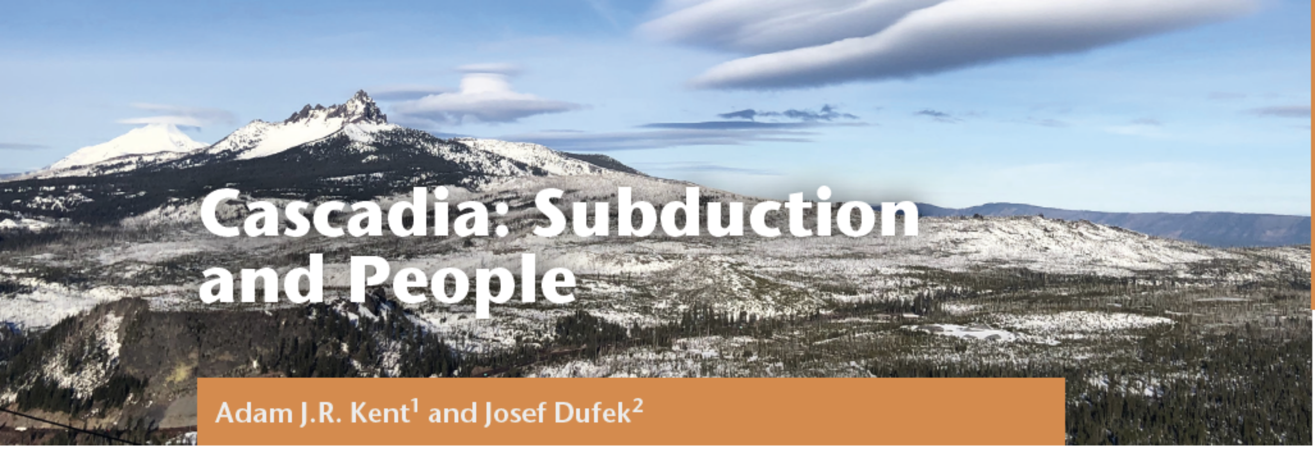

Winter lenticular clouds stack up behind Three Fingered Jack, an eroded Pleistocene shield volcano in the central Oregon High Cascades. PHOTO: ADAM KENT.

Cascadia: Subduction and People

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1811-5209/22/0018-0221$2.50 DOI: 10.2138/gselements.18.4.221

The well-studied Cascadia subduction zone has enriched our general understanding of global subduction zones. This *Elements* issue explores the interconnected set of processes that link geodynamics, tectonics, and magmatism at depth and the surface expressions of these processes, which shape the landscape and give rise to natural hazards in the Cascadia region. This issue also addresses the impact of subduction zone processes on human populations using cultural records, and reviews the state of knowledge of Cascadia while highlighting some key outstanding research questions.

KEYWORDS: Cascadia; subduction processes; hazards; tectonics; volcanism

INTRODUCTION

The Earth is an active planet, and geological processes both shape its surface and dictate the structure of its deep interior. While many geological processes operate slowly by the relatively steady accumulation of material and forces, others are rapid and abrupt—even on human timescales. Nowhere is the process of rapid alteration of the landscape clearer than in subduction zones, where some of the most powerful geologic forces are unleashed by earthquakes and volcanic eruptions, and where these forces sculpt landscapes and serve as a constant reminder of the power of the Earth system. Processes in subduction zones span a wide range of timescales from crustal generation over millions of years to eruptions and earthquakes with relevant timescales of hours or minutes.

Subduction zones have been a focus of inquiry for almost as long as geology has been studied, and one of the most influential regions in shaping our understanding of subduction is the subject of this issue, the Cascade subducton zone, also known as the Cascadia subduction zone, or simply as *Cascadia*. This convergent margin—squeezed in between strike-slip faults to the south and north—stretches from northern California in the south, through the states of Oregon and Washington (USA), to southern British Columbia (Canada) along the western coast of North America. The Cascadia subduction zone represents the latest configuration of a long and extensive history of subduction and accretion that has shaped western North America. The zone is recognized as an endmember "hot and dry" subduction system as a result of the relatively young and warm oceanic Juan de Fuca plate being subducted beneath the western North American plate (e.g., Syracuse and Abers 2006). The warm subducting Juan de Fuca plate is thought to release water, or dehydrate, at shallower depths than other subduction zones, hence delivering less water at depth leading to its typical characterization as a relatively "dry" subduction endmember (van Keken et al. 2011). Studies of Cascadia, including the volcanism, tectonics, and hazards of the region, have long played an important role in the development of modern subduction zone science.

