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Reducing Risk Where Tectonic Plates Collide—A Plan to Advance Subduction Zone Science

Circular 1428

U.S. Department of the Interior
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Front cover. A U.S. Geological Survey scientist surveys Loowit Creek drainage on Mount St. Helens, part of a long-term project to track sediment erosion and deposition in the channel. View to the north, with Spirit Lake and Mount Rainier in the background. U.S. Geological Survey photograph by Kurt Spicer.

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

U.S. Geological Survey, Reston, Virginia: 2017

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Suggested citation:
Gomberg, J.S., Ludwig, K.A., Bekins, B.A., Brocher, T.M., Brock, J.C., Brothers, Daniel, Chaytor, J.D., Frankel, A.D., Geist, E.L., Haney, Matthew, Hickman, S.H., Leith, W.S., Roeloffs, E.A., Schulz, W.H., Sisson, T.W., Wallace, Kristi, Watt, J.T., Wein, Anne, 2017, Reducing risk where tectonic plates collide—U.S. Geological Survey subduction zone science plan: U.S. Geological Survey Circular 1428, 45 p., https://doi.org/10.3133/cir1428.

ISSN 1067-084X (print)
ISSN 2330-5703 (online)
ISBN 978-1-4113-4150-0

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U.S. Geological Survey research geophysicist Kate Allstadt assists students in the GeoGirls program to deploy a seismometer at Mount St. Helens, Washington. The girls collected the seismometers two days later and analyzed the earthquake information recorded by the instruments. USGS photograph by Carolyn Driedger.

U.S. Geological Survey scientists Randy Jibson and Jonathan Godt investigate the Seaside landslide that was triggered by the 2016 magnitude 7.8 Kaikoura, New Zealand, earthquake, along a fault that experienced significant surface offsets. USGS photograph by Kate Allstadt.

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Executive Summary

When tectonic plates collide, the thrusting of one plate over the other (a process called subduction) leads inevitably to the world's largest earthquakes, powerful tsunamis, explosive volcanic eruptions, and massive landslides, both on land and offshore. As recent subduction zone earthquakes and tsunamis in Sumatra (magnitude [*M*] 9.1, 2004), Chile (*M*8.8, 2010), and Japan (*M*9.0, 2011); volcanic eruptions in the United States (Mounts St. Helens, Washington, 1980; Redoubt, Alaska, 1989, 2009) and Pinatubo in the Republic of the Philippines (1991); and major landslides (Oso, Washington, 2014) have demonstrated, these events have cascading consequences that reverberate around the globe.

Future such events are inevitable in our Nation's subduction zones, which encompass the States of Alaska, Washington, Oregon, northern California, commonwealths of Puerto Rico and the Northern Mariana Islands, and territories of American Samoa and Guam. Subduction zone events pose significant threats to lives, economic vitality, cultural and natural resources, and quality of life of the Nation's communities.

The U.S. Geological Survey (USGS) serves the Nation by providing reliable scientific information and tools to build resilience in communities exposed to subduction zone earthquakes, tsunamis, landslides, and volcanic eruptions. Improving the application of USGS science to successfully reduce risk from these events relies on whole community efforts, with continuing partnerships among scientists and stakeholders, including researchers from universities, other government labs and private industry, land-use planners, engineers, policymakers, emergency managers and responders, business owners, insurance providers, the media, and the general public.

Motivated by recent technological advances and increased awareness of our growing vulnerability to subduction-zone hazards, the USGS is uniquely positioned to take a major step forward in the science it conducts and products it provides, building on its tradition of using long-term monitoring and research to develop effective products for hazard mitigation. This science plan provides a blueprint both for prioritizing USGS science activities and for delineating USGS interests and potential participation in subduction zone science supported by its partners.

The activities in this plan address many USGS stakeholder needs:

- High-fidelity tools and user-tailored information that facilitate increasingly more targeted, neighborhood-scale decisions to mitigate risks more cost-effectively and ensure post-event operability. Such tools may include maps, tables, and simulated earthquake ground-motion records conveying shaking intensity and frequency. These facilitate the prioritization of retrofitting of vulnerable infrastructure;

- Information to guide local land-use and response planning to minimize development in likely hazardous zones (for example, databases, maps, and scenario documents to guide evacuation route planning in communities near volcanoes, along coastlines vulnerable to tsunamis, and built on landslide-prone terrain);

- New tools to assess the potential for cascading hazards, such as landslides, tsunamis, coastal changes, and flooding caused by earthquakes or volcanic eruptions;

- Geospatial models of permanent, widespread land- and sea-level changes that may occur in the immediate aftermath of great ($M \geq 8.0$) subduction zone earthquakes;

- Strong partnerships between scientists and public safety providers for effective decision making during periods of elevated hazard and risk;

- Accurate forecasts of far-reaching hazards (for example, ash clouds, tsunamis) to avert catastrophes and unnecessary disruptions in air and sea transportation;

- Aftershock forecasts to guide decisions about when and where to re-enter, repair, or rebuild buildings and infrastructure, for all types of subduction zone earthquakes.

Meeting the above needs of stakeholders aligns with the three themes of the plan: (1) improving our observations and models of subduction zone processes; (2) analyzing natural hazards and risk; and (3) providing forecasts and situational awareness. Realization of these scientific and technological goals will lead to innovative, resilience-building products, broadly summarized in table 1. All the scientific inputs noted have some relevance to all the products in the table.

Table 1. Potential products and key investments for building resilience.

Products	Description	Primary scientific inputs	Key investments*	Application
High-resolution hazard and risk assessments	Neighborhood-scale estimates of earthquake shaking, tsunami inundation, landslides, potential volcanic eruptions and lahars, and their consequences.	High-resolution topography, onshore and offshore; 3-D models of Earth structure; well-characterized faults, unstable slopes, and active volcanoes.	A–I	Building design codes, prioritized retrofitting, urban planning, and evacuation routing.
Scenarios	Science-based simulations of hypothetical subduction zone events and their impacts.	Chronologies of past subduction zone events from geologic field and laboratory studies.	G, H	Improved mitigation strategies.
Warning systems	Notice of strong earthquake shaking, volcanic eruptions and ground-failures, tsunamis, and landslides.	Multidisciplinary monitoring systems, onshore and offshore.	A, B, C	Rapidly implemented life- and property-saving measures.
New types of forecasts	Updated projections of aftershocks, landslides, volcanic debris flows, and ash clouds.	Rapidly acquired satellite and surface measurements.	A, B, C, I	Safer, faster, and more cost-effective response and recovery.
Novel assessments of cascading subduction zone events	Likelihoods of landslide-triggered tsunamis; earthquake-induced coastal land-level changes, flooding, and erosion.	Computer models simulating linked processes.	F, I	Rapid and effective mitigation, response, and recovery.

