



Tectonic controls on the origin and segmentation of the Cascade Arc, USA

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Abstract

The magmatic response above subducting ocean lithosphere can range from weak to vigorous and from a narrow zone to widely distributed. The small and young Cascade Arc, riding on the margin of the tectonically active North American plate, has expressed nearly this entire range of volcanic activity. This allows an unusually good examination of arc initiation and early growth. We review the tectonic controls of Cascade-related magmatism from its inception to the present, with new considerations on the influences of tectonic stress and strain on volcanic activity. The Cascade Arc was created after accretion of the Siletzia oceanic plateau at ~50 Ma ended a period of flat-slab subduction. This (1) initiated dipping-slab subduction beneath most of the northern arc (beneath Washington and Oregon) and (2) enabled the more southerly subducting flat slab (beneath Nevada) to roll back toward California. As the abandoned flat slab fragmented and foundered beneath Oregon and Washington, vigorous extension and volcanism ensued throughout the northwest USA; in Nevada the subducting flat slab rolled back toward California. Early signs of the Cascade Arc were evident by ~45 Ma and the ancestral Cascade Arc was well established by ~35 Ma. Thus, from ~55–35 Ma subduction-related magmatism evolved from nearly amagmatic to regional flare-up to a clearly established volcanic arc in two different tectonic settings. The modern Cascades structure initiated ~7 Ma when a change in Pacific plate motion caused partial entrainment of the Sierra Nevada/Klamath block. This block pushes north and west on the Oregon Coast Ranges block, breaking the arc into three segments: a southern extensional arc, a central transitional arc, and a northern compressional arc. Extension enhances mafic volcanism in the southern arc, promoting basalt decompression melts from depleted mantle (low-K tholeiites) that are subequal in volume to subduction fluxed calcalkaline basalts. Compression restricts volcanic activity in the north; volcanism is dominantly silicic and intra-plate-like basalts cluster close to the main arc volcanoes. The transitional central arc accommodates dextral shear deformation, resulting in a wide volcanic arc with distributed basaltic vents of diverse affinities and no clear arc axis.

Keywords Cascade Arc · Tectonic control of arc segmentation · Arc initiation

Introduction

The subduction of ocean lithosphere typically creates a volcanic arc near the margin of the overriding plate. Considering the complexities involved with arc creation, the large variations in rate and distribution of arc volcanism are not surprising. The underlying processes depend on factors such as the slab's thermal, compositional and physical state, slab geometry and nature of the mantle wedge where melt generation occurs, and the thermal, compositional and stress state of the overlying lithosphere through which melt stages, interacts and eventually erupts (Acocella and Funiello 2010; Acocella 2021). The Cascades Arc occupies a unique niche in the global panoply of arcs (see arc attribute compilation of Hughes and Mahood 2011). It is perhaps most

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noted for having a young, and thus hot subducting slab and for its slow and oblique convergence. The convergence rate in the north is 40–45 mm/year and declines to ~1 mm/year to the south (Figs. 1 and 2). The arc is young (<45 Ma) and short (~1300 km). In contrast to most arcs, there is little variation in the age of the down-going plate. Unlike the Andean continental arc, the Cascades Arc is built on crust of similar thickness (42 ± 3 km) and character, viz., Paleozoic to early Cenozoic accreted terranes (see summary in Hildreth 2007). Nevertheless, the Cascades Arc has remarkable along-strike diversity in the distribution of arc volcanoes and the abundance, types and distribution of basalts. We here review and examine the initiation of subduction and arc volcanism, and the segmentation of the arc in the context of its tectonic location in a dextral shear (Fig. 1), illustrating the importance of upper plate stresses in arcs.

The small Cascade Arc is built within the large, tectonically active Pacific-North America plate margin (Fig. 1). The volcanic arc (Fig. 2) currently experiences a strong gradient in stress and strain, from extensional in the south to compressive in the north (Wells and McCaffrey

2013; Wells et al. 1998); following this trend the volcanic response varies from highly productive to nearly quiescent (Fig. 3). Thus, this relatively compact arc presents an opportunity to address how the externally applied tectonic stress and resulting strains affect an arc's volcanic production and volcano distribution.

An interesting aspect of Cascade subduction is that, at ~50 Ma, dipping-slab subduction initiated in the northern portion of the subduction zone (Wells et al. 2014) and abandoned flat slab at the base of the Pacific Northwest (PNW) of USA (Schmandt and Humphreys 2011), whereas the southern subduction zone was left in an active flat-slab configuration whose slab dip then steepened by rollback (Timmermans et al. 2020). These two segments were separated from each other by a slab tear (Colgan et al. 2011; Darold and Humphreys 2013), and asthenosphere flow through the tear allowed a slab rollback that initiated from the tear (Colgan et al. 2011).

By 35 Ma, a Cascade Arc was well established along its entire length. Thus, the Cascadia subduction zone affords

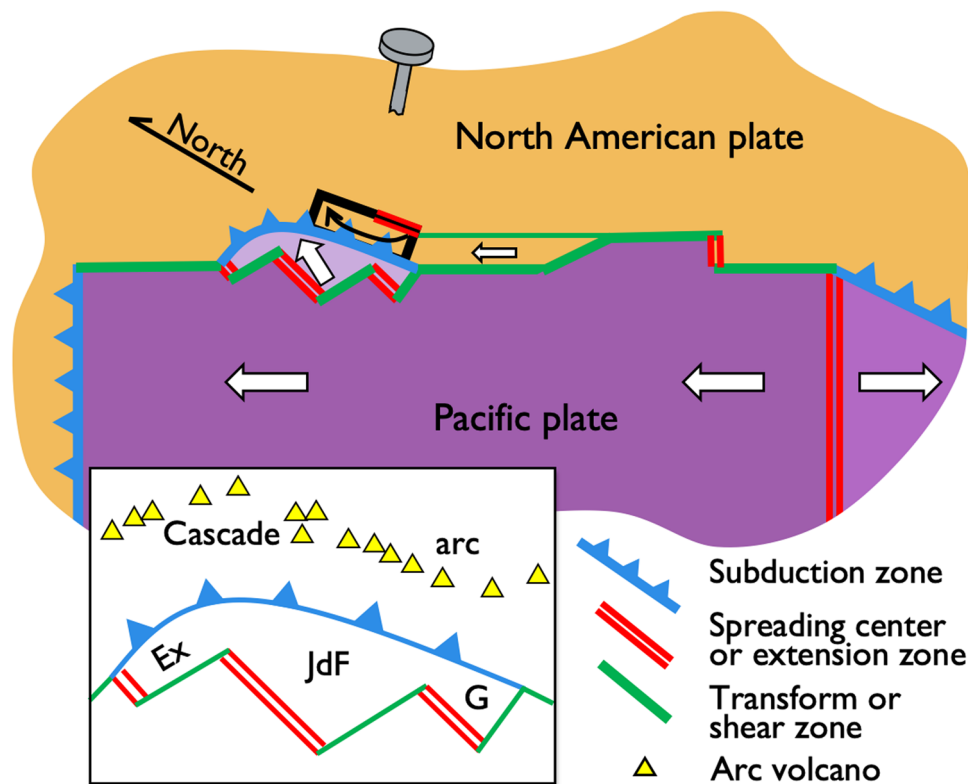


Fig. 1 Generalized representation of the Pacific, North American, and the small Juan de Fuca (with Gorda and Explorer) plates illustrating the overall dextral shear setting of western North America. Arrows show velocity (unscaled) with respect to North America. The uppermost green line represents the shear zone established in the North American plate, accommodated by the Walker Lane–Eastern California Shear Zone (Faulds et al. 2005), which allows the motion of the Sierra Nevada Klamath block (small white arrow). The black

rectangle represents the Oregon Coast Range block, rotating as it is pushed by the Sierra Nevada-Klamath block and extending along the portion shown with the double red lines. Inset shows an enlargement of the Cascadia subduction zone, showing its relation to the Cascade Arc. Also shown is the subducting Juan de Fuca (JdF), Gorda (G), and Explorer (Ex) oceanic plate system

