 The Origins of West Scotia Ridge Arc-Like Lavas

The presence of arc-like lavas from the W7 segment of the West Scotia Ridge is rather surprising and not well understood. These lavas have subduction signals in their primitive mantle-normalized incompatible trace element patterns (Fig. 2.3), and our new data reveal that they also deviate from MORB in isotope space, extending towards a subduction-like radiogenic Pb-Sr-Hf and unradiogenic Nd endmember similar to the South Sandwich Arc (Fig. 2.14). Additionally, their elevated volatile/refractory incompatible trace element ratios correlate with subduction signal and further support they melted from a mantle source affected by subduction processes (Fig. 2.7).

Published ^{40}Ar - ^{39}Ar ages of 137-93 Ma suggest that these lavas are much older than the West Scotia Ridge itself, which only began spreading ~ 30 Ma at the earliest (Maldonado et al., 2014; Riley et al., 2019). To reconcile the unique geochemistry and ages of these lavas, previous workers suggested the W7 segment crust was part of a down-faulted block of the Cretaceous Tierra del Fuegian Andes, parts of which were dragged >1200 km eastwards along the North Scotia Ridge fault during the opening of the Scotia Plate (Riley et al., 2019; Fig. 2.1b). However, our volatile data are inconsistent with this interpretation. Calculated P_{sat} for each sample fall within error of their P_{coll} , suggesting that since erupting, these lavas have not experienced any significant changes in bathymetry (Fig. 2.6). This is at odds with a supposed Tierra del Fuegian Andes origin, since the lavas would need to have survived substantial changes in depth over a ~ 100 Myr period of significant tectonic reconfiguration (e.g., Dalziel et al., 2013; Eagles and Jokat, 2014; van de Lagemaat et al., 2021). Furthermore, in discussing their geochronology, Riley et al. (2019)

acknowledged there is evidence of ^{39}Ar recoil, leaving open the possibility that the ages themselves could be artificially older.

We propose that these W7 lavas are recent melts (~ 6 Ma based on their proximity to the ridge axis) that sampled a subduction-modified mantle left behind by an earlier subduction zone—likely an ancient predecessor of the modern South Sandwich subduction zone (Fig. 2.1b). Tectonic reconstructions of the Scotia Sea region are greatly debated, but one thing most have in common is that roughly 20-30 Ma a subduction zone existed in the area where the W7 segment currently lies (Eagles and Jokat, 2014; van de Lagemaat et al., 2021). Based on the geochemistry of lavas at the W7 segment, it appears that some subduction-modified mantle was left behind as the Scotia Plate continued rapidly expanding eastwards. Whether this mantle remained as ambient asthenosphere or as metasomatized lithosphere is unclear. Regardless, there are undeniable geochemical similarities between W7 lavas and arc lavas from the South Sandwich subduction zone. In isotope space, the W7 samples bearing the strongest subduction signals coincide perfectly with lavas from the South Sandwich Arc, whereas the W7 lavas with the weakest subduction signals back-project towards N-MORB compositions (Fig. 2.14). This suggests that some portions of the West Scotia Ridge overlie mantle that was modified by subduction processes during the eastward migration of the South Sandwich Arc and the opening of the Scotia Plate. Our findings underscore the enduring impact subduction processes have on the upper mantle, even in regions that today are hundreds of kilometers from the nearest subduction zone. This calls into question our understanding of the lifetime and distribution of subduction-derived material persisting in the upper mantle across the Earth, something that has begun to be recognized at other ridges as well (Yang et al., 2021).

As previously discussed, these W7 lavas have higher S/Dy ratios (within the range of MORB) than the arc-like lavas from the Bransfield Strait, and they are the only sulfide saturated Strong Arc samples (Fig. 2.7e and 2.9). This suggests that these lavas did not lose S to degassing like the other Bransfield Strait lavas on account of their somewhat lower fO_2 (see Section 5.1.4 and Supplementary Table 2.S3 for details), despite their high H₂O contents (Fig. 2.5d) and strong evidence of subduction influence in their trace element and isotope compositions (Fig. 2.3 and 2.14, respectively). Even though some subduction-modified mantle underlies the W7 segment, the melts do not seem to be especially oxidized, which is unusual for subduction modified melts (e.g., Kelley and Cottrell, 2009; Cottrell et al., 2021). We cannot rule out the possibility that the subduction modified source component of the W7 lavas is part of the oceanic lithospheric mantle.

5.3 Equilibrium Pressure and Temperature Estimates

We estimated the pressure (P) and temperature (T) conditions of melts in equilibrium with the solid mantle using the H₂O contents, major element compositions, and Fe³⁺/Fe_T ratios at mantle conditions, which we determined iteratively using measured V olivine-melt partition coefficients for each compositional group (see Section 5.1.4 and Supplementary Table 2.S3 for details). At each iterative step, samples were fractionation-corrected to be in equilibrium with Fo₉₀ by adding equilibrium olivine in 0.1% increments, and then these corrected compositions were used to estimate mantle pressures and temperatures using the model of Plank and Forsyth (2016). Values for Fe³⁺/Fe_T were then re-calculated following the model of Kress and Carmichael (1991), and these steps were repeated until the values converged. Mantle Fe³⁺/Fe_T estimates for the Phoenix Ridge MORB and Bransfield Strait arc-like lavas were ~0.12 and ~0.19, respectively. These estimates are reasonable given the range of published values for MORB and back-arc lavas and

the uncertainties of the calculation. Though the Plank and Forsyth (2016) model is calibrated for melts in equilibrium with only olivine and orthopyroxene, we applied it here as a rough estimate of equilibrium P-T conditions for Phoenix Ridge and Bransfield Strait lavas.

The model requires fractionation-corrected primitive melt compositions, so we only used samples with MgO ~8.0 wt. % or greater, where we could be confident that they have only crystallized olivine. In the Phoenix Ridge, this is not a problem, since many of our glass samples are sufficiently primitive. However, in the Bransfield Strait, only a few published samples from Fretzdorff et al. (2004) are primitive enough to apply the model. For these primitive samples, we estimated their H₂O contents using representative H₂O/Ce values from our data and measured Ce contents from Fretzdorff et al. (2004). For Weak Arc lavas, we used a H₂O/Ce value of 668, and for Strong Arc lavas, we used a value of 1157 (Fig. 2.7a). These values come from samples in our study with similar incompatible trace element patterns to those of the selected Fretzdorff et al. (2004) high MgO lavas. Additionally, we applied the model to a set of primitive Quaternary South Shetland Island volcanic front samples from Haase et al. (2012) as analogs for Bransfield Strait Strong Arc lavas. Anderson et al. (2023) found that these lavas have very similar trace element and isotope compositions to Bransfield Strait Strong Arc lavas, distinct from older (> 30 Ma) South Shetland Island lavas. We estimated the H₂O contents of these Quaternary South Shetland lavas using the same representative Strong Arc H₂O/Ce value of 1157. More details on these selections are provided in Supplementary Table 2.S4.

Results for Phoenix Ridge MORB are all within error of each other, recording equilibrium conditions of ~1.35 GPa (~43 km depth) and ~1340° C (Fig. 2.15a). These conditions may reflect stalling at a boundary, possibly the lithosphere-asthenosphere boundary, since polybaric melt segregation along an adiabat would form a steep P-T trend (see reference adiabats in Fig. 2.15).

Assuming a mantle adiabatic gradient of 0.4° C/km (after Plank and Forsyth, 2016), the MORB samples would fall along an adiabat with a potential temperature of $\sim 1323 \pm 43^{\circ}\text{ C}$, which is reasonable for MORB (Klein and Langmuir, 1987; Falloon et al., 2007; Dalton et al., 2014; Fig. 2.15a).

Despite broad uncertainties in the model, the calculated equilibrium P-T of arc-like samples from the Bransfield Strait and Quaternary South Shetland Islands show resolvable variations in P at similar ranges in T (Fig. 2.15b). Given their steep trend in P-T, these melts may represent discrete partial melts that formed along an adiabat. If this is the case, the most incompatible trace element-depleted lavas should record the shallowest pressures, reflecting increasing extents of melting upon ascent. In fact, we observe strong correlations between modeled equilibrium P and incompatible trace element enrichment (Fig. 2.16). The results also show that the mantle began melting below the dry peridotite solidus, which is unsurprising because back-arc mantle should be elevated in H_2O . Assuming the results reflect final equilibration in the asthenosphere, the shallowest results would put the maximum depth of the lithosphere-asthenosphere boundary beneath the strait at $\sim 30\text{ km}$, broadly consistent with seismic data (Wiens et al., 2021). Again, assuming the same mantle adiabatic gradient of 0.4° C/km , the arc-like samples fall along an adiabat with a potential temperature of $\sim 1239 \pm 41^{\circ}\text{ C}$ (Fig. 2.15b). This is somewhat low compared to the back-arc estimates of Wiens et al. (2006) but not unreasonable for Bransfield Strait melts, which have higher H_2O contents than the melts they use—the imposed $\text{H}_2\text{O/Ce}$ values we use yield average H_2O contents of $\sim 2\text{ wt. \%}$ for our selected Bransfield Strait samples, compared to values $\leq 1\text{ wt. \%}$ in Wiens et al. (2006).

6. Conclusions

We have reported the first volatile element concentrations in the northern Antarctic Peninsula, revealing several important spatial and compositional relationships that hold broad implications for subduction worldwide.

Our findings support that as spreading rates slowed at the Phoenix ridge, preferential melting of less abundant, more fertile and volatile-rich E-DMM produced increasingly isotope and trace element enriched melt compositions.

In the Bransfield Strait, volatile enrichment corresponds strongly with increased subduction signal and increased degree of melting. These increases occur near the middle and NE portion of the strait, where the subduction-modified mantle is being forced by incoming sub-slab asthenosphere flowing toroidally around the slab's edges. Therefore, it is important to consider the potential influence sub-slab asthenosphere may have on the geochemistry of arc and back-arc lavas located near the edges of subducting plates at other subduction zones, especially those with slab windows and tears that offer easy pathways into the mantle wedge. Furthermore, several Bransfield Strait samples have strong subduction signals but unusually low volatile/refractory incompatible trace element ratios. We suggest these samples reflect flux melting of residual enriched mantle, brought beneath the Bransfield Strait via corner flow following recent generation of alkaline lavas in the far eastern regions of the Antarctic Peninsula, highlighting the heterogeneous nature of the mantle wedge.

New data on arc-like lavas from the W7 segment of the West Scotia Ridge suggest they were collected in-situ and erupted perhaps as recently as 6 Ma. Their trace element and isotopic compositions suggest the W7 segment overlies subduction-modified mantle left behind within the past ~30 Myr by the eastward-migrating South Sandwich Arc. The fact that this mantle remains

beneath an area that is now hundreds of kilometers from the nearest subduction zone illustrates the enduring and widespread effects of subduction modification on the upper mantle.

Finally, modeled equilibrium P-T for Phoenix Ridge MORB suggest they accumulated at relatively uniform conditions, possibly at the lithosphere-asthenosphere boundary. In contrast, modeled P-T for lavas from the Bransfield Strait suggest they are discrete partial melts that formed along a mantle adiabat. Estimated mantle potential temperatures for both sets of lavas are consistent with ranges for mid-ocean ridges and subduction zones, respectively.

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12.

Figures

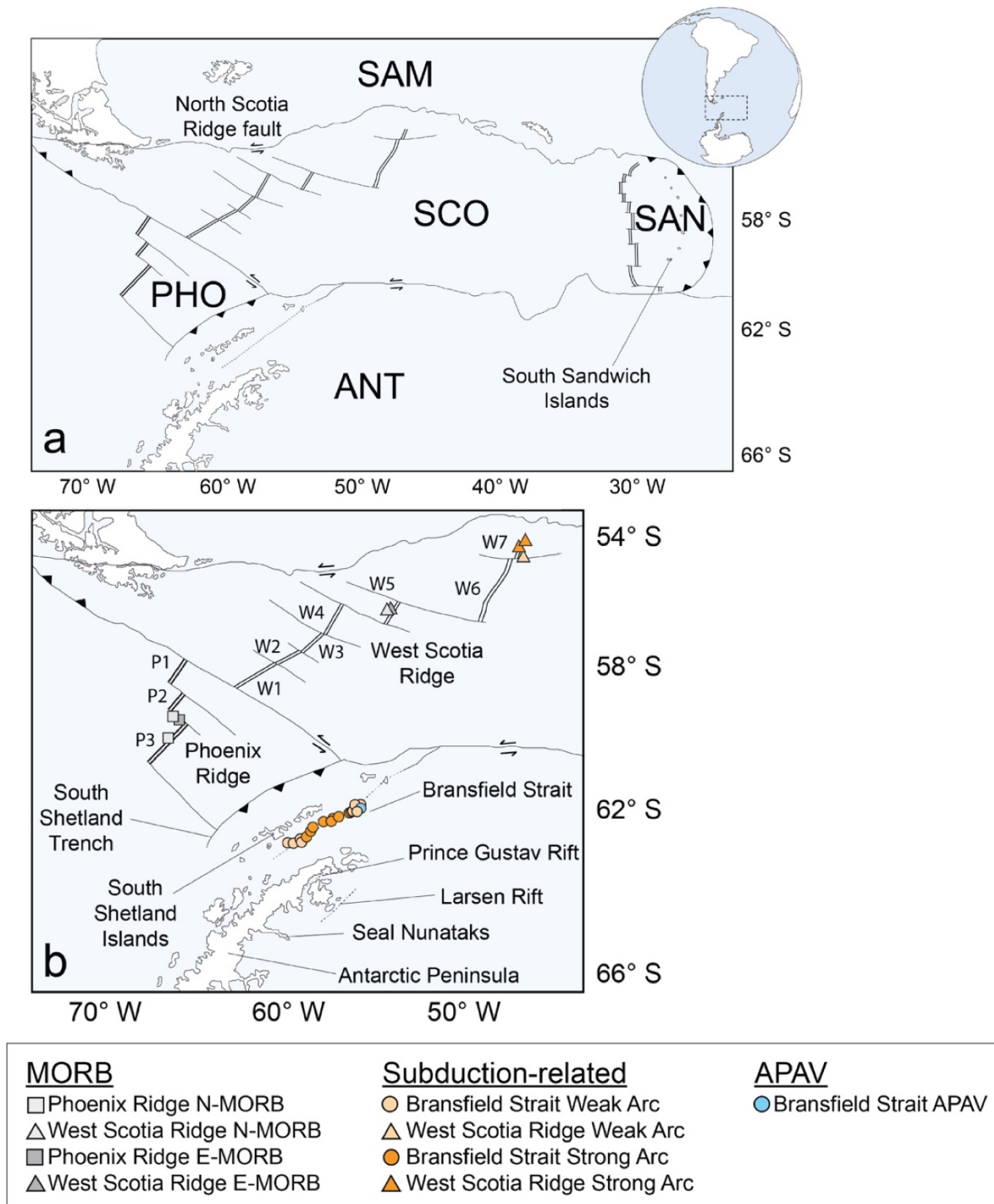
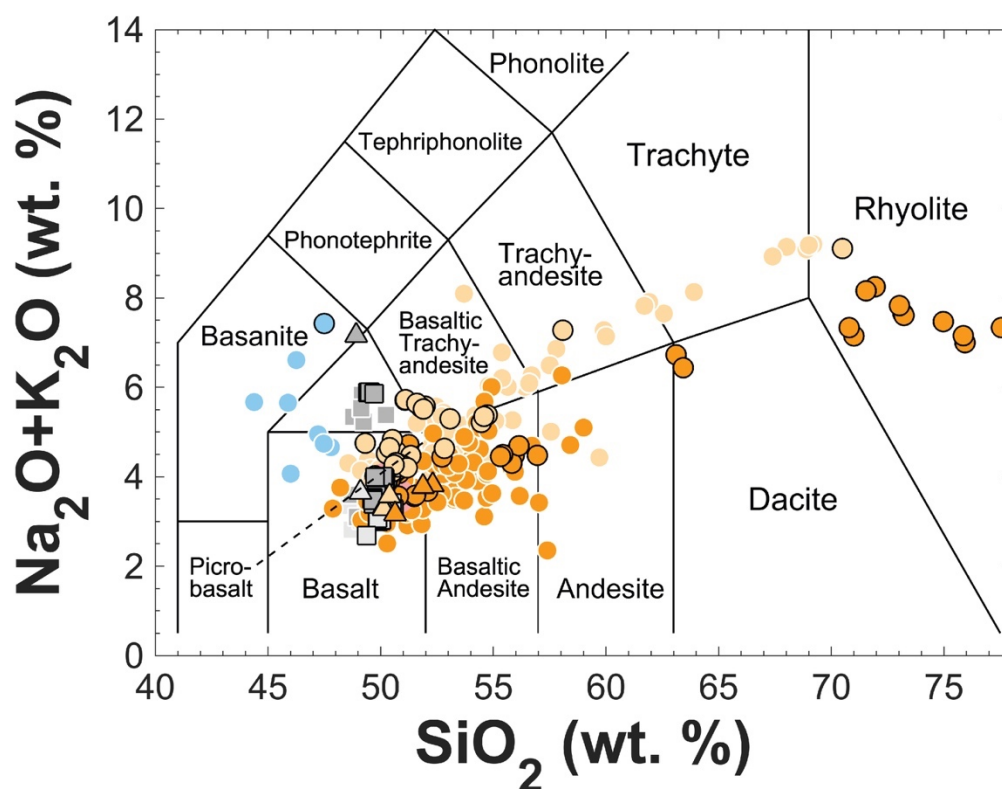


Figure 2.1: a) Map of the greater Antarctic Peninsula region showing the positions of the South American (SAM), Phoenix (PHO), Antarctic (ANT), Scotia (SCO), and Sandwich plates (SAN). Also pictured are the North Scotia Ridge fault and the South Sandwich Islands volcanic front of the South Sandwich subduction zone. b) Map of the northern Antarctic Peninsula, showing the

locations of the Phoenix and West Scotia mid-ocean ridges, the South Shetland trench, the South Shetland Islands volcanic front, the Seal Nunataks, and the Bransfield Strait, Prince Gustav Rift, and Larsen Rift back-arcs. Individual segments of the Phoenix (P1-P3) and West Scotia (W1-W7) ridges are also labeled. Dredge locations for samples from this study are marked by circles in the Bransfield Strait, squares in the Phoenix Ridge, and triangles in the West Scotia Ridge. Symbol colors correspond to the representative geochemistry of samples from each dredge.



MORB

- Phoenix Ridge N-MORB
- △ West Scotia Ridge N-MORB
- Phoenix Ridge E-MORB
- ▲ West Scotia Ridge E-MORB

Subduction-related

- Bransfield Strait Weak Arc
- △ West Scotia Ridge Weak Arc
- Bransfield Strait Strong Arc
- ▲ West Scotia Ridge Strong Arc

APAV

- Bransfield Strait APAV

Figure 2.2: Total alkalis vs silica diagram showing the compositions of the lavas from Anderson et al. (2023) used in this study, which are marked with black borders. Borderless symbols are published data from the Phoenix Ridge (Haase et al., 2011) and the Bransfield Strait (Baker et al., 1975; Weaver et al., 1979; Keller et al., 1992; Keller and Fisk, 1992; Keller et al., 2002; Fretzdorff et al., 2004; Kraus et al., 2013; Martí et al., 2013). The APAV (Antarctic Peninsula Alkaline Volcanic) group represents alkaline melts with unique isotope ratios and no clear subduction signals in their trace element compositions. Dashed line represents the alkaline-subalkaline boundary from MacDonald and Katsura (1964).

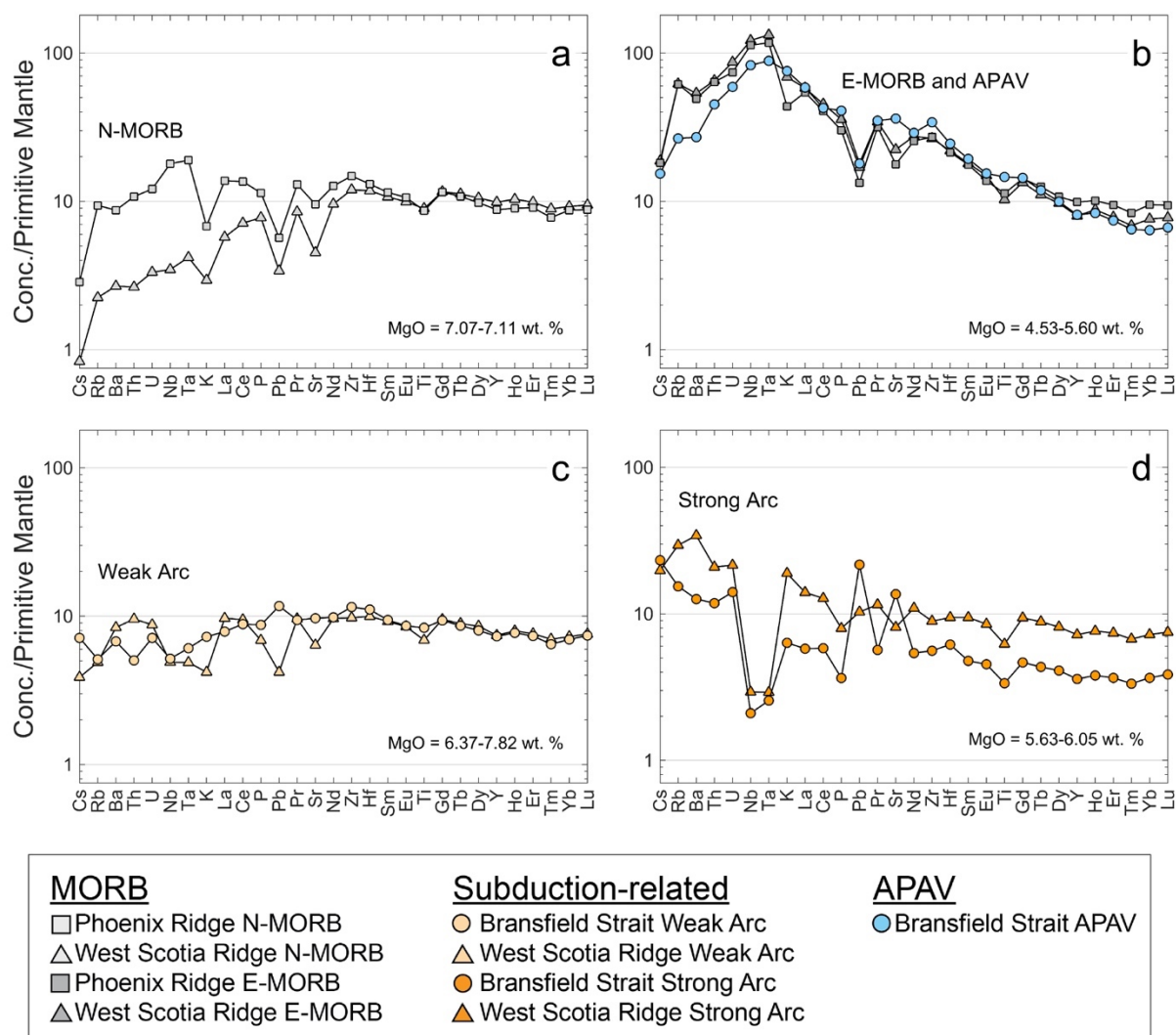


Figure 2.3: Primitive mantle normalized trace element diagram of representative a) N-MORB from the Phoenix and West Scotia ridges, b) E-MORB from the Phoenix and West Scotia ridges and APAV from the Bransfield Strait, c) Weak Arc lavas from the Bransfield Strait and West Scotia Ridge, and d) Strong Arc lavas from the Bransfield Strait and West Scotia Ridge. Primitive mantle composition is from McDonough and Sun (1995).

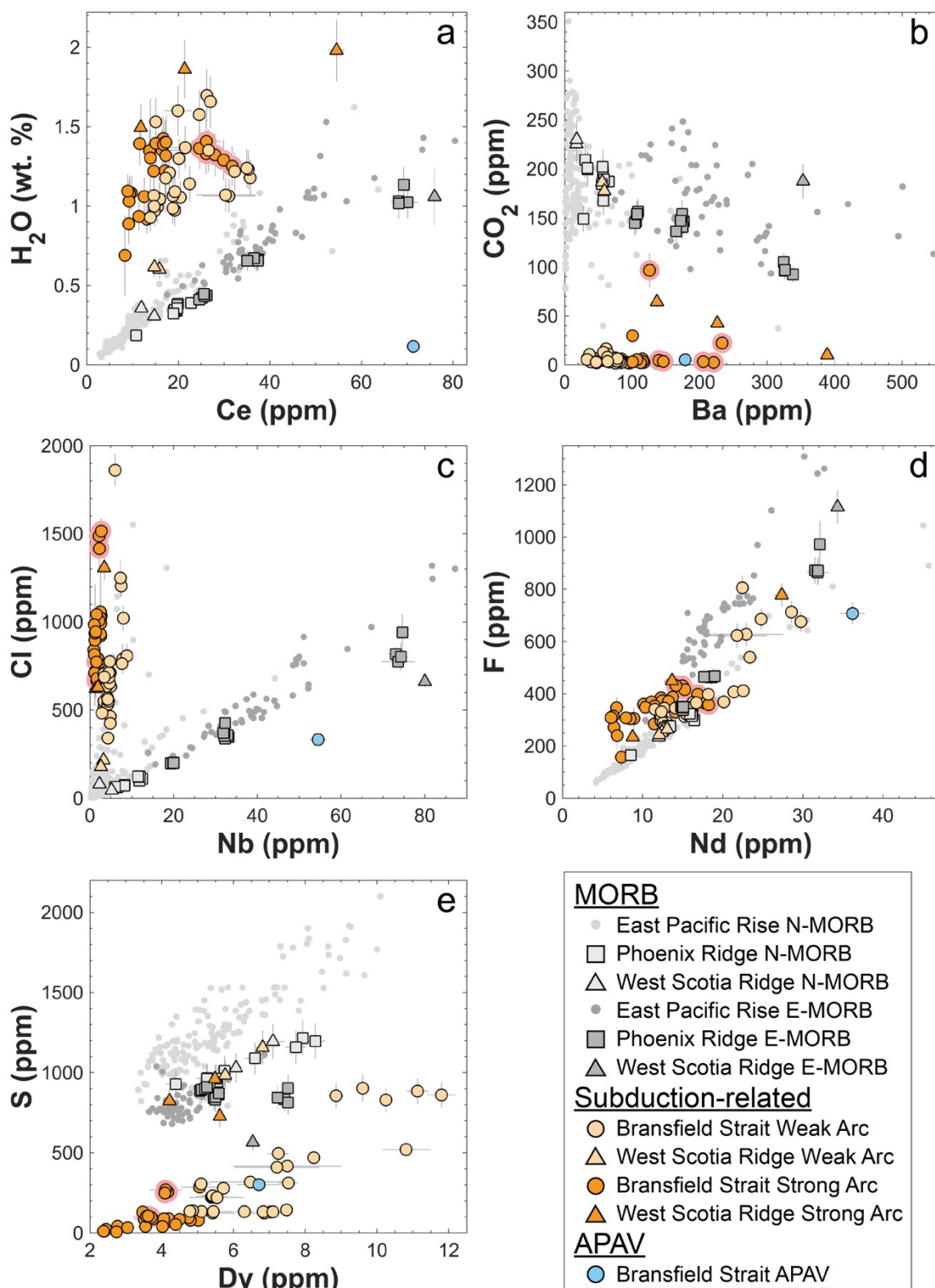
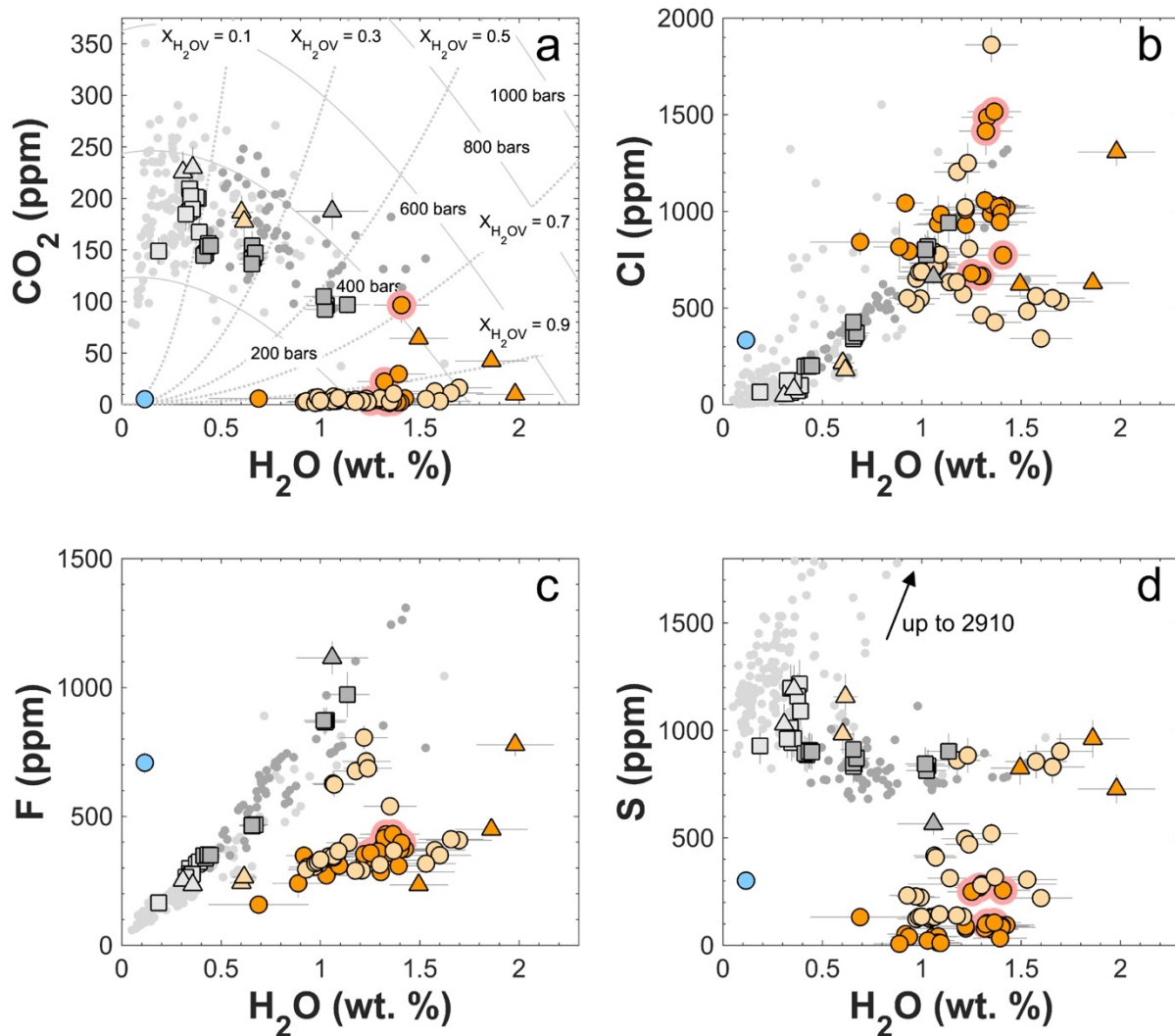


Figure 2.4: Variations in volatile contents vs refractory trace elements of similar incompatibility during mantle melting. a) H₂O vs Ce, b) CO₂ vs Ba, c) Cl vs Nb, d) F vs Nd, e) S vs Dy. Error bars

reflect each sample's 2σ standard error for each element. In cases where the volatile calibration error was larger than the standard error, that was used instead. Small gray circles here and in subsequent figures are published Pacific MORB from the East Pacific Rise (Shimizu et al., 2016). Dark gray represents E-MORB ($\text{Th/La} > 0.11$) and light gray represents N-MORB ($\text{Th/La} < 0.11$). Pacific MORB data here are not filtered for assimilation of hydrothermally altered crust and brines. Pink highlighted Strong Arc samples from the Bransfield Strait here and in subsequent figures represent Strong Arc lavas with incompatible trace element patterns distinct from other Bransfield Strait lavas. See Section 5.2.2 for details and discussion. All data here and in subsequent figures are filtered for $\text{MgO} > 3.0$ wt. %.



MORB

- East Pacific Rise N-MORB
- Phoenix Ridge N-MORB
- △ West Scotia Ridge N-MORB
- East Pacific Rise E-MORB
- Phoenix Ridge E-MORB
- △ West Scotia Ridge E-MORB

Subduction-related

- Bransfield Strait Weak Arc
- △ West Scotia Ridge Weak Arc
- Bransfield Strait Strong Arc
- △ West Scotia Ridge Strong Arc

APAV

- Bransfield Strait APAV

Figure 2.5: Variations in a) CO₂, b) Cl, c) F, and d) S vs H₂O in the northern Antarctic Peninsula submarine glasses and Pacific MORB (not filtered for assimilation of hydrothermally altered crust and brines; Shimizu et al., 2016). Error bars reflect each sample's 2σ standard error for each volatile. In cases where the volatile calibration error was larger than the standard error, that was used instead. Isobars and isopleths in a) were calculated for the composition of tholeiitic N-MORB sample 53DR-20 with the VESical web-app (v 1.0.1; Iacovino et al., 2021) using the model of Ghiorso and Gualda (2015) at 1200 °C.