*Key investments for forefront science and products:

A. Targeted, dense, land-based networks for monitoring earthquake, volcanic, and ground-failure processes.

B. Routine operation of multidisciplinary monitoring.

C. Partnerships to develop and operate permanent seafloor seismic and geodetic monitoring instrumentation.

D. Offshore sediment-core samples, images of subsurface geologic structures, temporary geophysical deployments.

E. High-resolution, multibeam bathymetry offshore, adjacent to airborne and space-based topographic imagery onshore.

F. Observationally constrained, three-dimensional models of the Earth's interior.

G. Expanded geologic field programs.

H. Laboratory capabilities for dating and analyzing the physical properties of rock samples.

I. Synoptic, integrative multidisciplinary computer models.

U.S. Geological Survey scientists tour the construction site of the new Amazon.com campus in downtown Seattle, Washington, and learn about how USGS information has been used to make the facilities more resilient when shaken by earthquake waves. USGS photograph by Joan Gomberg.

Introduction

We live on a dynamic planet, which is constantly in motion at multiple scales, from changing daily weather patterns to the shifting of massive tectonic plates. And, yet, nowhere is the Earth more geologically active than in regions where these tectonic plates collide, which are known as subduction zones (*see sidebar about subduction zones on p. 6*). Much of the United States lies within subduction zones: Alaska, Washington, Oregon, and northern California, the commonwealths of Puerto Rico and the Northern Mariana Islands, and the territories of American Samoa and Guam are all situated within subduction zones (fig. 1). Regions surrounding the Pacific Ocean where plates collide comprise the "Ring of Fire" because of the prevalence of volcanoes and earthquakes; outside the United States, Ring of Fire countries include Japan, the Republic of the Philippines, and the Republic of Indonesia. All these countries face subduction zone hazards, along with many nations in the Caribbean, eastern Indian Ocean, and around the Mediterranean Sea. In these areas, the constant motion of the Earth, usually slow and inexorable, can create catastrophes in an instant: the world's largest earthquakes can rupture the seafloor, generating powerful tsunamis; explosive volcanoes can thrust ash into the sky; landslides can reshape entire landscapes both on land and offshore. The tremendous magnitudes and frequencies of these hazardous events are unique to subduction zones, and they can have cascading consequences that reverberate around the globe. Subduction zone events pose significant threats to lives, property, economic vitality, cultural and natural resources, and quality of life.

Over the past 55 years, the Nation has experienced the 1964 magnitude (*M*) 9.2 Alaska earthquake, the 1980 eruption of Mount St. Helens, the 2014 Oso landslide, and numerous other smaller, but locally significant, subduction zone events (*see sidebar about historic events on p. 7*). Worldwide, in less than the span of a generation, we have witnessed firsthand the devastating power and global impact of subduction zone events: in 1991, the cataclysmic eruption of Mount Pinatubo in the Republic of the Philippines led to evacuation of 20,000 people and a sulfuric haze caused global temperatures to drop by 0.5 °C (0.9 °F) for the following two years. In 2004, the *M*9.1 Sumatra–Andaman earthquake and ensuing Indian Ocean tsunami resulted in more than 200,000 deaths in 14 countries, damaged fisheries in Japan, and triggered earthquakes as far away as Alaska. In 2010, offshore Chile—where building standards and preparedness levels are comparable to those in the U.S.—a *M*8.8 earthquake ruptured the seafloor. The quake triggered a tsunami, which damaged coastal towns and affected ports as far away as San Diego, California. The initial earthquake was followed by several *M*~7 aftershocks in the subsequent months, which struck immediately beneath population centers and caused more damage locally than the mainshock. Nearly 525 people died, and estimated economic losses range from $15–30 billion (U.S. dollars). In 2011, the *M*9.0 Tōhoku earthquake jolted Japan: skyscrapers swayed and pedestrians ran from falling debris during five minutes of sustained shaking, and the tsunami, with wave heights taller than 30 meters (100 feet), flung boats atop houses, flooded rural farms with seawater, and caused a meltdown at the Fukushima Daiichi Nuclear Power Plant. Nearly 16,000 people died, and the damages totaled more than $220 billion.

