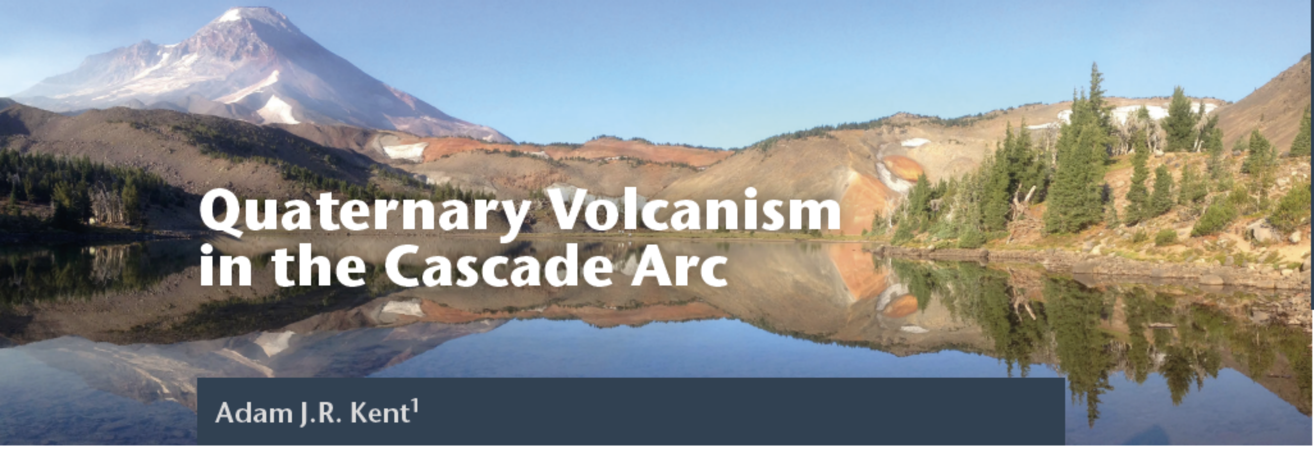

An early morning summer view of South Sister Volcano, viewed from Camp Lake. PHOTO: ADAM KENT.

Quaternary Volcanism in the Cascade Arc

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The Cascade arc has produced a remarkable diversity of volcanic rocks over the Quaternary period. The major stratovolcanoes that define the arc front are dominated by eruptions of andesitic and dacitic intermediate magmas, produced largely by fractionation, melting, assimilation, and mixing within the crust. In addition, relative to many other subduction zones, the arc has produced significant mafic volcanism. These more primitive magmas reveal complexity in mantle wedge dynamics, sources, and magma production processes, and suggest that there are significant differences along the arc in the amount of magma that enters the lower Cascade crust from the underlying mantle.

KEYWORDS: subduction; andesite; dacite; basalt; Cascade arc; stratovolcano; monogenetic

INTRODUCTION

The Cascade volcanic arc, which accompanies the Cascadia subduction zone, stretches over 1200 km from northern California to southern British Columbia (from ~40.3° N to 50.9° N). The arc is the result of ongoing eastward subduction of the Juan de Fuca plate and associated oceanic plates beneath western North America. In its current configuration, the arc has a ~45-My record of volcanism and plutonism, although subduction beneath western North America has a much longer history of volcanism and terrane accretion. The Cascade volcanic arc is considered to be a classic location for studying the causes, nature, and impact of arc volcanism, as the subduction of young oceanic crust results in thermal conditions that approach a "hot and dry" endmember within the global range of subduction zones. The arc also erupts significant amounts of mafic magma and a broad range of primary magma types relative to most other continental arcs. The proximity to large population centers and the ease of access to much of the arc also make it ideal for studying arc-related processes and hazards. As a result, there is a long history of scientific investigation of volcanism and volcanic rocks throughout the Cascades, and there are considerable local and regional data sets available. Studies of Cascade volcanoes were further promoted by the 1980 eruption of Mount St. Helens—a high-profile, formative event for North American volcanology and volcano monitoring. Today, further impetus for studying and understanding Cascade volcanism comes from the recognition that 10 Cascade volcanoes are assessed by the Unites States Geological Survey (USGS) as very high threat (Ewart et al. 2018).

A BROADER PLATE TECTONIC AND MAGMATIC CONTEXT FOR CASCADE VOLCANISM

The Cascade arc exists within the broader magmatic–tectonic context of the ongoing evolution of the western North American continental margin. Subduction and terrane accretion has occurred since at least the early Mesozoic, and much of this is represented in the older basement terranes that underlie the Quaternary Cascade arc. There are also older phases of magmatism associated with earlier episodes of subduction—including the Cretaceous plutonic and volcanic rocks of the northern Washington Cascades, the early- to mid-Eocene Clarno Formation, and the latest Eocene to Miocene John Day formations located to the east of the modern arc, as well as volcanic and plutonic rocks of the ancestral Miocene arc. The current geometry of the Cascade arc (FIG. 1) has been in place for at least the last ~7 My, but rotation of the Oregon forearc block and changes in the slab dip (Wells and McCaffrey 2013) have resulted in migration of the modern arc relative to the Miocene arc, shifting to the east in southern Washington, Oregon, and northern California, and to the west in northern Washington and along the Garibaldi arc further north. The modern plate tectonic setting and microplate interactions also produce a range of structural settings along the Cascade arc (FIG. 1), with southern transtension, central extension, and northern compression resulting from intersection of Basin and Range spreading with the arc, as well as northward motion of the Sierra Nevada block, rotation of the Oregon coast block, and collision with Paleocene and older basement terranes in central Washington (Hildreth 2007; Wells and McCaffrey 2013).