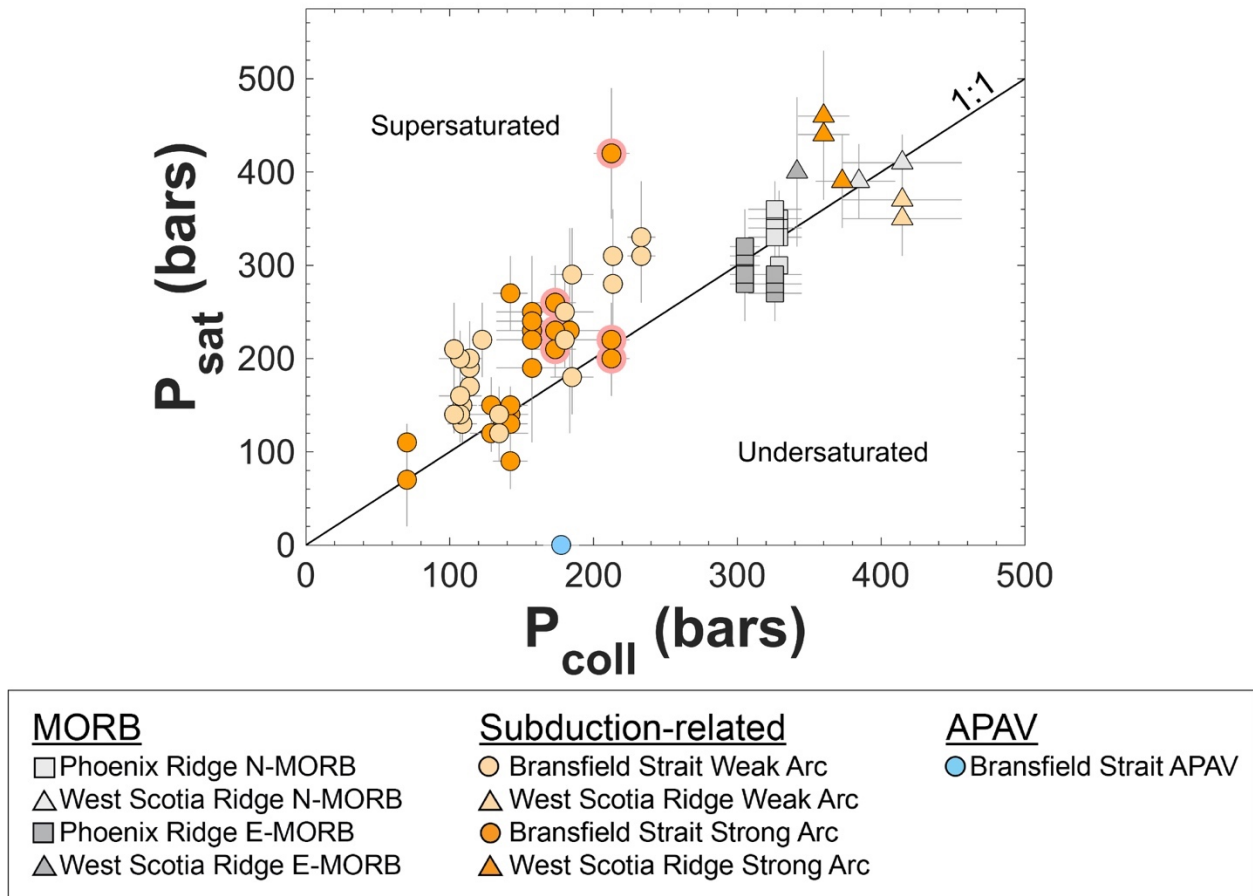


Figure 2.6: Modeled pressure of saturation (P_{sat}) vs pressure of collection (P_{coll}) for our samples. P_{sat} values calculated with the VESIcal web-app (v 1.0.1; Iacovino et al., 2021) using the model of Ghiorso and Gualda (2015) at 1200 °C. P_{coll} values were calculated using the average depth of each dredge. Vertical errors were calculated by propagating the uncertainties of our H_2O and CO_2 measurements through the model, though this does not account for errors in the model itself. Horizontal errors are calculated using the variation in depth for each dredge. Symbols plotting above, on, and below the 1:1 line represent CO_2 - H_2O supersaturated, saturated, and undersaturated lavas at their pressures of collection, respectively.

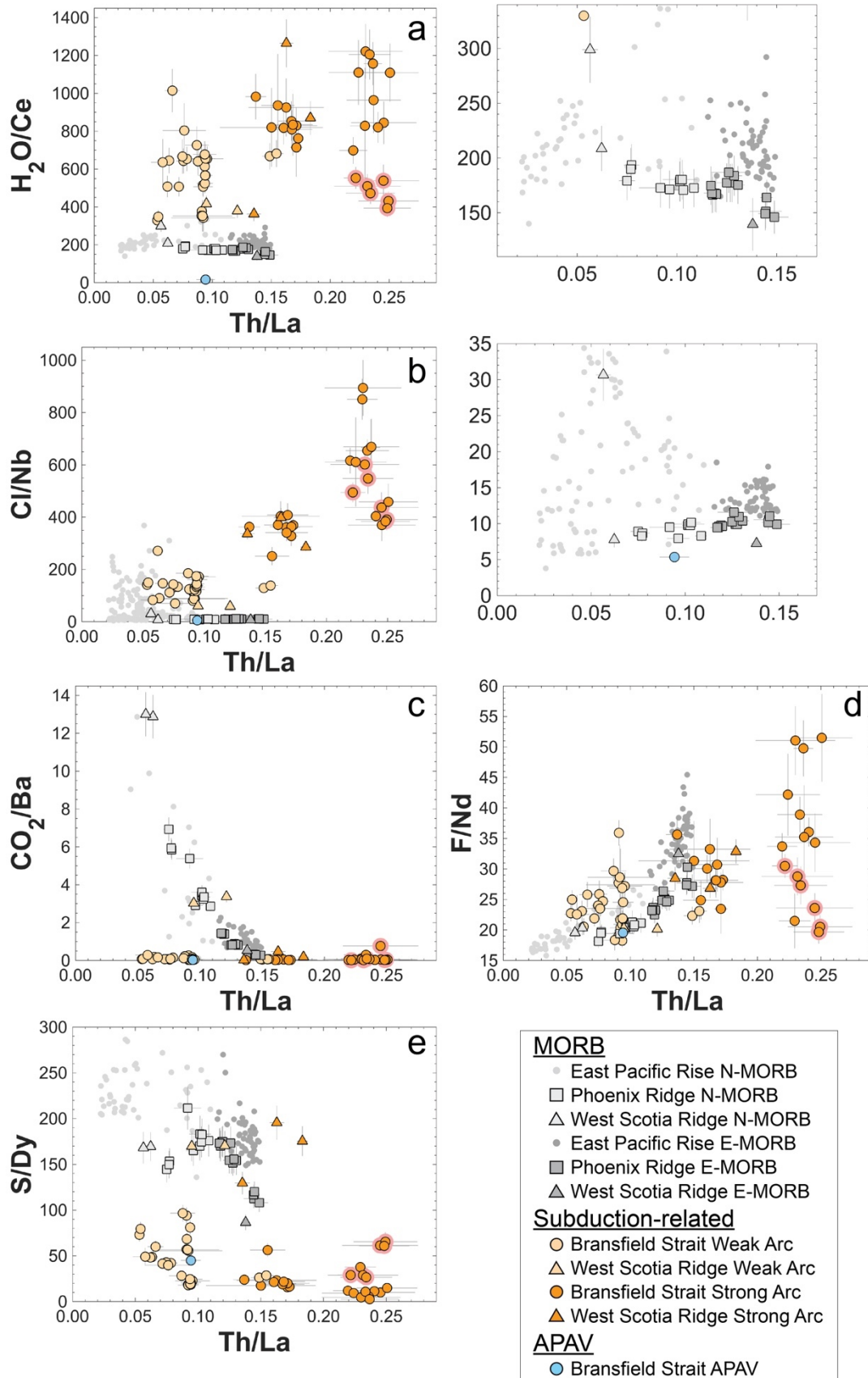
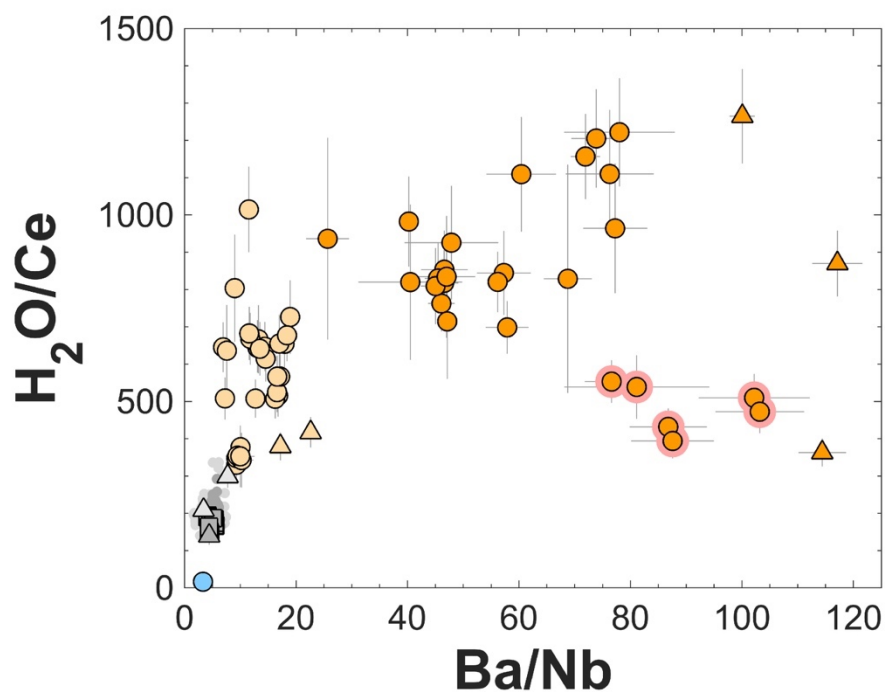


Figure 2.7: a) $\text{H}_2\text{O}/\text{Ce}$, b) Cl/Nb , c) CO_2/Ba , d) F/Nd , and e) S/Dy vs Th/La . Insets in a) and b) show expanded views of variations in $\text{H}_2\text{O}/\text{Ce}$ and Cl/Nb , respectively, for our MORB compared to Pacific MORB (Shimizu et al., 2016). Pacific MORB data in all panels except b) are filtered for assimilation of hydrothermally altered crust and brines. Errors for each ratio are propagated from each sample's 2σ standard error for each element. In cases where the volatile calibration error was larger than the standard error, that was propagated instead.



MORB

- East Pacific Rise N-MORB
- Phoenix Ridge N-MORB
- △ West Scotia Ridge N-MORB
- East Pacific Rise E-MORB
- Phoenix Ridge E-MORB
- △ West Scotia Ridge E-MORB

Subduction-related

- Bransfield Strait Weak Arc
- △ West Scotia Ridge Weak Arc
- Bransfield Strait Strong Arc
- △ West Scotia Ridge Strong Arc

APAV

- Bransfield Strait APAV

Figure 2.8: H₂O/Ce vs Ba/Nb for the samples in this study and Pacific MORB, which has been filtered for assimilation of hydrothermally altered crust and brines (Shimizu et al., 2016). Errors for each ratio are propagated from each sample's 2σ standard error for each element. In cases where the volatile calibration error was larger than the standard error, that was propagated instead.

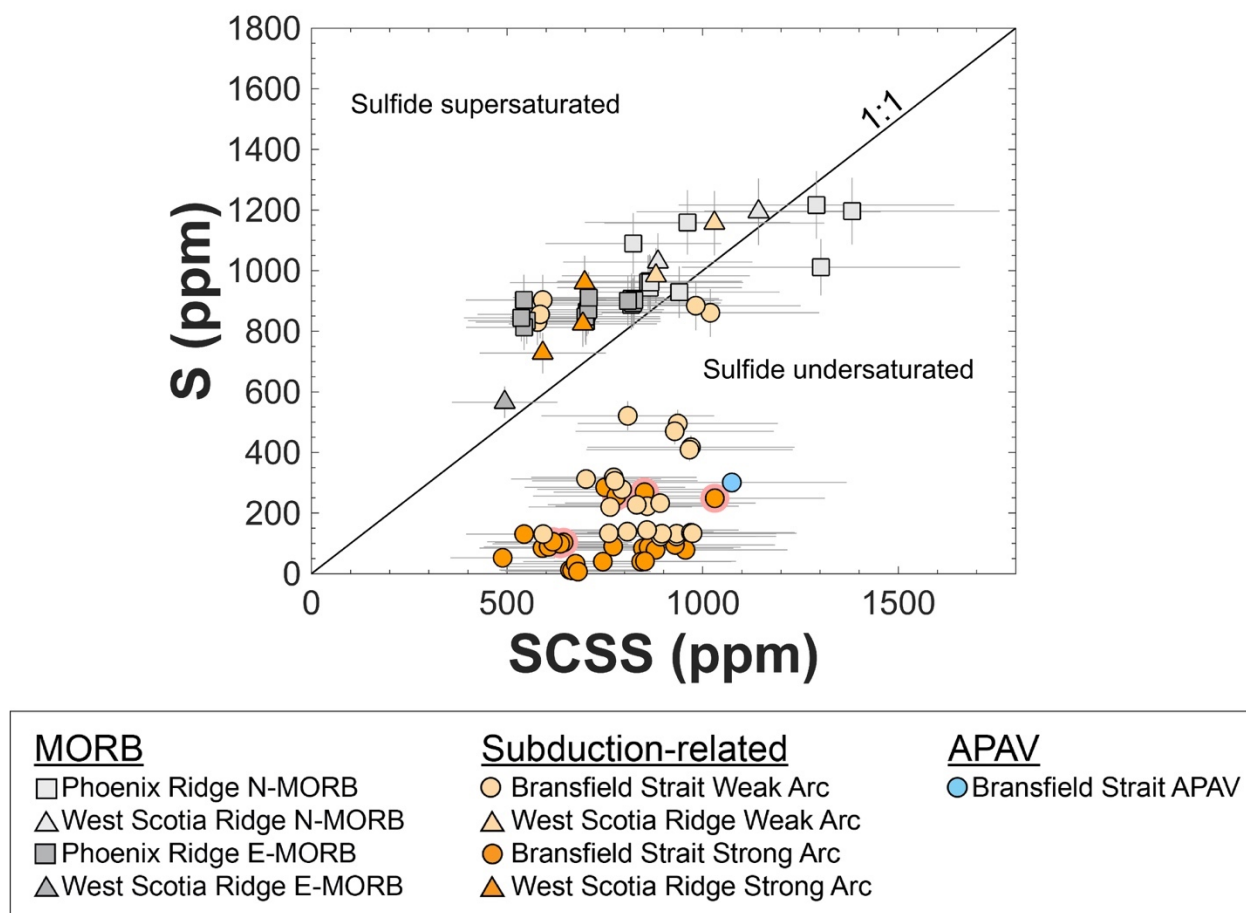


Figure 2.9: Modeled sulfur content at sulfide saturation (SCSS) vs measured S content using the model of Smythe et al. (2017). Given the errors of the model, the differences between the ideal and non-ideal sulfide solution models presented by Smythe et al. (2017) are negligible for our samples, so we use the ideal case. Samples plotting below the 1:1 line are sulfide undersaturated, whereas samples that fall within error of the line reached sulfide saturation prior to eruption. Vertical errors are each sample's 2σ standard error for S. In cases where the calibration error was larger than the standard error for S, that was used instead. Horizontal errors are provided by the model.

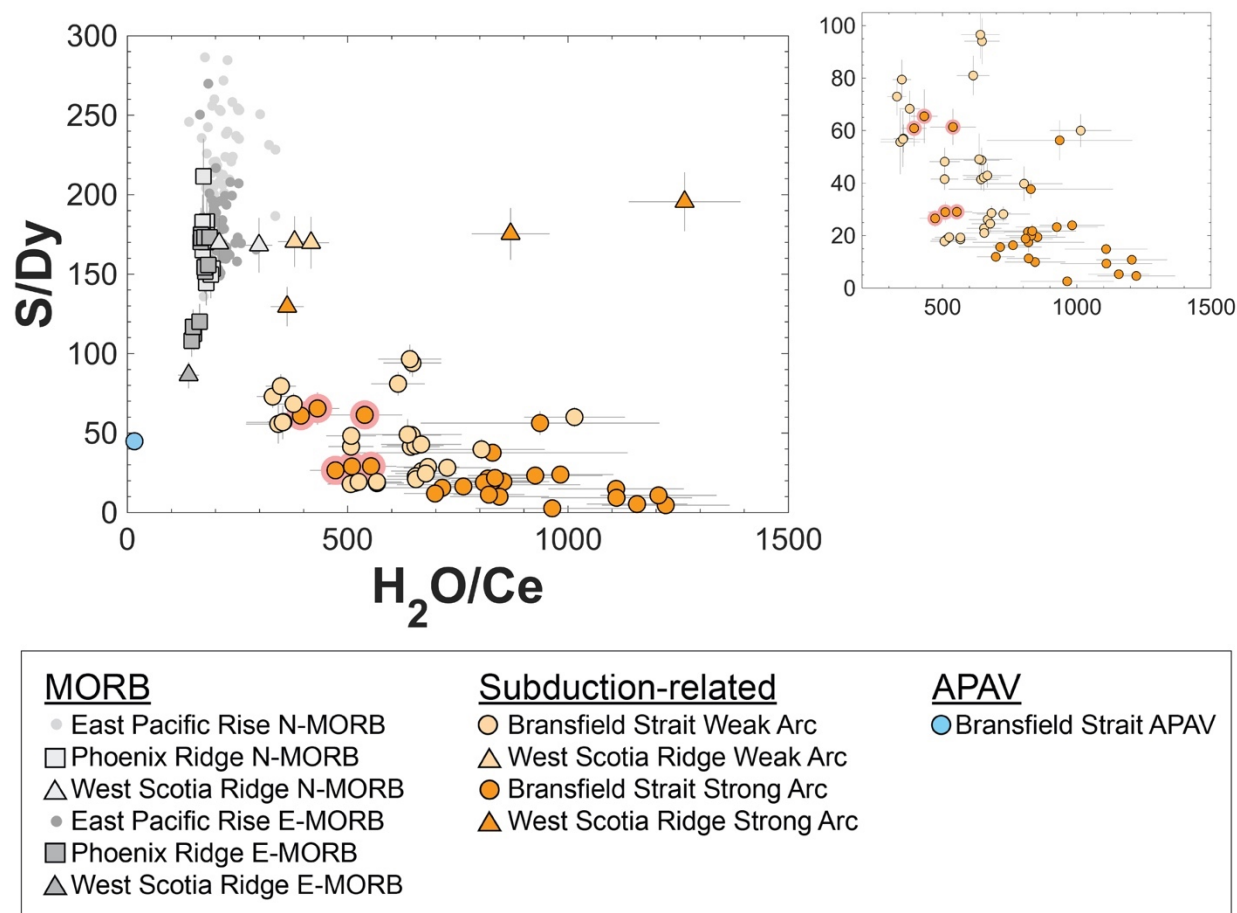
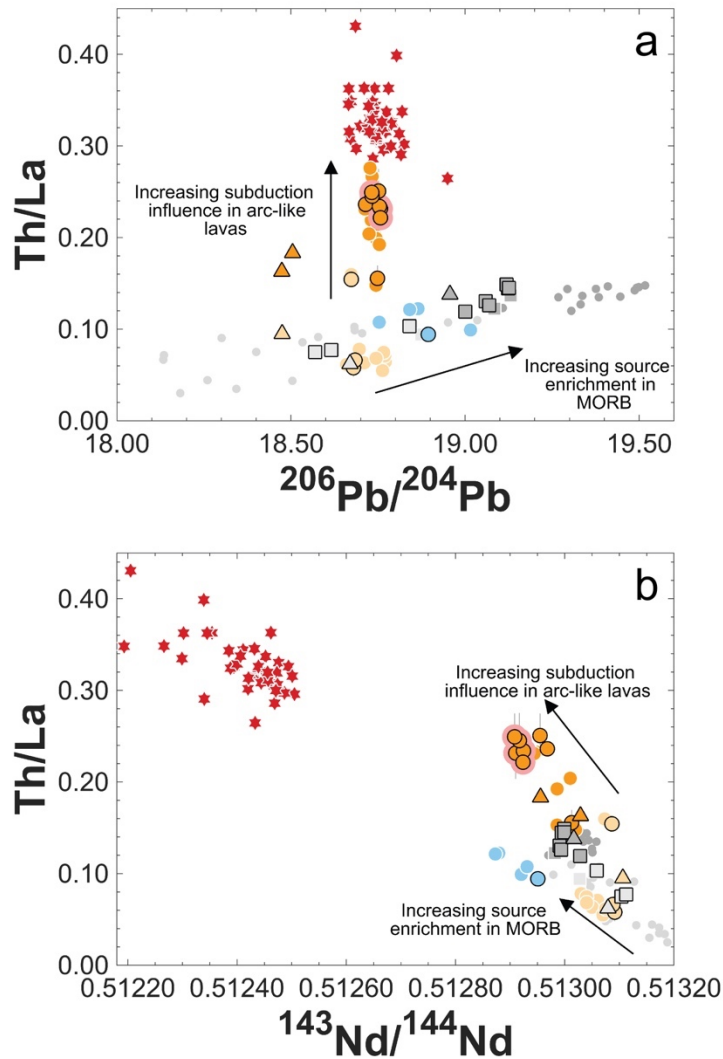


Figure 2.10: S/Dy vs H₂O/Ce for the samples in this study and Pacific MORB, which has been filtered for assimilation of hydrothermally altered crust and brines (Shimizu et al., 2016). Inset shows negative correlation for Bransfield Strait arc-like lavas. Errors for each ratio are propagated from each sample's 2σ standard error for each element. In cases where the volatile calibration error was larger than the standard error, that was propagated instead.



MORB

- East Pacific Rise N-MORB
- Phoenix Ridge N-MORB
- △ West Scotia Ridge N-MORB
- East Pacific Rise E-MORB
- Phoenix Ridge E-MORB
- △ West Scotia Ridge E-MORB

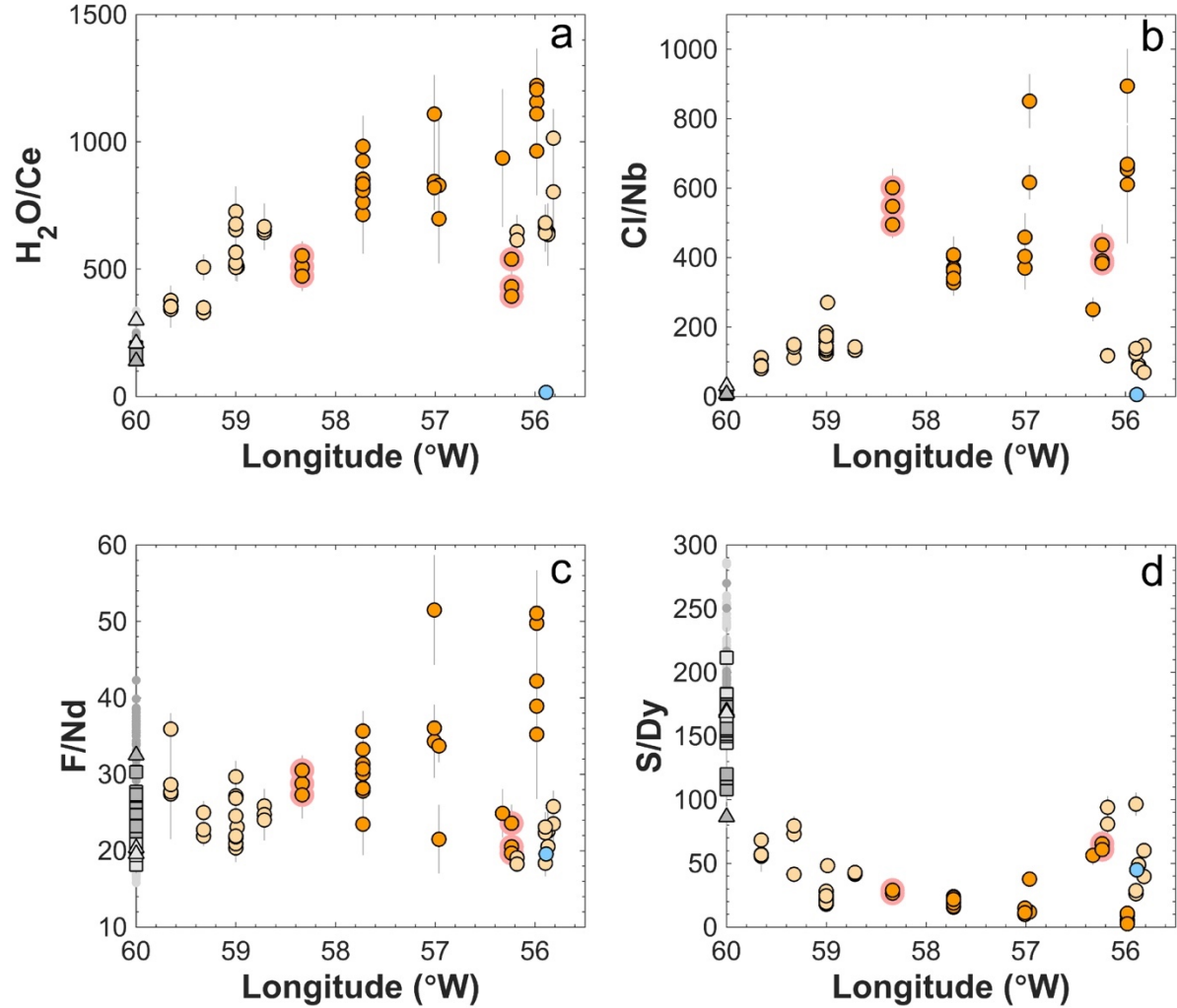
Subduction-related

- Bransfield Strait Weak Arc
- △ West Scotia Ridge Weak Arc
- Bransfield Strait Strong Arc
- △ West Scotia Ridge Strong Arc
- ★ Phoenix Plate Sediments

APAV

- Bransfield Strait APAV

Figure 2.11: a) Th/La vs $^{206}\text{Pb}/^{204}\text{Pb}$ and b) Th/La vs $^{143}\text{Nd}/^{144}\text{Nd}$ for our lavas (black borders) and published lavas (borderless) from the Phoenix Ridge (Haase et al., 2011), the Bransfield Strait (Keller et al., 1992; Keller and Fisk, 1992; Keller et al., 2002; Fretzdorff et al., 2004; Kraus et al., 2013), and the East Pacific Rise (filtered for assimilation of hydrothermally altered crust and brines; Shimizu et al., 2016). Red stars are data for sediments from the Phoenix Plate from Anderson et al. (2023). Vertical errors are propagated from each sample's 2 σ standard error for Th and La. Horizontal errors are smaller than symbols.



MORB

- East Pacific Rise N-MORB
- Phoenix Ridge N-MORB
- △ West Scotia Ridge N-MORB
- East Pacific Rise E-MORB
- Phoenix Ridge E-MORB
- △ West Scotia Ridge E-MORB

Subduction-related

- Bransfield Strait Weak Arc
- △ West Scotia Ridge Weak Arc
- Bransfield Strait Strong Arc
- △ West Scotia Ridge Strong Arc

APAV

- Bransfield Strait APAV

Figure 2.12: Variations in a) H_2O/Ce , b) Cl/Nb , c) F/Nd , and d) S/Dy vs longitude for Bransfield Strait lavas. Data for Phoenix and West Scotia Ridge MORB are plotted on the vertical axis for reference, along with Pacific MORB data from Shimizu et al. (2016), which was filtered for assimilation of hydrothermally altered crust and brines. Vertical errors are propagated from each sample's 2σ standard error for each element. In cases where the volatile calibration error was larger than the standard error, that was propagated instead.

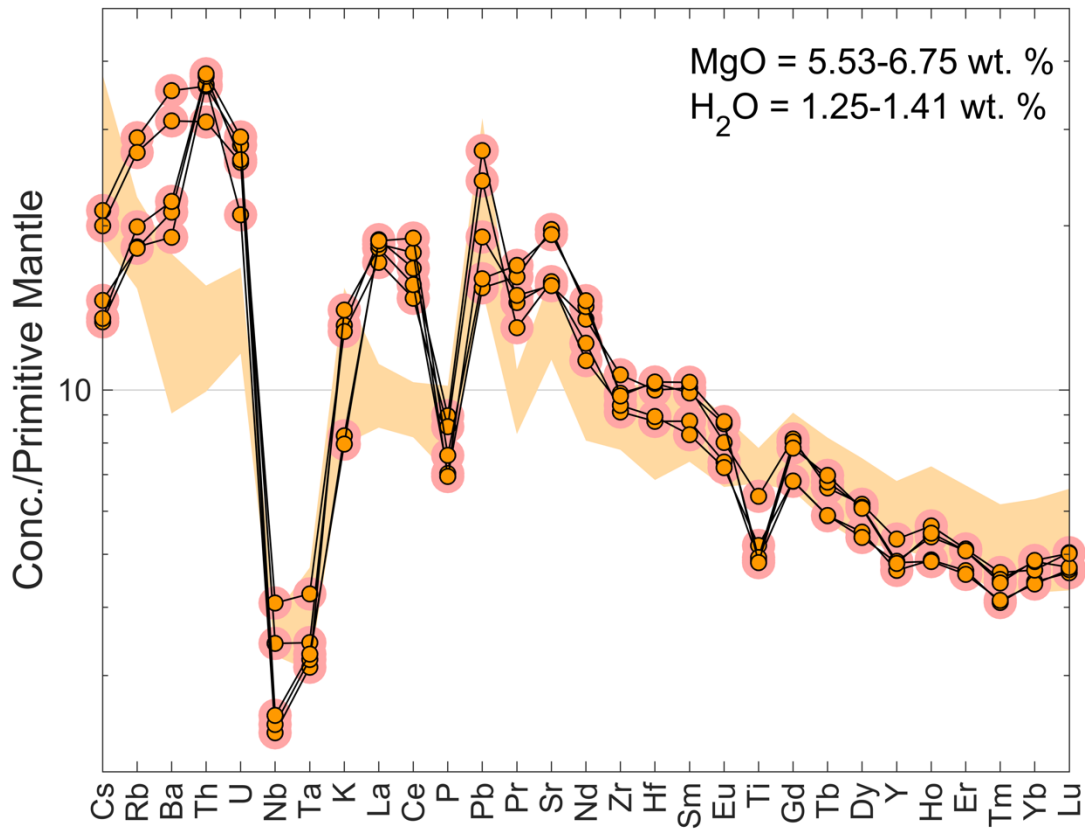
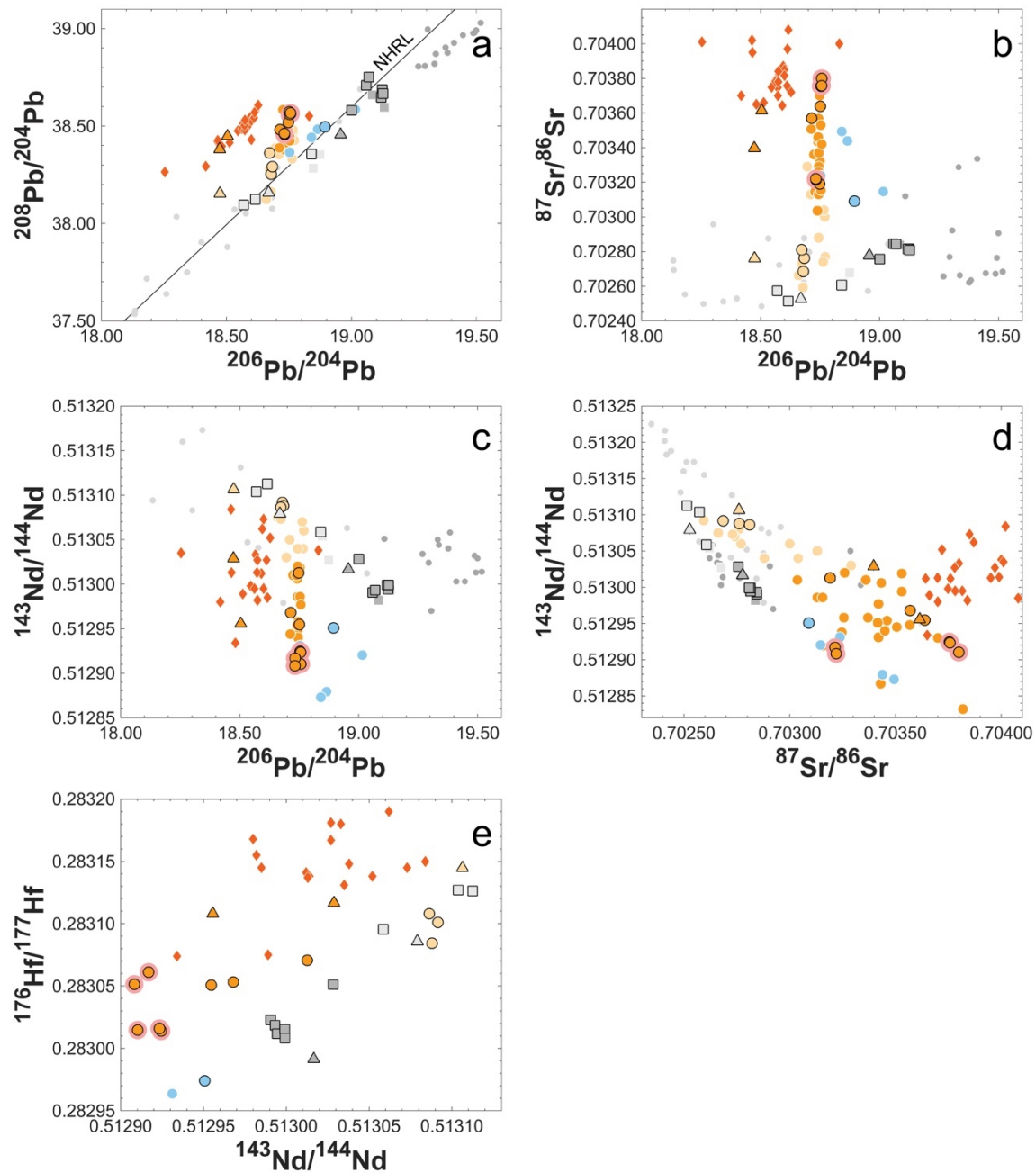


Figure 2.13: Primitive mantle normalized trace element diagram of Bransfield Strait Strong Arc lavas with distinct incompatible trace element compositions. Orange background field represents the range of all other Bransfield Strait Strong Arc lavas at comparable MgO and H₂O contents. Primitive mantle composition is from McDonough and Sun (1995). See Section 5.2.2 for details and discussion.



