Volcano, Earthquake, and Tsunami Hazards of the Cascadia Subduction Zone

Elizabeth G. Westby¹, Andrew Meigs², and Chris Goldfinger²

INTRODUCTION

At the time of the last great Cascadia earthquake, the Pacific Northwest’s population numbered in the tens of thousands. Now, it is counted in the millions. At risk from volcano, earthquake, and tsunami hazards are highly populated regions and the critical infrastructure that links them together. The destruction caused by the great Tōhoku subduction zone earthquake in northeastern Japan in 2011 cautions us not to underestimate subduction zone hazards (Uchida and Bürgmann 2021), and the powerful 1980 eruption of Mount St. Helens serves as a stark reminder that we live in the shadow of active volcanoes (Pallister et al. 1992). In Cascadia, the types of future hazards, and to some extent the responses needed, are relatively well known. The challenge is reaching a level of resilience and preparedness in advance of a major event.

Volcanic Risk in the Cascade Arc

The next eruption of a Cascade magmatic arc volcano could dramatically change the lives of hundreds of thousands of people and temporarily disrupt the lives of millions. According to the 2020 U.S. Census, more than 12 million people live in Washington, Oregon, and northern California, and populations are increasing in areas at risk from volcano hazards (Diefenbach et al. 2015). Aviation routes along the Cascade Range carry nearly 250,000 people daily through areas that could potentially be impacted by ash eruptions (Ewert et al. 2018).

Over the past 15,000 years, there have been at least 137 eruptive episodes in the Cascade arc that have generated a wide range of eruption styles—outpourings of lava, cone- and dome-building events, flank collapses, explosions, and ashfall (Hildreth 2007). Studies of this postglacial geologic record show that eruptions in the Cascade Range occur at an average rate of one to two per century (Hildreth 2007). The 1980–1986 and 2004–2008 eruptions of Mount St. Helens reminded Cascadia residents of the power of volcanic eruptions, and provided scientists with an opportunity to advance their understanding of volcanoes and develop new monitoring techniques and technologies (e.g., Figs. 1 and 2; Swanson et al. 1985; Moran et al. 2008; Dzurisin et al. 2015; Dzurisin 2018; Cervelli et al. 2021). These approaches have been applied in recent times to detect the slow re-pressurization of Mount St. Helens’ magmatic system (Dzurisin et al. 2015) and ground deformation (uplift) over a broad area west of South Sister, Oregon (Lisowski et al. 2021). These recent data coupled with historical geologic records warn us that Cascade Range volcanoes are active and will erupt again in the future.

The U.S. Geological Survey (USGS) evaluates the relative risk posed by U.S.-monitored volcanoes in a national volcano threat assessment (Ewert et al. 2005, 2018). The risk (“threat”) posed by the 161 active and potentially active volcanoes is based on a set of factors that take into account volcano hazards and societal exposure to these hazards. The threat ranking reflects the potential severity of impacts to communities, property, and infrastructure downstream and downwind and helps prioritize resources (Ewert et al. 2018). Of the 18 U.S. volcanoes in the “very high threat” category, 10 are in the Cascade Range. These include Mount St. Helens, Mount Rainier, Mount Shasta, Mount Hood, Three Sisters, Lassen volcanic center, Newberry Volcano, Mount Baker, Glacier Peak, and Crater Lake.

Given that it is only a matter of time until the next eruption, it is important that (1) scientists understand the eruptive histories of the Cascade Range volcanoes, prepare hazard assessments, and install robust monitoring instrument networks to distinguish “normal” or background activity from pre-eruptive behavior at volcanoes; (2) responding agencies and emergency officials are familiar with eruption hazards and have plans in place to meet the next crisis; and (3) people in areas at risk from volcano hazards know where to obtain trustworthy information and are ready to act. The following hypothetical “what if...” scenario is provided to stimulate discussions among scientists, responding agencies, emergency officials, and the public about the early phases of an event when uncertainties about

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how it might unfold are high, so we are ready to act quickly to collectively manage its consequences (Fig. 1; Paton et al. 2008).