Cascadia boasts an astounding variety of geological and geophysical features, including (but by no means limited to) variations in the amount and composition of volcanic products and the distribution and type of volcanic edifices; a diverse array of seismic features (e.g., seismic tremors, episodic tremors, slips) and preserved evidence for great earthquakes and rupture of the megathrust itself; and large variations in geophysical parameters such as crust and mantle seismic velocities and heat flow. The volcanic arc is also segmented in terms of volcano distribution and type, structural state, forearc structure, and magma chemistry.

Natural hazards associated with Cascadia also loom large in the public imagination as a representation of the power of subduction zone processes. This includes the recognition of the certainty and destructive potential of future earthquakes and tsunamis, as well as the irresistible detective story involved in understanding the history of large subduction zone earthquakes and tsunamis experienced by the region. The May 1980 eruption of Mount St. Helens likewise was a watershed moment in both the recent cultural and geological evolution of the Pacific Northwest region, influencing popular culture, representing a touchpoint in the field of volcanology, and serving as another devastating reminder of the power of subduction zones (FIG. 1).

This special issue explores many aspects of the Cascadia subduction zone, delving into its complex tectonic evolution and Quaternary volcanic history, the nature of current magma reservoirs, and, importantly, its impacts on people and cultures in terms of hazards and the influence of subduction zone geology.

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FIGURE 1 Eruption of Mount St. Helens on May 18, 1980. The eruption column reached the stratosphere and ash was dispersed downwind for hundreds of kilometers (Pallister et al. 2017). PHOTO COURTESY OF THE USGS.

TECTONICS AND VOLCANOES

The variable flux of melt from the mantle, subduction geometry, extension, and crustal structure have produced a remarkable range in the amount and composition of volcanic products throughout Cascadia (Till et al. 2019). Studies of Cascade volcanoes, such as Mount St. Helens, Mount Hood, Mount Shasta, and others, have also strongly influenced thinking regarding the nature and origin of subduction zone volcanism (e.g., Grove et al. 2002; Blundy and Cashman 2008; Kent et al. 2010). Cascadia is a relatively densely populated region, with 10 of the 18 U.S. volcanoes ranked as a "very high threat" located in the Cascade Range (Ewart et al. 2018). As a result, knowledge of these volcanoes and the magmatic systems that underlie them is critical to understand the potential hazards to human populations and infrastructure in the region.

GEODYNAMICS OF THE SUBDUCTION SYSTEM

The 1300-km-long Cascadia subduction system has long been a prime target for continental-scale geophysical observations, as well as high-resolution investigations of local tectonic and magmatic systems. This exceptional data coverage has made Cascadia a natural laboratory to observe the variable influences of subducting slab geometry, mantle flow, and tectonics on the overriding North American plate, and to address long-standing questions related to subduction systems in general. The Juan de Fuca plate, which subducts beneath North America, is young (less than 10 My) and relatively warm compared with other subducting slabs worldwide, hence Cascadia is considered to be a hot endmember of subduction zones. In this issue, Gao and Long discuss the components driving the subduction system that give rise to the characteristic landforms of Cascadia.

Subduction subjects the young oceanic Juan de Fuca plate to progressively higher pressures and temperatures as it descends into the mantle (FIG. 2). The release of fluids via dehydration is thought to occur progressively during its descent, but the slab itself may be initially less hydrated than those at many other subduction zones owing to its young and warm characteristics (Horning et al. 2016). This release of fluid (albeit less than at other arcs) lowers the melting temperature in the overlying mantle, sourcing volcanism over the width of the arc, although backarc melts in Cascadia may also be driven more by decompression (Till et al. 2013; Leeman 2020). While the kinematic template of two-dimensional corner flow that has dominated subduction studies is a prominent feature of the mantle below Cascadia, there may also be significant deviations as a result of flow around the margins of the slab, slab tears or holes, and remnants of plume–slab interactions (e.g., Long 2016).

Evolution of the North American plate, and the transition from compression-dominated tectonics in the north to extension-dominated tectonics in the south, significantly modifies crustal seismicity and magmatism. Clockwise rotation of the overriding plate (with the pole of rotation centered on northeastern Oregon) and arc migration over the past 16 My may have been modified and initiated by the accretion of the oceanic Siletz terrane and ongoing slab rollback at depth (Wells and McCaffrey 2013). Basin and Range extension also encroaches on Cascadia, particularly in its southern half, influencing the zones of seismicity and volcanic vent locations (Hildreth 2007).