Volcanism Along the Cascade Arc

The modern Cascade arc consists of at least 2500 distinct volcanic vents (Hildreth 2007; O'Hara et al. 2020), and if extensive forearc and rear-arc vent fields are also included, the number of known vents exceeds 3500 (Hildreth 2007). Vents represent a diversity of volcanic landforms including stratovolcanoes, calderas, domes, maars, shield volcanoes, cinder cones, tuyas (shallow volcanic intrusions beneath ice), and other features. Examples of some of these landforms are shown in FIGURE 2. The active stratovolcanoes that define the arc are dominated by small to moderate sized eruptions, although larger plinian and subplinian eruptions have also occurred (Hildreth 2007). Examples include Mount St. Helens, Mount Rainier, Mount Shasta,

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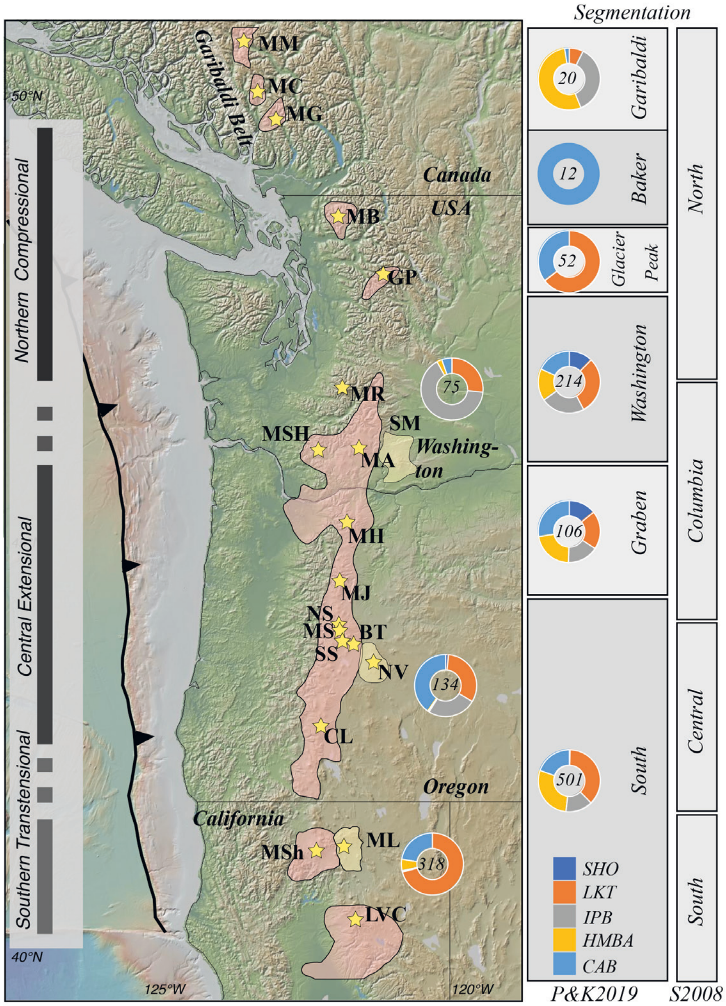

Figure 1 Map of the Cascade Range showing major edifices, from north to south. MM: Mount Meager; MG: Mount Garibaldi; MC: Mount Cayley; MB: Mount Baker; GP: Glacier Peak; MR: Mount Rainier; MSH: Mount St. Helens; MA: Mount Adams; MH: Mount Hood; MJ: Mount Jefferson; NS: North Sister; MS: Middle Sister; SS: South Sister; BT: Broken Top; NV: Newberry Volcano; CL: Crater Lake (Mount Mazama); MSh: Mount Shasta; LVC: Lassen volcanic center; ML: Medicine Lake; SM: Simcoe Mountain. Modified after Hildreth (2007) and Till et al. (2019). Major volcanic vent fields are shown in red for the forearc and arc and in yellow for the rear arc. On the right, two segmentation schemes are shown based on the compositions of primitive basalts from Pitcher and Kent (2019) and Schmidt et al. (2008), denoted P&K2019 and S2008, respectively. Pie charts show the proportions of primitive basalt types in each segment from Pitcher and Kent (2019), and central numbers show the number of individual analyses. Legend abbreviations are SHO: shoshonite and related compositions; LKT: low-K tholeiites, including high-Ba, low-K tholeiites; IPB: intraplate basalts; HMBA: high-magnesium basaltic andesites; CAB: calc-alkaline basalts. See text for more details about primitive basalt types.