The Blue Marble.
Image by NASA/Goddard Space Flight Center

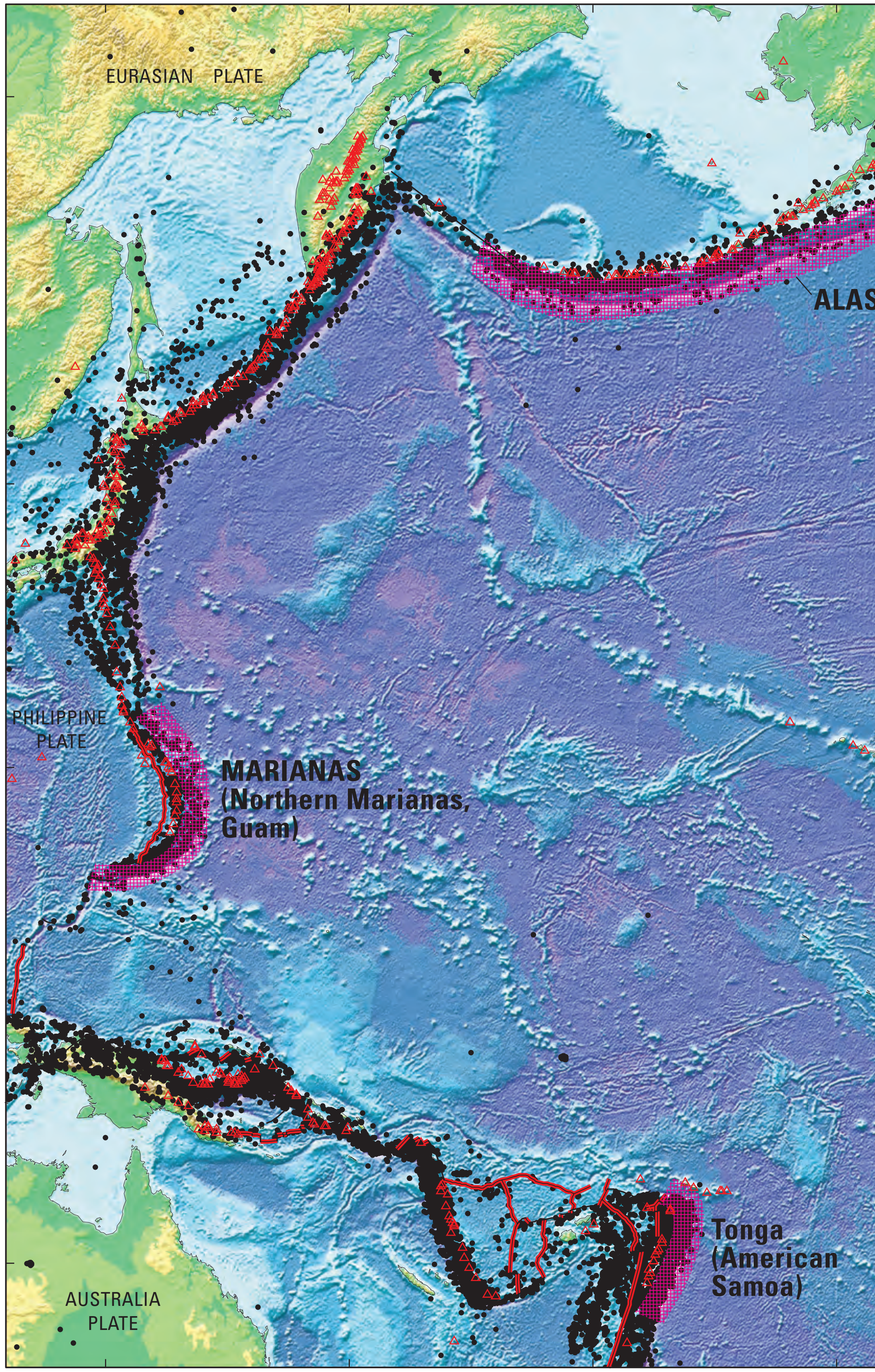


Figure 1. The Pacific Ocean basin and surrounding "Ring of Fire" subduction zones, where the tectonic plates collide, creating volcanoes, earthquakes, tsunamis, and mountainous landslide-prone terrain. Subduction zones are shown by high densities of earthquakes and volcanoes. Subduction zones within the United States and its territories are shaded pink. Other types of plate boundaries are shown with thin red lines. Colors reflect topography and bathymetry; darker blues and purple offshore are deeper water, while brown and orange are mountain ranges. Map simplified from Simkin and others (2006).

EXPLANATION

Plate tectonics

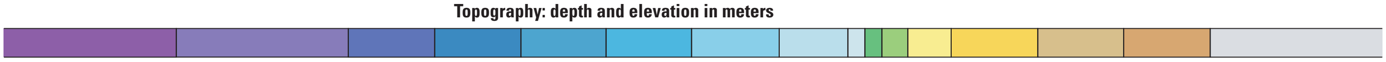
Subduction zones that are part of the United States and its territories

Divergent (sea-floor spreading) and transform fault boundaries—Red lines mark spreading centers. Thin black line marks the plate boundary, whether sea-floor spreading center or transform fault

Volcano

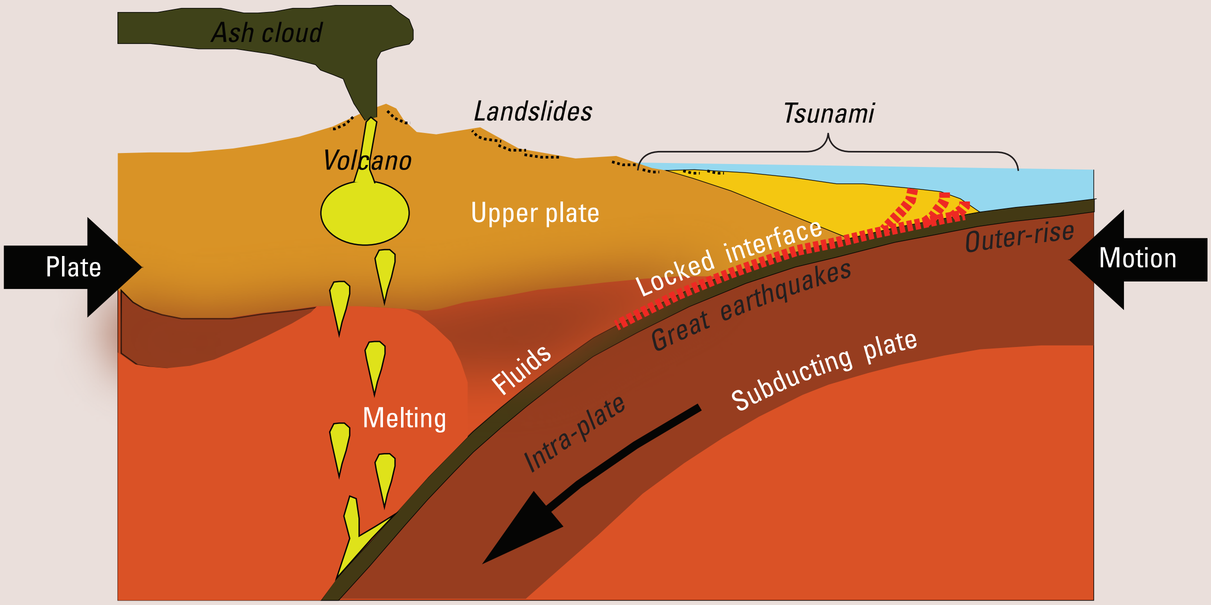
Earthquake, magnitude 5 or greater

Topography: depth and elevation in meters

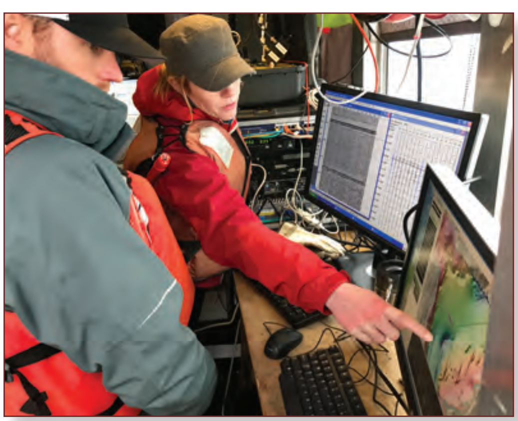



140°W
120°W
100°W
80°W
60°W
SKA
CASCADIA
JUAN DE FUCA PLATE
NORTH AMERICAN PLATE
PACIFIC PLATE
CARIBBEAN
(Puerto Rico,
U.S. Virgin Islands)
CARIBBEAN PLATE
COCOS PLATE
SOUTH
AMERICA
PLATE
NAZCA PLATE
0 200 400 600 800 1,000 1,200 KILOMETERS
70
60
50
40
30
20
10
EQUATOR
0 200 400 600 800 1,000 1,200 KILOMETERS