MORB

- East Pacific Rise N-MORB
- Phoenix Ridge N-MORB
- △ West Scotia Ridge N-MORB
- East Pacific Rise E-MORB
- Phoenix Ridge E-MORB
- △ West Scotia Ridge E-MORB

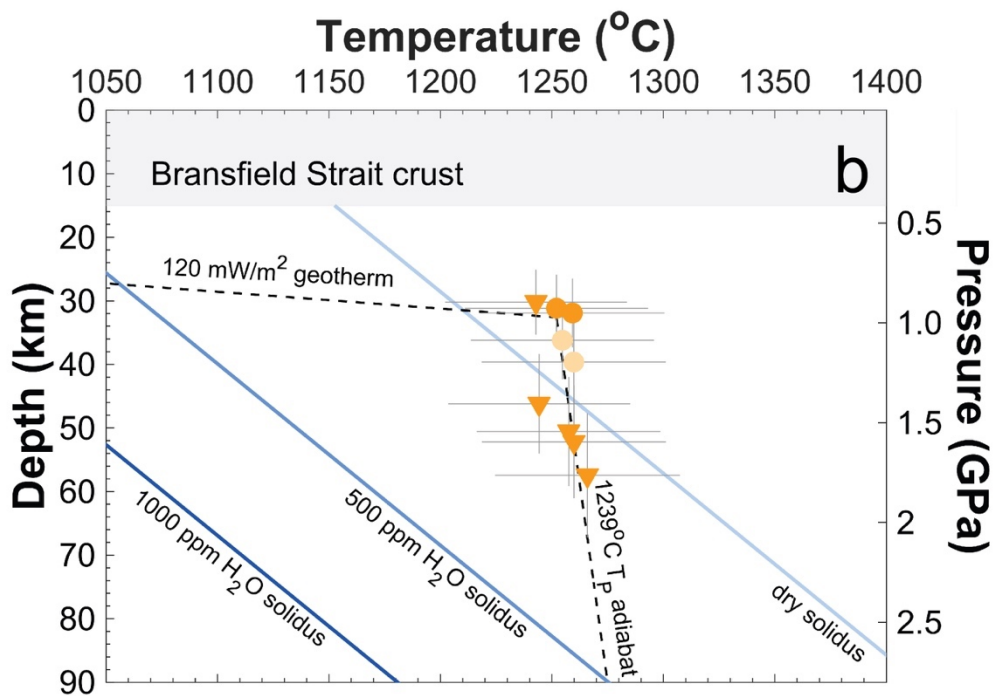
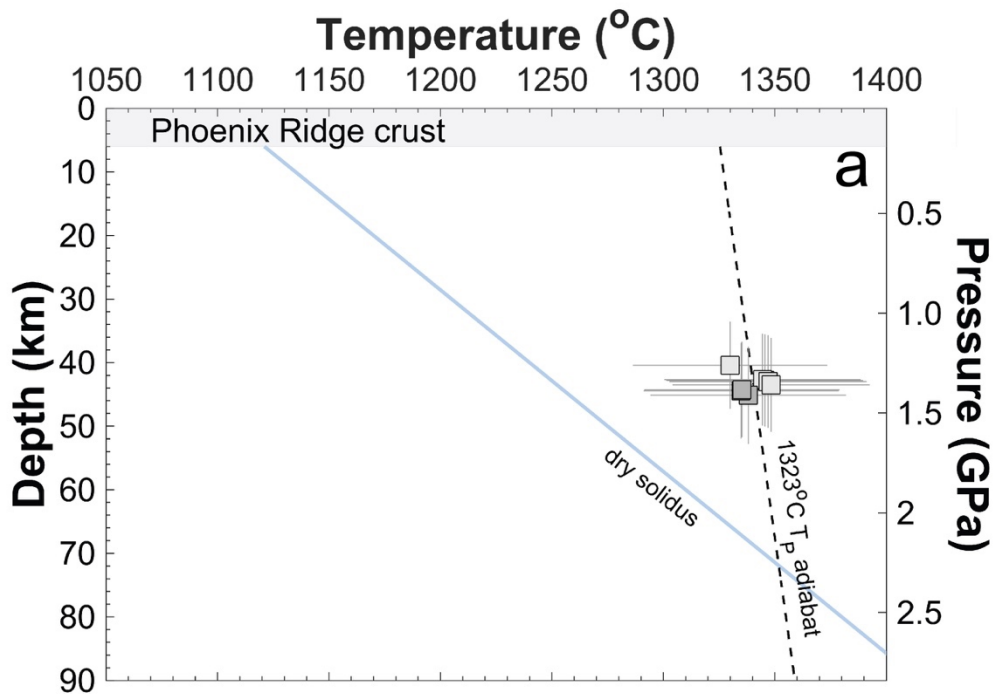
Subduction-related

- Bransfield Strait Weak Arc
- △ West Scotia Ridge Weak Arc
- Bransfield Strait Strong Arc
- △ West Scotia Ridge Strong Arc
- ◆ South Sandwich Islands Arc

APAV

- Bransfield Strait APAV

Figure 2.14: a) $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, b) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, c) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, d) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$, and e) $^{176}\text{Hf}/^{177}\text{Hf}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$ for lavas from the Phoenix Ridge (Haase et al., 2011; Anderson et al., 2023), West Scotia Ridge (Anderson et al., 2023), Bransfield Strait (Keller et al., 1992; Keller and Fisk, 1992; Keller et al., 2002; Fretzdorff et al., 2004; Anderson et al., 2023), East Pacific Rise (filtered for assimilation of hydrothermally altered crust and brines; Shimizu et al., 2016), and South Sandwich Arc (Leat et al., 2004; Barry et al., 2006). Symbols with black borders represent samples in this study. Errors for our data are smaller than the symbols.



MORB

- Phoenix Ridge N-MORB
- Phoenix Ridge E-MORB

Subduction-related

- Bransfield Strait Weak Arc (pub.)
- Bransfield Strait Strong Arc (pub.)
- ▼ Quaternary South Shetland Islands (pub.)

Figure 2.15: Equilibrium depths and pressures vs temperatures for a) Phoenix Ridge lavas (this study; marked with black borders) and b) Bransfield Strait (Fretzdorff et al., 2004) and Quaternary South Shetland Island (Haase et al., 2012) lavas, modeled using Plank and Forsyth (2016). Depths were calculated assuming 6 km and 15 km crust, respectively, assuming a crustal density of 2800 kg/m³ and a mantle density of 3250 kg/m³. Also plotted are the dry peridotite solidus from Plank and Forsyth (2016), and 500 and 1000 ppm H₂O solidi after Katz et al., (2003). Additionally, 1323° C and 1239° C adiabats in a) and b), respectively, were calculated assuming an adiabatic gradient of 0.4° C/km. A simple, steady-state conductive geotherm was calculated in b) using a 120 mW/m² surface heatflow (Lawver et al., 1995; Kaminuma and Nagao, 1996; Schreider et al., 2015), 15 km crust (Christesen et al., 2003), a lithospheric mantle heat production of 0.03 μ W/m³ (Rudnick et al., 1998), and a crustal heat production of 0.4 μ W/m³ (Rudnick et al., 1998). Error bars were calculated by propagating the uncertainties of equilibrium mantle Fo (± 1), melt Fe³⁺/Fe_T (± 0.03), and melt H₂O concentration ($\pm 5\%$ relative) through the model. See Section 5.3 of the text for details and discussion.

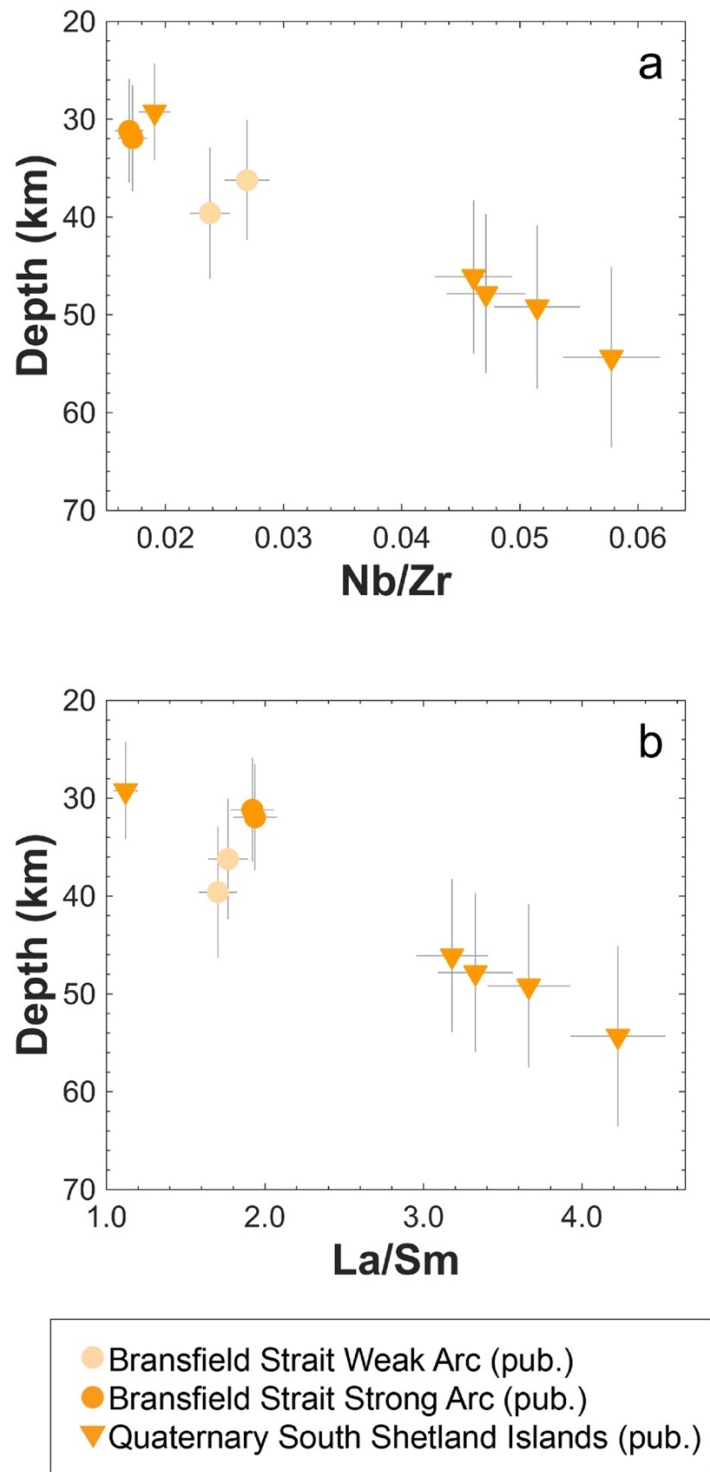
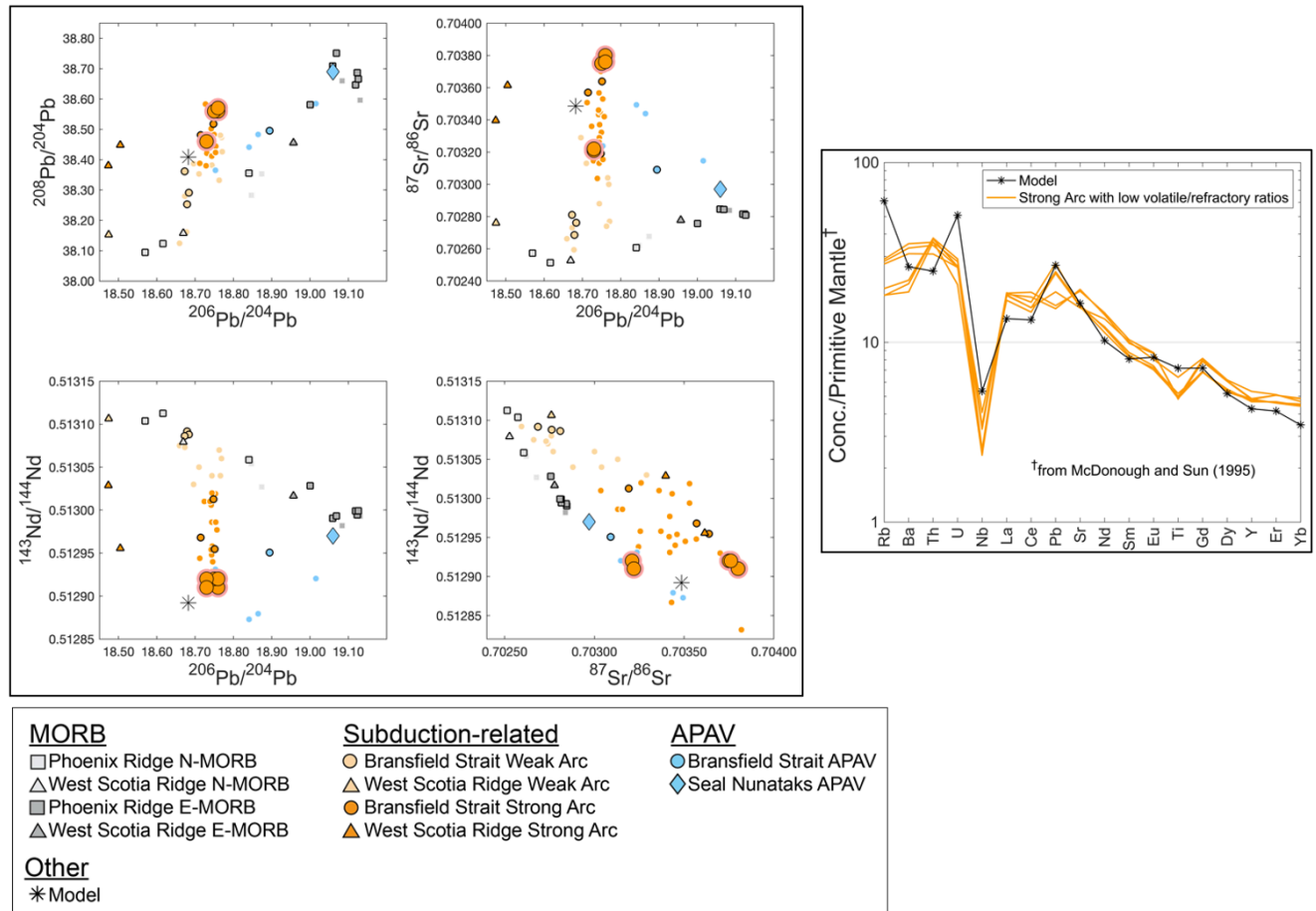


Figure 2.16: Modeled equilibrium depths and pressures vs a) Nb/Zr and b) La/Sm for Bransfield Strait (Fretzdorff et al., 2004) and Quaternary South Shetland Island (Haase et al., 2012) lavas. Vertical errors and depth calculations are the same as those in Figure 15. Horizontal errors are propagated from uncertainties reported by Fretzdorff et al. (2004) and Haase et al. (2012).



Supplementary Figure 2.S1: Results of a simple melting model to explain compositionally distinct Bransfield Strait Strong Arc lavas with low volatile/refractory trace element ratios (highlighted in pink in left panel). We first estimate the composition of the mantle in equilibrium with the alkaline lavas from the northern Antarctic Peninsula. We choose sample R3723.7 from the Seal Nunataks (blue diamond in left panel; see Supplementary Table 1) as a representative melt from the back-arc region behind the Bransfield Strait, since we assume mantle from that area is flowing towards the Bransfield Strait via corner flow. Solid-melt K_D values are calculated using the mineral-melt K_D values of Pilet et al. (2011) and the solid mineralogy of garnet lherzolite from Walter (1998). We speculate that the mantle underwent further depletion before being fluxed, and thus, we consider 2% non-modal batch melting in the garnet field using the melting reaction from Walter (1998). We flux the resultant solid 3% with a mixture of 30% sediments and 70% modeled fluids. The sediment composition comes from a weighted average of the compositions of Phoenix Plate sediments from Anderson et al. (2023) ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70818$; $^{143}\text{Nd}/^{144}\text{Nd} = 0.51241$; $^{206}\text{Pb}/^{204}\text{Pb} = 18.74$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.62$; $^{208}\text{Pb}/^{204}\text{Pb} = 38.56$). The fluid composition is calculated using the 6 GPa fluid-eclogite K_d values from Rustioni et al. (2021) at 5.5 wt. % Cl contents, multiplied by the altered oceanic crust Super Composite composition from Staudigel et al. (1996). A Pb concentration was not reported for the Super Composite, so the value is taken from the Kelley et al. (2003) Super Composite instead. We used the composition of hydrothermally altered oceanic crust from the Phoenix Ridge (Choe et al., 2007; Choi et al., 2008) to estimate the fluid isotope composition ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70300$;

$^{143}\text{Nd}/^{144}\text{Nd} = 0.51311$; $^{206}\text{Pb}/^{204}\text{Pb} = 18.53$; $^{207}\text{Pb}/^{204}\text{Pb} = 15.53$; $^{208}\text{Pb}/^{204}\text{Pb} = 38.03$). This same approach was used to estimate fluid compositions in Anderson et al. (2023). We progressively dehydrate the altered oceanic crust composition 10% before estimating the fluid composition that fluxed the region beneath the Bransfield Strait, but this step has little effect on most of the trace element contents. We then consider 3% non-modal batch melting in the garnet field of the sediment, fluid, and mantle mixture. We present the comparison between measured values and model results for the isotopic compositions on the left panel and the incompatible trace elements in the primitive mantle normalized diagram in the right panel.

Tables

Supplementary Table 2.S1: New major and trace element concentrations and isotope compositions for West Scotia Ridge, Bransfield Strait, and Seal Nunataks basalts from this study

Sample	Group	SiO ₂ (wt. %)	TiO ₂ (wt. %)	Al ₂ O ₃ (wt. %)	FeOt (wt. %)	MnO (wt. %)	MgO (wt. %)	CaO (wt. %)	Na ₂ O (wt. %)	K ₂ O (wt. %)	P ₂ O ₅ (wt. %)	Total
DR183.3	WSR N-MORB	50.16	1.83	14.98	10.21	0.17	7.11	10.62	3.22	0.13	0.20	98.62
DR183.4	WSR Weak Arc	50.13	1.39	15.77	8.39	0.14	7.82	11.15	3.11	0.18	0.18	98.24
DR183.5	WSR Weak Arc	50.40	1.68	15.21	9.40	0.18	6.93	11.05	3.37	0.21	0.24	98.66
DR 207.4	WSR Strong Arc	50.64	1.02	16.41	7.37	0.15	7.17	11.70	2.83	0.34	0.17	97.78
DR 209.1	WSR Strong Arc	52.31	1.29	15.61	8.64	0.17	5.29	9.58	2.88	0.94	0.30	97.01
DR 209.3	WSR Strong Arc	51.87	1.26	15.69	8.83	0.15	5.63	10.07	3.16	0.62	0.21	97.49
^a D16A	BS Strong Arc	50.09	1.18	15.95	8.55	0.15	6.22	11.48	3.19	0.73	0.31	97.84
^a D16B	BS Strong Arc	50.18	1.18	16.06	8.45	0.16	6.21	11.50	3.17	0.72	0.28	97.90
^a D16D	BS Strong Arc	50.41	1.24	15.87	8.77	0.16	6.04	11.18	3.21	0.71	0.28	97.86
^b R3723.7	Seal Nunataks	49.39	2.07	14.62	11.08	0.16	9.55	8.99	3.23	1.07	0.36	100.52

^aMajor and trace element data (italicized) from Anderson et al. (2023)

^bMajor and trace element data collected on whole rock powder at the GeoAnalytical Laboratory. See Anderson et al. (2023) for details on collecting isotope data for whole rock powder.

Supplementary Table 2.S1 (continued)

Cs (ppm)	Rb (ppm)	Ba (ppm)	Th (ppm)	U (ppm)	Nb (ppm)	Ta (ppm)	K (ppm)	La (ppm)	Ce (ppm)	P (ppm)	Pb (ppm)	Pr (ppm)	Sr (ppm)	Nd (ppm)	Zr (ppm)	Hf (ppm)
0.02	1.35	17.69	0.21	0.07	2.29	0.16	706	3.72	11.95	698	0.51	2.16	89.83	11.99	125.74	3.34
0.08	2.93	55.36	0.76	0.18	3.22	0.18	1007	6.27	15.89	619	0.63	2.44	127.24	12.05	102.43	2.82
0.06	3.72	58.66	0.46	0.14	2.59	0.17	1051	4.81	14.77	727	0.78	2.47	114.17	13.05	124.93	3.40
0.16	7.95	136.75	0.73	0.27	1.37	0.09	1273	4.48	11.82	436	1.54	1.78	155.11	8.74	73.31	2.07
0.40	25.54	388.88	3.50	0.97	3.40	0.18	8096	25.84	54.57	1121	2.42	6.71	447.72	27.35	118.63	3.16
0.42	17.66	226.03	1.66	0.44	1.93	0.11	4542	9.07	21.39	717	1.55	2.94	161.17	13.67	93.63	2.67
0.41	16.93	220.74	2.75	0.53	2.16	0.14	3127	11.88	26.08	807	3.71	3.49	320.59	14.96	98.83	2.52
0.45	17.38	233.25	2.86	0.57	2.26	0.13	3154	12.22	27.99	807	4.12	3.67	312.58	15.24	95.77	2.48
0.42	16.35	205.34	2.46	0.53	2.68	0.16	3071	11.10	24.67	771	3.63	3.30	314.30	14.15	98.43	2.53
0.12	8.38	99.63	2.16	0.82	26.85	1.75	8886	18.25	37.57	1562	1.68	4.61	415.39	19.61	139.66	3.52

Supplementary Table 2.S1 (continued)

Sm (ppm)	Eu (ppm)	Ti (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Y (ppm)	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Li (ppm)	Sc (ppm)	Cr (ppm)	Co (ppm)	Ni (ppm)
4.35	1.53	10773	6.32	1.11	7.10	42.43	1.54	4.32	0.61	4.07	0.64	7.58	38.43	147.03	38.80	67.92
3.74	1.31	8312	5.17	0.88	5.77	31.92	1.19	3.34	0.48	3.21	0.51	5.86	34.04	226.15	35.80	100.12
4.38	1.56	8750	6.17	1.05	6.81	38.63	1.45	3.99	0.56	4.01	0.59	6.55	36.90	173.61	35.05	56.05
2.77	1.03	4995	3.79	0.66	4.22	24.06	0.90	2.50	0.35	2.53	0.40	4.78	32.67	171.59	31.08	70.44
5.73	1.75	8054	5.97	0.94	5.62	30.74	1.12	3.13	0.44	3.08	0.48	6.79	32.65	47.76	30.23	25.95
3.84	1.31	7487	5.11	0.88	5.48	30.99	1.14	3.25	0.46	3.18	0.51	6.83	34.64	37.48	33.16	24.99
3.44	1.08	6053	3.76	0.59	3.57	20.53	0.73	2.02	0.28	2.00	0.31	6.57	33.63	110.15	25.46	28.77
3.56	1.14	5874	3.70	0.58	3.70	20.09	0.73	2.05	0.28	1.97	0.31	6.37	36.06	170.47	25.77	31.34
3.36	1.11	6253	3.71	0.58	3.62	20.77	0.72	2.01	0.28	1.95	0.32	7.07	33.77	129.98	25.52	27.82
4.71	1.6	12389	4.92	0.78	4.22	20.49	0.79	1.93	0.27	1.56	0.21	--	23.50	322.90	--	204.24

Supplementary Table 2.S1 (continued)

Cu (ppm)	V (ppm)	Cd (ppm)	Material for Isotopes	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	¹⁷⁶ Yb/ ¹⁷⁷ Yb	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb
54.52	232.18	0.13	--	--	--	--	--	--	--
59.33	174.25	0.11	--	--	--	--	--	--	--
60.82	243.60	0.13	glass	0.70276	0.51311	0.28315	18.47	15.54	38.15
68.49	154.15	0.09	glass	0.70340	0.51303	0.28312	18.47	15.57	38.38
46.95	296.75	0.11	--	--	--	--	--	--	--
41.75	239.08	0.11	glass	0.70361	0.51296	0.28311	18.51	15.58	38.45
102.60	176.59	0.10	glass	0.70380	0.51291	0.28302	18.76	15.61	38.56
104.79	197.45	0.12	glass	0.70376	0.51293	0.28301	18.75	15.61	38.56
104.53	177.19	0.10	glass	0.70376	0.51292	0.28302	18.76	15.61	38.57
51.77	205.92	--	powder	0.70297	0.51297	0.28301	19.06	15.61	38.69

Supplementary Table 2.S2: New volatile element concentrations for submarine glasses of this study

Sample	Group	Latitude (S)	Longitude (W)	Depth (m)	CO ₂ (ppm)	H ₂ O (wt. %)	F (ppm)	S (ppm)	Cl (ppm)
02DR-1	BS Strong Arc	-62.12	-57.01	1289	5	1.059	305	40	735
02DR-14	BS Strong Arc	-62.12	-57.01	1289	4	1.083	347	41	724
02DR-2	BS Strong Arc	-62.12	-57.01	1289	3	0.935	304	40	794
03DR-7	BS Strong Arc	-62.12	-56.89	545	12	0.766	1373	42	3914
03DR-9	BS Strong Arc	-62.12	-56.89	545	64	0.630	1385	40	4785
04DR-10	BS Strong Arc	-62.06	-56.96	703	3	0.778	495	88	1612
04DR-11	BS Strong Arc	-62.06	-56.96	703	6	1.134	717	125	1814
04DR-3	BS Strong Arc	-62.06	-56.96	703	3	0.918	348	52	1043
04DR-7	BS Strong Arc	-62.06	-56.96	703	6	0.690	158	131	841
07GTV-4	BS Strong Arc	-62.19	-57.28	1050	3	1.190	1088	22	3541
15DR-1	BS Strong Arc	-62.04	-56.33	1834	4	1.303	284	285	667
16DR-2	BS Strong Arc	-62.00	-56.24	2125	97	1.408	398	256	774
16DR-4	BS Strong Arc	-62.00	-56.24	2125	5	1.290	365	269	666
16DR-5	BS Strong Arc	-62.00	-56.24	2125	4	1.252	358	249	680
17DR-2	BS Weak Arc	-61.97	-56.18	2332	16	1.697	407	903	532
17DR-9	BS Weak Arc	-61.97	-56.18	2332	11	1.657	412	830	551
18DR-10	BS Strong Arc	-61.88	-55.98	1421	--	0.888	240	7	816
18DR-2	BS Strong Arc	-61.88	-55.98	1421	6	1.083	314	13	936
18DR-7	BS Strong Arc	-61.88	-55.98	1421	4	1.030	272	23	711
18DR-8	BS Strong Arc	-61.88	-55.98	1421	5	1.095	309	11	985
18DR-9	BS Strong Arc	-61.88	-55.98	1421	30	1.393	308	33	945
25DR-2	BS Weak Arc	-61.89	-55.82	2135	3	1.600	349	220	342
25DR-3	BS Weak Arc	-61.89	-55.82	2135	5	1.531	317	306	483
25DR-4	BS Weak Arc	-61.89	-55.82	2135	13	1.161	377	480	354
26DR-1	BS APAV	-61.93	-55.89	1775	5	0.116	708	301	333
27DR-1	BS Weak Arc	-61.96	-55.87	1800	11	1.368	367	317	425
27DR-5	BS Weak Arc	-61.96	-55.87	1800	6	1.300	313	279	464
28DR-1	BS Weak Arc	-61.99	-55.90	1850	3	1.176	290	139	635
28DR-3	BS Weak Arc	-61.99	-55.90	1850	4	1.209	291	133	571
28DR-9	BS Weak Arc	-61.99	-55.90	1850	13	1.576	369	855	561
38DR-4	BS Strong Arc	-62.18	-57.24	1335	4	1.539	1322	8	4175

Supplementary Table 2.S2 (continued)

38DR-6	BS Strong Arc	-62.18	-57.24	1335	6	1.443	1154	9	3740
40DR-5	BS Strong Arc	-62.19	-57.28	1063	5	1.616	1191	24	3671
D15A	BS Strong Arc	-62.23	-57.73	1572	2	1.348	360	84	987.1388
D15B	BS Strong Arc	-62.23	-57.73	1572	6	1.425	374	94	1017
D15E	BS Strong Arc	-62.23	-57.73	1572	5	1.352	385	74	1035
D15F	BS Strong Arc	-62.23	-57.73	1572	3	1.395	369	87	990
D15I	BS Strong Arc	-62.23	-57.73	1572	2	1.403	374	90	1029
D15J	BS Strong Arc	-62.23	-57.73	1572	3	1.222	330	78	931
D15K	BS Strong Arc	-62.23	-57.73	1572	4	1.317	387	78	1057
D15L	BS Strong Arc	-62.23	-57.73	1572	2	1.388	366	95	1024
D15M	BS Strong Arc	-62.23	-57.73	1572	--	1.401	371	85	992
D15N	BS Strong Arc	-62.23	-57.73	1572	--	1.220	353	88	1008
D16A	BS Strong Arc	-62.34	-58.34	1733	3	1.330	431	103	1487
D16B	BS Strong Arc	-62.34	-58.34	1733	22	1.322	416	98	1416
D16D	BS Strong Arc	-62.34	-58.34	1733	3	1.365	432	105	1516
D17B	BS Strong Arc	-62.19	-57.27	1109	2	0.930	1347	16	6055
D17C	BS Strong Arc	-62.19	-57.27	1109	3	1.763	1107	60	5247
D18C	BS Strong Arc	-62.19	-57.27	1070	3	1.068	1148	20	4874
D18D	BS Strong Arc	-62.19	-57.27	1070	4	1.163	1313	26	5265
D19A	BS Weak Arc	-62.58	-58.71	1343	2	0.994	316	223	6286
D19B	BS Weak Arc	-62.58	-58.71	1343	6	0.969	304	228	548
D19E	BS Weak Arc	-62.58	-58.71	1343	3	0.928	295	233	520
D20A	BS Weak Arc	-62.74	-59.32	1139	4	1.141	398	312	634
D20B	BS Weak Arc	-62.74	-59.32	1139	5	1.178	676	861	1204
D20C	BS Weak Arc	-62.74	-59.32	1139	6	1.231	713	884	1249
D21A	BS Weak Arc	-62.71	-59.65	1073	3	1.219	806	495	1021
D21B	BS Weak Arc	-62.71	-59.65	1073	4	1.063	628	417	790
D21C	BS Weak Arc	-62.71	-59.65	1073	2	1.238	686	470	808
D21D	BS Weak Arc	-62.71	-59.65	1073	3	1.070	623	409	764
D22A	BS Weak Arc	-62.65	-59.00	1088	3	1.041	345	123	730
D22B	BS Weak Arc	-62.65	-59.00	1088	4	1.054	346	131	712
D22C	BS Weak Arc	-62.65	-59.00	1088	2	0.973	319	122	652
D22D	BS Weak Arc	-62.65	-59.00	1088	3	1.045	345	132	719

Supplementary Table S2.2 (continued)

D22E	BS Weak Arc	-62.65	-59.00	1088	4	1.728	1670	31	9374
D23A	BS Weak Arc	-62.65	-59.00	1072	7	0.986	323	132	686
D23B	BS Weak Arc	-62.65	-59.00	1072	8	1.066	341	135	706
D23C	BS Weak Arc	-62.65	-59.00	1072	4	1.065	346	132	713
D24A	BS Weak Arc	-62.65	-59.00	1030	6	1.090	366	144	776
D24B	BS Weak Arc	-62.65	-59.00	1030	4	0.999	332	133	688
D2J	BS Weak Arc	-62.44	-58.41	--	3	1.482	1070	664	2814
DF86.32	BS Weak Arc	-62.69	-58.99	1226	3	1.350	540	521	1861
53DR-2	PR N-MORB	-59.75	-65.41	3291	200	0.385	319	1216	76
53DR-20	PR N-MORB	-59.75	-65.41	3291	209	0.341	298	1196	62
53DR-3	PR N-MORB	-59.75	-65.41	3291	201	0.376	314	1159	72
53DR-4	PR N-MORB	-59.75	-65.41	3291	187	0.340	278	1011	110
53DR-5	PR N-MORB	-59.75	-65.41	3291	167	0.390	324	1089	99
55DR-1	PR E-MORB	-59.84	-65.33	3052	97	1.135	972	903	941
55DR-12	PR E-MORB	-59.84	-65.33	3052	146	0.660	464	841	348
55DR-13	PR E-MORB	-59.84	-65.33	3052	154	0.656	467	832	339
55DR-15	PR E-MORB	-59.84	-65.33	3052	96	1.031	872	835	818
55DR-16	PR E-MORB	-59.84	-65.33	3052	92	1.023	865	813	775
55DR-17	PR E-MORB	-59.84	-65.33	3052	143	0.664	467	863	359
55DR-19	PR E-MORB	-59.84	-65.33	3052	141	0.656	463	848	354
55DR-4	PR E-MORB	-59.84	-65.33	3052	105	1.017	872	844	803
55DR-5	PR E-MORB	-59.84	-65.33	3052	136	0.655	465	911	427
55DR-8	PR E-MORB	-59.84	-65.33	3052	147	0.672	468	871	371
56DR-12	PR E-MORB	-60.33	-65.50	3262	147	0.422	338	887	200
56DR-13	PR E-MORB	-60.33	-65.50	3262	145	0.411	348	893	197
56DR-14	PR E-MORB	-60.33	-65.50	3262	154	0.432	351	902	199
56DR-18	PR N-MORB	-60.33	-65.50	3262	149	0.186	165	929	65
56DR-2	PR E-MORB	-59.84	-65.33	3052	156	0.436	350	907	204
56DR-3	PR E-MORB	-60.33	-65.50	3262	154	0.447	349	900	201
56DR-5	PR N-MORB	-60.33	-65.50	3262	194	0.346	269	944	120
56DR-6	PR N-MORB	-60.33	-65.50	3262	202	0.346	271	965	123
56DR-8GL	PR N-MORB	-60.33	-65.50	3262	190	0.356	276	962	123
56DR-8HY	PR N-MORB	-60.33	-65.50	3262	185	0.323	264	961	124
DR190	WSR N-MORB	-56.53	-53.79	3846	226	0.308	252	1029	46
DR191.3	WSR E-MORB	-56.47	-53.59	3415	188	1.059	1115	566	662
DR183.3	WSR Weak Arc	-54.54	-45.49	4147	230	0.357	234	1194	80
DR183.4	WSR Weak Arc	-54.54	-45.49	4147	187	0.603	243	983	216
DR183.5	WSR Weak Arc	-54.54	-45.49	4147	178	0.616	265	1157	179
DR 207.4	WSR Strong Arc	-54.29	-45.84	3730	64	1.494	234	824	622
DR 209.1	WSR Strong Arc	-54.08	-45.74	3600	10	1.980	778	728	1307
DR 209.3	WSR Strong Arc	-54.08	-45.74	3600	42	1.861	449	961	630

Supplementary Table 2.S3: Major and trace element concentrations of olivine phenocrysts and surrounding glass from samples in this study

Sample	Group	Material	SiO ₂ (wt. %)	TiO ₂ (wt. %)	Al ₂ O ₃ (wt. %)	FeOt (wt. %)	MnO (wt. %)	MgO (wt. %)	CaO (wt. %)	Na ₂ O (wt. %)	K ₂ O (wt. %)	P ₂ O ₅ (wt. %)	Total	V (ppm)	Modeled Fe ³⁺ /Fe ²⁺ (pre-eruptive)
18DR-2 ^a	BS Strong Arc	olivine	38.93	--	--	19.62	0.35	41.27	--	--	--	--	100.17	2.74	0.23
		glass	55.93	1.06	14.39	8.60	0.16	4.70	8.65	3.80	0.67	0.19	98.15	124.62	
25DR-4	BS Weak Arc	olivine	39.72	--	--	15.76	0.27	44.56	--	--	--	--	100.31	3.06	0.29
		glass	49.89	1.94	16.26	8.83	0.15	6.16	10.12	4.23	0.34	0.27	98.19	220.47	
28DR-3	BS Weak Arc	olivine	39.96	--	--	14.14	0.26	45.66	--	--	--	--	100.02	3.69	0.26
		glass	51.70	1.57	15.72	7.77	0.13	6.18	10.68	3.93	0.38	0.22	98.28	213.91	
DR 183.5	WSR Weak Arc	olivine	40.25	--	--	12.51	0.20	47.20	--	--	--	--	100.16	7.06	0.21
		glass	51.16	1.71	14.98	9.27	0.16	6.99	10.91	3.26	0.19	0.17	98.80	266.39	
DR 207.4	WSR Strong Arc	olivine	40.31	--	--	12.24	0.20	47.23	--	--	--	--	99.98	6.10	0.20
		glass	50.99	1.01	16.28	7.42	0.12	7.12	11.59	2.68	0.32	0.12	97.65	220.67	
DR 209.3	WSR Strong Arc	olivine	39.28	--	--	17.19	0.25	42.79	--	--	--	--	99.51	7.94	0.20
		glass	52.51	1.27	15.40	8.94	0.15	5.64	9.82	2.96	0.60	0.20	97.49	288.45	
^a Glass in contact with olivine could not be analyzed for this sample, so glass composition is taken from Anderson et al. (2023)															

Supplementary Table 2.S4: Water content estimates for published Bransfield Strait and Quaternary South Shetland Island lavas

Sample	Group	Target H ₂ O/Ce	Ce (ppm)	Estimated H ₂ O (wt. %) ^c
28DR-1	BS Weak Arc	668 ^a	14.60 ^c	0.97
25DR-2	BS Weak Arc	668 ^a	17.29 ^c	1.15
18DR-1	BS Strong Arc	1157 ^b	8.60 ^c	1.00
18DR-9	BS Strong Arc	1157 ^b	9.07 ^c	1.05
P.810.4	Quaternary SS	1157 ^b	26.81 ^d	3.10
P.1818.10	Quaternary SS	1157 ^b	29.39 ^d	3.40
P.1818.12	Quaternary SS	1157 ^b	37.03 ^d	4.28
P.1817.1	Quaternary SS	1157 ^b	5.55 ^d	0.64
P.810.3	Quaternary SS	1157 ^b	24.43 ^d	2.83
^a From 28DR-3				
^b From 18DR-2				
^c From Fretzdorff et al. (2004)				
^d From Haase et al. (2012)				
^c Calculated from the target H ₂ O/Ce value				

CHAPTER 3

The lithospheric origins of Cenozoic Antarctic Peninsula alkaline volcanism

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This work is in preparation for submission

Abstract

Throughout the Cenozoic, magmatism across the Antarctic Peninsula (the Phoenix Ridge, the Bransfield Strait, James Ross Island, and the Seal Nunataks) has produced predominantly alkaline, trace element- and isotope-enriched lavas distinct from the typical subduction- and rift-related lavas that dominate the region. Based on a detailed analysis of their compositions, we propose that these lavas were produced during recent melting of the lithospheric mantle, metasomatized within the past ~100 Myr by a combination of enriched mid-ocean ridge basalts and arc melts generated during West Antarctica's long history of subduction and rifting. We present a trace element metasomatism and isotope ingrowth model to support this interpretation. We then explore the potential relationship between these Antarctic Peninsula alkali basalts and the Cenozoic alkaline magmatism occurring more widely across West Antarctica (i.e., the Jones Mountains, Peter I Island, Mount Early, and Sheridan Bluff) and southern Patagonia. By re-applying our model more broadly to lavas across these areas, we find their geochemistry could be reasonably produced by the same process, with metasomatism occurring from the present up to possibly ~400 Ma.