QUATERNARY VOLCANISM

Volcanic arcs—the curved chains of volcanoes that parallel the interface between converging tectonic plates—are one of the most distinctive features of subduction zones. In the case of Cascadia, the arc front is delineated by the Cascade Range—the mountain range defined by the row of subduction-related volcanoes that march south–north through California, Oregon, Washington, and British Columbia.

In this issue, Kent describes the Quaternary to recent volcanic history of Cascadia. Although the modern geometry of the subduction zone is just the latest in a long history of subduction along the western North American margin, it has been established for at least the last ~5–8 My. Thus, the Quaternary history of Cascade volcanism is in large part the history of the modern subduction zone. The Cascade arc itself is largely defined by majestic stratovolcanoes—one of the most distinctive volcanic features of subduction zones worldwide. Stratovolcanoes are primarily built by repeated eruptions of andesitic and dacitic magmas. Many stratovolcanic eruptions are relatively small—producing dome complexes or lava flows; however, some eruptions are larger and more explosive in nature. Individual volcanoes along the arc show different proclivities for producing large versus small eruptions and for erupting certain types of magmas; the underlying reasons for these are explored in this issue.

A distinctive aspect of the Quaternary volcanic activity along the Cascadia subduction zone is that the arc has also erupted a large amount of basaltic magma. These magmas are often referred to as "primitive" as an indication that they have compositions that have changed relatively little following their formation in the underlying mantle wedge. Such basaltic magmas typically erupt away from large stratovolcanoes, in distributed fields of cinder cones and other smaller volcanic vents, or in one of several large

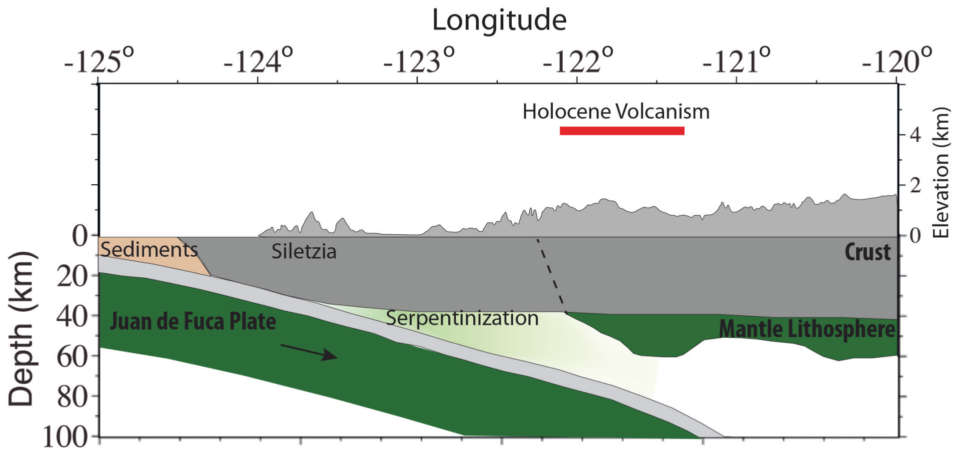

FIGURE 2 Cartoon cross section of Cascadia subduction at the latitude of central Oregon (BASED ON DELPH ET AL. 2018). This illustrates the oceanic Juan de Fuca plate subducting below North America. The crust is shown in grey and mantle lithosphere is indicated in green. Shallow dehydration results in serpentinization of the mantle wedge. The region of Holocene volcanism is indicated by a red bar for central Oregon, and the accreted Siletzia terrane is labeled with the eastern boundary indicated roughly by the dashed line. Surface topography (above sea level) is shown at an exaggerated scale (to the right) compared with the crust and mantle structures.

shield volcanoes that lie to the east of the Cascade arc. The relative abundance of such primitive magmas likely reflects local tectonic processes, such as the impingement of Basin and Range crustal extension into the southern part of the subduction zone, and provides considerable insight into the mantle processes that produce magmas in the Cascade arc and in other subduction zones. In the case of Cascadia, the presence of different types of basalt signifies the diversity of magma formation processes in the underlying mantle.

SUBTERRANEAN MAGMA RESERVOIRS

Many magmas that eventually erupt are sourced from reservoirs in the crust, where they accumulate, mix, and evolve geochemically in response to heat and mass exchange. Importantly, detecting the shallow storage of magmas provides one of the few direct clues to the potential hazard and size of future eruptions. Geophysical and geochemical approaches have inferred magma at multiple depths in the Cascade crust, including at Mount St. Helens, Newberry Volcano, and South Sister Volcano. In this issue, Dufek et al. discuss the implications of and evidence for magma storage beneath the Cascade volcanoes and how this provides insight into melt transport in other subduction systems.