Schematic Cross Section of a Typical Subduction Zone



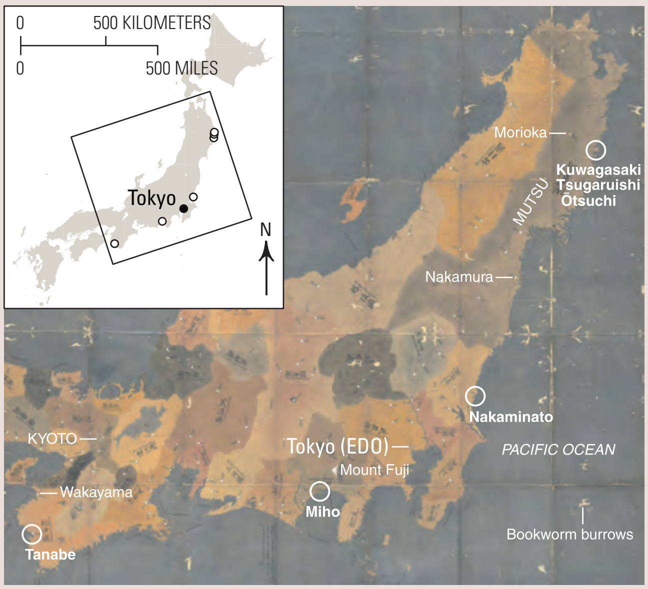
When tectonic plates converge (illustrated by the thick black arrows on either side of the image), one plate slides beneath the upper plate, or subducts, descending into the Earth's mantle at rates of 2 to 8 centimeters (1–3 inches) per year (red-brown slab with skinny arrow shows direction of motion). At shallow depths, less than about 25 kilometers (16 miles), the interface between the plates may become stuck, or "locked," and stresses build along these giant faults until they exceed the fault's strength and break free, causing an earthquake. These subduction zone earthquakes are the largest on Earth because of the massive size of the faults they may break. Other types of hazardous subduction zone earthquakes include deep, "intra-plate" earthquakes that occur within the subducting plate below about 30 kilometers (19 miles) below the surface or shallow, "outer-rise" earthquakes that occur just a few kilometers below the surface, where the plate begins its descent. Each of these types of subduction-zone earthquakes, along with more ubiquitous shallow earthquakes within the continental crust of the upper plate, has different characteristics. Large subduction zone earthquakes can suddenly elevate or depress the seafloor, creating a tsunami. Trenches form where the subducting plate begins its descent and can be as much as 11 kilometers (7 miles) deep. Thick layers of sediment may accumulate from the continental shelf to the trench, and may contain secondary faults that splay off the main interface fault (represented by the lines in the yellow-orange sediments in the figure). Trench sediments and the rocks of the subducting plate contain water that subduction transports to depths (labeled "fluids" on the diagram), where higher temperatures and pressures lead to melting of the subducting plate and mantle rocks, generating magma. The buoyant magma rises up to the surface, forming chains of volcanoes.



Scientists from the U.S. Geological Survey and the University of Washington deploy instruments in Lake Washington and Puget Sound, near Seattle, Washington, as part of an experiment to characterize the Seattle Fault and the potential for submarine landslides. U.S. Geological Survey photographs by Scott Bennett.

Historic Subduction Zone Earthquakes, Eruptions, Landslides, and Tsunamis in the United States

The most recent magnitude 9 or larger (*M*>9) subduction zone earthquakes and tsunamis in the United States were the *M*9.0 earthquake on January 26, 1700, in the Pacific Northwest (Cascadia) and the *M*9.2 earthquake in Alaska on March 27, 1964. Both of these events left deposits in coastal sediment layers, indicating widespread submergence of the coast.



Japanese historical accounts from 1700 document flooding along nearly 1,000 kilometers (about 620 miles) of Japan's coast (locations circled above on the historical and inset maps above) caused by the tsunami following the *M*9.0 Cascadia earthquake. From Atwater and others (2015).

Shaking during the 1964 Alaska earthquake was felt as far away as Seattle, Washington, and its tsunamis caused 129 fatalities and about $2.3 billion in property losses (2013 dollars). This massive shift of the Pacific Plate also caused widespread, permanent land-level changes, which are still visible at Girdwood, Alaska, where the land dropped almost 2 meters (6.6 feet); the sudden incursion of seawater killed the trees but left them standing, resulting in a "drowned" forest (above). Photograph from P. Haeussler, USGS.

On May 18, 1980, Mount St. Helens (above) erupted in Washington State, setting a U.S. historic record for the largest volcano-related number of fatalities (57) and property loss ($1.1 billion in 1980 dollars). Following one of the largest landslides in recorded history, it erupted with a blast that cleared 596 square kilometers (230 square miles) of forest, sent mud flows tens of miles down multiple drainages, and blanketed areas hundreds of miles downwind with ash. Photograph is figure 11 from Lipman and Mullineaux, 1981; copyright Keith Ronholm, 1980, published with permission.

On March 22, 2014, the Oso landslide in Washington State, seen in the aerial photograph above left, sent 18 million tons of sediment racing downhill at speeds averaging 64 kilometers (40 miles) per hour before stopping 1.5 kilometers (0.9 miles) away. It claimed 43 lives and 35 homes, covered a highway, and dammed a river. Economic losses exceeded $150 million. Photograph by M. Reid, USGS.

A Growing Sense of Urgency

Mega-disasters like the events in Sumatra, Chile, and Japan remind us of nature's power and have called into question our resilience to future events. In the Nation's subduction zones, the probability is high that at least one major earthquake, tsunami, volcanic eruption, or landslide will occur in the coming decades. Experience also has shown that smaller but more frequent events may be more hazardous locally than the larger, rarer ones. Localized volcanic hazards include lahars, landslides, lava and pyroclastic (avalanches of hot ash and gas) flows, toxic gas emissions, air blasts, and eruptive projectiles that may destroy structures and wildlife in their paths. Major eruptive events may be preceded by unrest lasting hours to months, presenting communications challenges to local populations. Locally destructive tsunami waves may be generated by rapid slip on nearshore faults or by submarine landslides. Landslides are particularly acute near subduction zones where geologic processes create steep, rapidly evolving topography. Moderate earthquakes in the *M*5–6 range that strike just beneath urban centers may disrupt all activity within them, sometimes causing major human and economic losses. The past five years have seen a confluence of activities contributing to a growing sense of urgency to prepare for these events. Recent media coverage, regional preparedness exercises, and technical advances all point to a unique opportunity to leverage interest and concern for subduction zone hazard mitigation.