1. Introduction

The Antarctic Peninsula has been the site of ongoing subduction since the late Proterozoic-Paleozoic accretion of Gondwana, and it is therefore no surprise that magmatism in the region has been geochemically dominated by subduction processes for a very long time (e.g., Smellie et al., 1984; Haase et al., 2012; Nelson and Cottle, 2017; Smellie et al., 2021). Yet despite this long history of subduction across the peninsula, a large fraction of recent (< 6 Ma) magmatism there lacks any clear geochemical indication of subduction influence (e.g., Hole et al., 1993; Košler et

al., 2009; Hole et al., 2021). Instead, enriched, isotopically distinct alkaline melts dominate the Cenozoic lavas collected along the length of the peninsula, occurring at least as far south as Alexander Island and as far north as the Bransfield Strait (Fig. 3.1; Hole, 1990; Hole et al., 2021; Anderson et al., 2023). Past scientists have attributed this alkaline magmatism to a change in mantle chemistry and a transition from flux to adiabatic melting caused by the cessation of subduction and the in-flow of fresh sub-slab asthenosphere through a widening slab window (e.g., Hole, 1990; Fretzdorff et al., 2004). However, in the northern region of the peninsula, where this alkaline magmatism has occurred abundantly, it is unclear whether subduction has actually stopped, since the area remains quite seismically active (Robertson Maurice et al., 2003). Furthermore, many of these alkaline lavas erupted before this presumed cessation (Hole et al., 1994; Hole, 2021). Importantly, it was also recently recognized that these lavas occur on both sides of the trench; not only in the South Shetland subduction zone back-arc itself amid lavas with clear geochemical signals of subduction influence, but also at the neighboring Phoenix Ridge (Anderson et al., 2023). Hole (2021) recently proposed these lavas may have melted from pyroxenite hosted in the slab, rather than the peridotitic sub-slab asthenosphere. Although the geochemical similarities between the widespread alkaline lavas throughout the region suggest they share a common origin, their source remains unresolved. Here we report new major and trace element contents and radiogenic isotope ratios of lavas from James Ross Island and the Seal Nunataks and use them to investigate the origins of their mantle source and assess what relationship this source may have to alkaline melts sampled more broadly across West Antarctica and Southern Patagonia.

2. Geologic Background

For nearly 200 Myr, the Antarctic Peninsula has been the site of both rifting from the breakup of Gondwana and the continuous subduction of the Phoenix Plate beneath the Antarctic Plate. Today, the South Shetland subduction zone of West Antarctica is mainly characterized by the South Shetland Islands volcanic front and the Bransfield Strait back-arc (Fig. 3.1). However, for much of its history, the trench extended along the full length of the peninsula. Only within the past ~50 Ma did this change, as segments of the Phoenix mid-ocean ridge began colliding obliquely with the subduction margin, forming a slab window beneath the peninsula as the trailing half of each segment became locked at the trench and the leading half continued to subduct (Barker, 1982; Hole, 1990; Guenthner et al., 2010; Hole, 2021). These progressive collisions are expected to have slowed subduction over time, with the last collision occurring ~4 Ma, based on magnetic data (Barker, 1982). It is around this time that the slab likely steepened to its current angle of ~70°, presumably thinning the overlying lithosphere and forming the Bransfield Strait back-arc (Park et al., 2012; An et al., 2015; Haase and Beier, 2021). As the final ridge segment collided with the trench and subduction slowed nearly to a halt, alkaline magmatism began on James Ross Island and in the Seal Nunataks, in the far back-arc region of the subduction zone (Fig. 3.1). This coincidence has led many workers to hypothesize that the combined slowdown of subduction and inflow of fresh sub-slab asthenosphere through the growing slab window triggered this magmatism (e.g., Hole et al., 1993; Hole et al., 1994). Yet, there is no clear progression of this alkaline magmatism associated with the propagation of the slab window over time (Fretzdorff et al., 2004; Košler et al., 2009; Hole, 2021; Altunkaynak et al., 2022). Thus, the relationship these lavas have to the region's history of subduction and rifting and the evolution of the mantle there remain uncertain.

3. Materials and Methods

Samples measured in this study were mainly analyzed as whole rock powders, although a few select samples were analyzed as naturally quenched submarine volcanic glasses (see Supplementary Table 3.S1). For the glasses, we conducted major and trace element analyses on three to five hand-picked chips of the freshest available glass, which we mounted in indium and polished using diamond grit paste down to 1 μm .

Whole rock major and select trace element (Ni, Cr, V, Ga, Zn) contents were collected using a ThermoARL Advant'XP + sequential XRF spectrometer at the Peter Hooper GeoAnalytical Laboratory at Washington State University (see lab for details <https://environment.wsu.edu/facilities/geoanalytical-lab>). Information on sample preparation, analytical procedure, accuracy, and precision are provided in Johnson et al. (1999). Based on analyses of duplicate samples made from the same whole rock powders (labeled as separate samples), the average analytical errors (2σ RSD) were $\sim 3.1\%$ for FeO, $\sim 2.1\%$ for Na₂O, $< 1.5\%$ for MnO and P₂O₅, and $< 1\%$ for all other major elements and $< 5\%$ for the select trace elements, except Ga ($< 9\%$), Pb ($< 15\%$), and Cu ($< 16\%$). On average, major element contents of seven Seal Nunataks samples previously reported by Hole (1990) and Hole et al. (1993) deviate from published values $< 5\%$ for all elements except MnO (6%).

The remaining whole rock trace element contents were measured on Li-tetraborate fused beads by ICP-MS using an Agilent 7700 quadrupole mass spectrometer at the GeoAnalytical Lab (see lab for details on sample preparation and processing, long term precision, and standards: <https://environment.wsu.edu/facilities/geoanalytical-lab>). The GeoAnalytical Lab reports that long term precision is $< 10\%$ (2σ RSD) for rare earth elements and $< 20\%$ for all other trace elements. Average analytical errors (2σ RSD) for duplicate analyses made on the same whole rock powders

are < 5% all elements except Rb (< 6.5%), Cs, U (both < 10%), and Pb (< 11%). On average, trace element contents of seven Seal Nunataks samples previously reported by Hole (1990) and Hole et al. (1993) deviate from published values < 5% for all elements except Nb (9%), Rb (12%), and U (22%).

Glass major element contents were collected using a Cameca SX-100 electron microprobe at Brown University. The operating conditions of the instrument consisted of 15 kV voltage, 10 nA current and a 10 μm diameter spot size. Reproducibility of repeated analyses on the three to five glass chips per sample was calculated, then averaged across all samples. For the glasses, the average reproducibility (2σ SE) for each oxide is < 0.25% for SiO_2 , < 0.4% for Al_2O_3 , < 0.9% for FeO_T and MgO , 1% for CaO , < 2.5% for TiO_2 , < 3.2% for Na_2O , < 6% for K_2O , < 8% for P_2O_5 , and < 11.5% for MnO .

Glass trace element concentrations were collected using a 193 nm wavelength excimer Analyte G2 laser ablation system coupled to a Thermo Scientific X-Series II quadrupole ICP-MS at Brown University. Samples were analyzed using a 150 μm spot and 10 Hz repetition rate. The average reproducibility (2σ SE) obtained for our glass samples is < 5% for all elements except Cs, Sr (both < 6%), and Pb (< 7%).

Isotope ratios were measured on whole-rock powders for all samples except one from James Ross Island (TD012120-1), where hand-picked glass chips were used instead. For the powders, about 1 g of sample was leached with 6N double distilled HCl for 1 hour at 100 °C and then rinsed with 18 M Ω water three times. During each rinsing step, samples were centrifuged to ensure the complete removal of any residual acid. The glass chips were leached with cold 2.5N HCl for 30 minutes. In each case, ~100 mg of material was dissolved in a double distilled HF(3):HNO₃(1) mixture and then processed through ion exchange chromatography. Sr, Nd, Hf,

and Pb isotopic compositions were measured on a Thermo Scientific Neptune Plus MC-ICP-MS at the Mass Spectrometer Analytical Facility, Brown University. To account for instrumental mass fractionation, we applied corrections using $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$, $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ and $^{179}\text{Hf}/^{177}\text{Hf} = 0.7325$ and an exponential law. Sample Pb solutions were spiked with NBS SRM-997 Tl standard prior to analysis with a Pb/Tl ratio of ~ 4 to correct for mass fractionation using an exponential law and $^{203}\text{Tl}/^{205}\text{Tl} = 0.418922$. Sr, Nd, and Hf isotope ratios are reported relative to NBS SRM-987 $^{87}\text{Sr}/^{86}\text{Sr} = 0.71024$, JNd-i $^{143}\text{Nd}/^{144}\text{Nd} = 0.512115$, and JMC-475 $^{176}\text{Hf}/^{177}\text{Hf} = 0.282160$, respectively. Pb isotope ratios are reported relative to the NBS 981 $^{206}\text{Pb}/^{204}\text{Pb} = 16.9356$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.4891$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.7006$ (Todt et al., 1996). The external precision on the ratios over the course of two years is 30 ppm for Sr (2σ) and Nd (2σ), 40 ppm for Hf (2σ) and 80 ppm (2σ) for Pb. All blanks were < 50 pg. The USGS reference materials BHVO-1 and BCR-2 were processed during the sample preparation and measured as secondary standards with the same instrument set up. Their isotope ratios are reported in Supplementary Table 3.S2 and agree well with the range of values reported in the GeoRem database. Comparisons of our measurements with published data from Hole (1990) and Hole et al. (1993) for six Seal Nunataks samples show average deviations of 0.35 and 0.59 ppm for Sr and Nd isotopes, respectively, and deviations of 157, 13, and 64 ppm for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$, respectively. The Pb deviations are somewhat high; however, considering the age of the published data and their associated analytical errors, our low blanks, and our consistent values for BHVO-1 and BCR-2, we rely on our analyses in the upcoming discussion to avoid interlaboratory biases.

4. Results

Nearly all James Ross Island and Seal Nunataks samples measured in this study are alkaline basalts, trachybasalts, and basaltic trachyandesites; however, some Seal Nunataks lavas extend to slightly subalkaline in composition (Fig. 3.2). At the same MgO contents, lavas from James Ross Island have slightly lower SiO₂, CaO, and TiO₂ and higher Al₂O₃, Na₂O, K₂O, and P₂O₅ than lavas from the Seal Nunataks (Fig. 3.3). James Ross Island lavas also extend to slightly lower MgO contents (~4-6 wt. %), and at these more evolved compositions the lavas follow trends of increasing FeO_T, Na₂O, TiO₂, K₂O, P₂O₅ and decreasing Al₂O₃, likely indicating plagioclase fractionation. Aside from these differences, the major element compositions of James Ross Island and Seal Nunataks lavas are roughly similar to each other and distinct from subduction- and rift-related magmatism across the Antarctic Peninsula. The major element compositions of our most primitive lavas (MgO ~8-10 wt. %) extend to higher TiO₂ and K₂O and lower CaO compared to MORB from the Phoenix Ridge and East Pacific Rise (Fig. 3.3). James Ross Island lavas also extend to higher Na₂O and P₂O₅ and lower SiO₂, but most Seal Nunataks lavas have concentrations closer to MORB, a distinction likely tied to the difference in alkalinity between lavas from each area. Our most primitive melts also have substantially higher Na₂O, TiO₂, K₂O, and P₂O₅ than arc and back-arc melts from the South Shetland Islands and Bransfield Strait. The lavas analyzed in this study generally overlap with other published Cenozoic alkali basalts from the Phoenix Ridge, the Bransfield Strait, and Alexander Island.

The incompatible trace element compositions of the James Ross Island and Seal Nunataks lavas measured in this study are also unique for melts from a subduction-dominated region, with marked differences from the Phoenix Ridge MORB and South Shetland and Bransfield Strait arc-like lavas (Fig. 3.4). The primitive mantle-normalized incompatible trace element patterns of James Ross Island and Seal Nunataks samples show no clear evidence of subduction influence on

their sources, despite erupting in an area with an extensive history of subduction. They do not have the extreme positive anomalies in fluid-mobile, large ion lithophile elements (LILE; e.g., Ba, U, K, Pb) or the significant relative depletions in high field strength elements (HFSE; e.g., Nb, Ta, Hf) typical of subduction-derived lavas (e.g., Kogiso et al., 1997, Rustioni et al., 2021). Our measured James Ross Island and Seal Nunataks lavas have steep heavy rare earth element patterns ($\text{La/Sm} = 2.94\text{-}4.58$) and strong negative Y anomalies, indicative of melting in the garnet stability field. The lavas also typically have positive Sr anomalies, negative Ba anomalies, and Pb anomalies that range from positive to negative (Fig. 3.4). These characteristics are broadly consistent with the trace element compositions of other Cenozoic alkaline lavas from across the peninsula. The least similar are the melts from the Phoenix Ridge; however, because their isotope compositions are consistent with the isotope compositions of other Cenozoic alkaline lavas, deviating from other Phoenix Ridge and Pacific MORB, we group them with the other instances of Antarctic Peninsula alkaline volcanism. Though broadly alike, the trace element compositions of James Ross Island and Seal Nunataks lavas also differ from each other slightly. For one, Seal Nunataks samples consistently have very slight negative Nb anomalies that are typically weaker or not present in the trace element patterns of James Ross Island samples (Fig. 3.4). Seal Nunataks lavas also have steeper heavy rare earth element slopes compared to James Ross Island lavas ($\text{Sm/Yb} = 2.69\text{-}4.51$ versus $1.63\text{-}2.48$ for James Ross Island). Many published James Ross Island samples from Altunkaynak et al. (2022) also display substantial positive Ta anomalies; however, at comparable MgO contents, our James Ross Island data lack this feature (Supplementary Figure 3.S1). It is possible these Ta anomalies are signals of the sources of these lavas or the processes that generated them; however, because these anomalies are also not present in published James Ross Island data from Košler et al. (2009), we do not consider them in our interpretations.

The isotopic compositions of our James Ross Island and Seal Nunataks samples form a broad trend between enriched MORB lavas from the Phoenix Ridge and a high $^{87}\text{Sr}/^{86}\text{Sr}$, low $^{143}\text{Nd}/^{144}\text{Nd}$ - $^{176}\text{Hf}/^{177}\text{Hf}$ endmember similar to the published sediments, arc lavas, and back-arc lavas from the South Shetland subduction zone (Fig. 3.5). In Pb-Pb isotope space, the data form a rough trend subparallel to MORB, displaced to higher $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ that again project from E-MORB towards sediments and subduction-derived lavas. Our lavas overlap with, and follow similar trends to, the other groups of Cenozoic alkaline lavas from across the peninsula, suggesting that they have all melted from similar sources. Interestingly, within the broad trend defined by the lavas there are several sub-trends. This is most clearly expressed in Pb isotope plots, where mixing trends are linear, and it is clear the lavas do not extend along a singular straight line.

5. Discussion

5.1 Signals of E-MORB and arc mixing in Antarctic Peninsula alkaline lavas

In many ways, the lavas from James Ross Island and the Seal Nunataks share clear resemblances –the majority of the lavas are alkaline, have strong garnet signals in their trace element patterns and occupy the same isotope space between E-MORB and arc lavas (Fig. 3.4 and 5). Both sets of lavas erupted at similar distances from the South Shetland trench in the far back-arc area of the subduction zone. Magmatism at each site has also occurred over similar periods, with the bulk of James Ross Island lavas erupting from ~6 to 0.7 Ma (Smellie et al., 2006) and Seal Nunataks lavas erupting from ~4 to 0.2 Ma (Hole, 1990). Furthermore, it has been well established that this alkaline magmatism extends beyond just these two areas, and we have already touched on the broad similarities between our samples and those from across the peninsula. Similar alkaline lavas have been found at least as far south as Alexander Island, where magmatism has

occurred from ~ 7 to < 1 Ma, although one measured dike suggests magmatism could have occurred as early as 15 Ma (Rex, 1970; Hole et al., 1993; Hole et al., 1994). These alkali basalts have also been collected alongside typical back-arc lavas in the Bransfield Strait (Fretzdorff et al., 2004; Anderson et al., 2023) and among MORB (both alkaline and tholeiitic) at the Phoenix Ridge (Choe et al., 2007; Choi et al., 2008; Anderson et al., 2023). Alkaline lavas have also been reportedly found in other areas of the peninsula (Hole et al., 1994; Košler et al., 2009).

Clearly the source of these lavas has melted abundantly along the peninsula throughout the Cenozoic, but attempts to characterize such a source have led to several conflicting explanations. Some have suggested that the source of these lavas is inflowing asthenosphere free of any subduction influences, which has passed through the slab window beneath the peninsula into the mantle wedge (e.g., Hole et al., 1994; Fretzdorff et al., 2004). Others have argued that this source must reside in the slab, itself (Hole, 2021). It has also been suggested that an OIB-like source persists in the region's upper mantle (Košler et al., 2009). However, the new and compiled data in this study reveal that a singular endmember source cannot sufficiently explain the geochemistry of these lavas. The melts vary widely in isotope composition and form broad trends that suggest mixing between E-MORB and subduction-derived components (Fig. 3.5). Košler et al. (2009) explored the possibility of mixing depleted mantle with a sediment component but argued that such a component would easily overwhelm the trace element compositions of the melts. However, the effects of subduction processes may not be so apparent if the component only carries weak signals of subduction influence, something equivalent to the source of a back-arc basalt, for instance. Panter et al. (2022) demonstrated how a mixture of E-MORB and subduction-derived sources could overprint obvious indications of subduction influence on the trace element compositions of alkaline lavas from Mount Early and Sheridan Bluff. This could similarly explain

the unique trace element patterns of the Antarctic Peninsula alkaline lavas, which lack the common signals of subduction influence and yet in many cases are distinct from MORB. Instead, they represent intermediate mixtures without the clear characteristics of either E-MORB or subduction-derived endmember (Fig. 3.4). For instance, the Nb-Ta peaks of E-MORB from the region may be counterbalanced by the negative Nb-Ta anomalies of arc lavas, depending on the strength of subduction influence (Fig. 3.4a-b). Indeed, evidence of subduction processes persists very subtly in the trace element compositions of the Antarctic Peninsula alkali basalts. The data correlate when plotting trace element ratios indicative of subduction signal, deviating from E-MORB towards subduction influenced lavas and subducting sediments from the South Shetland subduction zone (Fig. 3.6). The same can be seen when plotting many of these ratios against isotope composition (Fig. 3.7).

This weak signal of subduction influence cannot simply be the result of crustal assimilation since there are no clear correlations between isotope or trace element ratios and MgO or Ni content. Moreover, the majority of the Antarctic Peninsula alkaline lavas are relatively primitive, with MgO contents > 7.0 wt. %, limiting the opportunity for the melt compositions to be contaminated. Dense, ultramafic xenoliths are also frequently carried in these lavas, implying fast ascent rates that would further limit contamination (Altunkaynak et al., 2019; Gibson et al., 2020; Leat et al., 2023). The weak signal of subduction influence in the compositions of these lavas must therefore come from their mantle sources, not from shallow level contamination.

Moreover, the isotope compositions of Antarctic Peninsula alkaline lavas suggest that there is not a solitary arc endmember mixing with the E-MORB endmember but rather a spectrum of arc endmembers of different subduction strengths. The data form trends of varying slopes that project towards some of the weakest arc-like lavas in the Bransfield Strait and some of the strongest

(Fig. 3.5). For instance, in $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, the alkaline lavas project out towards back-arc lava compositions with $^{87}\text{Sr}/^{86}\text{Sr}$ values ranging from ~ 0.7030 to 0.7037 (Fig. 3.5e). Such a range in composition is hardly surprising, since mantle wedges never define only a single geochemistry. The compositions of arc and back-arc melts reflect mixtures between mantle and subducted sediments and fluids of ranging proportions (e.g., Stolper and Newman, 1994; Anderson et al., 2023), and the South Shetland subduction zone has a demonstrated history of this variability. Haase et al. (2012) found that volcanic front lavas from the South Shetland Islands have likely transitioned from being sediment-dominated to fluid-dominated since the Cretaceous. There is also strong evidence that the back-arc lavas from the Bransfield Strait have been influenced by spatial differences in subduction input to the region's depleted upper mantle (Fretzdorff et al., 2004; Anderson et al., 2023; Anderson et al., 2024). Thus, the Cenozoic alkaline lava sources could easily be composed of a mixture of an enriched MORB component and a range of subduction compositions. What is most important is that the Antarctic Peninsula alkaline lavas must have formed via mixing between E-MORB and arc components.

The conditions of melting are evidently closely tied to the extent of mixing between the E-MORB and arc components in these samples, since there are strong correlations between indicators of source composition, extent of melting, and pressure of melting (as suggested by garnet signal). Correlations between Δ alkalinity and $^{206}\text{Pb}/^{204}\text{Pb}$ suggest that extent of melting is tied to source composition, which may be sensible if the solidus temperatures of the E-MORB and arc components vary considerably (Fig. 3.8). This may explain the offset between most of the Cenozoic alkaline lavas from the peninsula and the Seal Nunataks lavas, which are isotopically more E-MORB-like, in Fig. 3.9. Perhaps this offset is produced by variations solidus temperature, as lavas melted from a source with a higher solidus temperature will begin melting deeper (i.e.,

have higher Sm/Yb) and be less alkaline. Alternatively, this offset could be controlled by differences in mantle potential temperature between the different areas, where melting of a hotter mantle will occur deeper and be less limited in extent. The data also suggest these relationships have been affected by the thickness of the lithosphere during melting in the Cenozoic. This is supported by the positive correlations between Δ alkalinity and Sm/Yb within groups of lavas from the same areas. Melting of the same source beneath a thicker lithosphere will produce more alkaline lavas with higher Sm/Yb. However, this relationship is complicated by the competing influence of source composition, which does seem to vary to a degree even between lavas from the same area, as indicated by their trace element and isotope compositions (Fig. 3.5-3.8). Thus, clearly the extent of mixing between the E-MORB and arc components is intimately linked to the melting conditions of the Cenozoic alkaline lavas.

5.2 Sources of Antarctic Peninsula alkaline volcanism: Asthenospheric vs slab-hosted vs lithospheric

In spite of these evident indications of mixing, direct mixtures of asthenospheric E-MORB and arc melts fail to reproduce many of the geochemical characteristics of the Antarctic Peninsula alkaline lavas. For one, their alkaline compositions are difficult to explain through simple mixing of E-MORB and arc melts, especially since counterintuitively, the lavas with the more arc-like isotope compositions are the most alkaline (Fig. 3.8). As discussed, there is likely a strong relationship between degree of melting and source composition, controlled by extent of mixing of E-MORB and arc components. Regardless, direct mixing of E-MORB with Bransfield Strait back-arc lavas cannot produce these increases in alkalinity, since past work has shown that Bransfield Strait back-arc lavas with the strongest signals of subduction influence are the least alkaline

(Anderson et al., 2023 and 2024). Additionally, most melts from the Phoenix Ridge and South Shetland subduction zone lack clear garnet signals, so their direct mixing would fail to produce the extreme garnet signals of the Antarctic Peninsula alkaline lavas (Fig. 3.4 and 3.9). It is also not clear how asthenospheric melts carrying isotopic signals of subduction influence would be generated at the Phoenix Ridge, where there should be no subduction-modified mantle, and at Alexander Island, where the alkaline lavas are < 15 Myr old yet overlie a ~50 Myr old slab window (Barker, 1982; Hole et al., 1993; Hole et al., 1994).

Because direct mixing of melts derived from the asthenosphere cannot produce the compositions of the Cenozoic alkaline lavas, we must explore alternate possibilities for their origins. Hole (2021) interpreted the low CaO contents of these lavas to be evidence that they melted from pyroxenite hosted in the subducted slab (Fig. 3.3). However, the low CaO contents of the lavas do not a priori rule out alternative source lithologies, as explained by Herzberg and Asimow (2008). Slab melting also does not explain the alkalinity of these lavas, which in many cases is extreme (Fig. 3.2, 3.8, and 3.9). It would also not reconcile the occurrence of these lavas in areas where no slab existed at the time of their genesis, such as at the Phoenix Ridge and Alexander Island.

For these reasons, we instead propose that these melts come from the metasomatized lithospheric mantle. Since the Paleozoic, subduction has occurred extensively along the western margins of what is now West Antarctica, doubtless producing arc melts of varying subduction strengths (e.g., Dalziel et al., 2013; Nelson and Cottle, 2019). These melts then mixed with E-MORB commonly found in back-arc environments, forming metasomatic veins in the lithospheric mantle (e.g., Langmuir et al., 2006; Hickey-Vargas et al., 2016; Chilson-Parks et al., 2022). Eventually, the widening slab window created a pathway beneath the peninsula for hot sub-slab

asthenosphere to heat and melt these veins throughout the Cenozoic, generating the Antarctic Peninsula alkaline lavas. Indeed, beneath the length of the peninsula there is a large low velocity body in the upper ~200 km of the mantle attributed to the inflow of warm asthenosphere through the vast slab window (Wiens et al., 2022). It may be possible that in some cases, some of the lithospheric mantle has also foundered into the convecting mantle, promoted by recent rifting and density instabilities caused by the presence of the metasomatic veins (e.g., Bird, 1979; Furman et al., 2016). This may explain the occurrence of these alkaline lavas at the Phoenix Ridge.

This interpretation resolves many of the outstanding questions about the Antarctic Peninsula alkaline lavas. For one, experimental and theoretical results have shown that small degree melts, frozen within the lithospheric mantle as metasomatic veins, can produce mafic alkaline compositions when melted (e.g., Pilet et al., 2008; Pilet et al., 2011). It also explains the evident signals of subduction influence in areas where there is no current slab or subduction-modified asthenosphere, since metasomatic veins in the lithospheric mantle may outlive active subduction and then persist in the convecting mantle following erosion and removal.

5.3 A comprehensive model for the origins of Antarctic Peninsula alkaline volcanism

We present a comprehensive model to support our interpretation, and an outline of the model's major steps is provided in Table 3.1. First, we take representative solid E-DMM and mantle wedge sources and correct their isotope compositions to a designated age in the past. We estimate the trace element compositions of these solids from the compositions of MORB and back-arc lavas from the Antarctic Peninsula, respectively. Our estimated E-DMM composition is not very different from the one given by Donnelly et al., 2004. The isotope composition of E-DMM today comes from measured E-MORB from the Phoenix Ridge, but the isotope composition of the

arc endmember is poorly constrained and could range significantly depending on the strength of the subduction signal, as previously discussed. For this reason, we use several representative endmember isotope compositions that span the range of our data and come from measured samples in the Bransfield Strait back-arc, the South Shetland Islands volcanic front, and the southernmost region of the Southern Volcanic Zone in Patagonia –areas that would have been in close proximity until the recent (~30 Ma) separation of South America from Antarctica (e.g., Dalziel et al., 2013). The samples these values come from do not have Hf isotope data, so their $^{176}\text{Hf}/^{177}\text{Hf}$ ratios were estimated using a regression of Nd and Hf isotope compositions of arc-like basalts from New Zealand, which overlap in Sr, Nd, and Pb isotope composition with arc lavas from the South Shetland Islands volcanic front (Gamble et al., 1996; Waight et al., 2017). We batch melt our past solids non-modally in the spinel field reasonable amounts (3% for E-DMM and 10% for the mantle wedge) to generate our metasomatizing magmas in the past. We then mix these two melts from 0 to 100% and dilute the mixtures with a trace element-free harzburgite (after Chilson-Parks et al., 2022; 10% melt to 90% harzburgite) to simulate lithospheric metasomatism. Following this dilution, we ingrow the simulated metasomatized lithosphere to the present-day and batch melt it non-modally in the garnet field. For the sake of the model, we make the simplifying assumption that this metasomatized lithospheric mantle melted 4%, although as discussed, in reality, the extents and pressures of melting of our samples are likely tied to the extent of mixing between the E-MORB and arc components. We expect that the lavas formed in the garnet field by low extents of melting, since variations in Sm/Yb correlate positively with alkalinity in our samples (Fig. 3.9; i.e., thicker lithospheric lids correspond to less melting). It is unlikely that the lithospheric mantle is melting without some input from the asthenosphere, so we then generate present-day asthenospheric melts from our same E-DMM source and mix that 20% with our present-day

lithospheric melts. Further details on all model parameters are provided in Supplementary Text 3.S1.

The results of this model match the compositions of the Antarctic Peninsula alkaline lavas remarkably well, covering their ranges in trace element concentrations and isotope ratios (Fig. 3.10-3.11). The model reproduces many of the notable trace element characteristics shared by most of these lavas, including negative Ba anomalies, variably steep negative heavy rare earth element slopes and negative Y anomalies associated with garnet signal, and the slight negative Nb anomalies of the Seal Nunataks samples. Our model results best match the compositions of the alkaline lavas when our modeled mantle wedge carries weak to moderate signals of subduction influence, analogous to the source of back-arc basalts from the Bransfield Strait. This is consistent with the trends they follow in isotope space, where the alkali basalts project towards Bransfield Strait back-arc lavas, as opposed to some of the more isotopically enriched arc lavas of the South Shetland Islands. The results also suggest that lithospheric metasomatism occurred relatively recently, as the isotopic compositions of the alkaline lavas are best matched by recent (0-100 Ma) ingrowth. Fig. 3.11 shows an example of the isotope model results for 50 Ma, but Supplementary Figures 3.S2 and 3.S3 show the results for 0 and 100 Ma for comparison. In reality, the data likely represent broad variations in numerous variables, and we do not attempt to match every composition perfectly by overcomplicating the model. The lava compositions could depend on metasomatic melt composition, age of metasomatism, extent of mixing between endmember compositions, degree of melting of the metasomatic veins, input from the asthenosphere, etc. In spite of these factors, we show that we can replicate the compositions of these lavas well using few and reasonable assumptions.

An interesting relationship that remains unresolved is the weak northward progression in isotope composition that Antarctic Peninsula alkaline volcanism seems to define. From Alexander Island in the south to the Bransfield Strait and James Ross Island in the north, there is a weak transition in isotope composition from more E-MORB-like to more arc-like (Fig. 3.5). This seems to indicate differences in either the strength or abundance of the metasomatizing arc melts along the length of the peninsula. However, with our limited data and the uncertainties surrounding the geologic history of the peninsula, we cannot draw any substantial conclusions about this progression.