A Hypothetical Reawakening and Eruption

For several days, scientists track an increase in seismicity. Hundreds of small earthquakes are located about 3 km beneath the summit. The largest earthquake is a magnitude 2.0, and none are felt on the surface. Seismologists at the USGS Cascades Volcano Observatory (CVO) and the Pacific Northwest Seismic Network confer, check locations, and analyze data from the network of continuously recording and transmitting seismic stations on and around the volcano. CVO provides a recap in its weekly update and for social media, noting that the volcano has had previous swarms with similar depths and magnitudes and that the activity is being closely monitored. None of the other volcano monitoring parameters, such as ground deformation or volcanic gas emissions, have significantly changed so the color code and alert level for the volcano (“Green/Normal”) remains the same (see Gardner and Guffanti 2006 for definitions).

Seismicity intensifies. Field teams install additional monitoring instruments to track seismicity, ground deformation, and gas emissions in areas of interest. CVO issues an Information Statement (the first of many) through the USGS Volcano Notification Service and communicates with emergency officials and land managers about activity, uncertainties, and a range of possible outcomes.

As the hypothetical timeline advances, there is an increase in steaming and scientists detect changes in volcanic gas compositions and emission rates. CVO raises the color code and alert level to “Yellow/Advisory” to indicate that the activity is above background levels and that the volcano may be entering a period of unrest that could lead to an eruption. Scientists evaluate event trees (Newhall and Hoblitt 2002) to consider a range of hazardous events and their likelihood.

CVO, along with monitoring and scientific partners, begins to implement volcano emergency coordination plans with federal, state, local, tribal, and other agency partners. Land managers restrict access, and local business owners agree to close tourist facilities in areas vulnerable to volcano hazards. Officials provide specific information to their constituents such as closures, evacuation routes, and actions to take during an emergency. Responding agencies begin mobilizing into an Incident Command System, a response system adopted by the Federal Emergency Management Agency in 2004 for coordinating responses to large events that impact multiple jurisdictions. A multi-agency Joint Information Center works to disseminate timely and accurate information to the public and news media, and rebuts disinformation and rumors.

Later, GPS instruments measure small ground movements near the summit and scientists process repeat radar satellite images that reveal deformation on the volcano’s flank. The color code and alert level are changed to “Red/Warning,” indicating a hazardous eruption is underway that includes ash hazards for aviation. Fragmented hot volcanic rock melts snow and ice on the upper flanks, and the muddy water rushes into a headwater channel. A small lahar (volcanic mudflow) is detected by seismic and infrasound sensors. Officials issue a rapid notification for potential flooding downstream.

Days after the color code and alert level were raised to “Red/Warning,” a larger explosive eruption blasts tephra and gases tens of kilometers into the atmosphere. Within minutes, the largest tephra pieces begin falling near the vent, melting snow and ice to generate lahars that funnel into stream channels and flow downstream. Finer ash fragments are carried by the wind, and scientists provide near-term forecasts of where ash would go and the depth of deposits in areas downstream based on computer models, observations, weather forecasts, and human judgment. Emergency officials issue alerts; people downwind are advised to stay indoors until ashfall ceases, and those in low-lying areas that are at risk from lahars are told to evacuate to high ground. Multiple agencies implement safety and response measures—local airports in areas affected by ashfall suspend service and airlines redirect flights around ash-contaminated airspace, roads are closed as falling ash reduces visibility, and a light rain makes roads as slippery as ice. There are localized power outages, and telecommunication systems are overwhelmed as people try to contact family and friends. Emergency services are fully engaged, and response times are sluggish for those in need.

In the aftermath of this hypothetical event, the landscape is transformed and the effects linger well into the future. Scientists work to re-establish monitoring networks as safety allows. Responding agencies continue to provide
long-term services for communities in need, and cities and counties have months of clean-up and repairs ahead. For many, ash is a health hazard that irritates the eyes and sinuses. Homes along the river channels downstream from the volcano are damaged, and low-lying farmland is inundated with several feet of mud, rock, and woody debris. For some property owners, cleanup is impossible (Christiansen and Peterson 1981; Newhall 2000).

**Living with Volcano Hazards**

Rarely does a volcano behave so predictably as the one in the previous hypothetical scenario. But many will provide warnings before an eruption. Eruptions involve the rise of magma toward the surface, which normally generates detectable earthquakes. Magma movement can also deform the ground surface and cause anomalous heat flow or changes in the temperature and chemistry of the groundwater and spring waters, as well as in gas emissions (Sparks 2003). But volcanoes do not follow a well-defined, predetermined sequence of events, and it is difficult to forecast exactly when an eruption will occur. Moreover, once it begins, an eruption may last for days to months and include intermittent activity for years, making it challenging to know how long the eruptive period will last, how the event will change over time, and what the consequences will be (Newhall and Hoblitt 2002; Sparks 2003).

