WHY STUDY THE CASCADE ARC?

Eugene D. Humphreys[1] and Anita L. Grunder[2]

DOI: 10.2138/gselements.18.4.219

The Cascade subduction zone (also known more generally as *Cascadia*) is but one of many subduction zones in the world. Why, then, is it so special and study-worthy in the global scheme? For a start, Cascadia represents an endmember setting for continental subduction zones—where compared with other subduction zones, the subducting oceanic lithosphere is young, warm, and subducting slowly. Cascade subduction is also unusual in other respects—for example, episodic tremors and slips are common but large earthquakes are uncommon, and the effects of toroidal mantle flow can be observed at the southern end of the subducted Juan de Fuca slab.

Here, we highlight three other aspects of the Cascade subduction zone that we believe make it specifically worthy of study: (1) its interaction with a continental shear zone; (2) its sudden initiation; and (3) its interactive history with an oceanic plateau and a mantle plume. Each of these characteristics provide an unusual opportunity for gaining a greater understanding of subduction zones and associated volcanic arcs around the world.

REGIONAL INTERACTIONS AND VARIATIONS

When viewed at the continental scale, Cascadia is a relatively short subduction zone embedded within a long right-lateral shear zone (Atwater 1970; Fig. 1). Although short, the region varies strongly in the stress regime imparted by the transtensional (i.e., combined shear and tension) tectonic setting, yielding a magmatic and geomorphological character defined by three distinct geomorphological segments: the Klamath–Sierra Nevada block pushes the Siletzia block away from the southern Cascades (Wells et al. 1998; Fig. 1). In response, extension in the backarc is encroaching on the southern part of the arc (California through the graben-faulted central Oregon Cascades) (Fig. 2). The impact of these environments can also be seen through the window of mantle geochemistry—as reflected in the composition of erupted basalts. In the extension-dominated southern segment, mafic volcanism is unusually abundant with low-K tholeiites (LKTs) subequal to

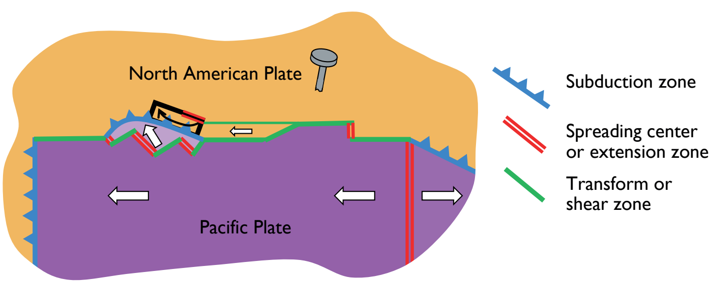

Figure 1 Generalized representation of the Pacific, North American, and small Juan de Fuca (with Gorda and Explorer) plates illustrating the overall dextral shear setting of western North America. Arrows show velocity (unscaled) with respect to North America. The upper thin green line represents the shear zone established in the North American plate, accommodated by the Walker Lane–eastern California shear zone, 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 area shown with the double red lines.