Mount Hood, South Sister, the Lassen volcanic center, Mount Baker, Glacier Peak, and Crater Lake (Mount Mazama)—all assessed as very high threat (Ewart et al. 2018). The names used herein for Cascade volcanic centers are their post-colonial designations, but we acknowledge that these centers and many other prominent features in the Cascade Range have other names that have long been used by the many Indigenous cultures of the region.

In addition to the stratovolcanoes that lie along the arc, there are two large basaltic shield volcanoes, Newberry Volcano (also assessed as high threat; Ewert et al. 2018) and Medicine Lake (Figs. 1 and 2), that lie east of the arc front in the rear arc, and have also seen significant Holocene eruptive activity. They consist of basalt-dominated shields with central calderas associated with significant eruptions of more silica-rich magmas, including rhyolites (e.g., Donnelly-Nolan et al. 2016). Some stratovolcanoes, such as Mount St. Helens, and to a lesser extent Mount Rainier, also lie in the forearc, west of the main-arc axis (Fig. 1).

As with many other arc volcanoes, individual Cascade volcanoes exhibit a characteristic spectrum of erupted compositions, and even volcanoes that lie close to each other along the arc have erupted quite different compositional ranges through time. For example, Mount St. Helens, which has erupted a wide range of compositions from basalt to dacite over the last ~300 ky, is located only ~70 km north of Mount Hood, which has erupted a much more monotonous set of andesites and low-silica dacites over the ~500-ky life of the current edifice (Kent et al. 2010). In this case, these differences in magmatic output are also reflected in the eruption style: Mount Hood has been dominated by eruptions of small domes and lava flows, with no known plinian activity, whereas Mount St. Helens has erupted lava flows and domes, as well as some of the larger plinian events known along the arc (Hildreth 2007). Systematic differences in the erupted compositions and/or eruption style between volcanoes are common in arcs and other environments, and long-term differences in their composition and other features reflect differences in the underlying magma plumbing systems—in turn driven by variations in long-term magmatic fluxes and differences in the physical state of the local crust (e.g., Till et al. 2019; O'Hara et al. 2020).

In addition to the well-known Cascade volcanoes—most of which have shown late Pleistocene and/or Holocene eruptive activity—there are a number of older and inactive central volcanoes along the Quaternary arc in various states of erosion. High levels of orographic precipitation and episodes of ice-age glaciation produced fierce competition between volcanic construction and glacial erosion, and deeply eroded remnants reveal the impressive ability of glaciers to rapidly remove volcanic edifices (e.g., Fig. 2). Examples include North Sister and Broken Top volcanoes near Bend, Oregon, and Goat Rocks, north of Mount St. Helens (e.g., Wall et al. 2019; Fig. 2). Many of these eroded edifices are stratovolcanoes dominated by intermediate magmas such as andesite and dacite (see Fig. 3 for an explanation of these terms), but there are also eroded mafic composite and shield volcanoes dominated by basalt and basaltic andesite, suggesting that the current dominance of intermediate composition stratovolcanoes along the Cascade arc may largely be a temporal coincidence.

Many Cascade volcanoes also represent long-lived regions of eruptive activity. The current edifices of most active Cascade volcanoes range in age from 300 ky to 600 ky, but also sit on or near older eroded edifices that reveal longer lived volcanism centered at the same geographic location. In many cases, remnants of older edifices may be up to 1–3 My older (Hildreth 2007; Wall et al. 2019), and distal tephra suggest that Three Sisters and Mount Jefferson may have remained as loci of eruptions for as long as ~5 My (e.g., Pitcher et al. 2017). The migration of vent locations at these individual systems through time may reflect local plate rotation rates (Wells and McCaffrey 2013), but in other cases controls on the local migration are less clear (Hildreth 2007).

Another distinctive feature of the Cascade arc is the large volume of spatially distributed mafic-dominated volcanism, and the high overall proportion of mafic magmas that are erupted (Figs. 1–3). Distributed volcanism occurs in volcanic fields containing large numbers of monogenetic or smaller polygenetic vents, predominantly erupting