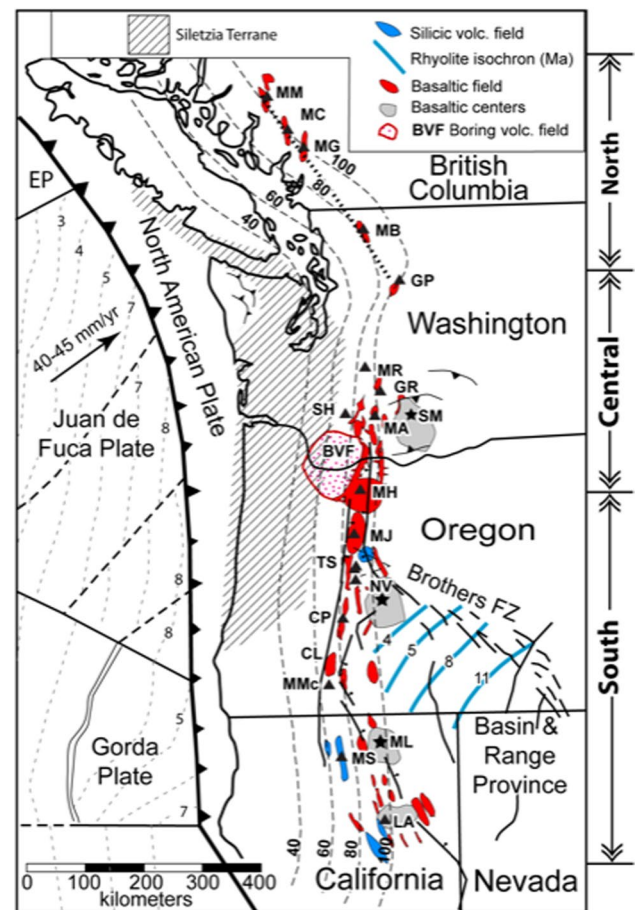
Fig. 2 Distribution of volcanism in the Cascade Arc, modified from Schmidt et al. (2008) and after Hildreth (2007). The main arc volcanoes (triangles) lie between 80 and 100 km above the top of the slab on crust that varies little from 42 ± 3 km in thickness (summary in Hildreth 2007). The crust thins strongly to the west and slightly to the east. Except where Siletzia terrane is indicated, the crust is made of Paleozoic accreted terranes stitched with Mesozoic plutons. Stars indicate rear arc volcanic centers. The northern arc is narrow and linear and near-orthogonal to subduction. Major volcanoes of the central arc are not aligned and are surrounded by abundant mainly mafic scoria cones and small shields. The southern arc volcanoes are associated with vent alignments that mimic regional extensional fault patterns. Rhyolite-cored rear-arc mafic centers (stars) are compositionally transitional between the arc and Basin and Range extensional volcanism. Mafic vent clusters (red) are distinguished from andesitic to rhyolitic vent clusters (blue). Westward-younging rhyolites of the NW Basin and Range (Ford et al. 2013) are indicated with blue isochrons. Main andesite-dacite arc volcanoes in the northern Cascade segment are MM, Mt. Meagher; MC, Mt. Cayley; MG, Mt. Garibaldi; MB, Mt. Baker; GP, Glacier Peak, also called the Garibaldi Volcanic Belt. The Silverthorne silicic volcanic center northwest of Mt. Meager is not shown. The central arc has no linear arrangement of the main volcanoes, which are MR, Mt. Rainier, the deeply glacially incised GR, Goat Rocks volcanic complex (Wall et al. 2019), MA, Mt. Adams, SH, Mt. St. Helens, and MH, Mt. Hood. Abundant distributed mafic vents distinguish the central segment and include the forearc Boring Volcanic Field (BVF; named for the town of Boring, OR), Indian Heaven and the rear arc Simcoe volcanic field (star SM) that is mainly IPB-like basalts. Mt. Hood lies at the junction with the southern arc, which is characterized by fault-parallel strings of mafic or felsic vents. The main peaks (north to south) are MJ, Mt. Jefferson; TS, Three Sisters (North, Middle and South Sister and nearby Broken Top), CP, Cappy Mountain, CL, Crater Lake (or Mt. Mazama), MMc, Mt. McLaughlin, MS, Mt. Shasta, and LA, Mt. Lassen. Rear-arc, rhyolite-cored mafic shields are Newberry Volcano (NV) and Medicine Lake Volcano (ML). For more detailed maps of vent distributions see Hildreth (2007). Behind and impinging on the southern arc lies the Basin and Range extensional province. The Brothers FZ is a concentration of NW-striking small normal faults that coincide with the High Lava Plains basalt province and the northern extent of the northwest Basin and Range. EP, Explorer plate

two examples of arc development in response to these two styles of flat- to dipping-slab transition.

For these reasons, the Cascade Arc provides a useful example to study how tectonic environment controls the emergence and maturation of a volcanic arc. Here we summarize the Cenozoic pre-Cascades history leading into a summary of the ancestral and modern Cascades, and the tectonic drivers behind the modern tectonic and magmatic segmentation of the arc.