The threat of geologic hazards lurking in the Nation's subduction zones was dramatically highlighted by the Pulitzer Prize-winning article, "The Really Big One" (Schulz, 2015), about the potential effects of a *M*9 earthquake in the Pacific Northwest's Cascadia Subduction Zone. The article spurred conversation across the country, drew attention to the lack of seismic readiness, and magnified concern for the region's capacity to respond to a major event. While the probability of a *M*9 earthquake occurring in the Nation's subduction zones has not changed over the past few decades, the rapid growth of populations in these zones and intertwined global economies means that increasingly more people and economic assets are at risk.

Similarly, the need to prepare for subduction zone hazards was underscored by both the 2014 Alaska Shield and 2016 Cascadia Rising exercises,[1] led by the Federal Emergency Management Agency (FEMA), which revealed weaknesses in response coordination and public readiness messaging. Those exercises focused on the immediate effects of great earthquakes on the Nation's built environment, public services, health, and economy, and they highlighted the need for effective coordination and integration among authorities at all levels—cities, counties, State and Federal agencies, the military, and tribal nations, as well as non-governmental organizations and the private sector—to conduct successful response operations.

Technological and scientific advances continue to create opportunities to observe and analyze the processes that cause natural hazards. These advances also enable the newfound knowledge to be translated into quantitative assessments and rapidly delivered information about likely effects of unfolding events (that is, situational awareness). These feed into decision-support products and effective risk-reduction policies and codes that are based on accurate knowledge of the severity and possible effects of hazardous events both before and after they occur. For example, the U.S. Geological Survey (USGS) issues an alert within 30 minutes of an earthquake worldwide, called a Prompt Assessment of Global Earthquakes for Response (PAGER) alert, that estimates economic losses and fatalities and thereby helps to direct response decisions and humanitarian aid. The National Science Foundation (NSF)-supported Ocean Observatories Initiative operates a cabled seafloor observatory that enables scientists to remotely observe and monitor, in real time, changes in undersea earthquake, volcanic, and other geologic activity in a few areas beneath the northeast Pacific Ocean. On the U.S. West Coast, the USGS and its partners are prototyping the ShakeAlert earthquake early warning (EEW) system, which will deliver warnings of impending ground shaking to people and infrastructure in harm's way seconds after an earthquake occurs.

Role of the USGS and Its Partners

The USGS serves the Nation by providing reliable scientific information to describe and understand the Earth in order to enhance and protect our quality of life. The USGS Natural Hazards Mission Area strives to minimize loss of life and property from natural disasters. Addressing this mission leverages the capabilities and expertise of other USGS programs that manage water, biological, energy, and mineral resources. Activities of the Natural Hazards Mission Area include real-time monitoring of subduction zone processes, which serves the goals of increasing scientific understanding, providing timely warnings, and delivery of rapid post-event information to decision makers and the public. Other key activities that address the USGS's mission include ongoing geologic and geophysical field studies, high-resolution topographic mapping, and operation of state-of-the-art laboratories; these provide data that underpin the USGS products delivered to its stakeholders. USGS scientists from many programs across the United States routinely partner with experts at the Federal, State, and local levels, and teams from diverse disciplines design and implement innovative approaches to help understand hazardous processes.

Improving the application of USGS science to successfully reduce risk from subduction zone events also relies on community efforts, including collaborations among scientists, emergency managers, resource managers, and businesses, as well as between international, Federal, State, and local authorities. The USGS is uniquely positioned to tackle complex scientific questions and work with stakeholders to translate

[1]https://www.fema.gov/cascadia-rising-2016

improved understanding of hazards in ways that are useful for decision-making (Holmes and others, 2013). The USGS, along with its partners, brings to bear multiple disciplines, a wide array of monitoring capabilities, and unique responsibilities to contribute to the safety and resilience of communities and resources at risk.

A Plan to Advance Subduction Zone Science for Society

The growing recognition of the scale of the threat posed by mega-disasters like great subduction zone earthquakes and tsunamis, combined with the confluence of activities focused on subduction zone hazards, creates a unique opportunity to leverage mounting momentum in this field. Recognizing this opportunity, USGS has developed this Subduction Zone Science Plan as a blueprint both for prioritizing USGS science activities, for delineating USGS resources, and potential participation in subduction zone activities supported by other agencies. To be most effective, this blueprint must be executed in collaboration with researchers from universities, other government labs, and private industry. This plan was undertaken by the USGS Natural Hazards Mission Area, and a writing team was drawn from multiple disciplines across regionally managed science centers. It is intended for current and future USGS scientists, USGS leadership, policy makers, colleagues in academic institutions, and partner agencies committed to advancing subduction zone science and risk reduction.

The Subduction Zone Science Plan addresses the needs of stakeholders and collaborators by focusing on three science themes: (1) advancing observations and models of subduction zone processes, (2) quantifying natural hazards and risk, and (3) forecasting and situational awareness. These three themes reflect the priorities outlined in the Natural Hazards Science Strategy Plan (Holmes and others, 2013). Each theme describes USGS accomplishments and current capabilities, discusses specific knowledge and capability gaps and scientific frontiers, and concludes with a summary of key questions (in the themes 1 and 2 subsections), needed research and facilities (investments), and products. Table 1 (on p. 2) broadly summarizes the information products that could be delivered by following the Subduction Zone Science Plan, which would lay the foundation for resilience-building actions. Key investments suggested for forefront science are listed following the table. Specific examples of these products are also found throughout the "Science Themes" section, and in the section titled "New Community Resources and Engagement."

The section "National and Global Partnerships" describes opportunities to leverage investments in subduction zone scientific research and facilities made by other organizations and to build new partnerships and capabilities.

The opportunities described herein build on a strong foundation of existing USGS and partner expertise and upon current understanding of the geologic hazards associated with subduction zones. Significant uncertainty remains, however, requiring new research and innovative applications to improve accuracy and meet new challenges. Addressing many of the gaps in knowledge and capabilities and the scientific frontiers identified in this plan will take a concerted effort across the USGS and its many partners, yet the Subduction Zone Science Plan holds promise to make the Nation more resilient when the next subduction zone event strikes, wherever it may occur.