5.4 Potential connection to broader Cenozoic alkaline volcanism

While the Antarctic Peninsula is the primary focus of our study, there is geochemical evidence that this subduction-driven metasomatism may have occurred much more broadly across the West Antarctic continent and potentially even as far as southern Patagonia. Throughout the Cenozoic, alkaline lavas bearing many of the characteristics of the Antarctic Peninsula alkaline lavas have erupted at the Jones Mountains, Peter I Island, Sheridan Bluff, and Mount Early (Hart et al., 1995; Panter et al., 2022) and throughout many of the Cenozoic mesetas of southern Patagonia (Fig. 3.12; e.g., Stern et al., 1990; D’Orazio et al., 2000; Gorrington et al., 2001). These lavas may even extend as far as the Adare Basin, since there, alkaline melts follow the same trends in isotope space as those from Jones Mountains and Peter I Island; however, because it has been speculated that Adare Basin melts may be influenced by a HIMU-affected source (Panter et al., 2018), we do not include them in our interpretations. The lavas we do consider from the greater West Antarctic continent and southern Patagonia are alkaline, with enriched trace element patterns that show no clear signs of subduction influence, yet they form the same mixing trends between

E-MORB and subduction endmembers in trace element ratio and isotope space (Fig. 3.13). The mixing trends do not appear to be controlled by crustal contamination, since these lavas are basaltic, indicating they have evolved less and had fewer opportunities to assimilate crust, and their isotope and trace element ratios (e.g., Th/La) do not correlate with decreasing MgO content. It is difficult to say whether these melts definitively sample the metasomatized lithosphere, since there is evidence that a plume may underlie Marie Byrd Land (Lloyd et al., 2020; Panter et al., 2021; Wiens et al., 2022; Panter and Martin, 2023), and many of the Southern Patagonia lavas are expected to have been affected by Enriched Mantle I components found in the South Atlantic (Søager et al., 2021; Mallick et al., 2023). However, the remarkable geochemical similarities between these lavas and Antarctic Peninsula alkaline lavas lead us to speculate that they could have formed by the same process. Panter et al. (2022) and Mallick et al. (2023) already similarly argued that Mount Early, Sheridan Bluff, and some Southern Patagonian lavas may sample the lithospheric mantle. We simply suggest that this process could be more widespread.

To test this possibility, we reapply our model with adjusted conditions to the alkaline West Antarctic continent and southern Patagonia lavas. Assumptions and parameters used for the adjusted model are provided in Supplementary Text 3.S2. The West Antarctic continent and Southern Patagonia lavas extend to much more radiogenic Sr and less radiogenic Nd and higher $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$, suggesting the metasomatizing arc lava carried stronger signals of subduction influence than in the peninsula (Fig. 3.13). This is supported by the especially flat primitive mantle-normalized trace element patterns in the most incompatible elements for Mount Early and Sheridan Bluff samples, which suggests that the enrichments in elements such as Nb and Ta in the E-MORB component were counterbalanced by especially strong depletions in those same elements in the arc component. Furthermore, in spite of broad ranges in

Sr and Nd isotope ratios, the Pb isotope ratios of Mount Early and Sheridan Bluff lavas hardly vary, suggesting the Pb isotope composition is heavily dominated by high sediment input (Fig. 3.13). For these reasons, we use a different mantle wedge composition estimated from Bransfield Strait lavas carrying the strongest signals of subduction influence. We emphasize that this composition differs only minorly from the original composition we use to model the alkaline lavas of the peninsula, mostly only differing to reflect a greater proportion of sediments being added to the mantle (e.g., higher Rb-Ba-Th-U-Pb and lower Nb-Ta). Similarly, we use a single but more extreme isotope composition for the arc endmember (from the South Shetland Islands volcanic front) as an example to demonstrate how these melts could be reproduced by the same metasomatic process. We reiterate that this composition is poorly constrained and could vary substantially. Further details and a comparison of the two model mantle wedge trace element compositions are provided in Supplementary Figure 3.S4.

The West Antarctic continent and Southern Patagonia lavas together form an echelon trends in isotope space, offset in $^{206}\text{Pb}/^{204}\text{Pb}$, which could be reasonably explained by differences in ingrowth age (Fig. 3.13). The isotope compositions of Mount Early, Sheridan Bluff, and Southern Patagonia lavas overlap with, or project even further along, the trends defined by the Antarctic Peninsula alkaline lavas, suggesting they are all similar in age. Indeed, our model supports metasomatism ages of ~0-200 Ma (Fig. 3.14). In contrast, the isotope compositions of Jones Mountains lavas suggest older ages, and our model supports metasomatism ages of ~400 Ma. Peter I Island lavas follow very similar trends to the Jones Mountains lavas, but ingrowth never seems to reach their extremely high $^{207}\text{Pb}/^{204}\text{Pb}$ values –up to 15.76, higher than the measured present-day sediment compositions of the region. However, there are several measured global sediment compositions that extend to even more extreme values (Plank and Langmuir,

1998; Plank, 2014), and Hart (1995) recognized the isotopic overlap between Peter I Island lavas and many of these sediments. Thus, it is possible the Peter I Island lavas were produced from a lithosphere that was metasomatized by an arc lava carrying a more extreme sediment composition that is not represented by the values used for our model. Considering the long history of subduction that West Antarctica has experienced and the distance that these Cenozoic alkaline lavas span, it is hardly remarkable that these lavas could sample metasomatic veins of such different ages, strengths of subduction signal, and sediment compositions.

6. Conclusion

We have presented new major element, trace element, and isotope data for a suite of alkaline lavas from James Ross Island and the Seal Nunataks, reinterpreting their origins and, more broadly, the origins of alkaline volcanism from across the Antarctic Peninsula. Their geochemistry suggests they originated from metasomatic veins in the lithospheric mantle, which were formed by infiltrating mixtures of E-MORB and arc melts within the past ~100 Myr. More recently, rifting, slab roll-back, and a widening slab window resulted in lithospheric erosion, which re-heated and melted these metasomatic veins, producing alkaline volcanism across the Antarctic Peninsula throughout the Cenozoic. Variations in the trace element patterns and trajectories of the isotope mixing trends of these lavas can be reasonably reproduced by our geochemical model using some basic assumptions. Furthermore, this same process can explain the geochemical similarities between the Antarctic Peninsula alkaline lavas and the alkaline magmatism of the West Antarctic continent, at the Jones Mountains, Peter I Island, Mount Early, and Sheridan Bluff, and even Southern Patagonia. Re-applying our model to lavas from these areas suggests that metasomatism in these areas has been ongoing, possibly since ~400 Ma.

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Figures

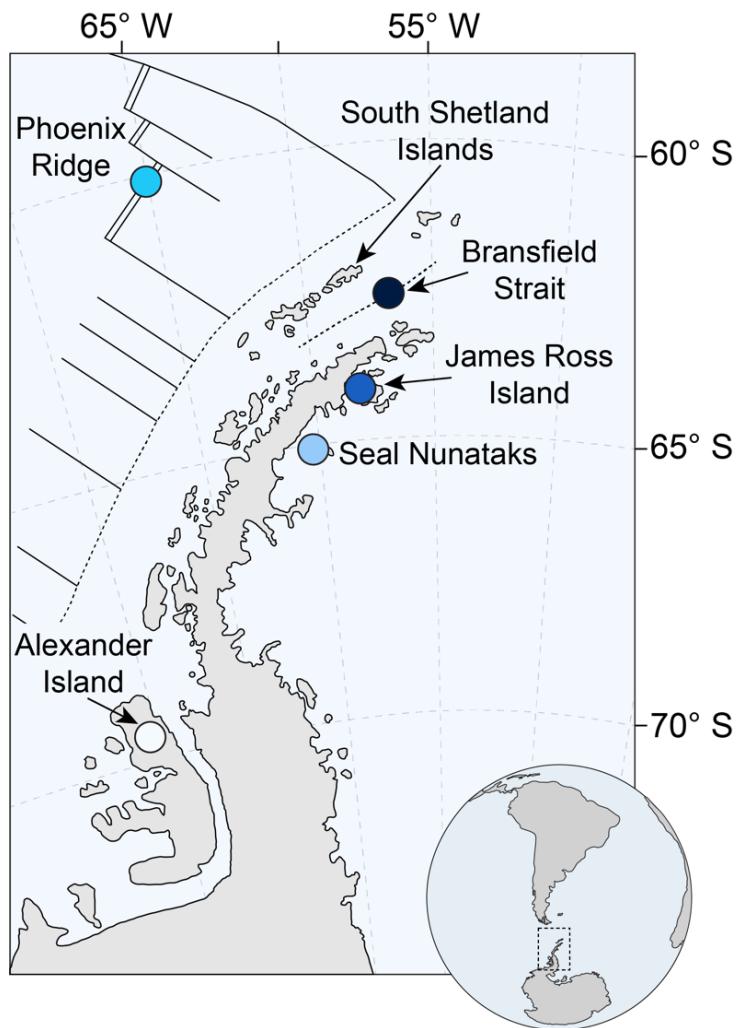


Figure 3.1: Map of the Antarctic Peninsula (after Hole, 1990) showing the main areas considered in this study, including the Phoenix Ridge, the South Shetland Islands, the Bransfield Strait, James Ross Island, the Seal Nunataks, and Alexander Island. The generalized sampling locations of the lavas that are the focus of this study are marked with symbols and colors corresponding to the representative geochemistry of each area.

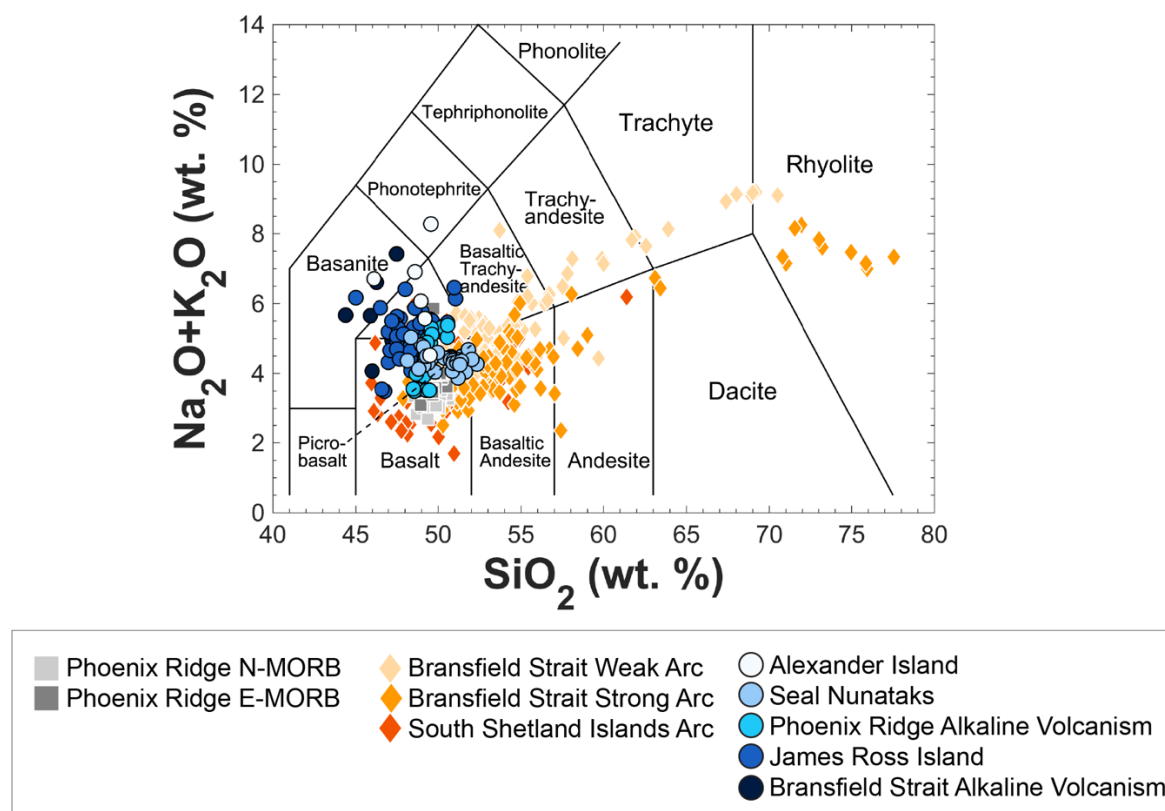


Figure 3.2: Total alkalis vs silica diagram showing the compositions of lavas from across the Antarctic Peninsula, including MORB from the Phoenix Ridge (Haase et al., 2011; Anderson et al., 2023), arc-like lavas from the Bransfield Strait back-arc (Baker et al., 1975; Weaver et al., 1979; Keller et al., 1992; Keller and Fisk, 1992; Keller et al., 2002; Fretzdorff et al., 2004; Kraus et al., 2013; Martí et al., 2013; Anderson et al., 2023) and South Shetland Islands volcanic front (Haase et al., 2012), and alkali basalts from Alexander Island (Hole et al., 1993), the Seal Nunataks (Hole, 1990; Hole et al., 1993; This study), the Phoenix Ridge (Choe et al., 2007), James Ross Island (Košler et al., 2009; Altunkaynak et al., 2022; This study), and the Bransfield Strait (Fretzdorff et al., 2004; Anderson et al., 2023). Dashed line represents the alkaline-subalkaline boundary from MacDonald and Katsura (1964). Black bordered symbols here and in subsequent figures represent the alkali basalts that are the focus of this study.

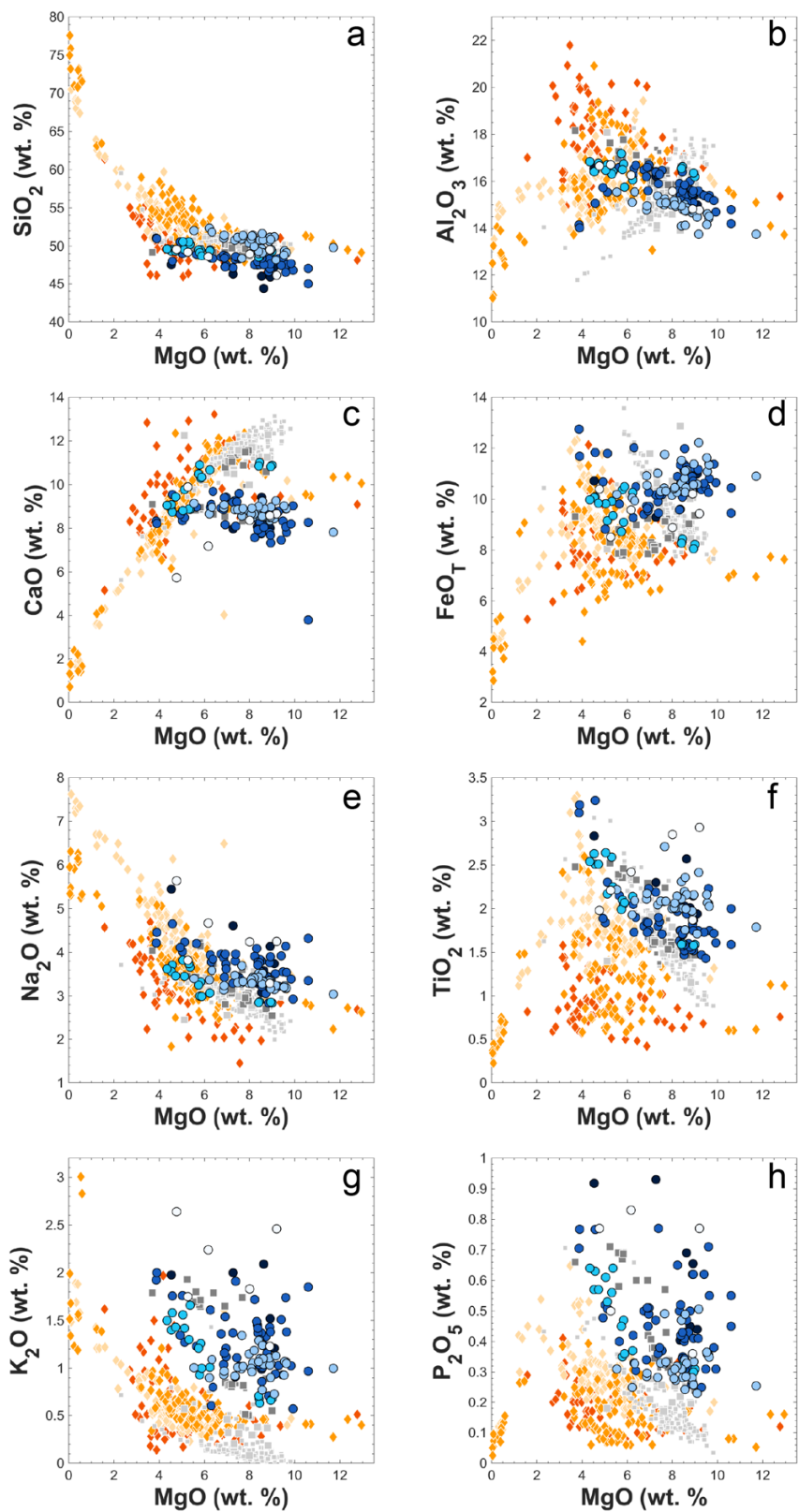


Figure 3.3: Variations in major element concentrations vs MgO for Antarctic Peninsula lavas, including new and published data from James Ross Island (Košler et al., 2009; Altunkaynak et al., 2022; This study) and the Seal Nunataks (Hole, 1990; Hole et al., 1993; This study) and published data from Alexander Island (Hole et al., 1993), the Phoenix Ridge (Choe et al., 2007; Haase et al., 2011; Anderson et al., 2023), East Pacific Rise (Shimizu et al., 2016), the Bransfield Strait (Baker et al., 1975; Weaver et al., 1979; Keller et al., 1992; Keller and Fisk, 1992; Keller et al., 2002; Fretzdorff et al., 2004; Kraus et al., 2013; Martí et al., 2013; Anderson et al., 2023), and the South Shetland Islands (Haase et al., 2012).

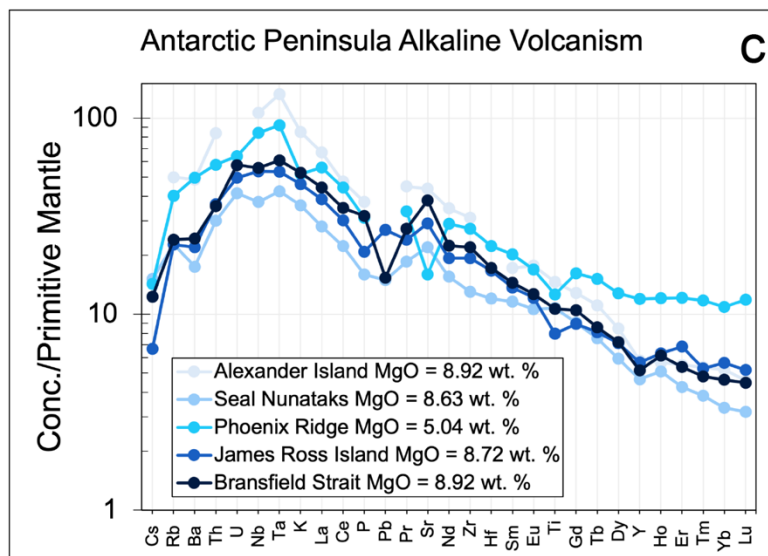
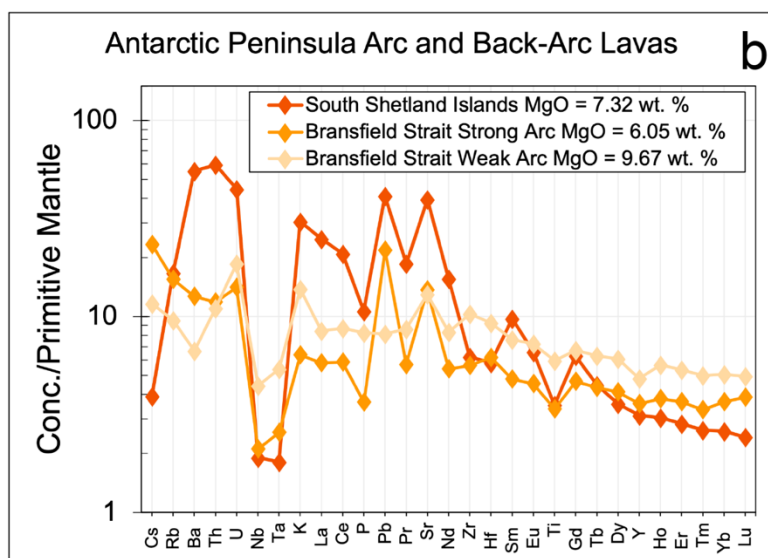
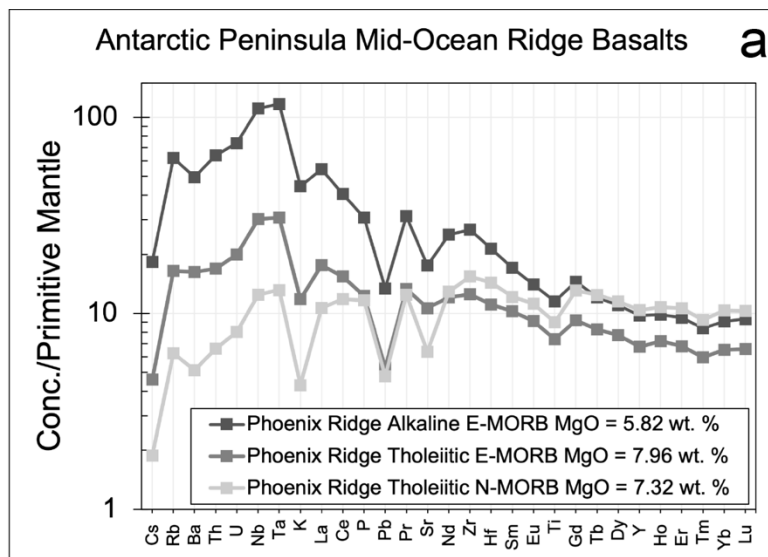
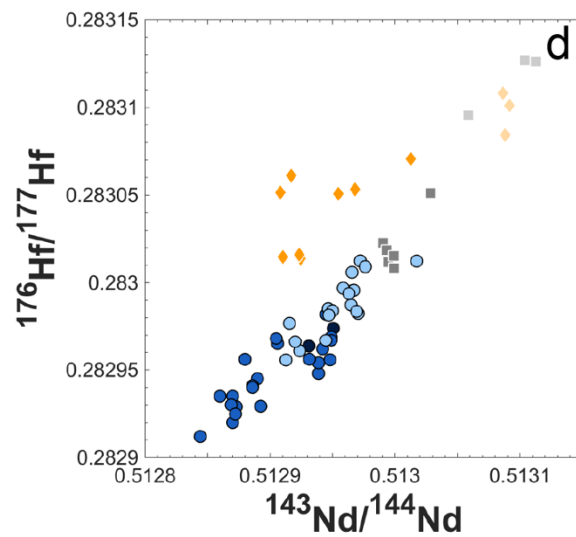
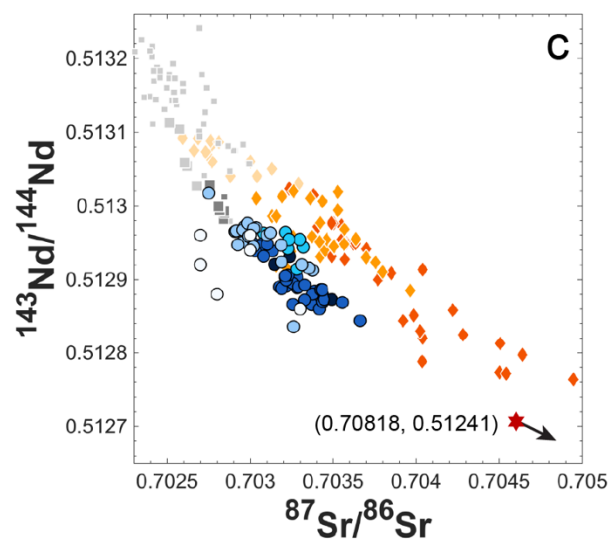
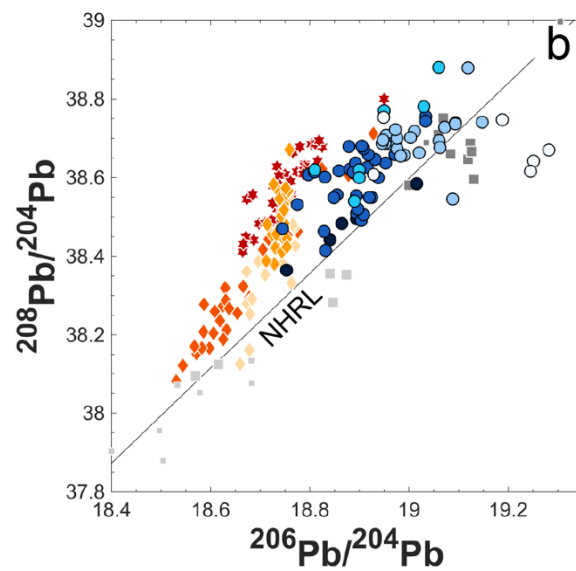
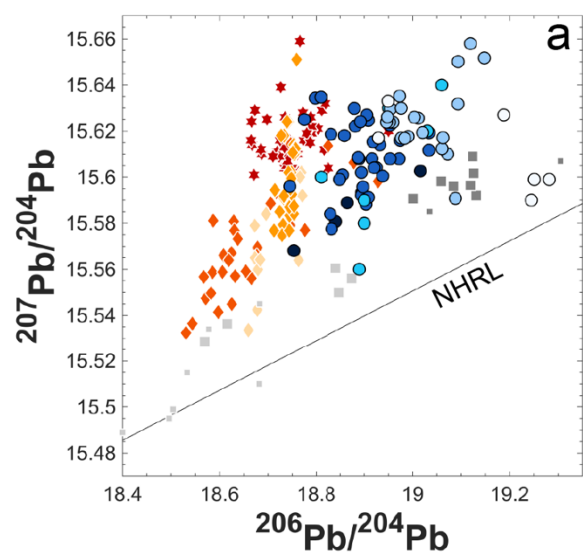


Figure 3.4: Primitive mantle normalized incompatible trace element diagram of representative Antarctic Peninsula lavas, including a) alkaline E-MORB, tholeiitic E-MORB, and tholeiitic N-MORB from the Phoenix Ridge (Anderson et al., 2023), b) arc lavas from the South Shetland Islands volcanic front (Haase et al., 2012) and arc-like lavas with weak and strong signals of subduction influence from the Bransfield Strait (Fretzdorff et al., 2004; Anderson et al., 2023), and c) distinct alkaline lavas from Alexander Island (Hole et al., 1993), the Seal Nunataks (This study), the Phoenix Ridge (Choe et al., 2007), James Ross Island (Kořler et al., 2009), and the Bransfield Strait (Fretzdorff et al., 2004). Primitive mantle composition is from McDonough and Sun (1995).



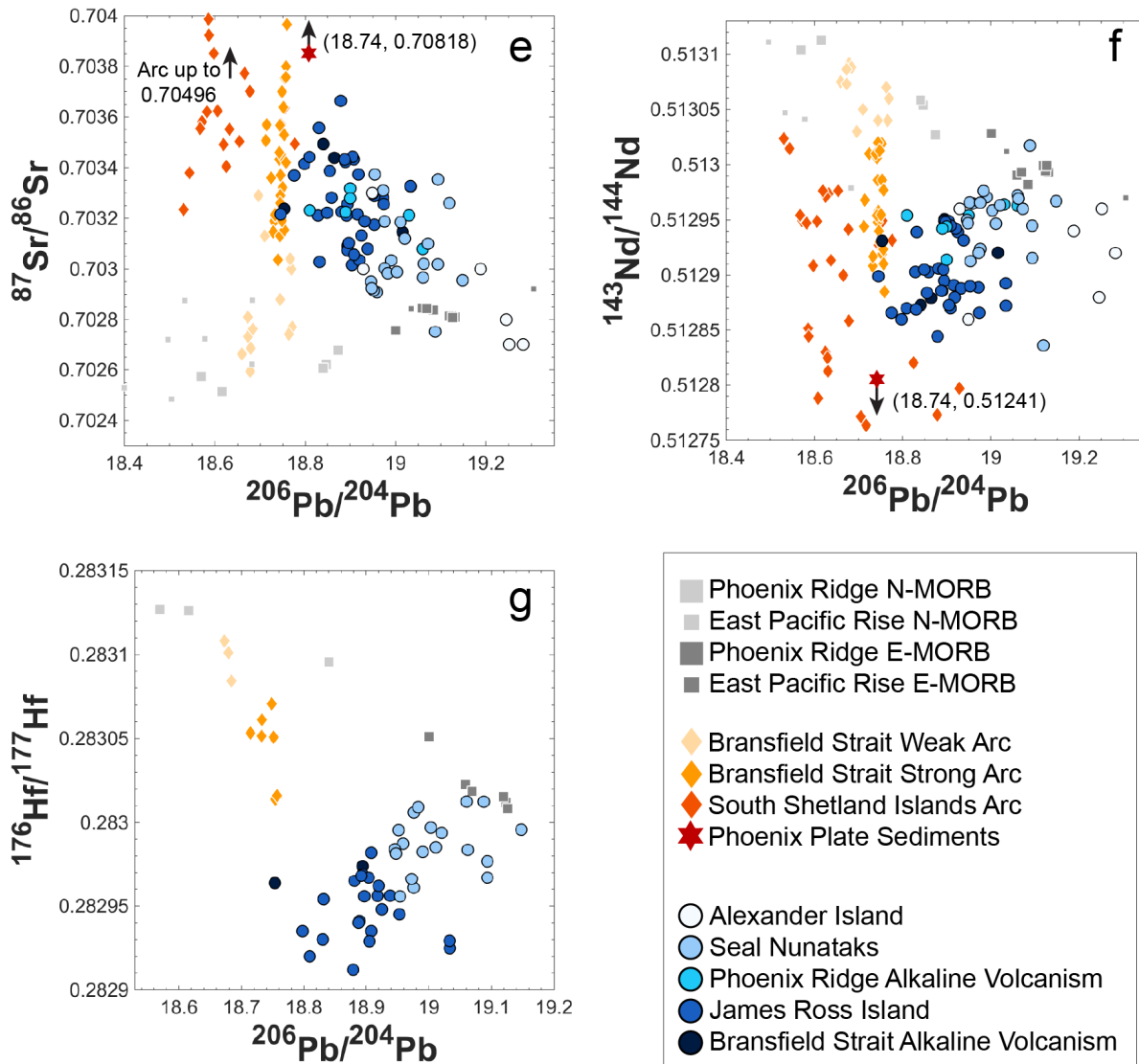


Figure 3.5: a) $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, b) $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, c) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$, d) $^{176}\text{Hf}/^{177}\text{Hf}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$, e) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, f) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, g) $^{176}\text{Hf}/^{177}\text{Hf}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ for lavas from the Phoenix Ridge (Choi et al., 2008; Haase et al., 2011; Anderson et al., 2023), the Bransfield Strait (Keller et al., 1992; Keller and Fisk, 1992; Keller et al., 2002; Fretzdorff et al., 2004; Anderson et al., 2023; Anderson et al., 2024), the South Shetland Islands volcanic front (Haase et al., 2012), Alexander Island (Hole et al., 1993), the Seal Nunataks (Hole, 1990; Hole et al., 1993; This study), James Ross Island (Kořler et al., 2009; Altunkaynak et al., 2022; This study), and subducting sediments from the Phoenix Plate in the Antarctic Peninsula (Lee et al., 2012; Anderson et al., 2023). Also plotted are the isotope compositions of MORB from the East Pacific Rise (Shimizu et al., 2016). Solid black lines in a) and b) are the Northern Hemisphere Reference Line from Hart (1984).

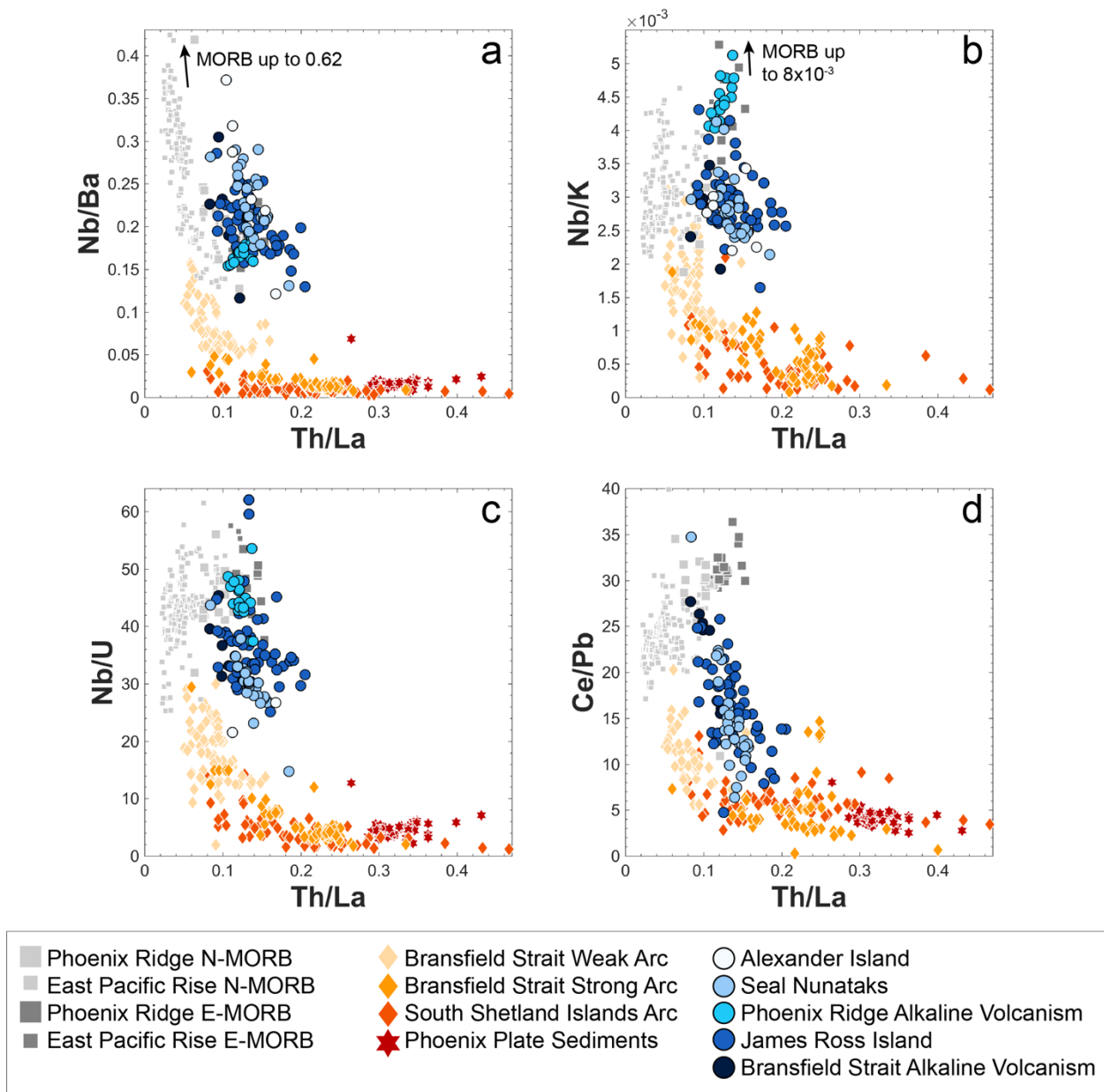


Figure 3.6: a) Nb/Ba, b) Nb/K, c) Nb/U, and d) Ce/Pb vs Th/La for lavas from the Antarctic Peninsula and the East Pacific Rise, along with subducting sediments from the Phoenix Plate.