Pre-Cascades history

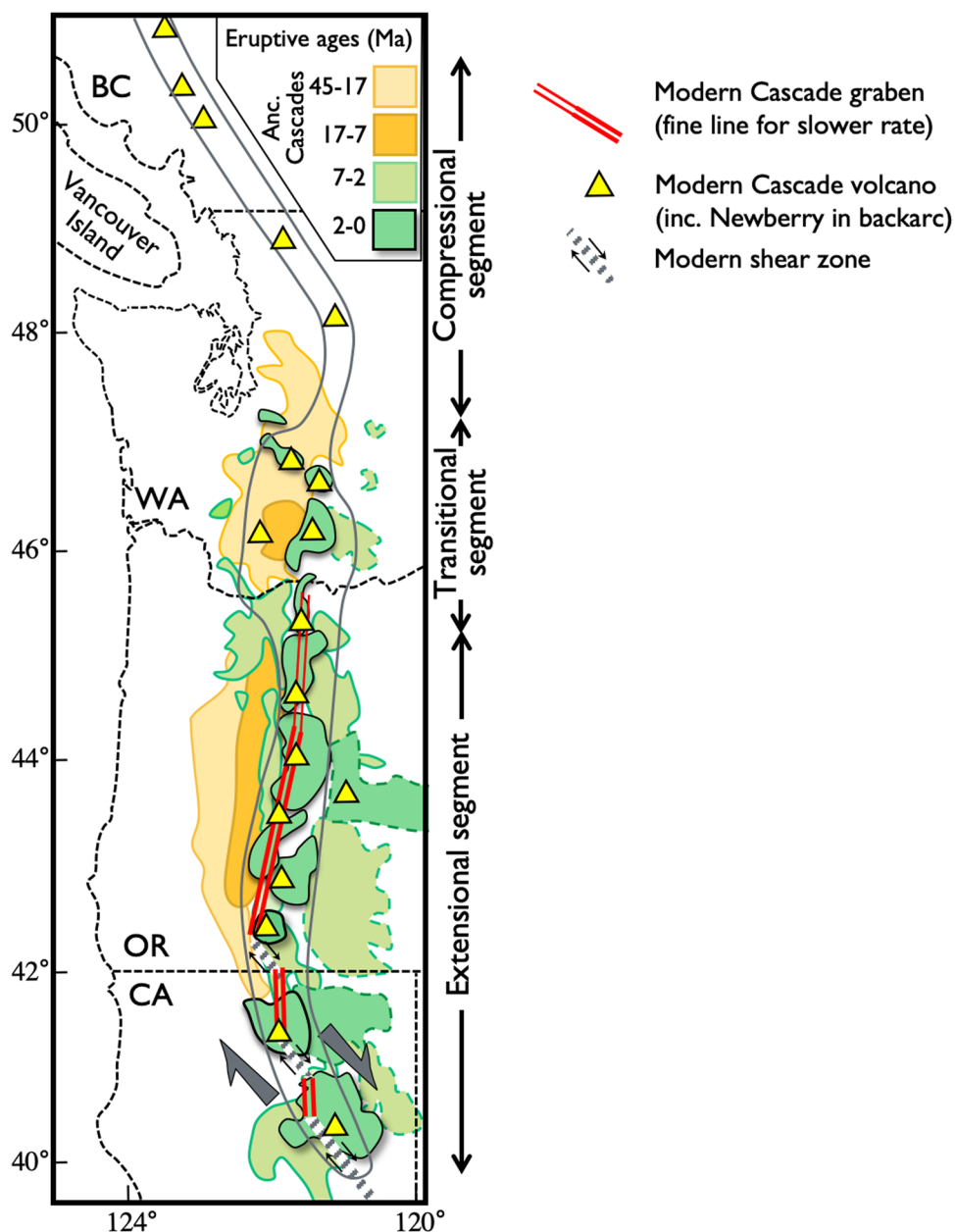
In the simplest sense, the western North America subduction margin has narrowed in width through time until all that remains is the subduction of a small remnant of Farallon plate—the Juan de Fuca plate (JdF, and connected Gorda and Explorer plates)—embedded within a wide transform margin



(Fig. 1; Atwater and Stock 1998). Farallon subduction prior to ~50 Ma occurred as a “flat” slab against the base of the PNW lithosphere (Schmandt and Humphreys 2011). With the slab separating the asthenosphere from North America, continental volcanism was absent (Dickinson and Snyder 1978; Humphreys 1995). Traction applied by the flat slab to the base of North America drove strong crustal shortening and thickening in Idaho, Montana, northeast Washington, and adjacent portions of British Columbia (Bird 1984; Carrapa et al. 2019).

Meanwhile, a spreading center separating the Farallon plate from an oceanic plate to its north incorporated the Yellowstone hotspot at ~56 Ma (Duncan 1982; Wells et al. 2014), creating the ~56–49 Myr old Siletzia large igneous province (of thickness up to 30 km, Trehu et al. 1994) on the Farallon plate (see Fig. 2 for most location names). This basalt-dominated offshore terrane then accreted to North America ~53–49 Ma (McCrorey et al. 2009; Wells et al. 2014) as Farallon plate motion carried it into the subduction zone. Siletzia sutured against the continent between the Klamath terrane to the south and Vancouver Island to the north (Fig. 2), and rocks similar to those found in the Klamath and north Cascades basement are exposed in the rear-arc of the southern Washington Cascades (Miller

Fig. 3 Volcanic and tectonic features of the Cascade Arc, illustrating the progression of Cascade Arc volcanism since arc initiation. A zone of shear and extension created by the partial entrainment of the western US margin (Fig. 1) drives extension, expressed as grabens impinging on and in the southern Cascade segment of the arc. This characteristic extension results in the abundant volcanism in this segment. The northern arc segment is in compression and is volcanically quiet. The central arc segment is a region of transition. Deformation and volcanism are distributed over a relatively wide area. The modern arc is outlined with a gray line. Abbreviations: CA, California; OR, Oregon; WA, Washington



1989), limiting the surface extent of Siletzia. With suturing, subduction initiated with a more typical normal-dip form of subduction west of Siletzia. This created the conditions for arc volcanism; early indications of arc activity are found by 45 Ma and the arc is well established by 35 Ma, built upon a basement of diverse terranes. Thus, the time lag between subduction initiation and well-developed arc was ~ 15 Myr.

Subduction initiation would have been forced by regional plate motions, focused in ocean lithosphere where a strong contrast in plate buoyancy was present (Lallemand and Arcay 2021) and probably where the lithosphere was weakened by the Yellowstone plume interaction (Gerya et al. 2015). Subduction initiation presumably occurred at one or both sites of Siletzia initial accretion and then propagated

toward the middle. Such propagation is energetically favored and has occurred in many other subduction zones (Zhou et al. 2020; Lallemand and Arcay 2021).

During the course of Siletzia accretion, the magmatic and tectonic activity across the entire PNW changed dramatically (Fig. 4). In central Oregon, Clarno volcanism began at 53.5 Ma (Bestland et al. 1999), and in central Washington, Pasco Basin crustal underplating presumably occurred during the 54–40 Ma extension of the large Pasco Basin (Catchings and Mooney 1988; Gao et al. 2011), which now lies beneath the Columbia River basalt flows (Fig. 3). This basin is kinematically related to eastern north Cascades basins (Catchings and Mooney 1988) and the nearby core-complexes in northeast Washington

(54–47 Ma, Kruckenberg et al. 2008) (Fig. 4). Tectonic and volcanic activity in northeast Washington is itself part of a large area of the PNW interior where Cretaceous compression and magmatic quiescence quickly transitioned to a tectonically tensile regime, in the Early Cenozoic, with core complex extension and attendant ignimbrite flare-up (Kruckenberg et al. 2008; Whitney et al. 2013) (Fig. 4). This includes the Kamloops, Challis, and Absaroka volcanic fields and scattered western Montana volcanism (Christiansen et al. 1992; Gaschnig et al. 2011). The amagmatic-to-flare-up transition propagated ignimbrite flare-up as part of south-sweeping belts of mainly andesite to dacite volcanism that has arc-like (calcalkaline) affinities. The subduction-like compositions result from influence of slab delamination as well as crustal contamination of the magmas (Gans et al. 1989; Best et al. 2016).

The activity brought on by Siletzia accretion involved changes in both the boundary conditions at the new subduction zone and the basal thermal conditions. We attribute the tectonic and magmatic transitions to the initiation of “unanchored” subduction, which favors slab rollback (Gurnis et al. 2004), by a 50% slowing of subduction rate (Wells et al. 1984) after Siletzia accretion, and by the coeval gravitational collapse of the previously thickened and now magmatically weakened crust of the core complexes (Fig. 4) (Coney and Harms 1984). Slab foundering beneath Idaho and adjacent Montana and Washington occurred by westward or southward delamination, as evidenced by the tomographically imaged relict slab currently dangling beneath central Idaho and northeast Washington (Schmandt and Humphreys 2011; Stanciu and Humphreys 2020; Fig. 4). The magmatic flare-up was excited by asthenospheric ascent driven by a fragmentation or foundering of the flat Farallon slab from the base of the PNW (Humphreys 1995; Schmandt and Humphreys 2011) and lithospheric extension (Catchings and Mooney 1988; White and Robinson 1992). Hence, Siletzia accretion not only initiated the dipping-slab subduction configuration, it also created a new environment upon which the Cascades were to be built.