Stakeholder Needs

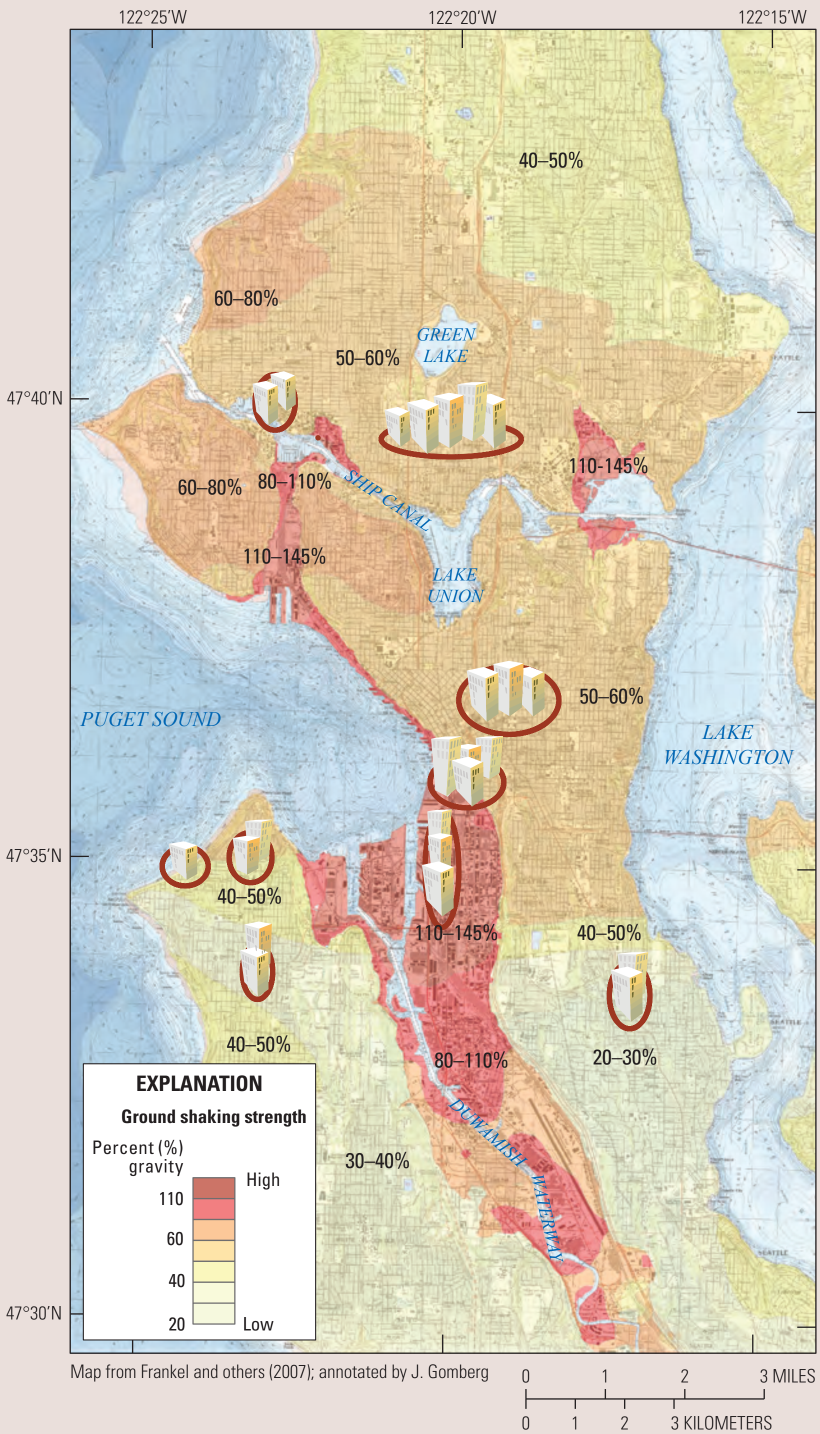
Earthquakes, tsunamis, volcanic eruptions, and landslides are common to subduction zones and can affect extensive areas and have far-reaching consequences. Stakeholders that benefit from the science detailed in this plan include land-use planners; civil, structural, and environmental engineers; policy makers; insurance providers; emergency managers and responders; infrastructure operators; business owners; the media; and the general public living near subduction zones. In addition, to most effectively communicate information, advances in the physical sciences must be coupled with social-science research and scientist-user collaborations. For nearly all potentially hazardous subduction-zone events, stakeholders need the following products, ordered from long-term planning to post-event response and recovery.

Vasily Titov (left, a scientist at the National Oceanic and Atmospheric Administration) and Bruce Jaffe (a U.S. Geological Survey scientist) by a tsunami warning sign in Pago Pago, American Samoa. The death toll from the 2009 magnitude 8 Samoa earthquake and tsunami on American Samoa would have been in the thousands if people hadn't known to go to higher ground after the earthquake. Photograph by Marie Chan Kau, Community and Natural Resources, American Samoa Community College.