Volcanic emergencies come with a wide range of uncertainties for scientists and the officials who are trying to manage them. Risk can be reduced with improvements in forecasting and monitoring, together with increased societal resilience achieved through raising awareness and the development of volcanic emergency management plans. Risk reduction necessitates a coordinated multi-agency collaboration among (1) volcano scientists and researchers to study, monitor, and develop hazard assessments at active volcanoes; (2) land managers and emergency officials for emergency coordination and planning, notifications, alerts, and community safety education; and (3) individuals in at-risk communities for awareness, preparedness, and readiness to act (Fig. 1).

**Earthquake and Tsunami Hazards of the Cascadia Subduction Zone**

Volcano hazards are part of the public consciousness as a result of the 1980–1986 and 2004–2008 eruptions of Mount St. Helens. In contrast, the idea that the Cascadia
The Cascadia subduction zone marks the Juan de Fuca–North American plate boundary (barbed line) and extends at a low angle under the western edge of North America in the Pacific Northwest. Possible rupture sites for \( M_w 8 \) and \( M_w 9 \) events are shown.

(A) Map of the Pacific, Juan de Fuca-Gorda, and North American plates and their boundaries.

(B) Block diagram showing the interseismic period, when convergence along the subduction zone interface (red line) causes gradual uplift in the overlying plate and gradual subsidence offshore. (C) The coseismic period, when earthquake rupture relieves accumulated strain, causing sudden subsidence in the onshore overriding plate and sudden uplift in the offshore overriding plate. Shallow rupture may generate a tsunami.

(D) Schematic diagrams of offshore (left) and onshore (right) stratigraphic evidence for deformation over the earthquake cycle. Modified from Walton et al. (2021).

Knowledge of past Cascadia earthquakes also exists in the extensive body of oral, sculptural, and other traditions of Indigenous peoples living along the U.S. West Coast (Ludwin et al. 2005). Oral traditions include a story of a battle between Thunderbird (representing the ground motion in the Earth) and Whale (representing tsunamis impacting the coastline) that vividly depicts the two principal effects of the 1700 and earlier earthquakes (Ludwin et al. 2005).
circum-Pacific region. The rapid submergence, inundation of coastal lowlands, and burial of the former forest soils with estuarine mud are indicative of a subduction zone earthquake (e.g., Fig. 3; Nelson et al. 2021). Offshore, great earthquakes create large, underwater, sediment-laden gravity avalanches that leave behind deep-sea deposits called turbidites. Turbidite deposits in basins on the continental slope and farther out in the ocean provide a long, continuous record of paleoseismic events that span the last 10,000 years (Adams 1990; Goldfinger et al. 2012).

Radiocarbon dating is the primary means of correlating records from the coastal and marine realms. Despite challenges associated with decadal-scale uncertainties of radiocarbon dates, as well as differences in interpretation, the temporal correspondence between the onshore and offshore paleoseismic records along the Cascadia margin is good (Goldfinger et al. 2012; Nelson et al. 2021). The records indicate that ruptures of the Cascadia margin can be full-length or a substantial length of the plate interface, as happened during the 1700 event (Satake and Atwater 2007). Events affecting a significant length of the plate boundary recur every 510–540 years. But segmented ruptures are also possible, and events on the southern end of the boundary occur more frequently with an average recurrence interval of approximately 240 years. The time-dependent conditional probabilities for segmented ruptures in the next 50 years are estimated at 10%–17% for the Washington State coast and Vancouver Island, Canada, and 15%–20% for the central and northern Oregon coast, rising to 32%–43% for the southern end of the subduction zone (Goldfinger et al. 2012).

Is a Future Rupture Inevitable?