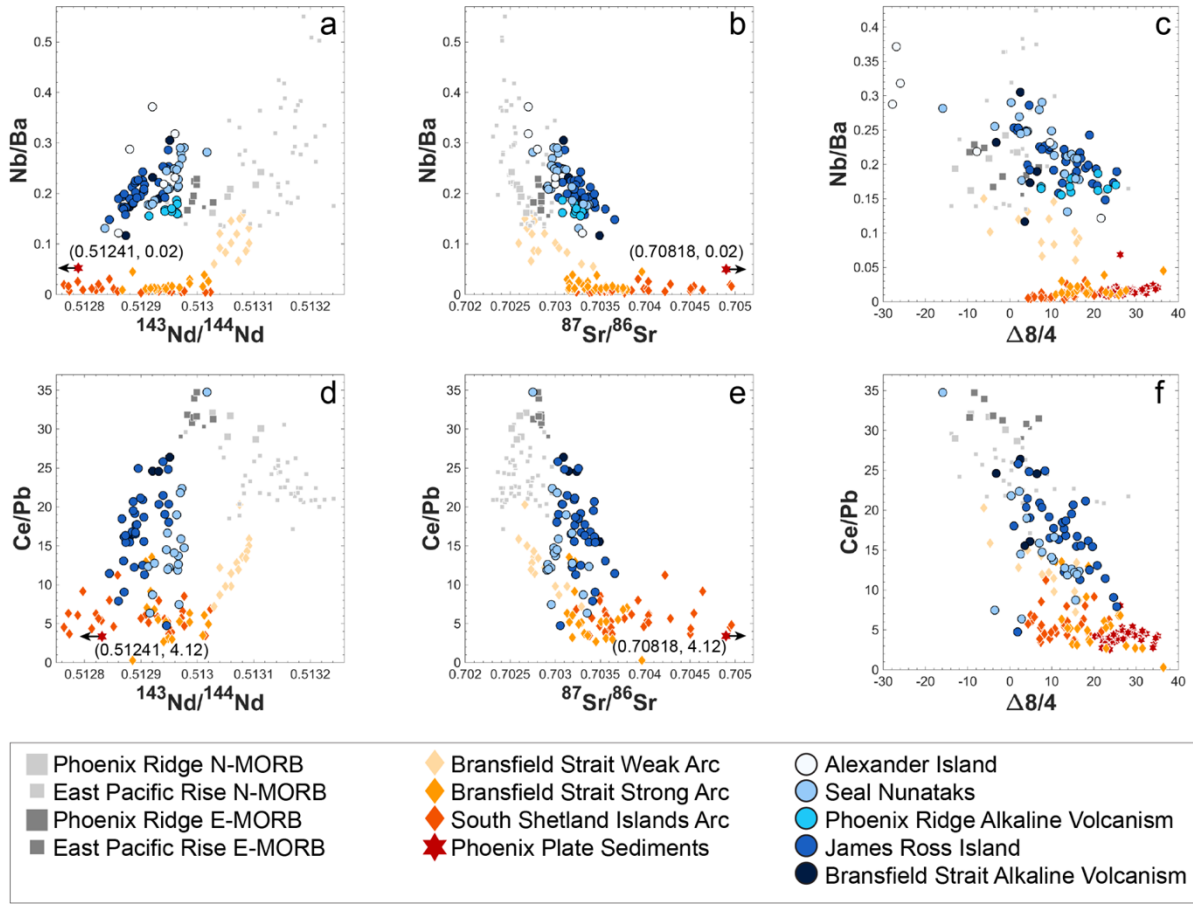


Figure 3.7: a) Nb/Ba vs $^{143}\text{Nd}/^{144}\text{Nd}$, b) Nb/Ba vs $^{87}\text{Sr}/^{86}\text{Sr}$, c) Nb/Ba vs $\Delta 8/4$, d) Ce/Pb vs $^{143}\text{Nd}/^{144}\text{Nd}$, and e) Ce/Pb vs $^{87}\text{Sr}/^{86}\text{Sr}$, f) Ce/Pb vs $\Delta 8/4$. Red stars with arrows and labels indicate the direction that the weighted average of the Phoenix Plate sediments plots.

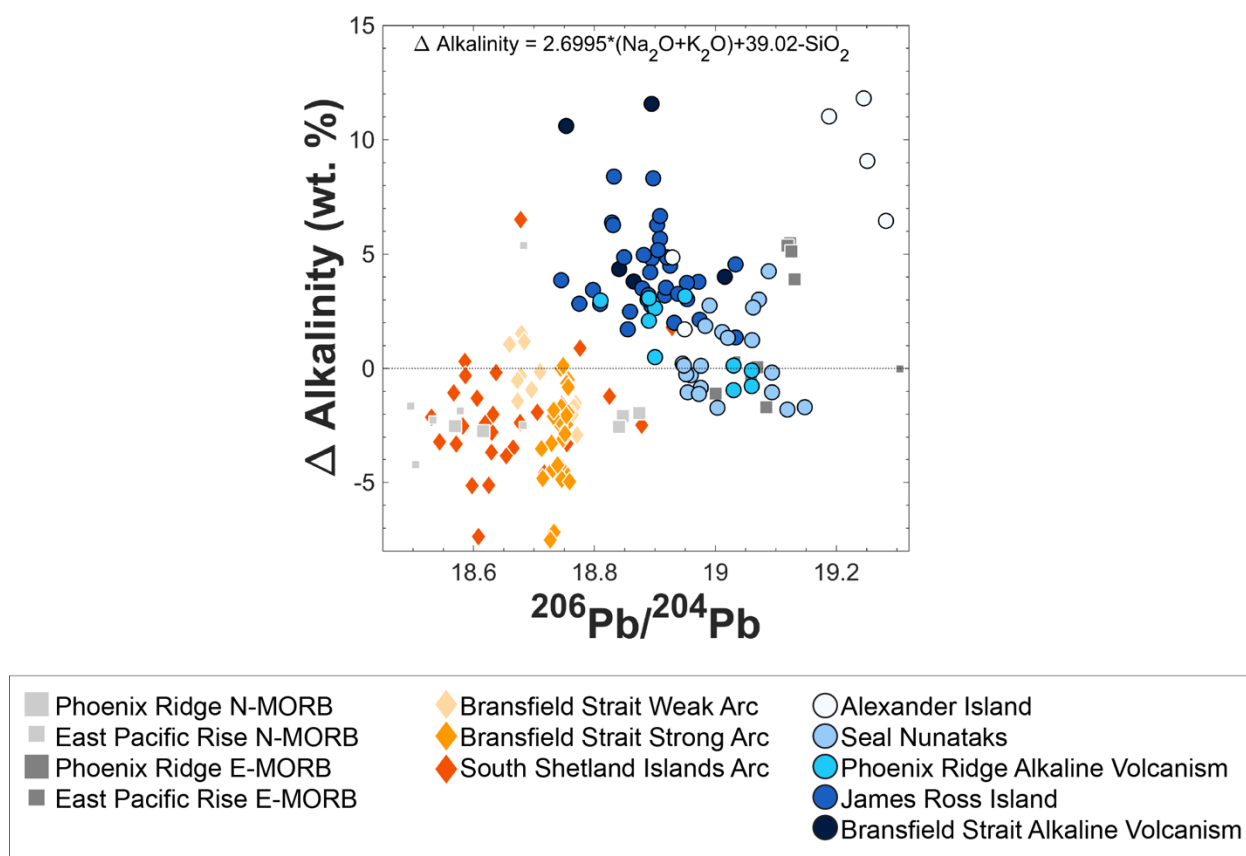


Figure 3.8: Δ Alkalinity vs $^{206}\text{Pb}/^{204}\text{Pb}$ for lavas from the Antarctic Peninsula and the East Pacific Rise. Also plotted is the line separating alkaline and subalkaline melts, along with the formula used to calculate Δ Alkalinity.

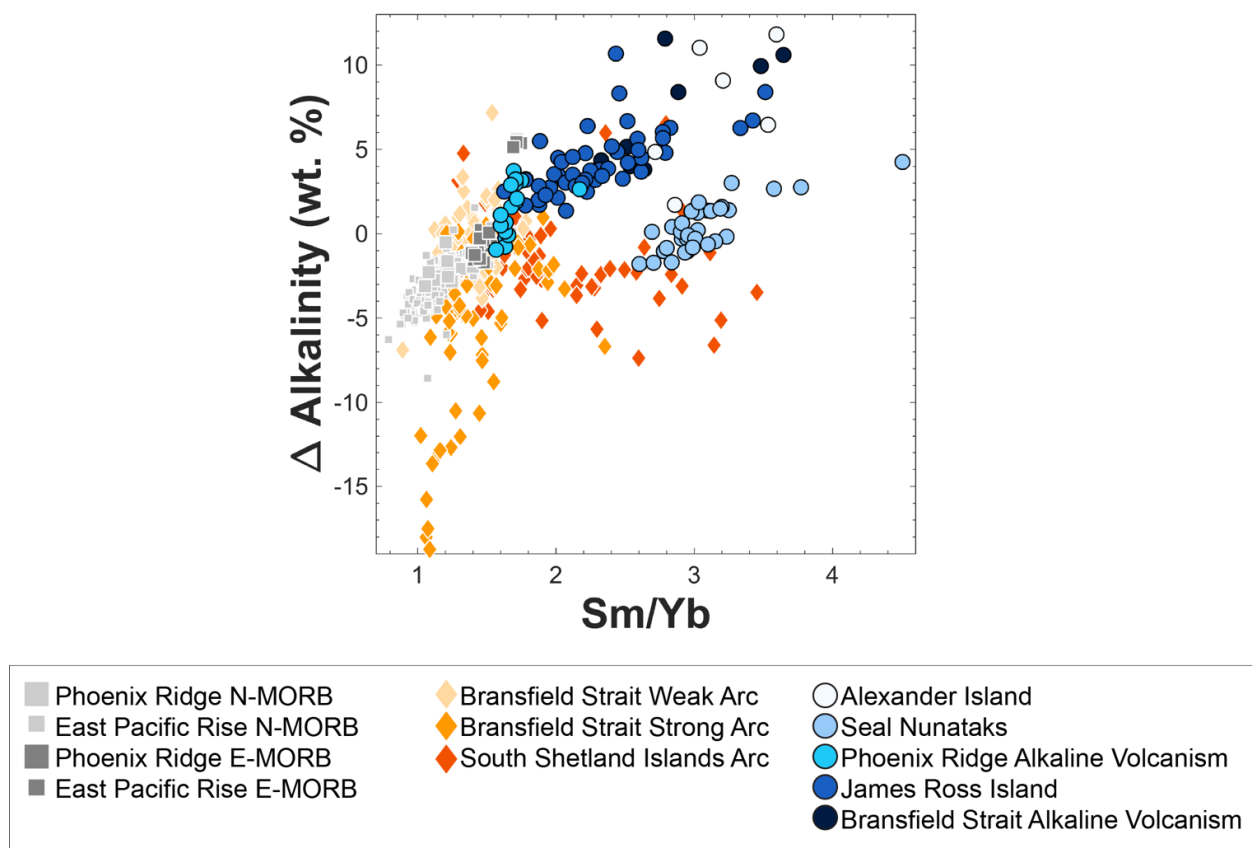


Figure 3.9: Δ Alkalinity vs Sm/Yb for lavas from the Antarctic Peninsula and the East Pacific Rise. The formula for Δ Alkalinity is shown in Fig. 3.8.

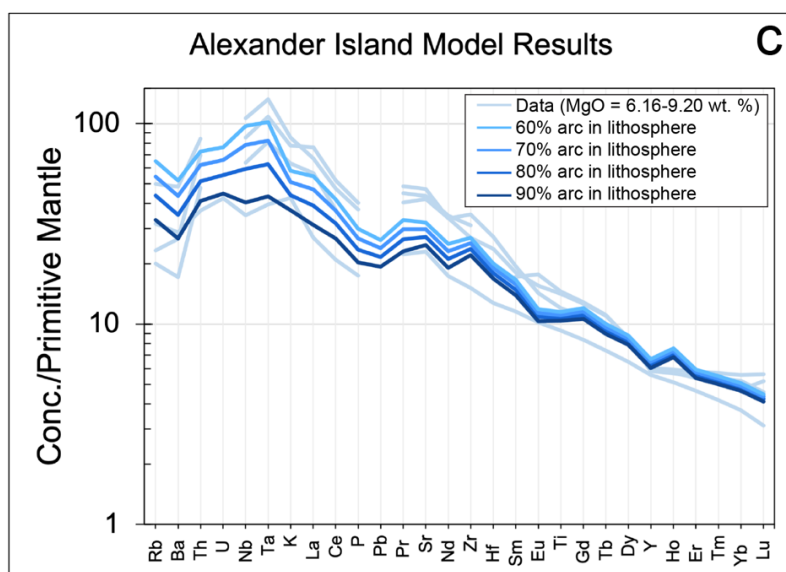
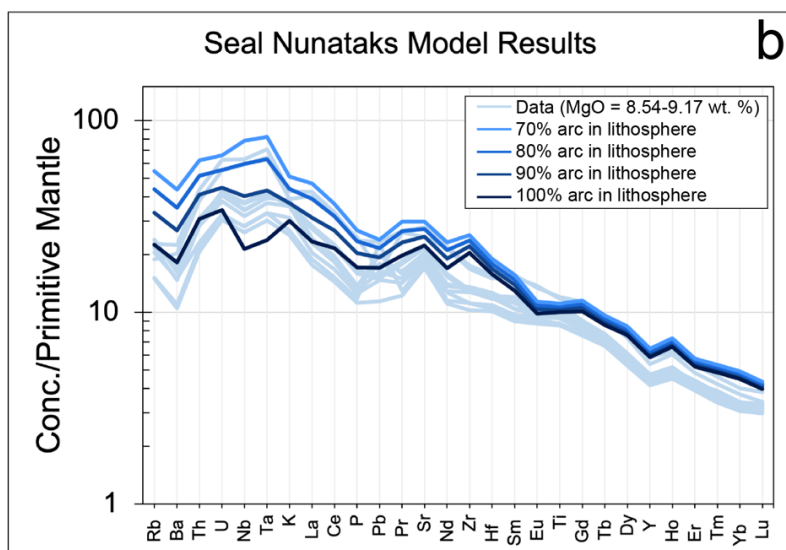
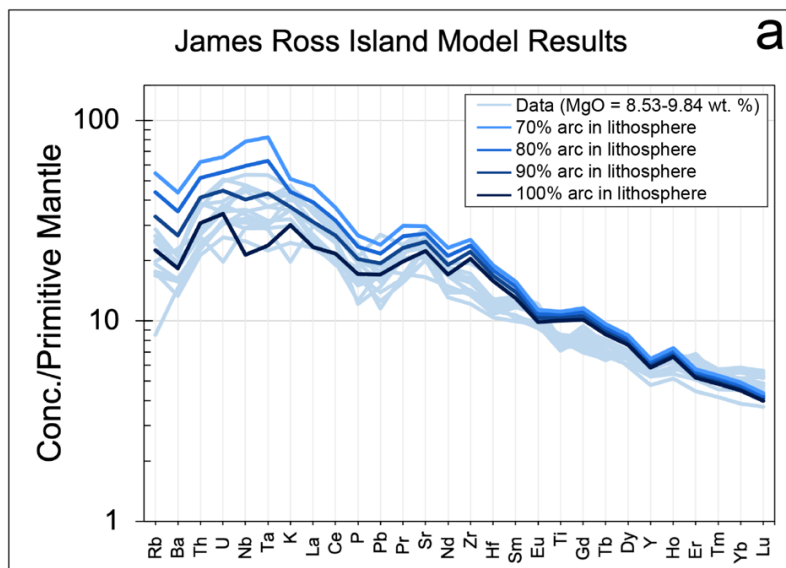
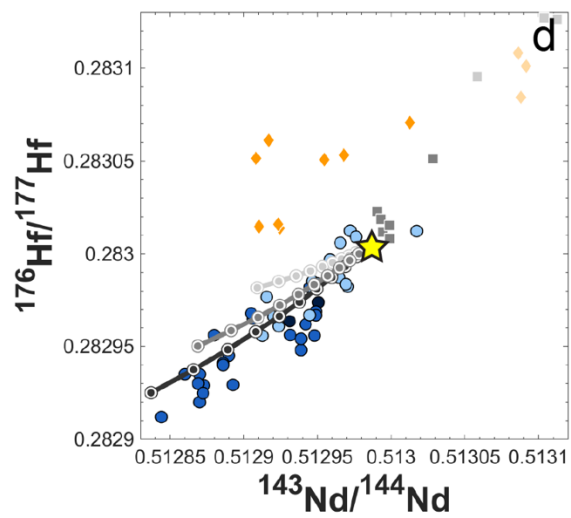
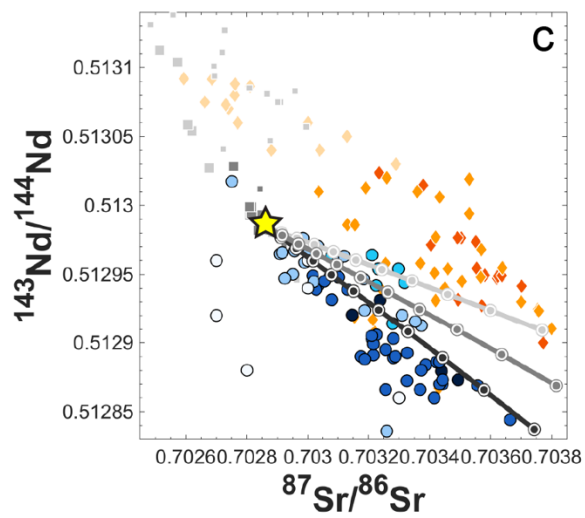
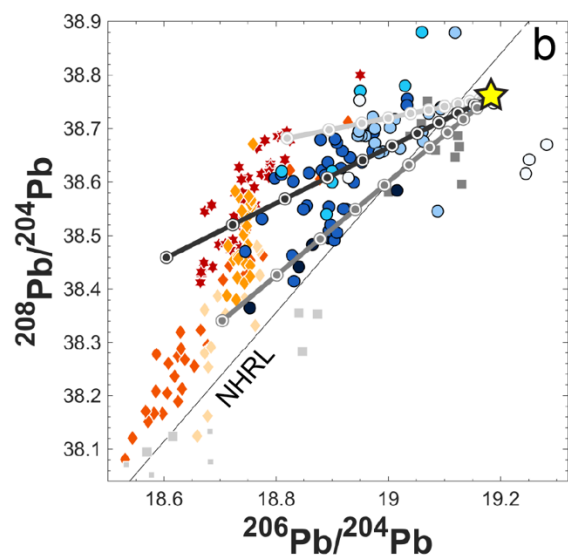
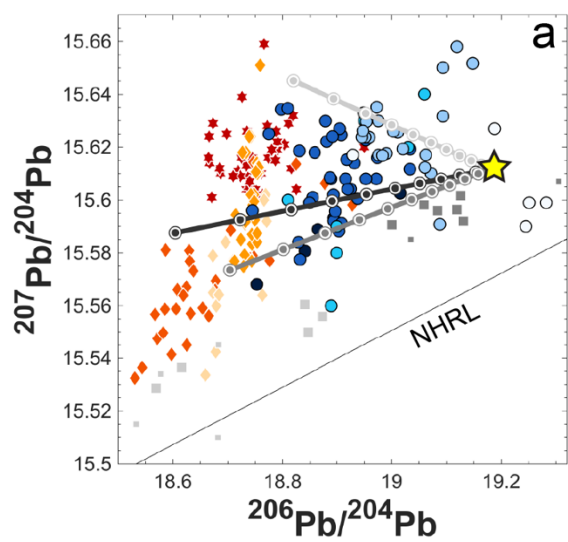


Figure 3.10: Primitive mantle normalized incompatible trace element patterns for representative model results plotted against measured samples from a) James Ross Island, b) the Seal Nunataks, and c) Alexander Island. The results are the final trace element compositions of present-day melts of lithospheric mantle metasomatized in the past by arc melts and E-MORB, then mixed today with modern asthenospheric melts (80% lithospheric, 20% asthenospheric). Each model result reflects different proportions of the metasomatizing arc melt in the past, but all conditions (e.g., extent of melting, endmember compositions, etc.) are otherwise the same.



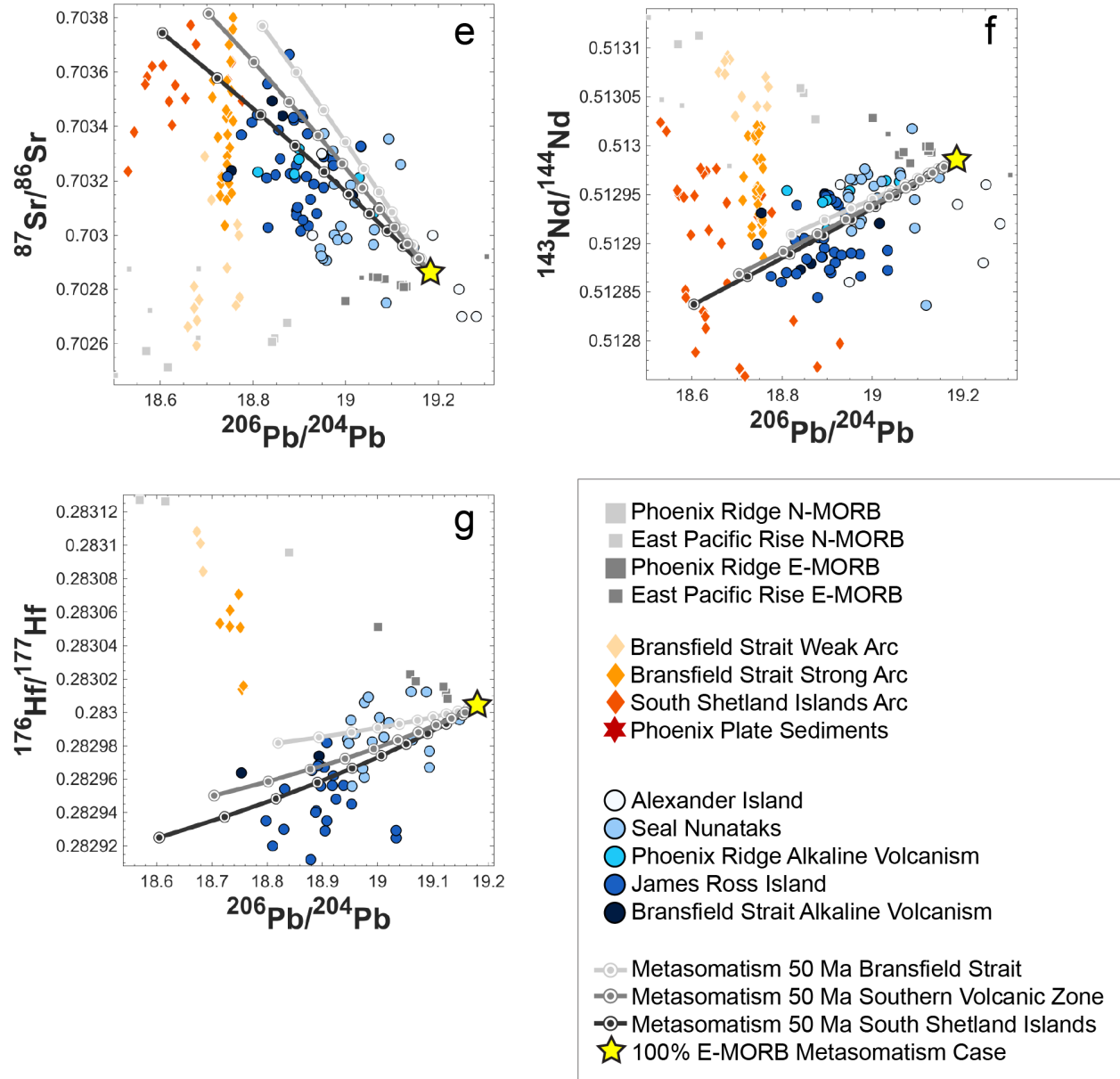


Figure 3.11: Model results showing a) $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, b) $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, c) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$, d) $^{176}\text{Hf}/^{177}\text{Hf}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$, e) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, f) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, and g) $^{176}\text{Hf}/^{177}\text{Hf}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ for our modeled melts today (gray lines with circles) and measured lavas and sediments from the Antarctic Peninsula. Each model curve represents the present-day isotope compositions of melts formed via lithospheric metasomatism 50 Ma by mixtures of arc and E-MORB melts from 0% E-MORB (end of each curve) to 100% E-MORB (yellow star), mixed today with modern asthenospheric melts (80% lithospheric, 20% asthenospheric). Because of the uncertainty in the isotope compositions of the past arc melts that metasomatized the lithosphere, we use three isotope compositions from the Bransfield Strait back-arc (Kraus et al., 2013), the South Shetland Islands volcanic front (Haase

et al., 2012), and the southernmost portion of the Andes Southern Volcanic Zone (Lopez-Escobar et al., 1993) that span a range of reasonable values. The results for each endmember are represented by a separate mixing curve. All model conditions are the same as those used to produce the results in Fig. 3.10.

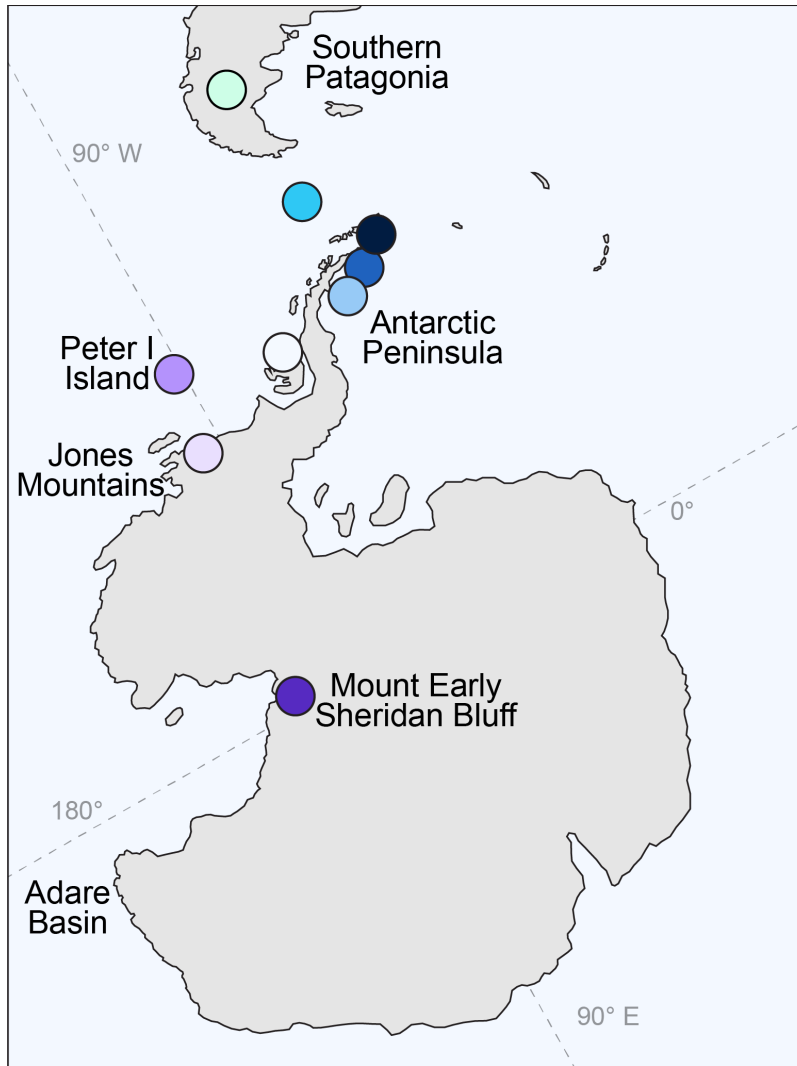


Figure 3.12: Map of the Antarctic Continent and southern Patagonia showing the generalized sampling locations of lavas of this study, marked with symbols and colors corresponding to the representative geochemistry of each area, including southern Patagonia, the Antarctic Peninsula, Peter I Island, the Jones Mountains, Mount Early, and Sheridan Bluff. The Adare Basin is also labeled, although it is unclear whether melts from the area are related to the process that formed the alkali basalts collected at the other locations.

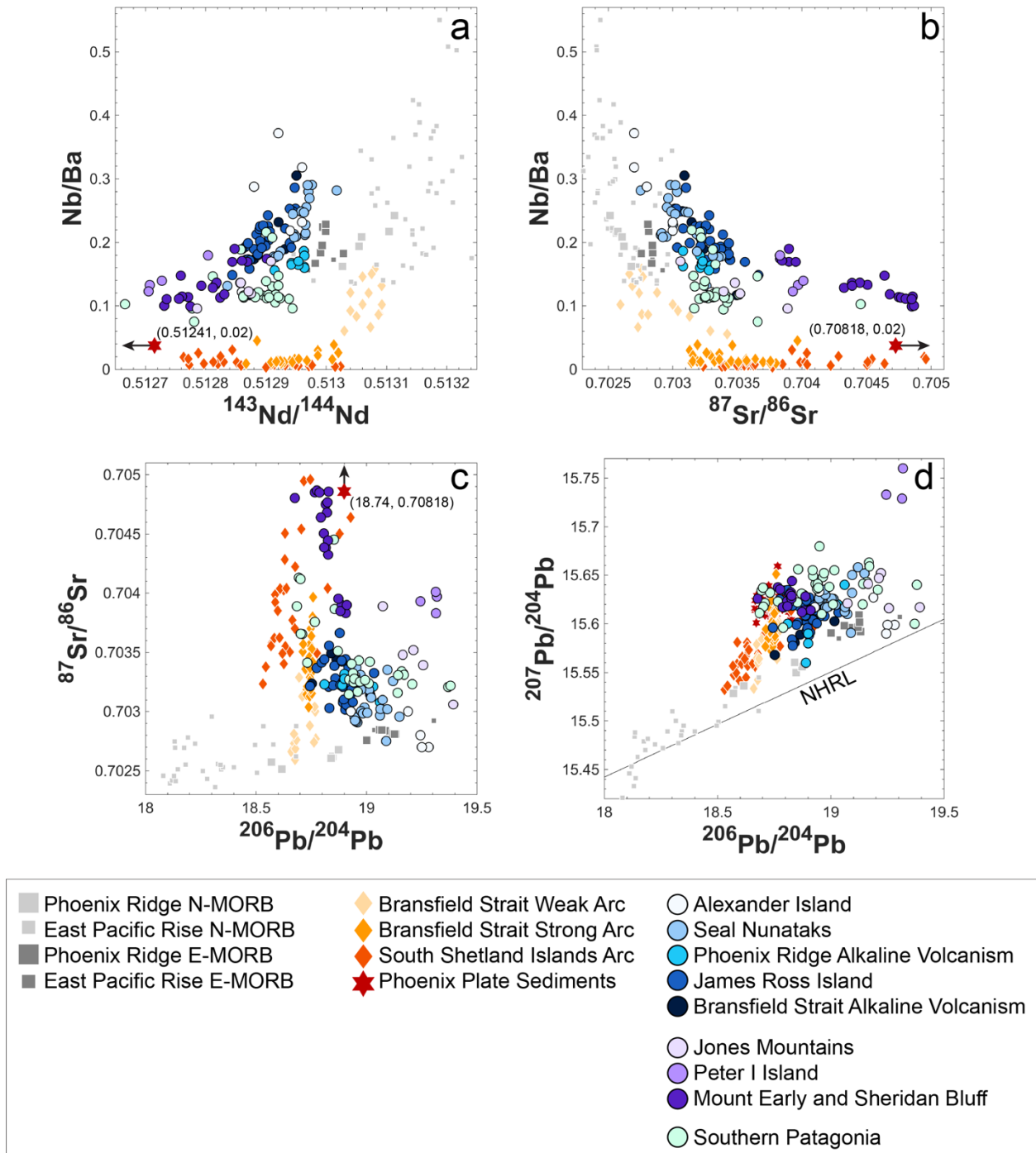


Figure 3.13: a) Nb/Ba vs $^{143}\text{Nd}/^{144}\text{Nd}$, b) Nb/Ba vs $^{87}\text{Sr}/^{86}\text{Sr}$, c) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, and d) $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ for lavas from the East Pacific Rise, the Antarctic Peninsula, the West Antarctic continent (Hart et al., 1995; Panter et al., 2018; Panter et al., 2022), and select lavas from several mesetas across southern Patagonian (Stern et al., 1990; Ramos et al., 1992; D'Orazio et al., 2000; Gorrying et al., 2001; Kay et al., 2004; Kay et al., 2007; Choo et al., 2012;

Kay et al., 2013; Mazzucchelli et al., 2016). Note of all southern Patagonian lavas, we only plot alkaline basalts that overlap in isotope composition with Antarctic Peninsula alkaline lavas and have no clear signals of subduction influence in their trace element patterns. Arrows and labels in a)-c) indicate the direction that the weighted average of the Phoenix Plate sediments plots.