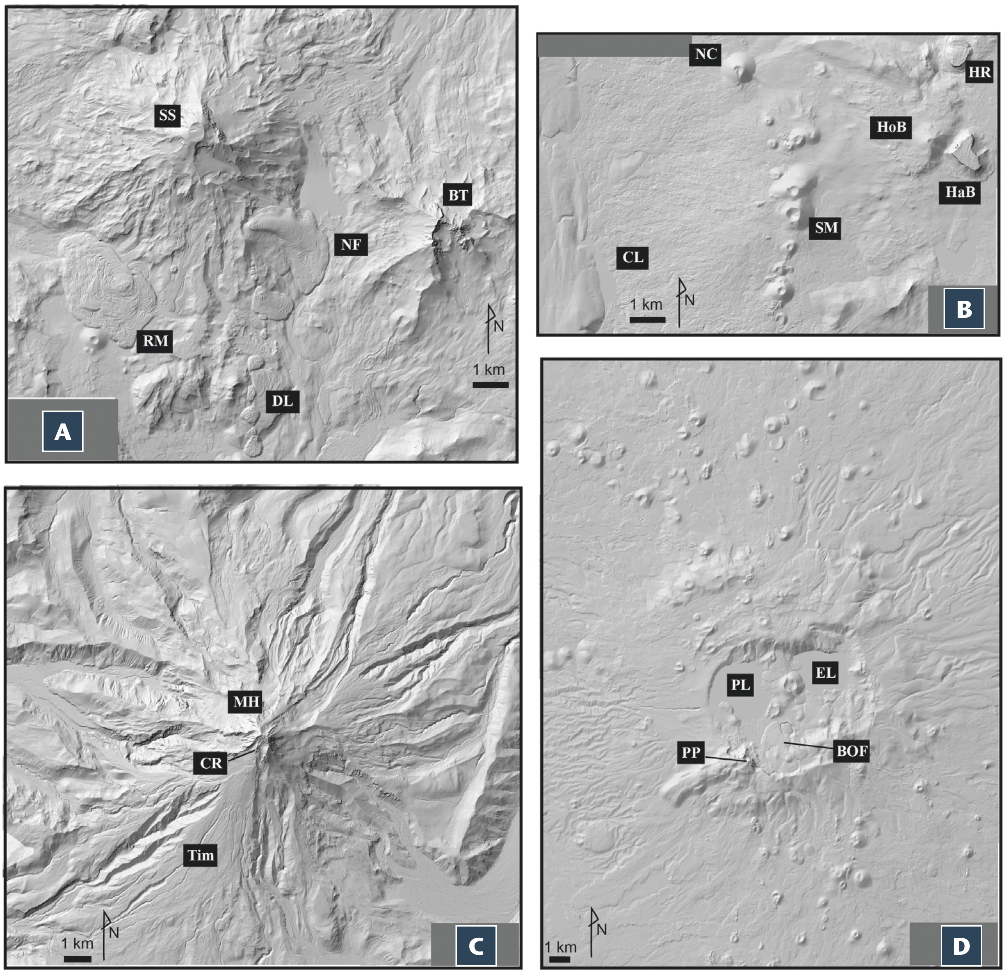

Figure 2 Light detection and ranging (lidar) bare earth images of different Cascade volcanoes. All lidar images are from the Oregon Department of Mineral Industry lidar viewer (www.oregongeology.org/lidar). (**A**) South Sister Volcano (SS) showing Holocene silicic domes and flows of the Newberry flow (NF), Rock Mesa dome (RM), and the Devil Lake dome chain (DL). The eroded edifice of Broken Top (BT), a Pleistocene volcano, lies to the east. (**B**) The Sand Mountain chain of cinder cones including the Nash Crater (NC), Sand Mountain cones (SM), and an apron of lava flows extending west to Clear Lake (CL) and the upper Mackenzie River. Also shown are the late Pleistocene tuyas of Hayrick Butte (HaB) and Hogg Rock (HR) and the small mafic stratocone of Hoodoo Butte (HoB). (**C**) Mount Hood (MH) stratovolcano showing Crater Rock (CR), a dome complex formed by the two most recent eruptions that occurred ~1500 and ~230 years ago. Also shown is the Timberline collapse surface (Tim), formed by sector collapse that occurred ~1500 years ago. (**D**) Newberry Volcano caldera and surroundings, showing abundant cinder cones and lava flows on the flanks; two caldera lakes, East Lake (EL) and Paulina Lake (PL); Paulina Peak (PP), the highest point on the caldera wall; and the ~1300-year-old Big Obsidian Flow (BOF).

basalts and basaltic andesites. The location of vents in these fields often exhibit a high degree of structural control (e.g., Fig. 2B; Guffanti and Weaver 1988; O'Hara et al. 2020). There is also ongoing recognition in the Cascades and elsewhere that the term "monogenetic" is often a misnomer, as volcanism at these centers can be petrologically complex and involve multiple magmatic sources. Mafic vents and mafic volcanic fields are arrayed unequally along the arc (Fig. 1). In the northern portion of the arc, mafic vents are largely restricted to the immediate vicinity of stratovolcanoes. South of the approximate latitude of Mount St. Helens, in regions associated with crust in extension or transtension, mafic vents occur in larger distributed fields that are also associated with higher heat flow and slower seismic wave speeds in the lower crustal and upper mantle (e.g., Guffanti and Weaver 1988; Till et al. 2019; O'Hara et al. 2020). Distributed volcanic fields also extend into the forearc, such as the inaptly named Boring Volcanic field (Evarts et al. 2009) that underlies the city of Portland, Oregon, and into the rear arc in several locations. Rear arc examples include fields associated with the large shield volcanoes of Newberry and Medicine Lake (e.g., Donnelly-Nolan et al. 2016) and the Simcoe field that lies southeast of Mount Adams (Figs. 1 and 2). The extent of forearc and rear-arc volcanism is such that the Cascades represent one of the widest known continental magmatic arcs (Leeman 2020).