While the above description provides a regional accounting of Eocene volcanism and tectonics in the PNW, there are several coincidental relationships associated with Siletzia accretion worth noting. The contact between Siletzia and the continent is mainly a set of west-vergent reverse faults that lacks a *mélange* zone, such as is common between accreted terranes that make up the basement collage of other subduction accretionary complexes. In a more regional sense, Siletzia and the physiographically low-lying Columbia Embayment (Fig. 4) happen to occupy the same latitudinal range, and they are each products of crustal extension that ended 50–45 Ma. The histories of Siletzia and the Columbia

Embayment appear to be closely linked, but the underlying processes relating the two are not well understood.

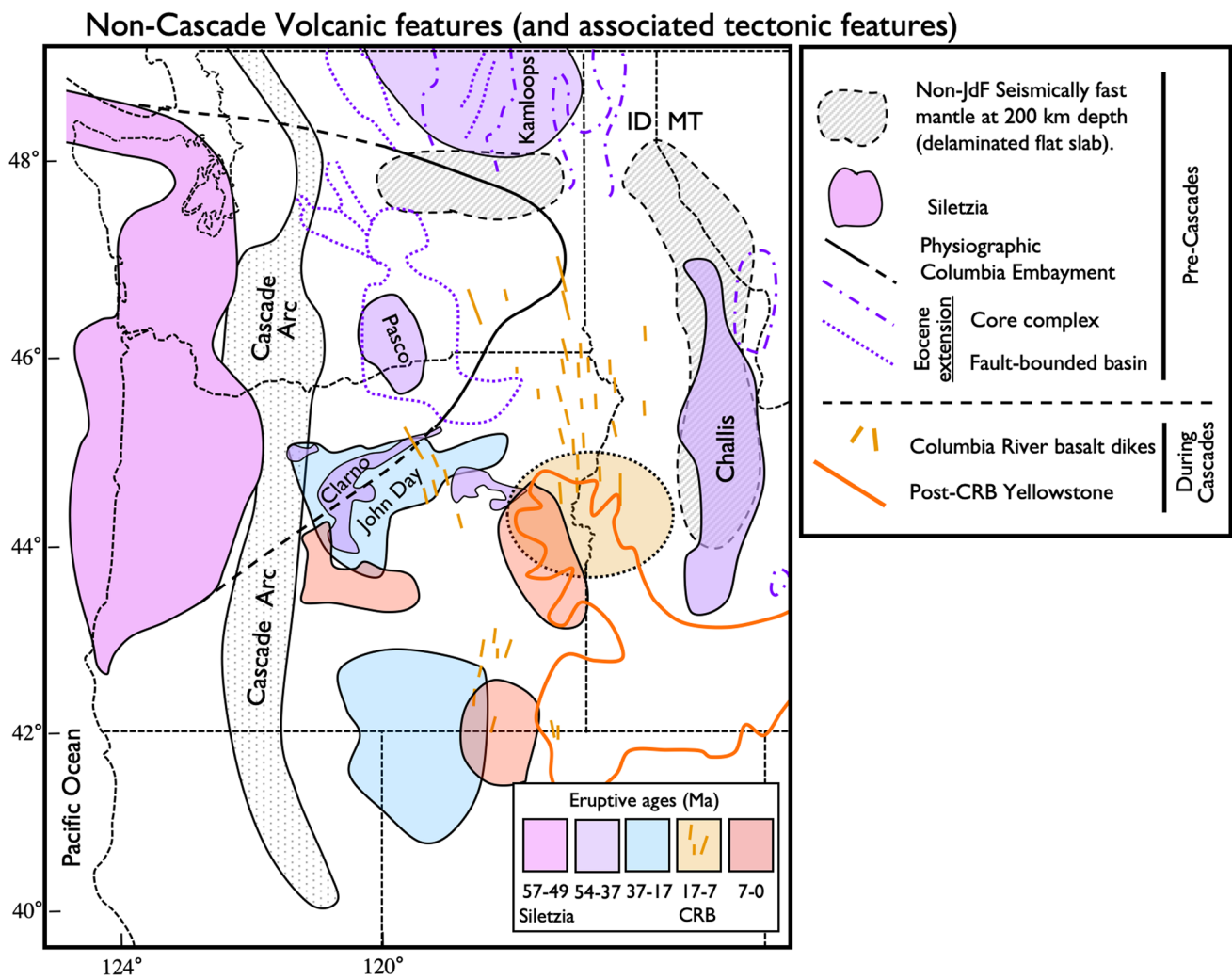
The ancestral arc, 45–7 Ma

Initiation of the ancestral central Cascade Arc is attributed to subduction at the newly formed Cascadia subduction zone outboard of Siletzia (Wells et al. 2014). The ancestral Cascade Arc south of Siletzia evolved from westward migration of volcanism following the southward sweep and rollback of the flat slab (Timmermans et al. 2020). This initial difference in slab dip was enabled by a slab tear near southern Oregon (Darold and Humphreys 2013; Colgan et al. 2011). The southern ancestral Cascades extend as far south as the southern Sierra Nevada, with volcanism being progressively extinguished as the Mendocino triple junction migrated north (Atwater and Stock 1998). Early northern Cascades volcanism might also have resulted from a rollback of a flat slab, necessitating a tear between the northern part of the subducting slab and the dipping central section.

Arrival of Siletzia induced a ~3-Myr period of shortening and right-lateral faulting (50–49 Ma) in Washington. Shortly after, Siletzia was intruded by magmas related to subduction initiation and to overriding the Yellowstone hotspot (Wells et al. 2014). In the north Cascade basement, 49–45 Ma dike swarms record right-lateral transtensional crustal deformation, expressing WNW-ESE extension (Miller et al. 2022).

The Cascade volcanic arc is well established by 35 Ma (Fig. 3). Onset of volcanism is as old as ~45 Ma, based on the distribution of ages of volcanic rocks in Washington to northern California (du Bray and John 2011). Mullen et al. (2018) place early arc magmatism at ~35 Ma in northern Washington (Chilliwack Batholith east of Mt. Baker) with onset ages decreasing to the north. From southern Washington through Oregon, arc volcanism began at ~43.5–35 Ma (Priest 1990) and at ~35 in the California ancestral Cascades (du Bray et al. 2014). Alkalic basalts and related alkalic intrusions (40–29 Ma) were erupted in the early forearc related to dextral transtension (Wells et al. 2014). In any case, the interval for subduction re-initiation between final accretion of Siletzia (51–49 Ma; Wells et al. 2014) and well-established arc volcanism at 35 Ma is on the order of 15 Myr.