Deformation of Earth’s surface occurs in the interval between earthquakes called the interseismic period. During this period, the plate interface stores the strain energy accumulated since the last event and that will be released in a future event (Fig. 3). As first argued after the 1906 earthquake on the San Andreas fault in California, Earth’s crust behaves elastically over short time periods and small strains. Given this behavior, the interseismic period ought to be marked by deformation that is opposite to the coseismic signal. For example, during an earthquake, a coastal area might experience sudden subsidence that, during the interseismic period, would transition to uplift as strain accumulated (Yousefi et al. 2020).

The fact that geodetic leveling surveys across the onshore upper plate of Cascadia show a tilt that decreases in amount and rate with distance east from the coast is evidence of interseismic strain accumulation, but this signal is not strong (Yousefi et al. 2020). Most geodetic data, however, are collected along the onshore region, where the locked zone of the plate interface transitions to a freely slipping fault. The locked portion of the plate boundary, which is the part storing strain, must therefore lie offshore. Planned future installations of seafloor geodetic instruments in Cascadia are thus an important and exciting development that will shed new light on along-strike variability, locking patterns, tsunami hazard, and a number of other key uncertainties concerning the behavior of the plate interface (Walton et al. 2021).

RAISING AWARENESS AND REDUCING RISK

Emergency officials’ responses to earthquake and tsunami hazards have been as vigorous as the scientific effort to understand the past behavior of the Cascadia subduction zone. Coastal tsunami inundation zones, evacuation routes, and products to inform the public about hazards appeared shortly after widespread scientific acceptance of the idea that Cascadia generates great earthquakes (Yeats 2004). In the last decade, the Oregon Department of Geology and Mineral Industries and the Washington State Emergency Management Division and Department of Natural Resources developed science-based tsunami hazard maps along the length of the coastline posted to public-facing webpages.

The challenge for the region is that much of modern society’s development occurred before knowledge of past events had accumulated, and as a result, much of the built infrastructure was not designed for the hazards of which we are now acutely aware. Today, responding to tsunami hazards is challenged by costs associated with moving or building earthquake- and tsunami-resilient structures. Votes on bond issues to generate, fund, replace, and relocate schools in some communities have failed to pass, and in 2019, the Oregon Legislature repealed a law prohibiting the building of schools and other critical facilities in tsunami inundation zones. Such difficulties, however, can be partially offset by locating clusters of the most vulnerable populations and targeting hazard mitigation to those communities (Wood et al. 2015). This type of analysis helped the city of Seaside, Oregon, for example, pass a school levy in 2016 to move three schools out of the tsunami inundation zone, facilitated by the donation of 80 acres of land from a timber company (Seaside School District 2016). Similarly, the nation’s first vertical evacuation structure, the Ocosta Elementary School, was erected in 2016 in Westport, Washington, because no high ground exists that residents can reach within about 15 minutes of an earthquake (Washington Military Administrator 2021).

Finally, an earthquake early warning system, an alert transmitted via warning systems to the public immediately after an event, now exists for the Cascadia region (Allen and Melgar 2019). Operated by the USGS, the “ShakeAlert” system uses fast-moving seismic waves generated by earthquakes to determine whether a large event has just occurred. The system delivers an alert to users across the Pacific Northwest within seconds, potentially giving people and agencies tens of seconds to take steps to mitigate the effects of ground motion created by later-arriving seismic waves. Early warning systems operating in Mexico, Japan, and other countries have been shown to be effective in minimizing casualties and economic losses associated with great earthquakes and are positively viewed by the public.

CONCLUSIONS

A frequently asked question posed to scientists and emergency officials is “You’ll let us know when the Big One is coming?” or “You’ll tell us when the volcano is going to erupt, won’t you?” It would be terrific if that could happen. However, it is nearly impossible to predict the times, locations, and magnitudes of earthquakes, and a volcano could provide days, weeks, or even months of unrest before erupting or it could return to background levels of activity.

We have a good understanding of the eruptive histories of Cascade arc volcanoes and have directly observed the eruptive cycle in recent times, and the earthquake record of past great Cascadia earthquakes now extends back 10,000 years. While preparations for coming volcanic eruptions and great earthquakes and associated tsunamis are underway, many efforts aimed at resiliency are just beginning. This will take many decades of sustained work and rethinking about what it means to live in a region where geological hazards occur infrequently, yet when they do, are of high consequence. We choose to live here and, as a result, must recognize and assess the hazards, work together to collectively prepare to respond, and minimize the hardships and costs of putting communities back together when they do.