Relative to many other continental arcs such as the Andes, Kamchatka, and Japan, the Cascade arc has seen a relatively limited number of "historic" eruptions—those documented since European exploration and settlement starting in the 1800s. In the Cascades, these include eruptions of the Lassen volcanic center in 1915 and Mount St. Helens in 1980–1986 and 2004–2008. The Lewis and Clark Corps of Discovery Expedition also documented changes in the Sandy (née "Quicksand") River in 1806 related to the 1780–1790 Old Maid eruption of Mount Hood, and early European settlers also recorded eruptions at Mount St. Helens in the 1850s. Overall, the Cascade arc averages 1–2 eruptions per century, although events such as the increased thermal activity and gas emissions at Mount Baker in 1975 and 1976, and ongoing interferometric synthetic aperture radar (InSAR)-measured inflation near South Sister also reinforce the fact that many volcanoes in the arc remain active and represent considerable future hazards (Ewart et al. 2018). Overall, despite the apparent dearth of historic eruptions, Quaternary eruption rates in the Cascades are broadly comparable with those of other arcs that have had more historic activity, such as the Alaskan Peninsula, the Southern Volcanic Zone of the Andean Arc, and Central America, in part because of the significant eruptive flux represented by the distributed volcanic fields (Hildreth 2007).

Formation of Intermediate and Evolved Magmas

As with most continental arcs, the active stratovolcanoes that lie along the Cascade arc are dominated by the eruption of intermediate magma compositions, particularly andesites and dacites (Hildreth 2007). More evolved silicic magmas occur, but are subordinate (Fig. 3). Rhyolite and rhyodacite are restricted to a handful of locations and/or time periods, such as the Pleistocene and Holocene rhyolites of South and Middle Sister and the Tumalo volcanic center (e.g., Hildreth 2007).

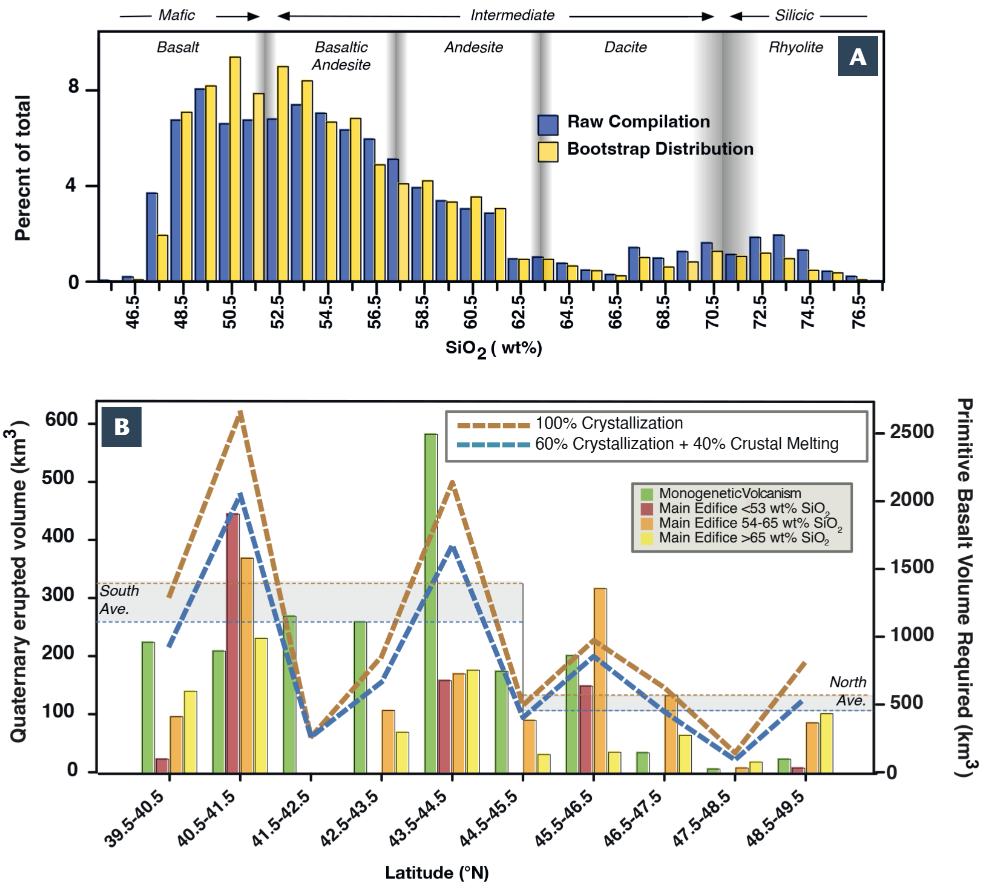

Figure 3 (**A**) Histogram showing the SiO_2 contents of ~13,000 quaternary volcanic rocks erupted along the Cascade arc. Data are from Pitcher and Kent (2019) and Till et al. (2019). The observed number of samples are shown both as the percent of total and the distribution modified by bootstrap resampling to minimize the impact of more highly sampled locations along the arc. See Till et al. (2019) for further methodology. Approximate compositional ranges of volcanic rock types and mafic, intermediate, and silicic terminology are also shown. (**B**) Histograms showing volume estimates of the volcanic rocks erupted along the Cascade arc in the Quaternary as a function of latitude. Figure modified from Till et al. (2019). Volume data are from Hildreth (2007). Also depicted are curves showing the estimated volumes of basalt required to produce the observed volcanic rocks, using a model of 100% fractionation and a mixture of crustal melting and crystal fractionation to produce the observed compositions. Grey boxes show the average volume of basalt required for the arc north and south of 45.5° N.