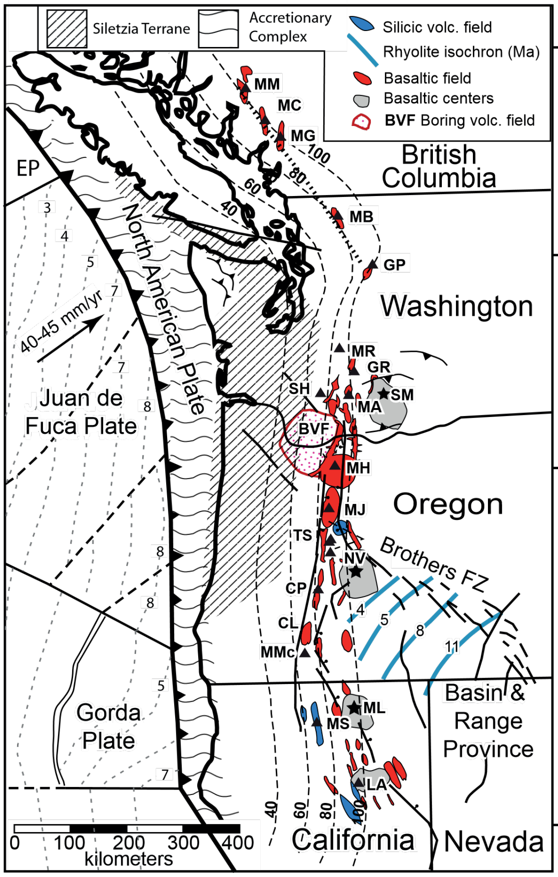

Figure 2 Distribution of volcanism in the Cascade arc modified from Schmidt et al. (2008) and Hildreth (2007). Main-arc volcanoes are indicated by triangles, and rear-arc volcanoes are indicated by stars. Mafic vent clusters (red) are distinguished from andesitic to rhyolitic vent clusters (blue). Westward-younging rhyolites of the Northwest Basin and Range (Ford et al. 2013) are indicated with blue isochrons. The crust has a thickness of 42 ± 3 km and thins strongly to the west and slightly to the east. Except for the Siletzia terrane, the crust consists of accreted terranes stitched with Mesozoic plutons. EP: Explorer plate. The main andesite–dacites in the northern arc are MM: Mount Meagher; MC: Mount Cayley; MG: Mount Garibaldi; MB: Mount Baker; and GP: Glacier Peak, also called the Garibaldi volcanic belt. In the central arc, there are MR: Mount Rainier; GR: Goat Rocks volcanic complex; MA: Mount Adams; SH: Mount St. Helens; and MH: Mount Hood. Abundant distributed mafic vents distinguish the central segment and include the forearc Boring volcanic field (BVF; named for the town of Boring, Oregon), Indian Heaven, and the rear-arc Simcoe volcanic field (star SM) that is mainly intraplate-like basalts. Mount Hood (MH) lies at the junction with the southern arc, with main peaks MJ: Mount Jefferson; TS: Three Sisters (and Broken Top); CP: Cappy Mountain; CL: Crater Lake; MMc: Mount McLaughlin; MS: Mount Shasta; and LA: Mount Lassen. The Newberry (NV) and Medicine Lake (ML) volcanoes are rear-arc, rhyolite-cored mafic shields.

the more arc-typical calc-alkaline basalts. Such LKT magmas are largely produced by decompression of upwelling mantle, which equilibrated and ascended from the mantle not far below the Moho (Till et al. 2013; Mullen et al. 2017). The extending backarc region of the southern segment is dominated by LKTs. Associated westward-migrating silicic magmatic centers, active since ~12 Ma (Fig. 2), and strong east–west mantle anisotropy are further evidence for westward encroachment of the Basin and Range extensional province into the arc itself. In stark contrast, in the northern arc, the shear setting and arched slab beneath the concave-out subduction zone drive across-arc contraction. Consequently, volcanism is largely limited to andesite- and dacite-

1 Department of Geological Sciences
University of Oregon
Eugene, OR 97403, USA
E-mail: genehumphreys@gmail.com

2 College of Earth, Ocean and Atmospheric Sciences
Oregon State University
Corvallis, OR 97331, USA
E-mail: grundera@geo.oregonstate.edu

dominated edifices with few proximal vents of mainly calc-alkaline basalts, and virtually no LKTs. Basalts with alkalic, intraplate affinities also increase northward. Where these two regions meet, in the central Cascades of southern Washington, a zone of complex deformation occurs. The axis of major andesite–dacite stratovolcanoes loses definition, and mafic vents are scattered over a 160-km-wide zone—making Cascadia at this location one of the widest volcanic arcs in the world. Here, calc-alkaline and LKT basalts occur across the arc and are joined by enriched intraplate-type basalts that are isotopically distinct from the Cascade array and increase in prominence eastward (e.g., Pitcher and Kent 2019).

SUDDEN INITIATION

The Pacific Northwest region, of which the Cascade volcanic arc constitutes a key part, hosts one of Earth's great continental volcanic provinces. This is largely a consequence of a remarkable transition from flat-slab to normal-dip subduction that occurred in the early Eocene (Darold and Humphreys 2013). The Cascade arc is the most recent manifestation of this transition, which occurred suddenly, but also in several distinct phases. Early Cenozoic flat-slab subduction was amagmatic and contractional, as was typical of the Laramide orogeny elsewhere. This phase ended quite suddenly with the ~50 Ma accretion of the mafic and buoyant Siletzia terrane, which caused subduction to step west of Siletzia and establish early Cascadia subduction. Foundering of the abandoned flat slab initiated a major ignimbrite flareup in the western U.S., and an abrupt change to a new, tensional environment (Gurnis et al. 2004) enabled the gravitational collapse (and attendant extension) of the Pacific Northwest interior. Meanwhile, normal-dip subduction at Cascadia created the conditions for arc volcanism to restart. Renewed Cascade volcanism followed Siletzia accretion by 10–15 Ma, with the earliest arc magmatism at ~45 Ma, and a well-developed volcanic arc was active by 35 Ma (e.g., Dragovich et al. 2016). South of Siletzia, a tear between the normal-dip Cascadia subduction and flat subducting slab beneath Nevada enabled rollback of the flat slab, which established the Ancestral Cascades. In this context, the Cascade arc is the most recent phase of a long and complex volcanic legacy in the Pacific Northwest.

YELLOWSTONE PLUME AND SILETZIA

An integral element in the history of Cascadia and the Pacific Northwest is the activity of the Yellowstone mantle plume (Camp and Wells 2021). Yellowstone's offshore creation of the Siletzia oceanic plateau created a buoyant structure that resisted subduction and accreted (Wells et al. 2014). Continued Farallon plate motion resulted in normal-dip subduction initiation, abandonment of the flat slab, and ultimately the Cascade arc. The mafic composition of Siletzia is the origin of its strength, which holds the forearc largely intact and transfers the stresses created by Cascadia's shear setting (Klamath-Sierra Nevada push and subduction obliquity; Wells et al. 1998) from the southern to northern Cascades. Re-emergence of the Yellowstone plume ~17 Ma beneath southeastern Oregon led to the Columbia River flood basalts, and the residual plume-warmed mantle may well be entrained in Cascadia corner flow and encroaching on the Cascadia mantle wedge in Oregon (Draper 1991).