- **Tools that provide high-fidelity, user-tailored information that facilitate targeted, neighborhood-scale decisions to mitigate risks cost-effectively and ensure post-event operability.**
  - Example need: city officials and engineers prioritize spending of a limited budget to retrofit buildings and infrastructure to be more resilient to earthquake shaking.
  - Requirements to address the need: estimates of likely event characteristics (for example, shaking intensity and frequency) at the neighborhood scale for the wide range of event types, sizes and frequencies. Information may be conveyed in maps, tables, or simulated shaking records (*see sidebar about neighborhood-scale maps on next page*).
- **Information to guide local land-use and emergency response planning to avoid development in hazardous zones and to plan evacuation routes.**
  - Example need: public safety officials need to plan evacuation routes and deliver warnings to communities near volcanoes, along low-lying coastlines vulnerable to tsunamis, next to active faults, and built on steep, landslide-prone terrain.
  - Requirements to address the need: thorough characterization of local volcanoes, faults, and unstable slopes near vulnerable populations and infrastructure, combined with up-to-date data and models of likely flow and wave paths. This information may underpin maps, databases, and scenario documents that describe evolving hypothetical events.
- **New tools to assess the potential for cascading hazards and risks.**
  - Example need: land-use planners considering building permit applications need to review slope stability to make appropriate decisions. More generally, stakeholders need to account for the cumulative impacts of cascading hazards, such as earthquake shaking that destabilizes slopes, which ultimately become landslides or submarine sediment flows.
  - Requirements to address the need: multidisciplinary monitoring systems, integrative computer models to anticipate cascading events and the consequences to natural and social systems. Science-based scenarios may effectively communicate plausible future event sequences.
- **Geospatial models of permanent, widespread land- and sea-level changes that may occur in the immediate aftermath of a great subduction zone earthquake.**
  - Example need: emergency managers need to anticipate the effects of submerged and damaged coastal roads, rails, pipelines and other infrastructure on disaster response and recovery. Sudden land subsidence in excess of meters (several feet) can occur after a great subduction zone earthquake, causing more widespread tsunami inundation, severe coastal erosion, shifting shorelines, and shoaling.
  - Requirements to address the need: predictive models of vertical land-level changes and effects on the coastal environment during and after big earthquakes, updated with land-based and remotely sensed geospatial observations.
- **More accurate forecasts of far-reaching hazards to avert catastrophes and unnecessary disruptions in air and sea transport.**
  - Example need: air-traffic controllers need to know when and how to reroute aircraft during a volcanic eruption. Explosive eruptions typical of subduction zone volcanoes can send ash clouds miles into the atmosphere, potentially invading aviation corridors that transport thousands of passengers and millions of dollars worth of cargo daily.
  - Requirements to address the need: coupled geologic and atmospheric models validated by real-time observations (ground-based and remotely sensed); interagency collaborations to clearly communicate hazards, ensure safe transportation, and minimize costly disruptions.
- **Information about aftershocks to guide decisions about when and where to re-enter, repair, or rebuild buildings and infrastructure after major earthquakes.**
  - Example need: emergency responders need to be able to assess the risk to crews working to locate survivors in weakened or collapsed buildings. Aftershocks can progressively weaken structures, and resulting shaking may be even stronger and more locally damaging than the initial event.
  - Requirements to address the need: updated and accessible aftershock forecasts informed by multidisciplinary data (for example, satellite imagery, seismic and geodetic signals) and underpinned by advanced knowledge of the types of earthquakes in subduction zones, regionally specific aftershock patterns, and effective strategies for risk communication.

Neighborhood-Scale Earthquake Ground Motion Maps

The U.S. Geological Survey (USGS) and the University of Washington are working together to produce state-of-the-art computer simulations of ground shaking from magnitude 9 earthquakes in the Pacific Northwest and to assess their associated impacts. These efforts are part of the M9 Project, funded largely by the National Science Foundation, in collaboration with USGS scientists. Because of the enormous size of these earthquakes, the simulations require supercomputers, and to be as realistic as possible they use the most accurate available models of the Earth and earthquake ruptures. In a similar USGS project, in 2007, simulations of all likely, potentially damaging earthquakes affecting the City of Seattle were used to create urban seismic hazard maps, including the one seen at right. These maps convey the earthquake shaking expected in Seattle in a user-specified time interval. The hazard was mapped at a neighborhood scale, which is useful for prioritizing retrofitting of Seattle's oldest and most vulnerable structures, like unreinforced masonry buildings, which are circled on the map. The maps are derived from ground motion simulations and show shaking levels that have a 10 percent likelihood of being exceeded (shown in red and yellow shades) within a 50-year time period. Shaking in reddish and darker brown areas would likely be damaging to buildings and infrastructure. Shaking strengths are displayed in terms useful for structural engineers, as a percentage of gravity (where 100 percent equals the downward gravitational pull of the Earth), from seismic waves with 1-second period.



Map from Frankel and others (2007); annotated by J. Gomberg

Science Themes of the Subduction Zone Science Plan

Theme 1: Advancing Observations and Models of Subduction Zone Processes

Information and products that support decisions promoting resilient communities rely on scientific understanding of the physical and sociological processes that give rise to potentially hazardous events. This section identifies the critical observations and research needed to build predictive models of geologic processes in subduction zones. The building blocks of these models are described in some detail, ordered approximately from the broadest to most focused in scope, and are followed by a summary of the key scientific questions, investments, and products. The knowledge gained from the research activities that underlie these models and from the model outputs is needed to make confident estimates of the likelihood and impacts of future events, and may translate into long-term cost savings by guiding more effective mitigation and loss-prevention measures.

A Foundation of Accomplishments and Capabilities

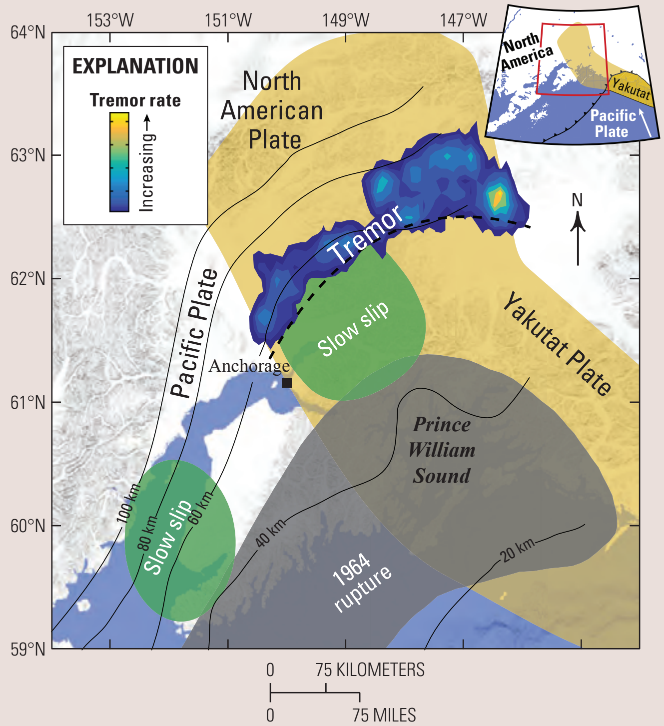
USGS scientists and their partners have made pioneering discoveries about subduction zone processes and their relations to society and the environment. Discovery about how subduction drives great earthquakes, tsunamis, volcanic eruptions, coastal subsidence, and landslides has proceeded at a remarkably fast pace, beginning in the 1960s with the recognition of plate tectonics and the origin of subduction zones by USGS scientists and their colleagues (Coats, 1962; Plafker, 1965). Since 2004, USGS geologists have worked with international colleagues to study deposits that recorded land-level changes and tsunami inundation following recent great earthquakes in Sumatra, Chile, and Japan, and have learned how to recognize similar deposits along U.S. coastlines. USGS and Canadian scientists were the first to propose that the Cascadia Subduction Zone produces great earthquakes (Heaton and Hartzell, 1987; Hyndmann, 1995). Along with Puerto Rican and international partners, the USGS has advanced understanding of earthquake and tsunami potential in the northeast Caribbean, including the potential for tsunamis to reach the Atlantic seaboard (ten Brink and others, 2014). Volcanologists from the USGS and partner universities have successfully forecast volcanic eruptions of Mount St. Helens (1980) in Washington State, of Mount Redoubt (1989–90, 2009) and Mount Augustine (2006) in Alaska, and of Mount Pinatubo (1991) in the Philippines. These forecasts gave emergency responders time to evacuate surrounding areas safely and reroute aircraft away from hazardous ash clouds, saving thousands of lives and millions of dollars.