The composition of the earliest volcanic rocks is mainly tholeiitic (high Fe/Mg at given SiO₂) basalts and basaltic andesites (Figs. 5 and 6), possibly related to slab window processes (du Bray and John 2011). The west side of the arc was at the strand line. By 35 Ma, the arc developed more typical arc compositions, with calcalkaline basalts joined by andesite, dacite, and rhyolite. While different



parts of the arc, in space and time, have distinct histories, overall the subduction character increases in time, as measured by increasing Ba/Nb in basaltic rocks (Fig. 6). Increase of Ba/Nb within age suites, and the steepening of the Ba/Nb pattern with respect to silica with time (Fig. 6), indicates crustal assimilation during differentiation and an evolution of that crust in time, respectively.

We propose that early Cascadia subduction beneath Siletzia is a period of slab rollback as Gurnis et al. (2004) model for nascent arcs and a period of reduced rate of subduction (Wells et al. 1984). Rollback, in turn, leads to a period of extension, and the consequent rapid influx of hot basalt produces a pulse of silicic magmatism through partial melting of the new arc crust not previously melted (viz., fertile). A silicic pulse is recorded in the northern Cascades, where high rates of pluton emplacement from 32 to 29 Ma are interpreted by Mullen et al. (2018) as a magmatic flare-up. This overlaps the flare-up of ignimbrites in the arc in central Oregon, which correlates to the John Day Formation. Priest (1990) recognized the interval of

35–17 Ma, dominated by the John Day ignimbrite flare-up, as the most voluminous period of silicic volcanism in the arc with an estimated volcanic production rate of $\sim 20 \text{ km}^3/\text{Ma}$ per km arc, of which 60% was silicic. Magmatic loci (intrusions and calderas) related to the John Day flare-up (Fig. 4) range from the present arc axis to 170 km east, defining an arc width of 130 km (170 km, corrected for extension and forearc rotation) (du Bray and John 2011; McClaughry et al. 2009). Back-arc alkalic basalts extend at least another ~ 100 km east, consistent with the ongoing phase of extensional tectonic excitation. We favor this model for delivering the John Day-age ignimbrite flare-up to the arc over models that involve the Yellowstone plume, as the plume would have been well to the south. Alternatively, the John Day ignimbrite flare-up may be reconciled with a piecemeal delamination of a piece of the Farallon slab, analogous to lithosphere delamination models used to explain ignimbrite flare-up in the central Andes (e.g., de Silva and Kay 2018).

Fig. 4 Volcanic and tectonic features of the Pacific Northwest, illustrating the pervasive volcanism that has occurred since the accretion of Siletzia. This includes effects of slab delamination, hot spot volcanism, and arc volcanism. Pre-Cascades volcanism in cool colors and post-Cascades volcanism in warm colors. Modern Cascade Arc, from Fig. 3, shown for reference. The physiographically low-lying Columbia Embayment is shown with a solid line, and is extended with dashed lines the two Siletzia sutures. Abbreviations: CRB, Columbia River Basalt; ID, Idaho; MT, Montana. 54–37 Ma: During and immediately following Siletzia accretion, delamination of the flat oceanic slab and the change in western margin boundary conditions initiated the Kamloops-Challis-Absaroka andesite-ryholite volcanic flare-up [1] and a regional extension that included core complexes [2]. The delaminated oceanic slab is imaged as slab-like structures beneath central Idaho and eastern Washington [3]. Disrupted flat Farallon slab beneath central Oregon produced Clarno volcanism [54–40 Ma; 4] and a large central Washington Pasco-area magmatic underplate. The area labeled Pasco is the imaged crustal underplate [5]. Pasco Basin extension created a deep sediment-filled valley. The dotted line around this is the sedimentary Pasco Basin [6]. New subduction initiated outboard of Siletzia with Cascade Arc onset ~45–35 Ma. 37–17 Ma: Voluminous ignimbrite volcanism of the 40–22 Ma John Day Formation [7] and alkalic basalts in the back arc, results from extension of the arc owing to roll back of the new and dynamically unsupported slab. The arc transitions from tholeiitic onset to calcalkaline volcanism. 17–7 Ma: Emergence of the Yellowstone plume in North America drives eruption of the Columbia River Basalt Group from dikes in eastern Oregon and adjacent Washington, Idaho, and Nevada. The main chamber, as proposed by [8], is shown with an orange oval spanning the Oregon-Idaho state line. These flows cover much of southern Washington and northern Oregon. Abundant pencontemporaneous silicic volcanism marks the onset of ENE migrating ignimbrite volcanism associated with migration of the hot spot (relative to North America) along the Snake River Plain to Yellowstone today. WNW-migrating silicic volcanism across the northwest Basin and Range initiates owing mainly to slab steepening and roll back or corner flow [9]. 7–0 Ma: Extensional tectonics arrive in the arc related to north- and westward propagation of the Basin and Range driven by westward shift of Pacific plate motion. LKT basalts become a prominent and distinctive part of the southern arc that is cut by grabens and is 100 km wide. Continued northerly compression and a bend in the subduction zone to orthogonal convergence contribute to a narrow, linear arc in the north. Volcanism in the central arc is widely distributed owing to abundant transtensional and transpressional faulting [10], [1]. Armstrong and Ward (1991) and Christiansen et al. (1992), [2] Armstrong and Ward (1991), and Whitney et al. (2013), [3] Schmandt and Humphreys (2011), and Stanciu and Humphreys (2020), [4]. Bestland et al. (1999), Catchings and Mooney (1988), and Darold and Humphreys (2013), [5]. Underplate area is $\Delta V_s > 6\%$ at 25 km from Gao et al. (2011), and discussed by Catchings and Mooney (1988) and Perry-Houts and Humphreys (2018), [6]. Sedimentary Pasco Basin is $\Delta V_s < 4\%$ at 5 km from Gao et al. (2011), and discussed by Catchings and Mooney (1988), [7]. Summary by McClaughry et al. (2009), [8]. Wolff and Ramos (2013), [9]. Gao and Long (2022, in press), Ford et al. (2013), and Draper (1991), [10]. Blakely et al. (1997) and Brocher et al. (2017)

Although the distribution of the ancestral western Cascades in Oregon suggests eastward migration of the arc axis, the distribution mainly tracks the clockwise rotation of the forearc (Wells and McCaffrey 2013, Figs. 3 and 5). Westward movement is a product of accelerated opening of the Great Basin (starting ~17 Ma) and the northern motion of

the Sierra Nevada/Klamath (SN/K) block causing clockwise rotation, starting ~8 Ma (Atwater and Stock 1998). In contrast, in the northern Cascades the ancestral arc axis migrated slightly west (Fig. 5), indicating slab steepening or rollback (du Bray and John 2011; Mullen et al. 2018) or an eastward drift of the forearc (Wells and McCaffrey 2013). Increasingly oblique subduction, except in the northernmost segment (Figs. 2 and 3), and decreasing convergence rate, caused a decrease in productivity throughout the arc, although the southern arc received an influx of extension-associated basalts after 7 Ma.