A number of geophysical measurements indicate the accumulation and movement of magmas in the Cascadia crust. The combination of measurement campaigns, along with an understanding of how the presence of partial melt changes the physical properties of the crust, can be used to deduce the location and size of molten regions. For example, seismic and magnetotelluric measurements have resolved different regions of the magmatic system beneath Mount St. Helens (FIG. 3). These investigations have shown in detail how a preexisting structure can modify melt pathways and the locus of volcanism (Kiser et al. 2016; Bedrosian et al. 2018). Ongoing deformation near South Sister Volcano provides additional evidence for active magma accumulation (Lisowski et al. 2021). Likewise, Newberry Volcano's magmatic system has been resolved using seismic tomography (Heath et al. 2015) and the overlying crust is the locus of the highest measured heat flux in the Cascades (Keith and Bargar 1988; Blackwell et al. 1990).

The rock record is replete with evidence of past magma accumulation at different levels in the crust. The exsolution of volatiles to form bubbles and the composition of crystalline phases are sensitive to pressure and have been used as geobarometers. The radioactive decay of some elements incorporated into crystals, as well as the diffusion of chemical species in crystals, mark the timescales of past processes. In the Cascades, this combination of the crystal record of fossil magmatic systems and the active detection of magma using geophysics indicate that most magmatic systems (past and present) are built by the accumulation and transport of melt at multiple levels in the crust. The eruption of Mount St. Helens provided a rare instance in which this transcrustal magmatic system was simultaneously resolved with both geophysical and geochemical measurements (Saunders et al. 2012). These observations have motivated the proposal and design of more comprehensive geophysical networks to better understand these evolving magmatic systems.

SUBDUCTION, HAZARDS, AND PEOPLE

As a departure from the emphasis on geological material and processes, this issue also delves into the relationship between the Cascadia subduction zone and the human populations and cultures that have lived in this area. In Cascadia, this includes multiple Indigenous cultures, as well as populations that arrived with and after European settlement. Moore and Robinson (2022 this issue) explore the influence of subduction on human societies in Cascadia using cultural records and oral histories, including dramatic subduction-related phenomena such as great earthquakes, tsunamis, and volcanic eruptions that can be readily recognized in oral traditions and other cultural sources from Indigenous groups. They make an excellent case that the subduction-shaped landscapes of Cascadia, and the geological processes that form them, influence almost every detail of the lives of the people who live in this region. One way this influence manifests is in access to critical physical resources, one notable example for Indigenous cultures being the availability of obsidian from multiple Cascade locations. Obsidian is a material with great value and importance for practical, spiritual, and ceremonial purposes; as a result, Cascade-derived obsidian can be found across North America. Other volcanic materials, such as pumice and basalt, were also critical resources for Indigenous residents.