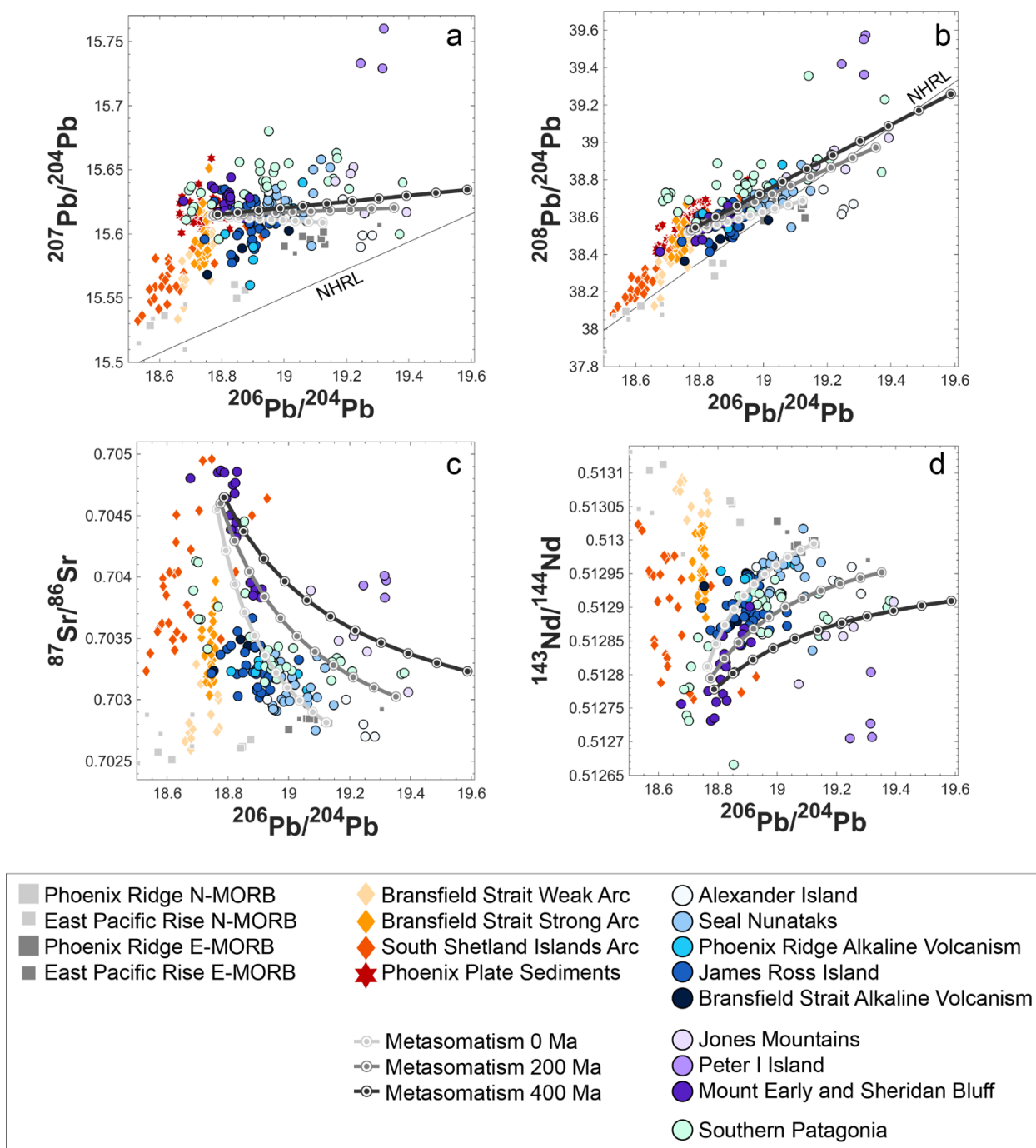
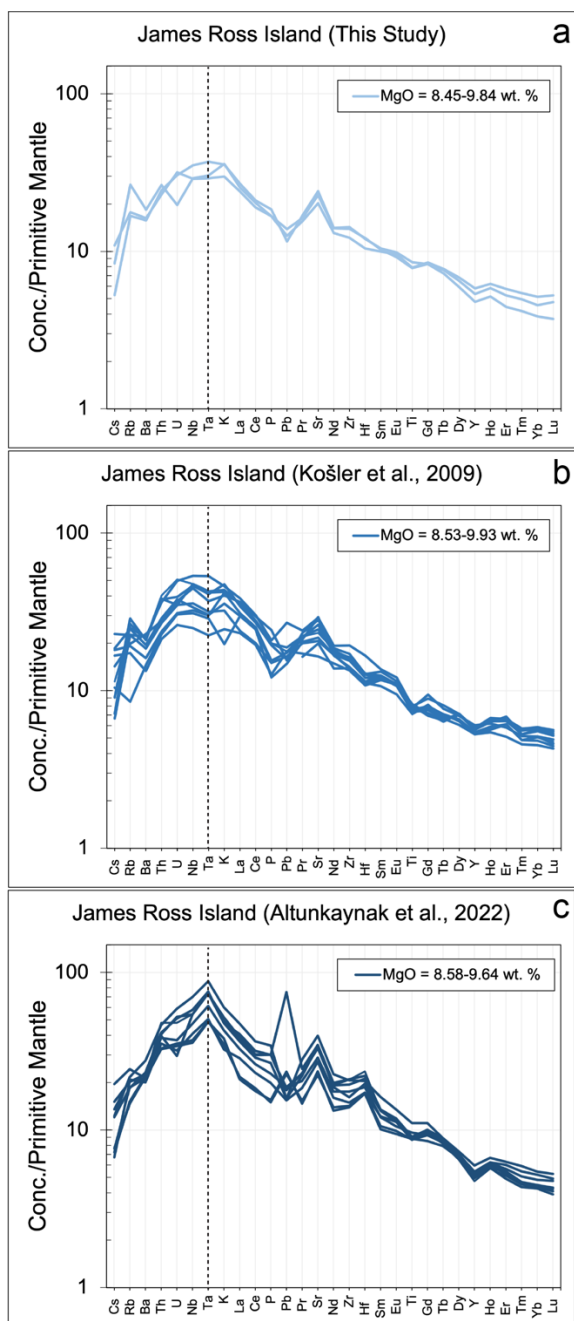
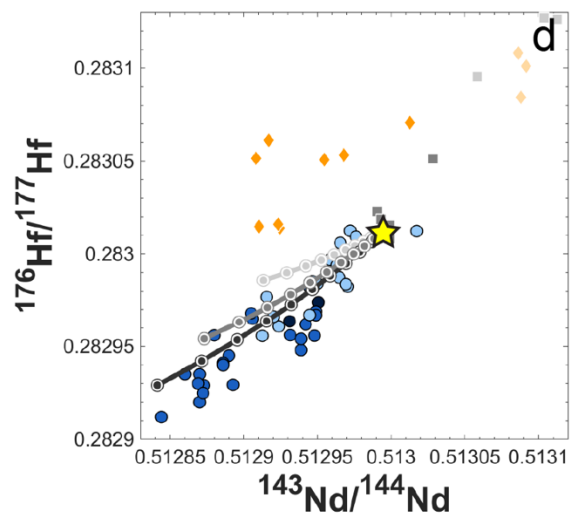
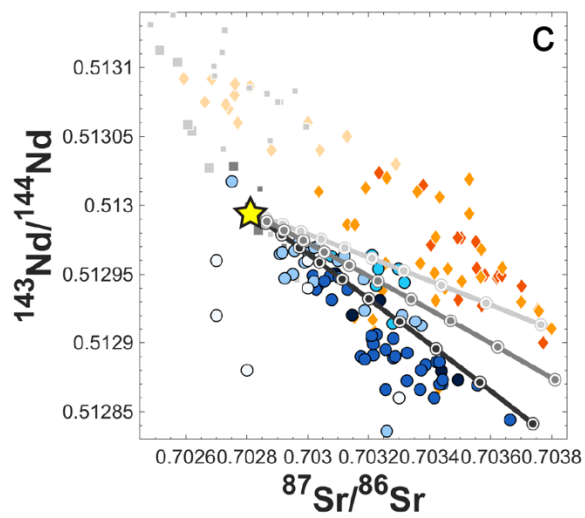
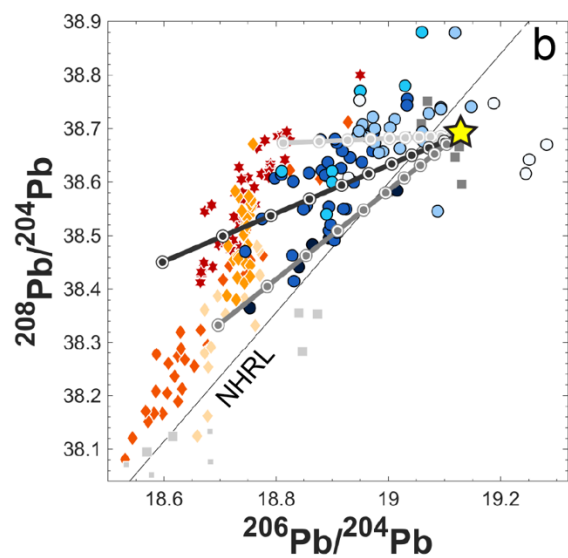
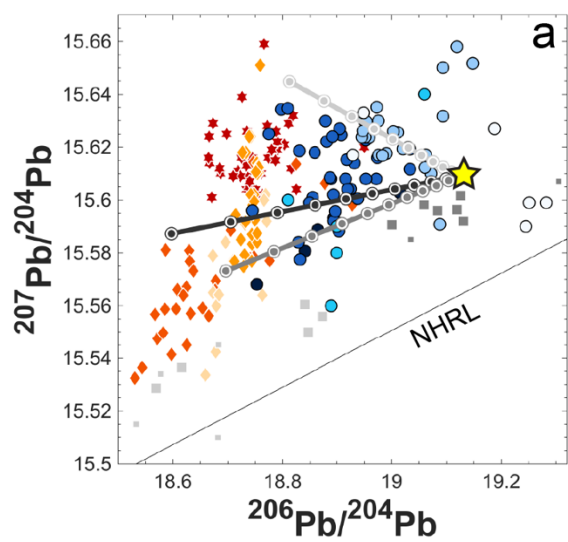


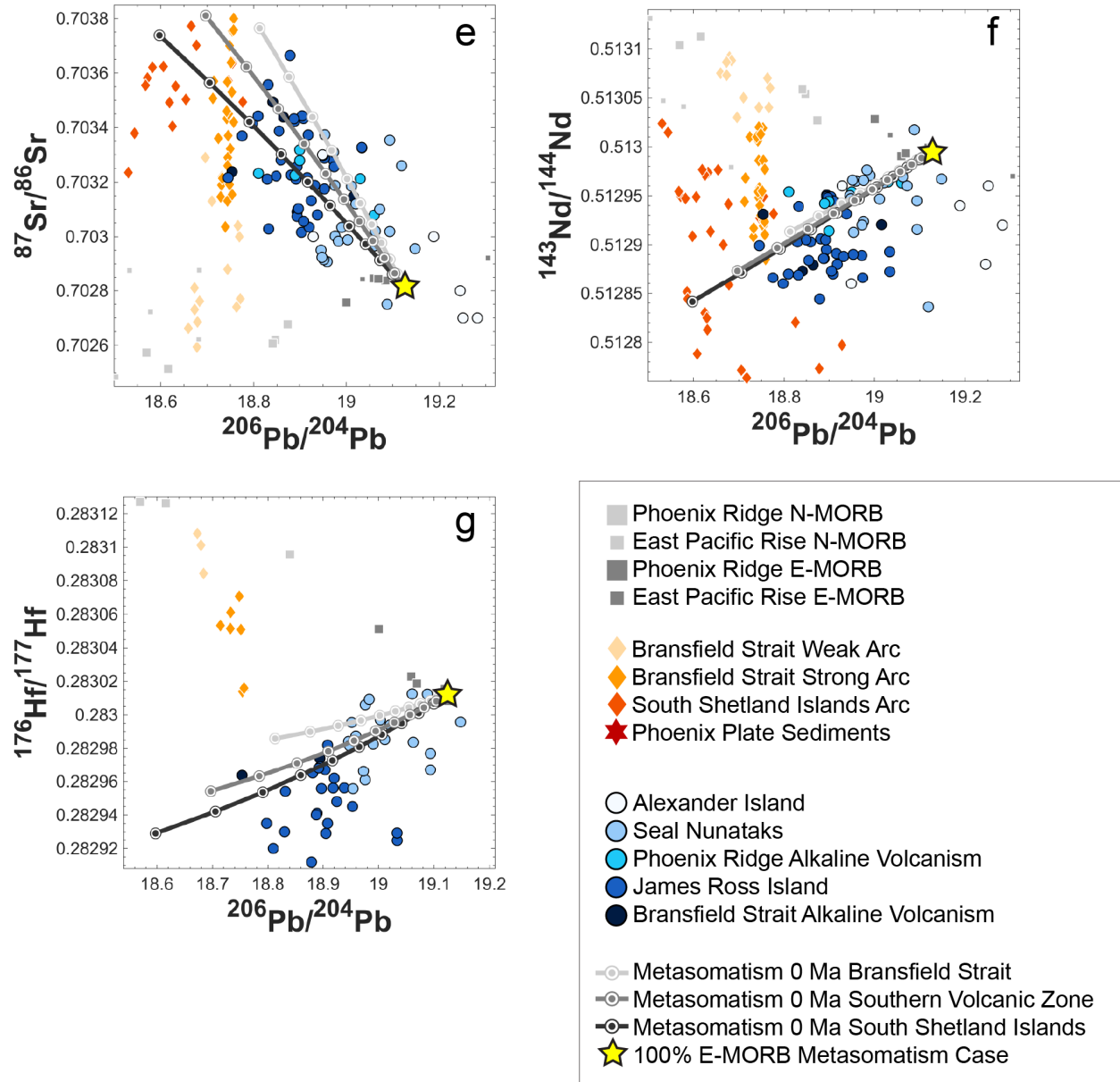
Figure 3.14: Model results showing a) $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, b) $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, c) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, and d) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ for our modeled melts today (gray lines with circles) and measured lavas and sediments from the Antarctic Peninsula, the West Antarctic continent, and Southern Patagonia. Each model curve represents the present-day isotope compositions of melts formed via past lithospheric metasomatism by mixtures of arc and E-MORB melts from 0-100% E-MORB, mixed today with modern asthenospheric melts (80%

lithospheric, 20% asthenospheric). Here, each mixing curve represents the same model conditions, including the isotope composition of the metasomatizing arc melt (which comes from the South Shetland Islands volcanic front; Haase et al., 2012), but different ages of metasomatism (0, 200, and 400 Ma).

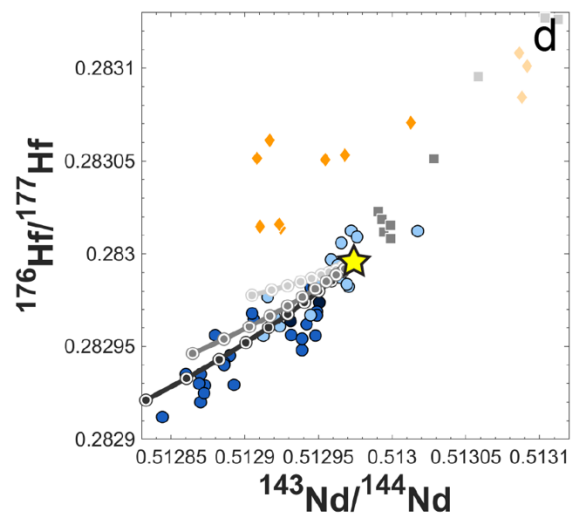
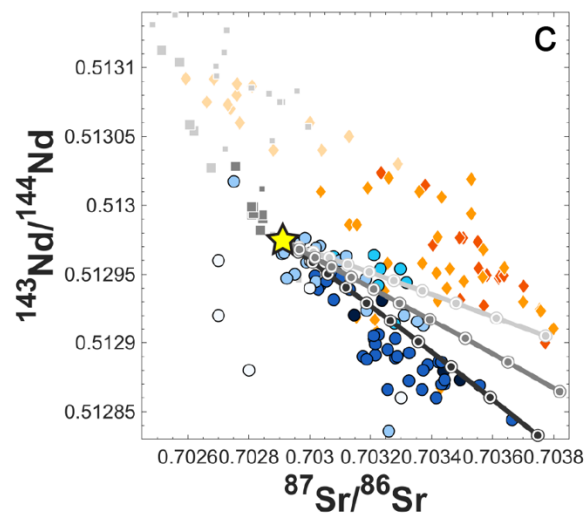
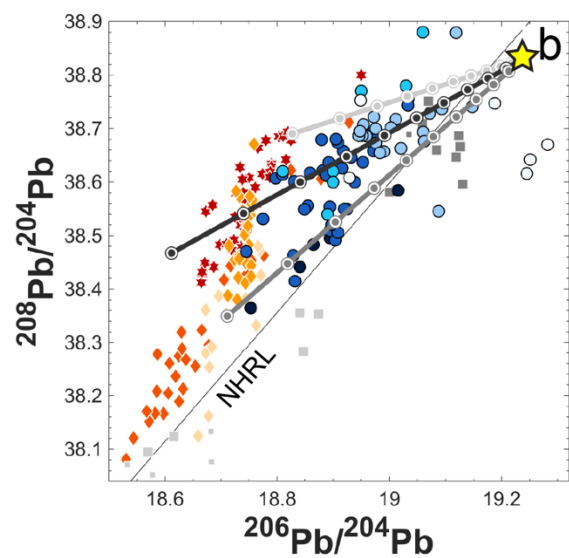
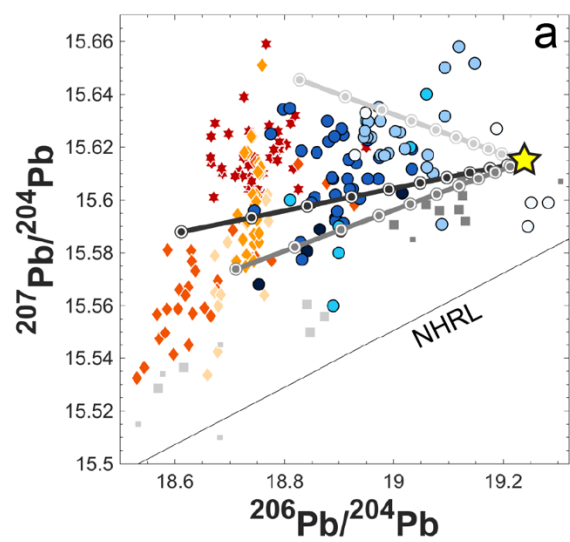


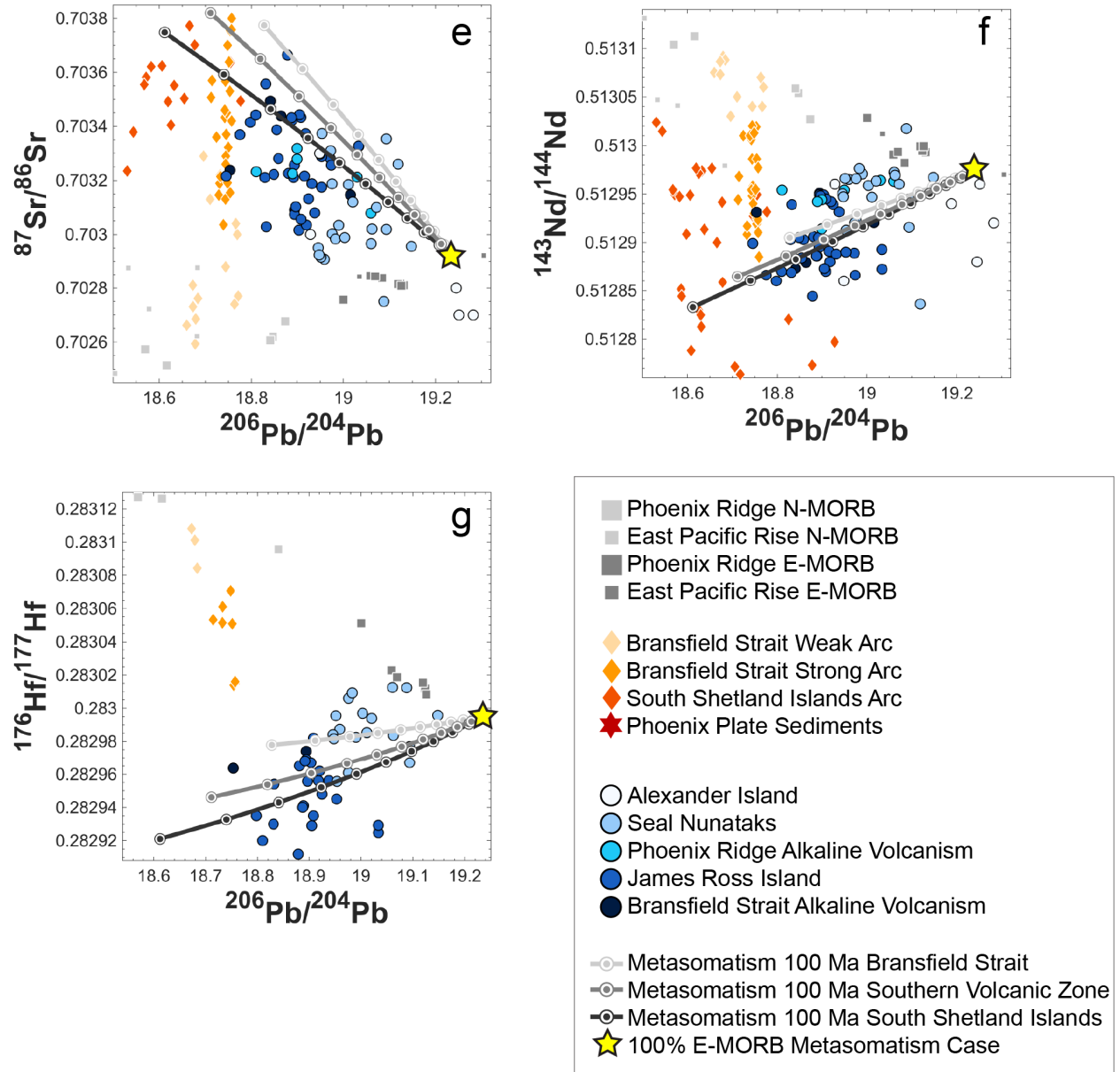
Supplementary Figure 3.S1: Primitive mantle normalized incompatible trace element patterns of James Ross Island lavas from a) This study, b) Kořler et al. (2009), and c) Altunkaynak et al. (2022) at a limited range in MgO (8.45-9.93 wt. %). Primitive mantle composition is from McDonough and Sun (1995). Vertical dashed lines in each plot denote Ta, for which there is a significant positive anomaly in Altunkaynak et al. (2022) data that is not present in the data of this study or those of Kořler et al. (2009) at similar MgO contents.



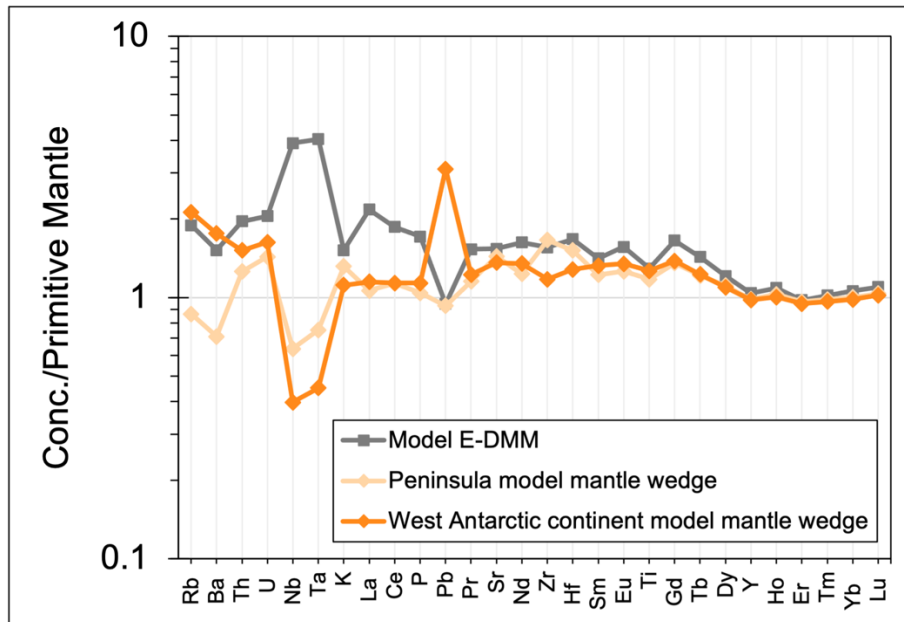


Supplementary Figure 3.S2: Model results showing a) $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, b) $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, c) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$, d) $^{176}\text{Hf}/^{177}\text{Hf}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$, e) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, f) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, and g) $^{176}\text{Hf}/^{177}\text{Hf}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ for our modeled melts today (gray lines with circles) and measured lavas and sediments from the Antarctic Peninsula. Each model curve represents the present-day isotope compositions of melts formed via lithospheric metasomatism 0 Ma and mixed with asthenospheric melts today using the parameters described in Supplementary Text 3.S1.

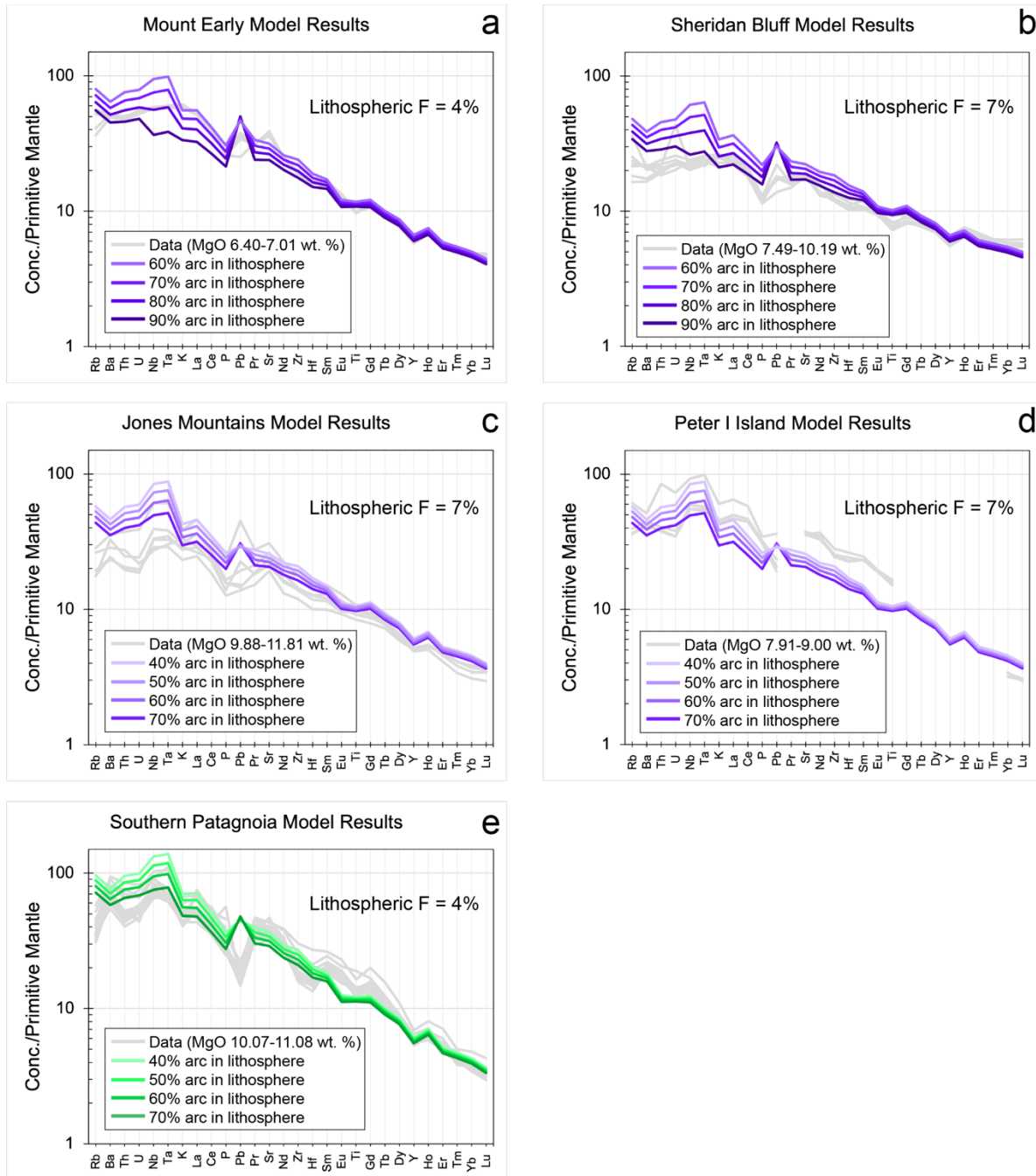




Supplementary Figure 3.S3: Model results showing a) $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, b) $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, c) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$, d) $^{176}\text{Hf}/^{177}\text{Hf}$ vs $^{143}\text{Nd}/^{144}\text{Nd}$, e) $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, f) $^{143}\text{Nd}/^{144}\text{Nd}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, and g) $^{176}\text{Hf}/^{177}\text{Hf}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ for our modeled melts today (gray lines with circles) and measured lavas and sediments from the Antarctic Peninsula. Each model curve represents the present-day isotope compositions of melts formed via lithospheric metasomatism 100 Ma and mixed with asthenospheric melts today using the parameters described in Supplementary Text 3.S1.



Supplementary Figure 3.S4: Primitive mantle normalized incompatible trace element diagram of the E-DMM source used in our lithospheric metasomatism model, along with the two mantle wedge trace element compositions used to model Antarctic Peninsula and West Antarctic continent alkaline volcanism. Note that the major differences between the two mantle wedge compositions occur in elements affected by subduction influence (i.e., fluid and sediment input). These solid compositions are estimated using the geochemistry of lavas from the South Shetland subduction zone. Primitive mantle composition is from McDonough and Sun (1995).



Supplementary Figure 3.S5: Example primitive mantle normalized incompatible trace element diagrams of data and model results for a) Mount Early, b) Sheridan Bluff, c) the Jones Mountains, d) Peter I Island, and e) Southern Patagonia. Variations in the extent of lithospheric melting for each set of results are listed in each plot. The model results for the Jones Mountains, Peter I Island, and Southern Patagonia fit the steeper heavy rare earth element slopes in the data better with 4% garnet in their sources today as opposed to 3%. Data from Stern et al. (1990), Hart et al. (1995), D’Orazio et al. (2000), Choo et al. (2012), and Panter et al. (2022).

Tables

Table 3.1: Outline of model steps and details

Step	Description	Details
1	Starting compositions of E-DMM and mantle wedge sources	• E-DMM and mantle wedge trace element compositions are estimated from MORB and back-arc lavas from the Antarctic Peninsula, respectively • E-DMM isotope compositions are taken from E-MORB from the Phoenix Ridge • Three sets of mantle wedge isotope compositions are taken from representative lavas from the 1) Bransfield Strait back-arc, 2) South Shetland Islands volcanic front, and 3) Andes Southern Volcanic Zone • The isotope compositions of the endmember sources are then corrected to their respective values at the designated age of metasomatism in the past
2	Generating metasomatizing melts in the past	• Past E-MORB melts are then generated by 3% non-modal batch melting the E-DMM source in the spinel field using the modal mineralogy and melting reaction of Kinzler and Grove (1992) and the mineral-melt KD values listed in the Supplementary Table 3.S3 • Past arc melts are then generated by 10% non-modal batch melting the mantle wedge source in the spinel field using the modal mineralogy and melting reaction of Kinzler and Grove (1992) and the mineral-melt KD values listed in the Supplementary Table 3.S3
3	Metasomatizing the lithospheric mantle in the past	• The past E-MORB and arc melts are then mixed from 0 to 100% • The resultant mixtures are then diluted with a trace element-free harzburgite composed of 80% olivine and 20% orthopyroxene in proportions of 10% melt and 90% harzburgite
4	Ingrowing the metasomatized lithosphere to the present and re-melting	• The isotopes of the metasomatized lithospheric mantle are then ingrown to the present-day • Present-day lithospheric melts are then generated by 4% non-modal batch melting of the metasomatized lithospheric mantle in the garnet field using a modal mineralogy after the depleted MORB mantle of Workman and Hart (2005), the melting reaction of Walter (1998), and the mineral-melt KD values listed in Supplementary Table 3.S3
5	Mixing the lithospheric melts with asthenospheric melts today	• Present-day asthenospheric melts are then generated by 7% non-modal batch melting of the present-day E-DMM composition from Step 1 in the garnet field using a modal mineralogy after the depleted MORB mantle of Workman and Hart (2005), the melting reaction of Walter (1998), and the mineral-melt KD values listed in Supplementary Table 3.S3 • Present-day lithospheric and asthenospheric melts are then mixed in proportions of 20% asthenospheric and 80% lithospheric to produce the final melt compositions of the model

Supplementary Table 3.S1: New major and trace element concentrations and isotope compositions for James Ross Island and Seal Nunataks lavas of this study