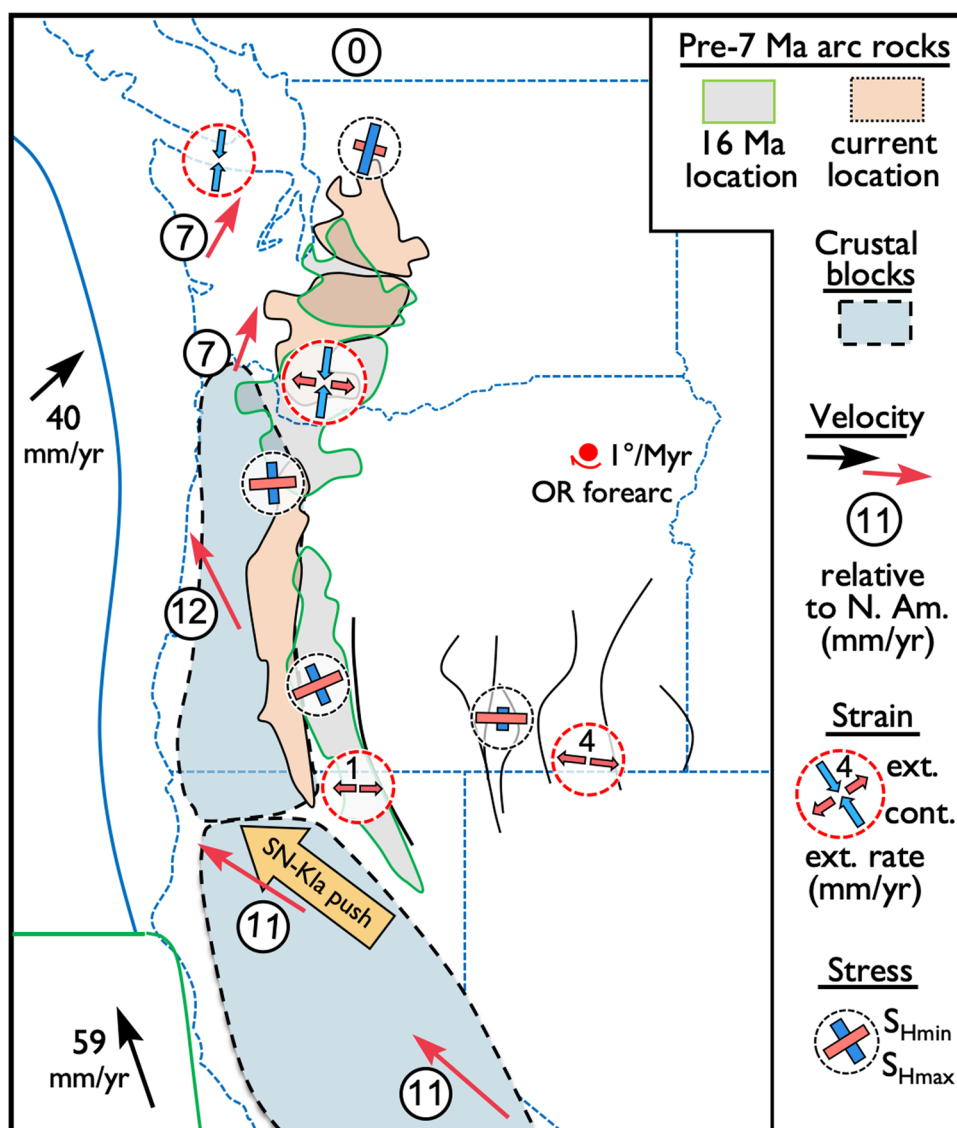
Blueprint for the modern arc 7–0 Ma

At ~8 Ma, Pacific motion rotated clockwise (accommodating less North American extension) and the SN/K block became more strongly entrained with the motion of the Pacific Plate (Atwater and Stock 1998). The Juan de Fuca plate attained its current kinematic configuration around 6–5 Ma (Wilson 1993), as the spreading direction rotated clockwise and its easterly velocity slowed. This created the modern arc architecture, which we divide into three tectonic segments: the south, extension-dominated arc, the north compression-dominated arc, and the central transitional segment (Figs. 3 and 5) that roughly correspond to the three-fold fore-arc segmentation based on block motions by Wells et al. (1998). Pioneering work by Guffanti and Weaver (1988) used vent distributions to define 5 segments in the arc. The northern arc and central arc described here match their segments 1 and 2, respectively. We group their segments, 3–5 into the southern arc. Each segment has distinctive vent distributions (Hildreth 2007; Fig. 2), with a narrow and straight northern arc, a wide central arc without a clear arc axis, and a complex southern arc.

Corresponding architecture of the subarc mantle has been explored by assessing the proportions and characteristics of basalts along the arc (Schmidt et al. 2008; Mullen et al. 2017; Pitcher and Kent 2019). The three main basalt types arc-typical, subduction-fluxed calcalkaline basalts (CAB), low-K, high-alumina tholeiites (LKT) similar to MORB, and intra plate-like basalts (IPB) that are enriched in high field strength elements (e.g., Nb, Ti) (e.g., Bacon et al. 1997; Conrey et al. 1997, and summaries by Schmidt et al. 2008; Mullen et al. 2018; and Pitcher and Kent 2019). CAB are common along the entire arc. LKT basalts occur most prominently in the south arc segment. IPB are least common and occur mainly in the central and northern segment.

LKT basalts are near-dry decompression melts and equilibrated 5–10 km below the Moho (Till et al. 2013; Carlson et al. 2018). The LKT share trace-element depleted characteristics of MORB, but have high Sr, Ba, and Pb indicating input of an older subduction component

Fig. 5 Modern tectonic framework of the Cascades. The general setting is one of dextral shear (Fig. 1), in which North America is contained from significant expansion by the Pacific plate but is relatively unconfined and allowed to expand over the subducting Juan de Fuca plate. The Sierra Nevada/Klamath block (southern blue area) is entrained by the Pacific plate (Fig. 1) and pushes against the Oregon Coast Range block (northern blue area), driving its southern end NW over the Juan de Fuca plate. This results in moving the Oregon Cascades ancestral arc northwest (shift from green outline areas to tan areas) and off of the volcanic axis; extending the active Oregon arc and back arc Basin and Range; and adding N-S compression to the Washington arc, which drives pure and simple shear strain distributed in the central arc (southern Washington and adjacent Oregon). Map is modified from Wells and McCaffrey (2013). Resulting stresses, strains, and block velocities are shown



and occur widely in the arc and back arc (e.g., Jordan et al. 2004; Hildreth 2007). We attribute this old subduction signature to the effect of the shallow Farallon slab on the lithosphere under the PNW, consistent with He isotopic data of the LKT province of eastern Oregon being slightly displaced from MORB values toward lithosphere (Graham et al. 2008). Based on high-precision Pb isotope work (Mullen et al. 2017) indicates that CAB and LKT basalts define a modern Cascadia subarc mantle that is a binary mixture between variably depleted Pacific MORB-like mantle and slab input like North Cascadia sediments. They find no component of cratonically influenced Astoria fan sediments (Columbia River fan). IPB-like basalts have little or no subduction signature and are not on the mixing line defined by the CAB and LKT. An additional enriched mantle source(s) is required. In the northern Cascades,

the IPB source is attributed to a Pacific hot-spot influence (Mullen and Weis 2015; Mullen et al. 2017). In the central arc, deviation from the mixing line (Adams array of Mullen et al. 2017) may reflect relict Siletzia mantle (Schmidt et al. 2008) or a yet to be identified mantle source.