The production of the intermediate composition magmas that dominate the Cascade stratovolcanoes reflects a range of different petrological processes. Intermediate composition magmas can be produced in several ways, and there are compelling examples of magmas produced by a single process—such as crystal fractionation (e.g., Grove et al. 2003) or crustal melting (e.g., Smith and Leeman 1987; Conrey et al. 2001; Blatter et al. 2017; Waters et al. 2021). However, in many other cases, petrological, mineralogical, and geochemical data suggest that intermediate magmas form via combinations or multiple stages of crustal melting, assimilation, fractionation, and mixing. This reflects the potential importance of all these processes during magma formation and transport in the transcrustal magma systems that underlie major volcanoes, and the relatively high water contents of primary magmas that feed most arc magma systems (e.g., Smith and Leeman 1987; Hildreth 2007; Feeley et al. 2008; Kent et al. 2010; Sisson et al. 2014; Leeman 2020). Attempts to assess the extent of crustal versus mantle contributions in Cascade intermediate magmas are often hampered by a lack of radiogenic isotopic diversity between mantle-derived magmas and the typically young and primitive Cascade basement, although oxygen isotope studies suggest that the incorporation of lower crustal material into intermediate magmas can be significant (e.g., Feeley et al. 2008; Sisson et al. 2014).

Zircon and U-series studies suggest that the magmas erupted at many Cascade stratovolcanoes are stored within the crust for at least 10^4–10^5 years prior to eruption (e.g., Claiborne et al. 2010; Cooper and Kent 2014). However, as with many other arcs, there are few geophysical indications that magma that is sufficiently liquid-rich to be considered rheologically "eruptible" (typically considered to be greater than ~40%–50% liquid) is currently stored in large volumes beneath active volcanoes. Most intermediate Cascade magmas are also relatively crystal-rich (more than ~20% crystals; e.g., Salisbury et al. 2008; Kent et al. 2010; Waters et al. 2021), consistent with magma residence under long-term conditions of crystal growth and stability. More recent geophysical investigations at Mount St. Helens and Newberry Volcano suggest that a silicate liquid-bearing crystal mush is present within the subsurface (Dufek et al. 2022 this issue), although it remains unclear if this material is sufficiently liquid-rich to be rheologically mobile. A lack of geophysically resolved magma reservoirs is a common observation in arc settings, even for volcanoes that are demonstrably active. This may be in part reflective of the resolution of the techniques involved and the difficult imaging geometries presented by subvolcanic magma systems, but is also consistent with evidence for long-term magma storage at relatively cool near-solidus temperatures (e.g., Cooper and Kent 2014). Such magmas must be remobilized quickly prior to eruption via magma recharge, volatile accumulation, or other initiation process, and the presence of rheologically eruptible magma may thus be a transient feature beneath Cascade stratovolcanoes.

In comparison with other continental arcs, the rate at which larger caldera-forming eruptions occur along the Cascade arc is relatively low (Hughes and Mahood 2011). Over the Quaternary, at least four major caldera eruptions are known—the most recent being the ~61 km^3 dense-rock equivalent eruption of Mount Mazama that produced Crater Lake ~7.7 Ma. There were also major caldera-forming eruptions at the Lassen volcanic center, Newberry Volcano, and Kulshan caldera in northern Washington (Hildreth 2007). The lower rate of caldera-forming eruptions may ultimately relate to the lower trench normal convergence rate of the Cascade subduction zone (currently ~32 mm/y) and the presence of relatively primitive basement terranes in many areas (Hughes and Mahood 2011). However, transient periods of higher production and eruption of silicic magmas (and presumably caldera-forming eruptions) have also been documented. The most recent of these—associated with the transition to the modern arc geometry at 5–8 Ma—resulted in a ~600-ky period with over a factor of ~10 increases in volumetric eruption rate and ignimbrite frequency eruptions relative to the "background" Quaternary rate for the Cascade arc (Pitcher et al. 2017).

Primitive Magmas of the Cascade Arc

In addition to the high overall abundance of mafic magmas, the Cascade arc also reveals an intriguing variety of primary magma types (Figs. 1 and 4), which in turn suggest a diversity of magma formation processes and sources (e.g., Bacon et al. 1997; Conrey et al. 1997; Grove et al. 2003; Schmidt et al. 2008; Rowe et al. 2009; Mullen et al. 2017; Pitcher and Kent 2019; Leeman 2020). Common primary magma types include low-potassium tholeiites (LKTs) (also known as high-aluminium olivine tholeiites). These have low concentrations of K and other large ion lithophile elements (LILEs), such as Rb and Ba, lower abundances of H_2O and other volatile species, and low ratios of LILEs to high field strength elements (HFSEs). LKTs are considered to predominantly be the result of decompression melting of dry or damp mantle, with minimal input from components derived from the subducted slab (e.g., Conrey et al. 1997; Leeman 2020; Till et al. 2013). The highest abundances of LKTs occur in regions characterized by on-arc extension or transtension in the southern half of the arc (Pitcher and Kent 2019; Leeman 2020), although the low overall rates of extension (~1 mm/y) are not necessarily compatible with a model where extension alone drives asthenospheric uplift and decompression—and more complex mantle wedge dynamics are likely involved.