To wrap up, the unusual characteristics of the Cascadia subduction zone, in concert with a wealth of geophysical, geochemical, and other data, provide opportunities to better understand the initiation and development of a volcanic arc and its interactions with the greater geodynamic environment. Beyond the oft-considered slow subduction of hot oceanic lithosphere, we draw attention to the remarkable regional volcanic flareup that accompanied Cascadia subduction initiation, the importance of tectonic stress on volcanic arc deformation and magma emplacement rates, and the influence of a mantle plume on subduction development.

REFERENCES

Atwater T (1970) Implications of plate tectonics for the Cenozoic tectonic evolution of western North America. Geological Society of America Bulletin 81: 3513-3536, doi: 10.1130/0016-7606(1970)81[3513:IOPTFT]2.0.CO;2

Camp VE, Wells RE (2021) The case for a long-lived and robust Yellowstone hotspot. GSA Today 31: 4-10, doi: 10.1130/GSATG477A.1

Darold A, Humphreys E (2013) Upper mantle seismic structure beneath the Pacific Northwest: a plume-triggered delamination origin for the Columbia River flood basalt eruptions. Earth and Planetary Science Letters 365: 232-242, doi: 10.1016/j.epsl.2013.01.024

Dragovich JD and 12 coauthors (2016) Geologic map of the Granite Falls 7.5-minute quadrangle, Snohomish County, Washington. Washington Division of Geology and Earth Resources Map Series 1, doi: 10.13140/RG.2.2.14972.13441

Draper DS (1991) Late Cenozoic bimodal magmatism in the northern Basin and Range Province of southeastern Oregon. Journal of Volcanology and Geothermal Research 47: 299-328, doi: 10.1016/0377-0273(91)90006-L

Ford MT, Grunder AL, Duncan AR (2013) Bimodal volcanism of the High Lava Plains and northwestern Basin and Range of Oregon: distribution and tectonic implications of age-progressive rhyolites. Geochemistry, Geophysics, Geosystems 14: 2836-2857, doi: 10.1002/ggge.20175

Gurnis, M, Hall, C, Lavier, L (2004) Evolving force balance during incipient subduction. Geochemistry, Geophysics, Geosystems 5: Q07001, doi: 10.1029/2003GC000681

Hildreth W (2007) Quaternary magmatism in the Cascades - geologic perspectives. U.S. Geological Survey Professional Paper 1744: 125 pp, doi: 10.3133/pp1744

Mullen EK, Weis D, Marsh NB, Martindale M (2017). Primitive arc magma diversity: new geochemical insights in the Cascade arc. Chemical Geology 448: 43-70, doi: 10.1016/j.chemgeo.2016.11.006

Pitcher BW, Kent AJR (2019) Statistics and segmentation: using big data to assess Cascades arc compositional variability. Geochimica et Cosmochimica Acta 265: 443-467, doi: 10.1016/j.gca.2019.08.035

Schmidt ME, Grunder AL, Rowe MC (2008). Segmentation of the Cascade arc as indicated by Sr and Nd isotopic variation among diverse primitive basalts. Earth and Planetary Science Letters 266: 166-181, doi: 10.1016/j.epsl.2007.11.013

Till CB and 6 coauthors (2013) Depths and temperatures of <10.5 Ma mantle melting and the lithosphere-asthenosphere boundary below southern Oregon and northern California. Geochemistry, Geophysics, Geosystems 14: 864-879, doi: 10.1002/ggge.20070

Wells RE, Weaver CS, Blakely RJ (1998) Fore-arc migration in Cascadia and its neotectonic significance. Geology 26: 759-762, doi: 10.1130/0091-7613(1998)026<0759:FAMICA>2.3.CO;2

Wells R and 6 coauthors (2014) Geologic history of Siletzia, a large igneous province in the Oregon and Washington Coast Range: correlation to the geomagnetic polarity time scale and implications for a long-lived Yellowstone hotspot. Geosphere 10: 692-719, doi: 10.1130/GES01018.1

ABOUT THE AUTHORS

Eugene Humphreys is a geophysicist who uses teleseismic methods to image the upper mantle and crust, and kinematic and dynamic modeling of crustal deformation to address the tectonic and magmatic processes making continents. He received his BS and MS from the University of California Riverside (USA) and his PhD from Caltech (USA). He recently retired from the University of Oregon (USA). He was active in the IRIS seismic program and with initiating and developing the EarthScope program. Most of his research has been aimed at understanding Cenozoic and ongoing processes active in constructing the western US.

Anita Grunder is a petrologist and volcanologist. She uses the temporal, petrologic, and geochemical record of volcanic rocks in variable tectonic settings to address how magmas evolve as they traverse the crust, the feedback between crust and magma during persistent magmatism, and how volcanic petrology informs the plutonic record. Her work focuses on the Cascades and Andean arcs and on extensional and hot spot magmatism in the Pacific Northwest. She is professor emerita at Oregon State University (USA).