Southern arc

As the Pacific plate moves NNW past the North American plate, it entrains the mechanically strong SN/K block, accommodated by ~11 mm/year of right-lateral deformation in the Walker Lane Belt and Eastern California Shear Zone (Faulds et al. 2005) (Figs. 1 and 5). The SN/K block is misaligned with the Oregon Coast Ranges block by ~30° (Fig. 3). The force resulting from

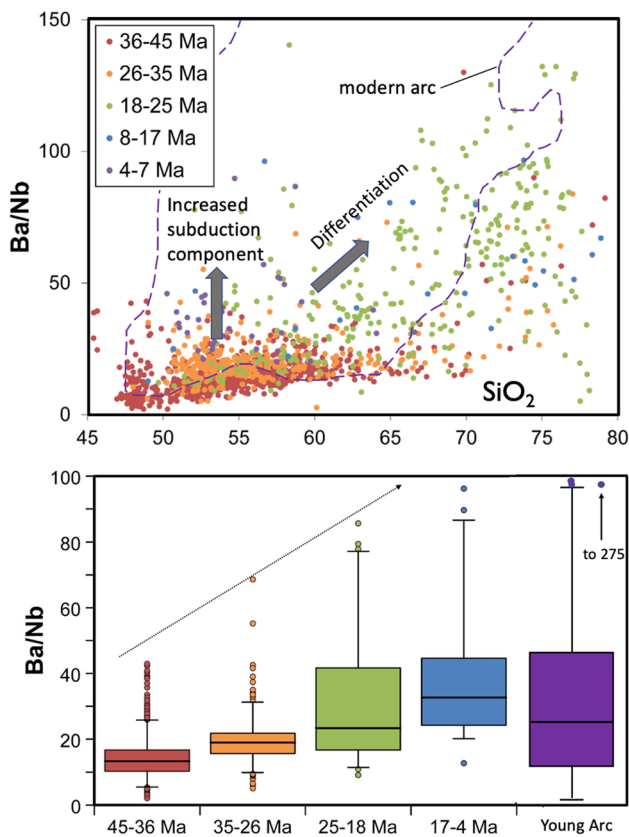


Fig. 6 Upper panel: Ba/Nb versus SiO₂ (weight percent) of the Cascades Arc. Overall, the arc has evolved from a dominantly mafic volcanic composition with low Ba/Nb not much different from mid-ocean ridge basalts to a more evolved (silicic) arc with elevated Ba/Nb. Among mafic compositions, where fractionation does not increase Ba/Nb (owing to similar compatibility of Ba and Nb), Ba (and Sr) increase is caused by more subduction flux among mafic compositions (see lower panel). General increase of Ba/Nb with SiO₂ reflects differentiation from basalts by crystal fractionation (as Ba becomes more incompatible) and is enhanced by crustal assimilation. The arrow indicating differentiation is a schematic trajectory for Fractional Crystallization coupled with crustal Assimilation (AFC). The increasingly high Ba/Nb with time among the silicic part of the suite indicates increasing crustal assimilation and (or) evolution of the crust with time. Data and field of modern Cascades from compilation of from du Bray and John (2011). Lower panel: Ba/Nb of mafic rocks (<55 wt% SiO₂) shown as box and whiskers. The box encompasses 50% of the data that lie close to the mean, which is the horizontal line. The whiskers represent the 25th and 75th quartile of the data from the mean, with points outside the range as dots, mainly distributed to higher Ba/Nb. In the younger arc, Ba/Nb reaches the highest values. For the young arc, the data are screened not only for <55 wt% SiO₂, but also for MgO > 6. Note the decrease in mean of the young arc. This reflects addition of abundant LKT that lack arc-like Ba/Nb enrichment

SN/K motion pushes the Oregon Coast Ranges both north (parallel to the subduction zone) and west (over the subduction zone), a motion that is well described by rotation about a pole (Wells and McCaffrey 2013, Fig. 5). Contributing to the northward transport of the Oregon

Coast Range is the oblique subduction of the Gorda/JdF plate. The southern arc is in transtension as the forearc rotates clockwise and the Basin and Range extends (Fig. 5).

The most distinctive attributes of the southern Cascades Arc are as follows: (1) Basin and Range normal faults flank its eastern side and invade the arc, and (2) distinctive LKT are dominant to subequal to CAB (Pitcher and Kent 2019). The southern arc in Oregon is ~ 100 km wide and largely mafic, owing to the many extension-related mafic centers (Hildreth 2007). LKT magmatism results from upwelling mantle beneath the northwest Basin and Range, driven by extension, corner flow in response to a possible steepening Cascadia slab and trench rollback (Gao and Long 2022 in press), and toroidal flow around the southern margin of the subducting JdF plate (ibid., Zandt and Humphreys 2008; Carlson et al. 2018). Westward flow of the upwelling mantle into the arc is recorded in a pattern of west-northwest migrating silicic volcanism across the northwest Basin and Range since ~ 11 Ma (Fig. 2) and strong east–west anisotropy of the upper mantle (Long et al. 2009; Gao and Long 2022, in press).

A pulse of LKT basalt across the High Lava Plains at ~ 7.5 Ma (Jordan et al. 2004) immediately precedes arrival of LKT and intra-arc extension where the Basin and Range terminates into the arc (e.g., Priest et al. 2013). A brief flare-up of ignimbrite volcanism (6.2–5.5) ensued as this pulse of basalt partially melted the crust (Pitcher et al. 2022). The hot, dry (damp), reducing nature of these rhyolites is akin to rhyolites of the High Lava Plains as well as to rhyolites of the Cascades rear-arc volcanoes, Newberry and Medicine Lake (Fig. 2), and is unlike cold, wet and oxidizing rhyolites typical of arcs, including elsewhere in the Cascades (ibid.). In the southern Oregon Cascades, extension in the arc began about 4 Myr ago (Priest et al. 2013), and the LKT front immediately behind the arc advanced westward at ~ 10 km/Ma since ~ 3 Ma, with simultaneous narrowing of the arc.

The most iconic but least typical volcano of the southern segment is Mount Shasta. At ~ 450 km³, it is the most voluminous Cascades volcano (Hildreth 2007) and has a large array of Mg-rich basalts through dacites. Grove et al. (2002) make a compelling case for slab-margin melt contribution to fluxing of the mantle wedge, based on high water content and inferred residual garnet in primitive high-Mg Shasta basalts.

Northern arc

In the north, subduction obliquity ends at a bend in subduction zone orientation. At this bend, Vancouver Island acts as backstop to the northward translation of the Cascadia

forearc. The concave-out polarity of the bend causes an arch in the subducting JdF plate (Chiao et al. 2002); the resulting shallow subduction leads to increased compression in the forearc. The net result is NNE compression of the northern Washington arc (Fig. 5; Wells and McCaffrey 2013). Mafic vents associated with major Canadian Cascade Arc volcanoes are distributed in a N-S pattern, slightly oblique to the arc axis (Fig. 2), consistent with dextral transpression.

In the northern arc, the main volcanoes are well aligned and the arc is most narrow (~25 km; Hildreth 2007). Unlike the rest of the arc, this segment is dominantly (~75%) dacite and rhyodacite. The arc locus at Glacier Peak and Mt. Baker has migrated to the southwest for a respective ~4 to 11 Ma (Fig. 3), interpreted as slab steepening resulting from the reduced convergence rate (Mullen et al. 2018) and an eastward motion of the upper plate (Wells and McCaffrey 2013).