Calc-alkaline basalts (CABs) have higher ratios of LILEs to HFSEs (Fig. 4), similar to basalts found in many other subduction zone settings; this suggests the involvement of one or more slab-derived components in magma genesis. Compared with LKTs, Cascade CABs also have higher abundances of H_2O and other volatiles and result from H_2O-flux melting of the mantle wedge by hydrous fluids or melts derived from the subducting slab (e.g., Bacon et al. 1997; Rowe et al. 2009; Ruscitto et al. 2011; Walowski et al. 2016), although it is possible that melting of older slab-fluid metasomatized asthenosphere and/or lithosphere also contributes to CAB formation (e.g., Bacon et al. 1997; Rowe et al. 2009; Leeman 2020). Calc-alkaline basaltic magmas are distributed throughout the arc (Fig. 1), consistent with a broadly constant subduction flux, and like many other subduction zones, they may also be the primary basalt type most commonly associated with the development of intermediate magmas at stratovolcanoes. In addition to

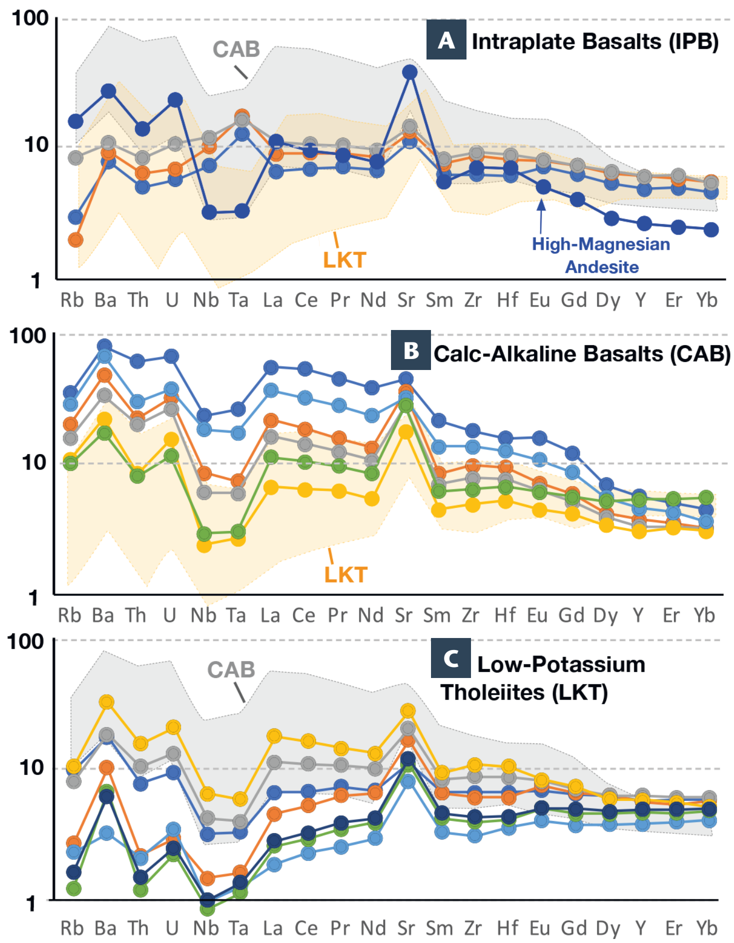

Figure 4 Primitive mantle–normalized trace element variations in primitive Cascade arc basalts, showing representative compositions of trace elements in (**A**) intraplate basalts (IPB), (**B**) calc-alkaline basalts (CAB), and (**C**) low-potassium tholeiites (LKT). A single high-magnesian andesite is also shown. For comparison, fields representing the range of the LKT and CAB compositions are also shown. All data are from Mullen et al. (2017).

CABs, there are volumetrically minor primary magmas that include highly enriched absarokitic/shoshonitic, primitive basaltic andesite, and high-magnesian andesite magmas that appear to relate to H_2O-flux melting of variably depleted mantle peridotite (Conrey et al. 1997; Rowe et al. 2009; Ruscitto et al. 2011).

The Cascade arc also hosts basalts with intraplate (IPB) compositions, also known as enriched intraplate-, oceanic island-, or HFSE-type basalts. These have high incompatible element abundances without the depletion of HFSEs characteristic of subduction zone magmas (Fig. 4) and, in that way, resemble intraplate or ocean island basalts. Intraplate basalts occur preferentially within the Garibaldi volcanic belt, as well as in the southern portion of the Cascades, and are common in the rear arc Simcoe volcanic field and at Newberry Volcano (Pitcher and Kent 2019; Leeman 2020).