Sample	Location	Latitude (S)	Longitude (W)	Altitude (m)	Material for Major and Trace Elements	SiO ₂ (wt. %)	TiO ₂ (wt. %)	Al ₂ O ₃ (wt. %)	FeO (wt. %)	MnO (wt. %)	MgO (wt. %)	CaO (wt. %)
DJ1708.4	James Ross Island	-64.35	-57.59		glass	48.34	1.73	16.55	12.01	0.13	6.29	9.09
DJ1727.21	James Ross Island	-63.86	-58.1		glass	48.33	1.90	16.68	10.48	0.15	6.37	9.68
SY020620-2 light	James Ross Island	-63.86	-58.1	153	powder	49.44	1.56	16.40	10.61	0.16	8.44	8.75
SY020720-4	James Ross Island	-63.86	-58.05	155	powder	47.67	1.71	15.18	11.37	0.16	9.83	8.19
TD012220-3 fine	James Ross Island	-64.08	-58.39	228	powder	48.36	1.58	15.85	11.98	0.17	8.55	8.71
TD012220-1	James Ross Island	-64.08	-58.39	239	glass	49.63	2.30	15.54	11.79	0.14	5.11	8.49
TD012120-1	James Ross Island	-64.08	-58.34		glass	48.00	3.24	15.06	11.83	0.17	4.57	9.54
DJ1723.9	James Ross Island	-63.81	-57.92		glass	50.55	1.88	15.73	10.68	0.17	4.92	8.64
SY020620-2 dark	James Ross Island	-63.86	-58.1	153	powder	51.04	3.09	14.14	12.75	0.19	3.86	8.32
TD012220-3 coarse	James Ross Island	-64.08	-58.39	228	powder	50.96	3.18	14.02	11.68	0.17	3.88	8.21
R3710.1	Seal Nunataks	-65.01	-60.31	210	powder	49.66	2.19	15.00	10.81	0.14	8.54	9.09
R3710.3	Seal Nunataks	-65.01	-60.31	210	powder	49.55	2.15	14.77	11.37	0.15	8.95	8.96
R3710.6	Seal Nunataks	-65.01	-60.31	210	powder	49.13	2.16	14.87	11.14	0.15	8.63	8.90
R3713.4	Seal Nunataks	-65.07	-60.25	125	powder	49.10	2.35	14.13	11.10	0.15	8.57	9.23
R3715.1	Seal Nunataks	-65.07	-60.25	190	powder	51.04	2.10	14.78	10.91	0.14	6.86	8.93
R3717.1	Seal Nunataks	-65.08	-60.4	230	powder	50.77	2.00	14.81	10.30	0.14	8.46	8.56
R3717.2	Seal Nunataks	-65.08	-60.4	230	powder	51.42	2.00	14.93	10.34	0.14	8.14	8.51
R3717.3	Seal Nunataks	-65.08	-60.4	230	powder	51.14	1.95	14.74	10.29	0.14	8.90	8.35
R3718.1	Seal Nunataks	-65.08	-60.4	200	powder	50.64	1.97	14.66	10.31	0.14	8.87	8.48
R3718.2	Seal Nunataks	-65.08	-60.4	200	powder	50.77	1.99	14.73	10.44	0.14	8.60	8.51
R3719.1	Seal Nunataks	-65.08	-60.4	200	powder	49.80	1.78	13.75	10.90	0.15	11.70	7.81
R3720.1	Seal Nunataks	-65.08	-60.4	250	powder	50.38	2.00	14.99	10.14	0.14	7.98	8.78
R3723.4	Seal Nunataks	-65.15	-60	100	powder	49.06	2.05	14.42	11.37	0.16	9.61	8.87
R3723.7	Seal Nunataks	-65.15	-60	100	powder	49.38	2.06	14.62	11.08	0.16	9.55	8.98
R3723.9	Seal Nunataks	-65.15	-60	100	powder	49.12	2.02	14.51	11.34	0.16	9.63	8.90
R3726.1	Seal Nunataks	-65.07	-60.25	25	powder	51.41	2.17	14.95	10.54	0.14	6.88	9.07
R3728.1	Seal Nunataks	-64.98	-60.36	152	powder	50.75	2.04	15.38	11.01	0.14	7.35	8.84
R3728.2	Seal Nunataks	-64.98	-60.36	152	powder	51.63	1.75	14.76	10.27	0.14	8.56	8.54
R3728.3	Seal Nunataks	-64.98	-60.36	152	powder	49.29	2.11	14.95	11.52	0.15	8.40	9.00
R3728.5	Seal Nunataks	-64.98	-60.36	152	powder	51.20	1.71	14.48	10.58	0.14	9.09	8.44
R3736.1	Seal Nunataks	-65.1	-60.08	150	powder	48.81	2.16	14.16	11.62	0.16	9.53	9.02
R3736.7	Seal Nunataks	-65.1	-60.08	150	powder	48.14	2.41	13.75	12.21	0.17	9.17	9.25
R3738.3	Seal Nunataks	-65.03	-60.03	368	powder	50.85	1.86	14.75	10.56	0.14	8.93	8.51
R3738.6	Seal Nunataks	-65.03	-60.03	368	powder	49.95	2.14	15.17	10.27	0.14	8.20	8.65
R3738.8	Seal Nunataks	-65.03	-60.03	368	powder	50.91	2.00	15.18	10.40	0.14	8.07	8.64
R3739.2	Seal Nunataks	-65.1	-60.03	200	powder	51.82	2.09	15.55	9.93	0.14	6.32	8.95
R3740.3	Seal Nunataks	-65.07	-60.25	100	powder	52.02	2.21	15.54	10.18	0.14	5.52	9.14
R3742.3	Seal Nunataks	-65.05	-60.18	90	powder	48.35	2.71	15.25	11.75	0.14	7.66	8.55
R3745.1	Seal Nunataks	-65.16	-59.93	175	powder	50.91	2.08	15.00	10.43	0.14	7.64	8.82
R3745.3	Seal Nunataks	-65.16	-59.93	175	powder	51.12	2.08	15.08	10.30	0.14	7.48	8.85
R3745.6	Seal Nunataks	-65.16	-59.93	175	powder	51.40	2.08	15.09	10.31	0.14	7.71	8.90
R3746.1	Seal Nunataks	-65.16	-59.93	175	powder	51.31	2.06	15.00	10.45	0.15	8.11	8.91
*Measured with LA-ICP-MS for glass												

Supplementary Table 3.S1 (continued)

Na ₂ O (wt. %)	K ₂ O (wt. %)	P ₂ O ₅ (wt. %)	Total	Cs (ppm)	Rb (ppm)	Ba (ppm)	Th (ppm)	U (ppm)	Nb (ppm)	Ta (ppm)	*K (ppm)	La (ppm)	Ce (ppm)	*P (ppm)	Pb (ppm)	Pr (ppm)	Sr (ppm)	Nd (ppm)	Zr (ppm)
3.77	0.60	0.33	98.87	0.37	10.47	71.47	1.26	0.42	14.00	0.74	5,267.24	11.46	26.92	1,320.02	1.99	3.47	318.03	14.89	119.32
3.84	0.80	0.30	98.57	0.35	13.81	86.33	1.59	0.55	17.92	0.99	6,805.83	13.49	30.84	1,316.31	2.30	4.03	415.04	17.30	160.38
3.32	1.03	0.34	100.11	0.17	15.86	121.13	2.09	0.39	19.15	1.11	8,618.22	16.45	33.95	1,502.69	2.07	4.13	452.32	17.50	146.09
3.38	1.02	0.37	98.94	0.11	10.05	103.87	1.93	0.61	23.06	1.36	8,527.00	17.41	35.17	1,658.46	1.72	4.31	478.43	17.59	149.62
3.22	0.86	0.34	99.65	0.22	10.59	107.30	1.82	0.64	18.98	1.07	7,143.94	15.56	31.79	1,501.82	1.87	3.95	401.64	16.34	127.75
4.23	1.27	0.50	99.03	0.40	17.83	152.67	2.66	0.92	34.42	1.95	11,408.47	22.45	46.53	2,188.36	2.75	5.69	391.46	23.74	213.65
4.65	1.75	0.76	99.61	0.31	17.55	170.20	2.64	1.08	48.70	2.67	15,350.06	28.83	62.58	3,121.75	2.52	7.78	645.89	32.79	295.47
4.11	1.34	0.47	98.53	0.78	29.62	184.64	3.79	1.23	31.05	1.67	11,699.40	23.59	50.44	1,946.12	5.21	5.89	413.45	23.04	203.62
4.21	1.92	0.70	100.26	0.50	28.10	219.27	4.59	0.67	42.03	2.42	15,976.13	34.56	71.23	3,075.25	4.01	8.75	369.04	36.70	309.25
4.45	2.00	0.76	99.37	0.20	25.63	227.47	4.51	1.15	48.67	2.74	16,611.84	37.38	76.62	3,348.51	4.12	9.43	337.59	38.96	310.08
3.40	1.05	0.33	100.27	0.36	13.65	116.47	2.38	0.86	24.66	1.57	8,792.55	18.26	37.78	1,478.69	2.35	4.69	442.36	19.82	137.90
3.36	1.04	0.33	100.68	0.31	13.22	114.26	2.32	0.83	24.25	1.51	8,684.67	17.62	36.20	1,457.57	2.25	4.54	428.99	19.18	134.75
3.29	1.03	0.32	99.67	0.31	13.64	115.32	2.38	0.84	24.58	1.56	8,629.84	18.12	37.27	1,435.48	2.23	4.71	437.84	19.41	136.52
3.51	1.23	0.48	99.92	0.35	13.67	147.83	3.46	1.26	41.35	2.61	10,288.41	27.51	55.55	2,135.11	3.49	6.74	550.77	27.44	183.93
3.13	0.93	0.28	99.14	0.44	12.55	106.86	1.98	0.68	19.02	1.21	7,736.95	13.72	29.02	1,245.71	2.35	3.78	403.12	16.75	121.20
3.37	1.10	0.28	99.83	0.30	13.70	104.91	2.35	0.80	22.12	1.47	9,143.68	15.83	32.70	1,230.78	2.68	4.03	391.14	17.40	141.04
3.43	1.05	0.27	100.28	0.30	13.95	102.79	2.38	0.80	21.78	1.39	8,773.45	15.20	31.43	1,193.25	2.64	3.92	402.03	16.84	140.92
3.36	1.03	0.26	100.21	0.32	13.00	97.10	2.24	0.77	20.84	1.37	8,580.39	14.84	30.69	1,162.81	2.43	3.81	375.51	16.08	133.79
3.34	1.10	0.28	99.83	0.33	14.36	106.60	2.42	0.82	22.36	1.46	9,191.83	15.73	32.43	1,228.60	2.97	4.03	399.27	17.10	139.55
3.33	1.10	0.28	99.94	0.33	14.32	108.00	2.45	0.84	22.58	1.46	9,145.05	15.73	32.78	1,244.17	2.68	4.15	405.43	17.52	142.36
3.04	0.99	0.25	100.22	0.28	12.46	95.16	2.13	0.72	19.84	1.30	8,294.48	14.00	28.91	1,113.38	2.41	3.57	366.80	15.59	124.78
3.29	1.14	0.29	99.18	0.24	12.36	116.90	2.57	0.87	24.18	1.57	9,538.20	16.81	34.58	1,308.01	3.30	4.32	429.16	18.15	145.87
3.16	1.06	0.35	100.16	0.15	8.99	101.41	2.24	0.73	27.67	1.71	8,862.28	18.27	37.36	1,550.70	1.74	4.67	438.03	19.26	145.29
3.23	1.07	0.35	100.51	0.12	8.37	99.62	2.16	0.81	26.84	1.75	8,885.73	18.25	37.56	1,561.53	1.67	4.61	415.38	19.60	139.66
3.18	1.05	0.34	100.29	0.11	8.30	100.75	2.11	0.79	26.18	1.69	8,718.02	17.75	36.56	1,521.67	1.65	4.49	407.66	18.93	137.03
3.23	0.97	0.29	99.70	0.39	12.43	109.34	2.02	0.68	19.33	1.27	8,055.41	14.49	30.68	1,293.63	4.81	3.99	399.99	17.39	123.10
3.46	0.91	0.28	100.22	0.30	11.23	92.56	1.92	0.69	21.10	1.35	7,633.71	15.22	31.60	1,233.40	2.30	4.00	393.14	17.22	127.69
3.27	0.77	0.24	99.96	0.23	9.06	72.72	1.73	0.63	18.57	1.21	6,421.75	12.23	25.47	1,060.13	3.41	3.27	363.07	14.39	117.24
3.42	1.06	0.31	100.26	0.23	11.02	90.40	2.36	0.87	26.27	1.69	8,871.41	16.32	33.63	1,354.30	2.27	4.27	427.88	17.84	148.15
3.14	0.73	0.23	99.77	0.22	8.98	69.19	1.64	0.61	17.22	1.11	6,065.03	11.40	24.19	1,007.06	1.71	3.11	340.43	13.86	107.89
3.20	0.92	0.36	99.98	0.28	9.83	104.94	2.08	0.78	25.96	1.60	7,697.74	17.59	36.41	1,592.67	1.91	4.57	449.58	19.46	132.01
3.23	1.12	0.50	100.01	0.20	11.31	133.55	3.03	1.11	38.75	2.36	9,377.78	26.18	53.14	2,209.74	2.43	6.62	491.63	27.02	176.82
3.16	0.90	0.25	99.96	0.34	12.30	98.98	1.84	0.65	18.41	1.21	7,488.34	13.21	28.12	1,125.96	2.20	3.62	368.16	15.87	117.15
3.41	1.18	0.31	99.46	0.33	14.20	128.58	2.18	0.79	25.61	1.62	9,848.47	16.80	35.16	1,392.65	2.32	4.41	461.36	18.79	141.78
3.37	0.99	0.27	100.04	0.30	12.61	107.67	1.96	0.71	20.94	1.35	8,291.99	14.69	31.50	1,218.13	2.20	3.93	414.72	17.14	129.76
3.58	1.09	0.32	99.82	0.28	12.28	102.33	2.37	0.87	25.04	1.62	9,060.80	18.21	37.60	1,431.34	2.59	4.71	457.00	19.85	158.45
3.40	1.00	0.30	99.50	0.48	14.07	114.27	2.22	0.76	20.48	1.30	8,349.64	15.01	31.89	1,352.74	3.65	4.14	428.90	18.40	131.02
3.69	1.34	0.49	99.98	0.05	7.64	117.34	1.76	0.75	33.06	2.08	11,146.58	21.09	43.77	2,142.27	1.25	5.55	557.02	23.80	168.67
3.30	0.99	0.32	99.67	0.35	12.13	110.47	2.29	0.79	23.76	1.50	8,261.70	17.26	36.41	1,431.25	2.36	4.56	440.76	19.86	143.97
3.30	1.00	0.32	99.73	0.33	12.42	113.57	2.31	0.79	24.09	1.52	8,378.55	17.48	36.66	1,439.16	2.67	4.63	451.36	19.99	146.72
3.33	1.01	0.33	100.34	0.37	12.52	111.08	2.28	0.77	23.57	1.46	8,457.85	17.16	36.07	1,454.36	3.63	4.62	446.16	19.91	144.77
3.28	0.96	0.30	100.57	0.23	11.29	101.52	2.03	0.70	22.59	1.40	7,987.34	15.85	33.43	1,352.55	2.73	4.24	438.42	18.41	136.89

Supplementary Table 3.S1 (continued)

Hf (ppm)	Sm (ppm)	Eu (ppm)	Ti (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Y (ppm)	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Ni (ppm)	Cr (ppm)	Sc (ppm)	V (ppm)	Ga (ppm)	Cu (ppm)	Zn (ppm)	Co (ppm)
2.79	3.90	1.39	10,058.87	4.73	0.77	4.69	25.32	0.93	2.52	0.34	2.40	0.36	62.61	163.59	25.03	181.90	23.22	57.02	121.89	43.87
3.51	4.32	1.52	11,496.89	5.10	0.84	4.99	26.51	1.01	2.65	0.36	2.42	0.35	59.97	152.08	26.37	195.74	22.92	51.31	101.69	41.13
3.42	4.16	1.41	9,409.06	4.51	0.75	4.36	23.00	0.86	2.29	0.33	2.00	0.32	158.26	275.45	25.86	162.85	18.74	48.65	91.21	
3.38	4.22	1.51	10,288.53	4.49	0.71	3.98	20.53	0.76	1.94	0.28	1.70	0.25	218.70	316.60	22.43	166.26	15.95	43.75	97.19	
2.94	4.04	1.47	9,510.94	4.62	0.76	4.58	25.04	0.92	2.53	0.36	2.27	0.35	162.18	254.60	28.04	173.59	17.50	45.92	97.99	
4.71	5.70	1.81	13,215.18	6.51	0.99	6.05	31.40	1.15	2.99	0.41	2.79	0.41	35.80	143.97	27.66	193.76	24.94	62.18	121.33	33.96
6.07	7.80	2.43	17,906.03	8.31	1.29	7.32	37.99	1.38	3.63	0.48	3.17	0.46	21.38	95.58	33.70	252.64	26.49	73.30	113.11	31.73
4.27	5.15	1.62	10,463.08	5.71	0.91	5.61	30.67	1.13	3.10	0.42	2.89	0.44	20.85	121.08	29.78	208.67	24.71	31.47	105.24	31.94
7.00	8.62	2.55	18,568.87	9.32	1.47	8.73	46.89	1.74	4.69	0.66	4.06	0.62	23.45	47.95	31.89	253.97	23.91	97.16	126.82	
7.21	9.30	2.77	19,107.97	10.26	1.70	10.08	54.84	2.04	5.49	0.83	4.93	0.75	30.93	64.17	34.32	235.66	24.21	104.75	117.72	
3.44	4.87	1.66	13,168.72	4.93	0.76	4.12	20.41	0.77	1.86	0.26	1.49	0.22	154.35	283.90	21.85	231.50	21.33	49.46	109.73	
3.32	4.58	1.56	12,932.80	4.72	0.73	3.99	19.68	0.74	1.84	0.25	1.48	0.21	159.18	297.97	22.54	227.26	19.36	41.87	105.98	
3.39	4.70	1.63	12,951.76	4.92	0.74	3.99	20.03	0.76	1.86	0.26	1.47	0.21	162.55	291.35	21.96	231.38	19.99	47.06	109.98	
4.41	6.19	2.11	14,137.26	6.11	0.92	4.94	23.07	0.89	2.11	0.28	1.64	0.23	181.79	295.33	22.35	207.39	21.51	41.13	109.46	
3.19	4.46	1.65	12,641.87	4.84	0.75	4.18	20.16	0.78	1.92	0.26	1.60	0.22	121.82	290.73	22.92	212.85	19.48	41.15	98.69	
3.52	4.44	1.55	12,019.79	4.68	0.73	4.08	19.55	0.75	1.90	0.26	1.54	0.21	143.69	293.70	20.97	186.91	19.85	46.57	99.63	
3.54	4.30	1.51	12,006.00	4.58	0.73	3.99	20.04	0.75	1.82	0.25	1.47	0.21	135.65	263.28	21.84	185.27	19.20	45.06	100.55	
3.36	4.23	1.49	11,710.05	4.46	0.70	3.84	18.73	0.73	1.80	0.25	1.43	0.21	156.32	296.80	20.53	182.70	19.89	44.45	101.89	
3.51	4.25	1.55	11,834.59	4.57	0.71	3.96	19.70	0.75	1.86	0.26	1.49	0.22	148.62	299.50	21.14	183.92	20.40	41.96	106.50	
3.58	4.52	1.54	11,974.60	4.69	0.74	3.98	19.94	0.75	1.92	0.25	1.49	0.22	135.59	288.72	20.67	186.70	20.19	36.76	101.64	
3.19	3.89	1.36	10,712.02	4.02	0.63	3.52	17.22	0.67	1.65	0.23	1.34	0.20	226.70	414.47	19.27	167.02	18.77	39.73	100.09	
3.62	4.46	1.58	11,994.87	4.82	0.74	4.03	20.18	0.76	1.92	0.26	1.53	0.21	128.13	287.52	21.75	189.33	18.64	38.77	97.25	
3.57	4.65	1.68	12,308.67	4.84	0.76	4.18	21.45	0.79	1.97	0.26	1.55	0.22	209.64	316.18	22.79	200.87	20.45	48.56	103.10	
3.52	4.70	1.60	12,388.89	4.91	0.77	4.22	20.48	0.78	1.93	0.27	1.55	0.21	204.23	322.89	23.50	205.92	18.57	51.76	104.10	
3.41	4.58	1.59	12,146.94	4.78	0.73	4.09	19.71	0.77	1.93	0.26	1.53	0.21	211.61	325.55	22.96	204.21	21.34	49.10	103.40	
3.26	4.69	1.70	13,023.68	5.02	0.78	4.37	20.74	0.80	1.93	0.28	1.58	0.21	113.76	260.51	24.23	210.95	20.76	39.67	104.57	
3.32	4.37	1.60	12,247.54	4.90	0.77	4.26	21.48	0.81	2.00	0.28	1.62	0.24	144.36	352.11	22.72	229.05	19.60	54.29	104.92	
2.94	3.81	1.40	10,535.22	4.19	0.66	3.68	18.39	0.69	1.73	0.23	1.34	0.20	148.51	327.12	21.35	175.18	19.87	44.78	98.83	
3.56	4.41	1.52	12,657.49	4.64	0.72	4.02	19.59	0.74	1.83	0.24	1.45	0.21	133.69	278.08	23.24	240.37	20.16	27.68	108.00	
2.86	3.64	1.34	10,262.49	4.11	0.66	3.55	17.88	0.67	1.70	0.22	1.34	0.20	162.38	357.19	20.72	171.73	18.80	41.30	99.50	
3.28	4.70	1.68	12,950.87	4.95	0.77	4.16	20.56	0.78	1.92	0.25	1.50	0.24	201.64	332.65	23.21	230.34	19.38	48.72	108.04	
4.23	6.34	2.06	14,478.88	6.18	0.95	5.15	25.01	0.93	2.32	0.31	1.77	0.25	185.72	295.93	23.72	219.55	19.58	57.22	113.85	
3.09	3.95	1.46	11,192.04	4.38	0.68	3.78	18.45	0.71	1.79	0.24	1.41	0.20	156.43	332.71	22.09	184.99	17.81	36.38	97.67	
3.54	4.69	1.61	12,841.24	4.71	0.73	3.87	19.14	0.74	1.79	0.24	1.47	0.19	126.23	244.78	21.89	202.67	21.10	48.30	98.16	
3.33	4.36	1.57	12,041.96	4.53	0.72	3.86	19.21	0.71	1.87	0.24	1.47	0.21	139.80	281.76	20.67	191.19	19.36	38.18	97.68	
3.92	4.99	1.78	12,542.91	5.11	0.78	4.30	20.93	0.80	1.95	0.27	1.54	0.22	75.84	215.17	22.52	196.01	21.74	28.01	99.84	
3.48	4.90	1.77	13,293.11	5.23	0.83	4.50	22.14	0.83	2.08	0.28	1.67	0.23	55.53	190.25	23.64	214.20	21.60	26.84	100.80	
4.28	5.86	2.09	16,251.68	5.95	0.87	4.44	20.44	0.76	1.83	0.24	1.30	0.17	134.50	166.11	18.70	193.72	21.36	45.96	121.00	
3.66	4.92	1.75	12,473.81	5.16	0.81	4.32	21.55	0.81	2.05	0.28	1.63	0.23	122.15	276.65	22.33	188.96	20.94	30.65	98.23	
3.70	5.10	1.80	12,511.90	5.34	0.82	4.44	21.94	0.82	2.07	0.28	1.62	0.24	115.81	270.73	23.69	194.11	20.12	32.71	98.84	
3.61	4.99	1.75	12,497.59	5.19	0.81	4.44	21.73	0.82	2.05	0.27	1.61	0.23	119.07	278.36	22.42	201.38	20.13	28.02	100.16	
3.46	4.65	1.65	12,365.01	4.95	0.77	4.23	20.73	0.78	1.94	0.27	1.55	0.23	127.92	295.76	23.96	195.53	19.72	25.02	97.64	

Supplementary Table 3.S1 (continued)

Material for Isotopes	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	¹⁷⁶ Hf/ ¹⁷⁷ Hf	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb
powder	0.703325	0.512872	0.282924	19.033	15.619	38.755
powder	0.703079	0.512931	0.282956	18.938	15.600	38.599
glass	0.703102	0.512947	0.282955	18.897	15.595	38.520
powder	0.703327	0.512892	0.282929	19.033	15.611	38.743
powder	0.703184	0.512946	0.282985	19.011	15.625	38.717
powder	0.703033	0.512970	0.282982	18.990	15.617	38.657
powder	0.703373	0.512912	0.282955	18.953	15.629	38.707
powder	0.702908	0.512964	0.282987	18.959	15.623	38.685
powder	0.702915	0.512965	0.282995	18.951	15.623	38.686
powder	0.702950	0.512950	0.282984	18.945	15.623	38.686
powder	0.702923	0.512947	0.282981	18.947	15.626	38.695
powder	0.702965	0.512972	0.283012	19.060	15.612	38.693
powder	0.703353	0.512915	0.282976	19.093	15.650	38.739
powder	0.703002	0.512965	0.283005			
powder	0.702955	0.512967	0.282995	19.147	15.651	38.740
powder	0.702983	0.512976	0.283009	18.983	15.616	38.654
powder	0.702988	0.512958	0.282996	19.003	15.626	38.701
powder	0.703120	0.512963	0.282993	19.020	15.619	38.663
powder	0.703020	0.512969	0.282983	19.062	15.617	38.676
powder	0.703187	0.512923	0.282960	18.975	15.629	38.699
powder	0.703018	0.512944	0.282967	19.093	15.631	38.736
powder	0.703309	0.512920	0.282966	18.972	15.635	38.721
powder	0.702750	0.513017	0.283012	19.088	15.590	38.545

Supplementary Table 3.S2: Isotope compositions for secondary standards analyzed alongside James Ross Island and Seal Nunataks samples of this study

Standard	Material for isotopes	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{176}\text{Hf}/^{177}\text{Hf}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
BHVO-1 n=1	powder	0.703491	0.512983	0.283100	18.671	15.560	38.308
BCR-2 n=1	powder	0.705050	0.512642	0.282859	18.753	15.618	38.719

Supplementary Table 3.S3: Mineral-melt K_D values used in our model

	ol	cpx	opx	sp	gt
Rb	0.00018	0.0007	0.0006	0	0.0007
Ba	0.0003	0.00068	0.001	0	0.0007
Th	0.00001	0.0008	0	0	0.0015
U	0.0004	0.0008	0	0	0.005
Nb	0.005	0.0077	0.0031	0	0.02
Ta	0.005	0.0077	0.0031	0	0.02
K	1.00E-09	0.0072	0.00001	0	0.00001
La	0.0004	0.0536	0.002	0	0.01
Ce	0.0005	0.0858	0.003	0	0.021
P	0.00029	0.14	0.009	0	0.001
Pb	0.00001	0.072	0.003	0	0.0005
Pr	0.001	0.1	0.0048	0	0.045
Sr	0.00019	0.13	0.007	0	0.006
Nd	0.001	0.19	0.0068	0	0.087
Zr	0.01	0.12	0.01	0	0.32
Hf	0.005	0.26	0.01	0	0.32
Sm	0.001	0.29	0.01	0	0.217
Eu	0.002	0.47	0.013	0	0.4
Ti	0.02	0.38	0.024	0	0.2
Gd	0.002	0.48	0.016	0	0.498
Tb	0.002	0.48	0.019	0	0.75
Dy	0.002	0.44	0.022	0	1.06
Y	0.005	0.4	0.028	0	2.11
Ho	0.002	0.42	0.026	0	1.53
Er	0.002	0.39	0.03	0	3
Yb	0.0015	0.43	0.049	0	4.03
Lu	0.0015	0.43	0.06	0	5.5

Supplementary Text

Supplementary Text 3.S1: Parameters and assumptions for the Antarctic Peninsula lithospheric metasomatism model

To simulate lithospheric metasomatism, we begin with representative solid E-DMM and mantle wedge compositions. We estimate the trace element compositions of these solids from the compositions of MORB and back-arc lavas from the Antarctic Peninsula. We selected the isotope compositions of each endmember from representative measured samples from the region. For E-DMM these values come from E-MORB from the Phoenix Ridge. For the mantle wedge, we use three different isotope compositions (one from the Bransfield Strait back-arc, one from the South Shetland Islands volcanic front, and one from the Andes Southern Volcanic Zone) to represent the potential range in isotope values, as this endmember is more difficult to constrain. There are no Hf isotope data for these samples, so their $^{176}\text{Hf}/^{177}\text{Hf}$ ratios were estimated using a regression of Nd and Hf isotope compositions of arc-like basalts from New Zealand, which overlap in Sr, Nd, and Pb isotope composition with arc lavas from the South Shetland Islands volcanic front (Gamble et al., 1996; Waight et al., 2017). We correct the isotope compositions of each source to a specified age in the past. While lavas used from the Bransfield Strait and Southern Volcanic Zone lavas erupted recently, the South Shetland Island lava is Cretaceous in age and thus we calculated the isotope composition of its source at its eruption age in the past (Leat and Riley, 2021). For each run of the model, we corrected the isotope compositions of these solids to the designated age of metasomatism we use.

We then non-modally batch melt these sources to generate E-MORB (3% melting) and arc melts (10% melting) in the spinel field using the modal mineralogy and melting reaction of Kinzler and Grove (1992) and the mineral-melt K_D values listed in the Supplementary Table

3.S3. We mix these melts 0 to 100% and dilute the mixtures with a trace element-free harzburgite in proportions of 10% melt and 90% harzburgite to simulate metasomatism in the lithospheric mantle. Then, we ingrow the isotopes of this metasomatized lithospheric mantle to the present and non-modally batch melt it 4% in the garnet field using a modal mineralogy after the depleted MORB mantle of Workman and Hart (2005), the melting reaction of Walter (1998), and the mineral-melt K_D values listed in Supplementary Table 3.S3.

We mix the resultant lithospheric melts with an asthenospheric melt today, which we generated using the same E-DMM source (this time with a present-day isotope composition) we use to generate our metasomatizing E-MORB in the past. We produced the asthenospheric melt by non-modally batch melting the source 7% in the garnet field (see above for solid mineralogy and melting reaction). The final melt compositions shown in Figure 3.10-3.11 are mixtures of 20% asthenospheric and 80% lithospheric melts. Figure 3.11 shows the results for a 50 Ma metasomatism scenario, and Supplementary Figures 3.S2 and 3.S3 show the results if metasomatism instead occurred 0 and 100 Ma, respectively.

Supplementary Text S2: Parameters and assumptions for the West Antarctic continent and Southern Patagonia lithospheric metasomatism model

We apply the same model as detailed in Supplementary Text 3.S1 with a few adjustments to show that melts from the West Antarctic continent and Southern Patagonia could reasonably be produced by the same process. As explained in the text, the isotope and trace element compositions of the West Antarctic continent and Southern Patagonia lavas, especially those from Mount Early and Sheridan Bluff, suggest that there the metasomatizing arc melts carried stronger signals of subduction influence than those at the Antarctic Peninsula. For this reason we

use a different mantle wedge trace element composition, estimated from Bransfield Strait lavas carrying the strongest signals of subduction influence, and a single, more extreme isotope composition from the South Shetland Islands volcanic front. A comparison of the trace element compositions of the mantle wedges used in each version of the model is shown in Supplementary Figure 3.S4. All parameters used for this model are otherwise the same as those listed in Supplementary Text 3.S1, and results for 0, 200, and 400 Ma metasomatism ages are presented in Figure 3.14 of the text. However, lavas from Sheridan Bluff, the Jones Mountains, and Peter I Island are less alkaline than many of the lavas from the peninsula and Mount Early, suggesting that in reality they may have formed from higher extents of melting. This is supported by the less enriched concentrations of the most incompatible elements in Sheridan Bluff lavas compared to Mount Early lavas. Furthermore, the lavas from Peter I Island and Southern Patagonia have much more extreme Sm/Yb (average of ~ 4.8 compared to ~ 2.6 in the peninsula), suggesting stronger garnet signals associated with deeper average pressures of melting. For these reasons, in Supplementary Figure 3.S5 we show example modeled trace element compositions for each location, keeping all parameters the same but slightly adjusting the extent of lithospheric melting and the proportion of garnet in the lithospheric and asthenospheric sources (4% instead of the 3% used otherwise).

CONCLUSION

In this thesis I present a substantial new geochemical dataset collected on a comprehensive suite of lavas from the northern Antarctic Peninsula, an ideal, yet under-studied site to better understand subduction processes. I use this new dataset in conjunction with an extensive published geochemical dataset to reinterpret the origins of magmatism throughout the region, establish the key mantle sources contributing to this magmatism, trace the movement and distributions of these sources, and relate all these factors to the broader structural and tectonic history of West Antarctica. These new interpretations, which build off each other with each chapter of this thesis, help to address many of the significant outstanding questions and uncertainties about the history of the region, and in pursuing answers to these questions I have collected and reported the first ever volatile contents (CO_2 , H_2O , Cl, F, S) and some of the first Hf isotope data for lavas from the northern Antarctic Peninsula.

Chapter 1 establishes the key compositional components that persist in the upper mantle beneath the northern Antarctic Peninsula today using new and published major element, trace element, and radiogenic isotope data for lavas from the South Shetland Islands volcanic front, Bransfield Strait back-arc, and the neighboring Phoenix and West Scotia mid-ocean ridges. The majority of melts from the region bear clear indications of influence from subduction processes, resulting from the introduction of subducted sediments and fluids to a depleted MORB mantle akin in composition to the asthenosphere beneath the nearby Phoenix Ridge. Throughout the Bransfield Strait back-arc, the strength of this signal varies significantly, and this variability correlates spatially along the back-arc, revealing that the sub-slab asthenosphere has flowed toroidally around the slab's edges into the mantle wedge. This flow has produced MORB-like melts at the back-arc's edges and forced the bulk of the subduction-modified mantle into the area

beneath the central back-arc, where melts with the greatest subduction signals occur. Furthermore, the geochemical similarities between Phoenix and West Scotia Ridge lavas indicate that they are underlain by asthenosphere of comparable geochemistry, and their combined similarities with Pacific MORB suggest that this asthenosphere has flowed from beneath the Pacific plate into the regions beneath the two ridges. Finally, the presence of rare alkaline lavas in the back-arc with distinct isotope compositions and trace element patterns suggests the presence of an additional unique component in the region's upper mantle. The geochemical similarities between these melts and those sampled at James Ross Island and the Phoenix Ridge indicate that this component is widespread.

Having identified the key components in the region's upper mantle, Chapter 2 utilizes new volatile element data from the Bransfield Strait, Phoenix Ridge, and West Scotia Ridge to investigate how these components vary in volatile composition. Back-arc lavas carrying the strongest signals of subduction influence in their trace element and isotope compositions are also the most volatile enriched. This variation is also expressed spatially along the length of the Bransfield Strait back-arc. The most volatile depleted lavas with the weakest signals of subduction influence occur at the edges of the strait. The most volatile enriched lavas with the strongest signals of subduction influence occur near the center of the strait, and these melts are the least alkaline, suggesting greater extents of melting driven by the higher volatile contents of their mantle sources. These observations support the model presented in Chapter 1 and suggest the sub-slab asthenosphere is flowing toroidally into the mantle wedge at the strait's edges. Notably, a subset of back-arc lavas deviates from this relationship, bearing especially strong subduction signals yet have comparatively depleted volatile compositions. We speculate that these lavas represent flux melting of residual enriched mantle dragged beneath the back-arc

following recent alkaline magmatism in the far back-arc at James Ross Island. In the Phoenix Ridge, trace element and isotope enrichment correspond well with volatile enrichment, a straightforward relationship that, when combined with published eruption ages and past spreading rates, suggests that the less abundant but more fertile, volatile-rich enriched MORB mantle increasingly dominated the compositions of melts at the ridge as spreading slowed. Using the Bransfield Strait and Phoenix Ridge volatile data, we estimated the mantle potential temperatures beneath each area, and the results are in good agreement with published ranges for back-arcs and mid-ocean ridges. Finally, we investigate the origins of the strong subduction signals found in lavas from the W7 segment of the West Scotia Ridge. We highlight the geochemical similarities between these lavas and melts from the South Sandwich Arc and suggest that the W7 lavas sample a mantle component that was left behind by the arc as it migrated eastwards over the past ~30 Myr.

Chapter 3 explores the origins of the alkaline magmatism that has occurred along the length of the Antarctic Peninsula throughout the Cenozoic. We combine new major element, trace element, and isotope data for a suite of alkali basalts from James Ross Island and the Seal Nunataks with published data for geochemically similar alkaline melts from across the region. A detailed analysis of their compositions reveals that these melts formed from mixing between E-MORB and arc-like components. However, direct mixtures of E-MORB and arc melts fail to reproduce the unique compositions of the alkali basalts. Thus, we suggest that these lavas were produced during recent detachment of the lithospheric mantle, which was metasomatized within the past ~100 Myr by mixtures of E-MORB and arc melts during West Antarctica's extensive history of rifting and subduction. This interpretation is supported by a simple model to simulate metasomatism, and we demonstrate that by adjusting the age of metasomatism it can more

broadly explain the widespread Cenozoic alkaline magmatism found across the West Antarctic continent (i.e., Peter I Island, the Jones Mountains, Mount Early, and Sheridan Bluff) and even southern Patagonia. Metasomatism in these areas may have occurred as long ago as 400 Ma or in some cases as recently as the present-day.