The proportion of IPB to CAB increases to the north toward the slab tear between the JdF and Explorer plates (Venugopal et al. 2020). Excepting Glacier Peak, the northern arc volcanoes make an isotopic array between a subduction-fluxed depleted (MORB source-like) mantle, which has less slab contribution than in the High Cascade array, and an enriched source. The slab contribution increases northward, tracking with less dehydrated slab (ibid.). The enriched source yielding IPB-like basalts is attributed to mantle similar to NE Pacific seamounts leaking around or through the slab (Mullen et al. 2017) or caused by deep melting at the slab tear (Venugopal et al. 2020). Basalts near Mt. Baker and Glacier Peak volcanoes (Fig. 2) are dominantly CAB and high-Mg basaltic andesite (albeit few primitive) that are interpreted as slab fluxed melts of depleted mantle (Sas et al. 2017) and are not like the wet slab-edge melts inferred at Mt. Shasta volcano.

Central arc

The northward velocity of the arc and forearc diminishes rapidly between northern Oregon and central Washington, accommodating 4 mm/year of N-S shortening (Fig. 5). Earthquakes occur throughout this area, transitioning from transtension in the south to transpression in the north (Brocher et al. 2017) with N-S maximum horizontal compression (Fig. 5). The resultant shear deformation is accompanied by pull-apart type geometries that distribute deformation and magmatic pathways over a wide area. The central Cascades Arc is uncommonly wide, 160 km, including the frontal arc mafic centers, e.g., the Boring volcanic field, and the rear-arc, mainly alkali basalt (IPB) Simcoe volcanic field (Fig. 2). The major volcanoes are not aligned. Mt. St. Helens and Mt. Rainier volcanoes lie trenchward of the northward projection of the Oregon arc axis, which trends northward from Mt. Hood to Adams

volcanoes and through the recently extinct Goat Rocks center. The structural complexity of the central arc can account for the wide distribution of volcanoes and a slab tear is not mandated. The central arc is separated from the northern arc by a 120-km long volcanic gap that coincides with the change in orientation of the arc and curvature of the subduction zone (Fig. 2).

The central arc has subequal proportions of CAB, LKT, and IPB (by number of analyses; Pitcher and Kent 2019). IPB compositions occur mainly in the eastern arc and rear-arc, particularly in the Simcoe volcanic field. Sparse absarokitic basalts occur across the transect and compositionally track best with IPB. The basalts fall mainly on the High Cascades Pb isotopic array, but IPB of Mt. Adams and Simcoe volcanic field define a separate Adams array (Mullen et al. 2017). The enriched component could be Pacific seamount-like mantle leaking through the slab, as in the northern Cascades (Mullen et al. 2017), but a relict mantle domain associated with Siletzia is plausible and proximal (Schmidt et al. 2008; Leeman et al. 2005).

The breadth of the central arc has invited examination of cross-arc transects from Mt. St. Helens to Simcoe volcanic field. The proportion of IPB is greater eastward, and deeper mantle equilibration is inferred (25–50 km near St. Helens; 60–90 under Simcoe). Rapid dehydration of the subducting slab, commensurate with its young, hot character and commensurate with B and Li isotope variation (Leeman et al. 2004), has not affected the character of more deeply derived subduction flux (Leeman et al. 2005; Hildreth 2007). The eastward K₂O increase among more silicic rocks in this arc segment reflects their crustal history. Unusually K-poor dacites distinctive of Mt. St. Helens are influenced by partial melting of K-poor, mafic crustal rocks and are not slab melts (Smith and Leeman 1987).

Young, hot, slow

The Cascades Arc noted for having a young and hence hot down-going plate and a low (orthogonal) convergence rate. The buoyant slab is shallow under the forearc and then steepens rapidly (Schmandt and Humphreys 2011), presumably owing to the ocean crust's transition to eclogite. The hot slab is thought to drive shallow dehydration and accounts for relatively low water concentrations in Cascades Arc basalts compared to other arcs (3.4 vs. 4–6%; Plank et al. 2013). While the high incidence of LKT is distinctive of the Cascade Arc and uncommon in other arcs, the CAB of the Cascades are not unusual compared to other arcs. The substantial overlap in mantle equilibration temperatures of CAB (estimated mantle extraction depth 48–55 km and initial temperature 1185–1323 °C) and LKT (39–60 km; 1295–1383 °C) and proximal eruption of distinct basalts in

the southern arc make clear that the dispersal of subduction flux into the mantle wedge is heterogeneous and complex and not simply layered (Donnelly-Nolan et al. 2013; Priest et al. 2013; Till et al. 2013; Carlson et al. 2018; cf Leeman et al. 2005).

Despite the slow orthogonal subduction rate (20 mm/year in Oregon to 40 mm/year in Washington), the total erupted Quaternary volume (6400 km³) is similar to continental arcs built on immature crust (viz., southern Andes and the central America; Hildreth 2007); albeit inferred mantle input rate declines to the north (Till et al. 2019). The overall productivity, despite slow subduction, we attribute to mantle upwelling driven by the overall extension that is greatest in the southern the arc (Fig. 3; Blakely et al. 1997; Wells and McCaffrey 2013). The resultant structurally disrupted, leaky crust, accounts for the high abundance of scattered volcanic vents and a diffuse arc in the central and southern Cascades.

Conclusion

The Cascade Arc is young (~45 to 0) and relatively short (1300 km), built on a region of complex tectonic history. We emphasize control on Cascade Arc volcanism created by two tectonic events: subduction initiation and deformation-controlled arc segmentation.

The key tectonic event for onset of the arc was the ~50 Ma accretion of the Siletzia large igneous province, which necessitated initiation of subduction outboard of Siletzia and the abandonment of flat-subducting slab beneath the Pacific Northwest interior. Early indications of the new arc are seen ~5 Myr after initiation, and a well-developed arc is present at 35 Ma, ~15 Myr after initiation. Regional extension excited by young unanchored subduction enhanced early magmatic production, and a transition from the eruption of largely mafic (tholeiitic) lavas to calcalkaline volcanism and a pulse of ignimbrite activity. Subduction south of accreted Siletzia was left in a flat slab configuration, but soon roll-back steepened the slab. Thus, the Cascade Arc preserves a northern portion that involved a newly created subduction zone and a southern portion that involved propagation of a volcanic front into an area previously underlain by flat slab. These kinematic and volcanic aspects of Cascade initiation have been largely unrecognized in the past.

Starting at ~7 Ma, the Cascade forearc began rotating clockwise while moving north. This created a stress field that established an arc segmentation: extension in the southern arc, compression in the northern arc, and complex shear deformation in the central arc. This results in (1) abundant volcanism in the southern arc with basalts formed by decompression melting of depleted mantle (low-K tholeiites) subequal to subduction enriched calcalkaline (subduction)

basalts; (2) restricted volcanism focused on the narrow, linear northern arc, where calcalkaline basalts are joined by intraplate-like basalts, probably from entrained Pacific mantle; and (3) a wide and volcanically complex transitional region between, lacking an arc axis and with diverse basalts.

The Cascade Arc thus affords some unusual opportunities for the study of arcs. Cascade Arc history is relatively well understood, and we recognize two primary tectonic controls on its development. The first involves activity beneath the arc as two sections of subducting slab each approach dynamic equilibrium. Subduction initiation was rather sudden and slab edges resulted, creating strong temporal and spatial gradients. The second and more recent tectonic control involves the creation of strong along-arc gradients in stress and strain acting within the arc's lithosphere itself.

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