The range of primitive magma types described above, and variations in their spatial distributions, suggest a complexity of primary magma generation processes in the Cascadia subduction zone. However, processes and sources that occur in all subduction zones, such as variations in the extent of melting, type and amount of slab component added, and degree of prior depletion of the mantle wedge, can explain much of the observed variety of primary basalts

(Conrey et al. 1997; Rowe et al. 2009; Mullen et al. 2017). In this scenario, CABs result from H_2O-flux melting and LKTs and IPBs from decompression melting of variably depleted or enriched asthenospheric mantle as a result of corner flow or flow through slab windows. Recent high-precision isotope studies also support this, showing that LKTs, CABs, and many IPBs have isotopic compositions that lie in a range between local Juan de Fuca mid-ocean ridge basalt (representing ambient depleted mantle) and subducted sediment. The diversity of Cascade primary mantle-derived magmas largely reflects variability in the contribution and composition of the slab-derived flux and single mantle wedge composition, rather than a broader variety of isotopically distinct mantle reservoirs (Mullen et al. 2017). However, one important exception is the Pb isotope compositions of IPBs from the Mount Adams region and from the Garibaldi volcanic belt, which point to contributions from an enriched mantle endmember and thus show that, in at least some locations, slab geometry also allows for the presence or entry of more enriched mantle sources in the subduction zone.

Along Arc Variations in Cascade Volcanism

In addition to studies that address the behavior of individual Cascade volcanic systems, there is also significant interest in understanding Cascade volcanism and the magmatic systems that underlie volcanoes at more regional scales. For example, many studies have noted distinct differences in the compositions and proportions of the different primitive magma types erupted along the arc, and have used erupted magma compositions and vent abundances as a basis for arc segmentation schemes (e.g., Guffanti and Weaver 1988; Schmidt et al. 2008; Pitcher and Kent 2019). Pitcher and Kent (2019) used an expanded data set (with over 12,000 Quaternary samples and over 2000 mafic lava compositions) to show that the arc could be divided into six statistically robust segments on the basis of their mafic lava compositions (Fig. 1). These segments are differentiated (and distinct from rear-arc volcanic fields) in their proportions of different primary basalt types present and in the compositions of magma erupted in each segment. While the primary drivers of compositional segmentation appear to be differences in the depth, degree, and type of mantle melting plus variable enrichment with slab-derived components, there are also clear relationships between segmentation schemes and the larger structural features of the arc. For example, greater proportions of LKT and IPB occur in the southern portion of the arc areas that are undergoing extension or transtension and in some rear-arc volcanic fields (e.g., Schmidt et al. 2008; Pitcher and Kent 2019; Leeman 2020).

Arc-scale variations in Quaternary volcanism are also evident in differences in the total volume of erupted magma along the arc (Fig. 3B), where regions of high eruption rates correlate with higher crustal heat flow and lower seismic wave speeds within the lower crust and upper mantle (Till et al. 2019; O'Hara et al. 2020). Variations in erupted volumes, crustal heat flow, and lower crustal and upper mantle seismic velocities are best explained by variations in the rate of supply of mafic magma to the base of the crust over the Quaternary, and Till et al. (2019) estimated that the mantle-derived magma flux at the base of the crust is roughly a factor of two higher in the southern Cascades relative to the northern portion of the arc (Fig. 3B). If this is the case, then much of the arc-scale variations in erupted volume, composition, and eruption style appear ultimately related to differences in mantle fluxes, rather than differential crustal responses to a broadly constant magma flux.

QUESTIONS FOR THE FUTURE

The Cascade arc is one of the most studied in the world and has an array of geological, geochronological, petrological, geochemical, geophysical, and other data available. Despite this, there are important questions that remain about the magmatic arc—many of which also correspond to research priorities in other subduction settings.

- How does magma storage and the dynamics of crustal magma transport and evolution vary in response to different magma flux rates and different crustal stress states? There is an emerging appreciation of the role of so called *transcrustal* magma systems—systems that transport and store magma en route from the mantle to the surface—in controlling the long-term behavior of many volcanoes. Within the transcrustal system, there are likely important feedbacks between magma fluxes and the physical and chemical state of the crust, and such feedbacks will also strongly influence erupted compositions.
- What are the processes that initiate eruptions at Cascade volcanoes, and how might we recognize these prior to future eruptions? Cascade volcanoes spend the vast majority of their time in a state of quiescence, thus recognizing systems that are building toward new eruptions is critical. Is activity such as shallow seismicity, deep long-period earthquakes, or inflation a prelude to eruption, or is it part of a waxing and waning magmatic background that may not always be associated with new activity? What are the critical processes that occur within the transcrustal magma systems beneath Cascades volcanoes that ultimately lead to new eruptions?
- How do dynamics within the mantle wedge and rear arc, together with variations in subduction parameters along the arc, contribute to differences in the erupted compositions and volumes of different types of primary mafic magmas? Do variations in the primary basaltic compositions or mantle fluxes play the larger role in dictating the nature of volcanism?

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