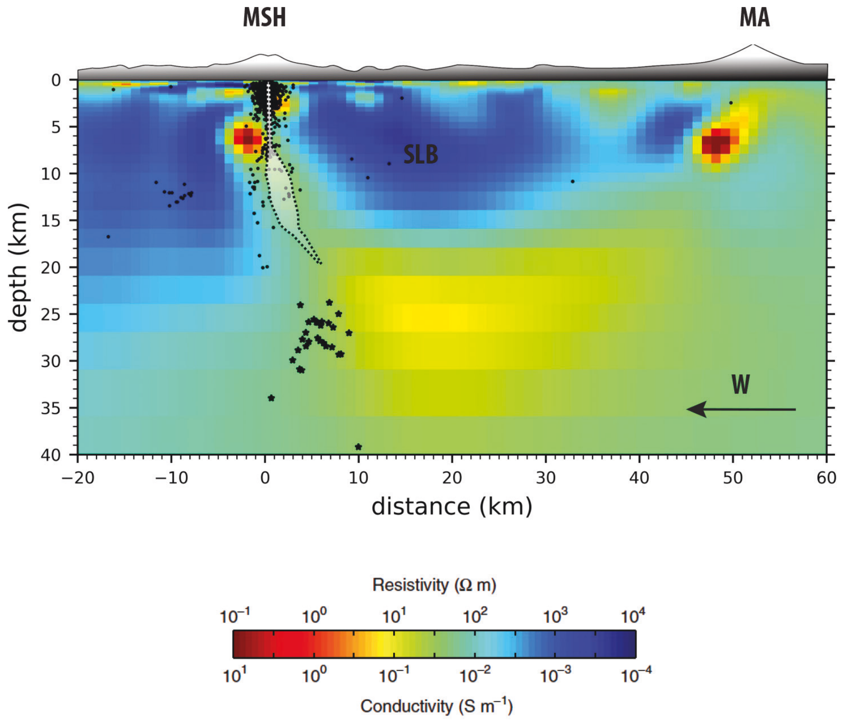

FIGURE 3 Resistivity model along a transect of the crust based on magnetotelluric data (model results courtesy of P. Bedrosian based on Bedrosian et al. (2018), and modified from the transect in Dufek et al. (2022 this issue)). The transect is at 46.25° N and shows the structure below Mount St. Helens (MSH) and Mount Adams (MA). The high-resistivity structure between the volcanic edifices is the Spirit Lake Batholith (SLB); this preexisting structure has been inferred to redirect the ascent of magma in the upper crust. Seismicity is indicated by the black points, with stars indicating deep, long-period events.

European colonization and settlement saw great changes in the Cascadia region, but the ubiquitous impact of the subduction zone on the people who reside in this region persisted and continues to the present day. Examples include the critical role of the volcanoes of the Cascade Range and their snowpack on water resources and the availability of critical mineral resources such as gold, mercury, and copper formed in volcanic hydrothermal mineral deposits. As a parallel to the importance of volcanic material to Indigenous cultures, scoria mined directly from numerous scoria cones provides essential traction for winter driving. Likewise, recreational opportunities associated with the Cascade volcanoes are annually worth many millions of dollars to local economies. Finally, representations of dramatic events, such as the eruption of Mount St. Helens, can be seen echoed in modern cultural material, such as Hollywood movies like "Dante's Peak," and there is an understandable fascination with future earthquakes and tsunamis.

Subduction zones are home to most of Earth's largest earthquakes, tsunamis, and volcanic eruptions. Thus, a major motivation for studying subduction zones is to understand more about the impact of these geologic hazards on human populations and infrastructure. For example, one reason that several Cascade volcanoes are classified in the highest threat category (Ewart et al. 2018) is their proximity to population centers and infrastructure. Projected causalities and damages resulting from a future megathrust earthquakes and tsunami are also daunting (Walton et al. 2021).

In this issue, Westby, Meigs, and Goldfinger explore the volcanic, earthquake, and tsunami hazards of the Cascadia subduction zone in more detail. Cascadia has played an important role in the development of scientific thought and understanding of subduction zone hazards. The dramatic sector collapse and eruption of Mount St. Helens in 1980 led to significant advances in the understanding of subduction zone volcanic systems and the organization and infrastructure required to effectively monitor these volcanoes. The broad diversity of volcano and magma types found in the Cascades translates to a broad set of volcanic hazards that can potentially impact the region. Eruptions occur at an average rate of one to two per century, but events such as the renewed activity at Mount St. Helens in 2004–2008 and the ongoing uplift at South Sister Volcano remind us that Cascadia is a volcanically active region and that future eruptions are a certainty.

The development of scientific thought surrounding great earthquakes and tsunamis in Cascadia is a fascinating story—starting with a belief in the 1960s and 1970s that the subduction zone did not generate earthquakes, followed by a detailed geological and geophysical "detective story" to unlock the tremendous wealth of onshore and offshore records of earthquakes and tsunamis. This is a story with a clear and important point—that the region covered by the Cascadia subduction zone will experience major earthquakes and tsunamis in the future. The estimated probabilities for the occurrence of large earthquakes in the next few decades (itself determined on the basis of the geologic records of past earthquakes) are significant, and there have been at least 19 megathrust events identified in the past 10 ky (Walton et al. 2021). Accompanied in recent years by dramatic and visceral footage from great earthquakes and tsunamis in Sumatra, Indonesia in 2004 and in Tōhoku, Japan in 2011, the message from the Cascadia geologic record is clear: these events will occur in the future (possibly in the near future) and the time to prepare is now.

In a final contribution to this issue, Grunder and Humphreys provide a perspective enriched by their collective experience spent unlocking the secrets of Cascadia. They ask what it is that makes the Cascadia subduction zone so worthy of scientific investigation. The answer acknowledges the importance of studying continental subduction in such a hot and dry setting, but also looks further. Humphreys and Grunder (2022 this issue) highlight a continental-scale perspective—where Cascadia is a relatively short subduction zone embedded in a continental-scale, right-lateral shear zone. Interactions with other geodynamic elements of North America, such as the Yellowstone mantle plume and Basin and Range extension, are also important and collectively help produce the remarkably broad diversity of geodynamic, magmatic, and structural settings that are observed along the length of this unique subduction zone.

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