Monitoring of subduction zone events and processes gives us an unsurpassed ability to accurately recognize hazards, produce quantitative hazard assessments, and issue timely and appropriate warnings. The USGS maintains the Global Seismographic Network in partnership with the National Science Foundation (NSF) and the Incorporated Research Institutions for Seismology (IRIS) consortium, and operates the National Earthquake Information Center, which determines and disseminates authoritative products describing global earthquakes within minutes of their occurrence. Within the United States, the USGS oversees the Advanced National Seismic System, which includes regional networks operated by university and other government agency partners. Together, these seismic networks document where and how often earthquakes occur, which allows scientists to investigate how earthquake source parameters and geologic setting control shaking intensity at the surface, including in subduction zones. Data from these seismic networks are key components of the National Oceanic and Atmospheric Administration's (NOAA) tsunami warning infrastructure. Geodetic monitoring of ground motions conducted by the USGS and its partners has revealed slow ground deformation associated with stress accumulation and release during the earthquake cycle, episodically creeping faults (*see sidebar about tremor and slow slip on p. 13*), and magma movement beneath volcanoes. The NSF's EarthScope program (http://www.earthscope.org/) has added significantly to the Nation's geodetic monitoring capabilities. A growing number of synthetic aperture radar (SAR) satellite constellations operated by international governments and private companies, as well as by the U.S. National Aeronautics and Space Administration (NASA), will continue to increase the frequency with which imagery is available. For instance, within the next 5–10 years, new imagery of U.S. volcanoes will be available as often as every 4 days.

Monitoring by the USGS and its partners shows that volcanoes express unrest in a variety of ways that are diagnostic of their potential for eruption. Monitoring before, during, and after the 1980 eruption of Mount St. Helens, for example, provided a wealth of close-in observations that have informed models of processes preceding, during, and following major eruptions. Similarly, landslide monitoring has identified conditions that control initiation and movement, enabling development of regional landslide hazard assessments and forecasts.

In some cases, monitoring technology developed for one hazard has been applied to another, leveraging equipment and design. For example, during the 2004–2005 eruption of Mount St. Helens, "spider" instruments were first used to augment permanent volcano monitoring. These instruments may be easily deployed by helicopter-sling operations and can collect measurements of earthquake motions, ground and glacier movement, rates of lava dome extrusion (eruption), and volcanic gas emissions. Following the Oso landslide in 2014, the USGS redeployed three spiders to help detect additional landslide movement.

Tremor and Slow Slip Illuminate Potential Earthquake Faults



Analyses of data from global positioning systems (GPS) and other geodetic networks have revealed that portions of faults sometimes slip slowly, in continuous gradual movement for hours to years, without emitting seismic waves, and often repeatedly. Although not hazardous themselves, slowly slipping fault patches can add stress to adjacent stuck (locked) regions of the fault that are likely to generate damaging earthquakes. Seismic tremor (weak seismic vibrations from swarms of overlapping tiny earthquakes) often is a by-product of these slow-slip episodes. Tremor is observed on seismic networks, is more easily detected than slow slip, and indicates that slow slip is occurring even when not observable directly. Tremor and slow slip most often occur in subduction zones, just below the locked portions of the plate interface where stresses accumulate and are released in great earthquakes. In this example, from south-central Alaska where three tectonic plates converge, new tremor observations (mostly dark blue patches) span the width of the Yakutat Plate (yellow). The termination of tremor at the boundaries of the Yakutat Plate indicates the boundary between it and the overriding North American Plate is an active fault, capable of generating a very large earthquake. Previously, scientists thought that only the Pacific-North American Plate boundary (shown as depth contours to the top of the subducting Pacific Plate) was active. As in many subduction zones, the areas with episodes of slow slip (green) occur along the edges of the region that slipped in a great earthquake (here, the 1964 *M*9.2 event, whose rupture area is shown in gray). It is still a mystery why the areas that have experienced slow slip episodes at this location do not coincide with the tremor. Image from Wech (2016).

Gaps in Knowledge and Capabilities, and Scientific Research Frontiers

Characterizing Past Hazardous Events to Forecast the Future Using Onshore Clues

Knowledge and capability gap.—Hazard and risk assessments and forecasts invoke the guiding principle that the past is a reliable predictor of the future, yet constructing chronologies of past fault slip episodes, volcanic eruptions, tsunamis, and landslides remains a major challenge. Chronologies of past events must be derived using geologic clues, because instrumental records extend back only hundreds of years at best—far shorter than the recurrence interval for great subduction zone earthquakes or the eruptive cycles of some volcanoes. Construction of long-term chronologies relies on studies of major events recorded in rocks, sediment, and landscapes. Linking observations from multiple sites to a single causative event relies on the ability to date them sufficiently accurately.

Frontier research—New laboratory approaches and facilities, coupled with expanded geologic field studies, will constrain event chronologies that are accurate enough to determine whether events on a given fault, volcano, or landslide surface are recurring events and thus can be used as guides to future events. Targeted geologic field studies in the Nation's subduction zones will collect, analyze, and interpret samples using new sediment-core physical scanning methods, high-resolution potential-field and seismic imaging, and analyses of microfossils. New and refined dating methods and facilities will be used.

Refining Subduction Zone Earthquake Chronologies Using Offshore Clues

Knowledge and capability gap.—Estimates of the recurrence rates of great subduction zone earthquakes differ significantly depending on whether they are derived from offshore or onshore geologic studies. In some places, rates are unknown. It is especially important to resolve the differences in recurrence rates of Cascadia earthquakes having *M* 8–9 that are inferred from studies of submarine sediment and mud flow deposits (turbidites) with those based on measurements of coastal uplift and subsidence from marsh stratigraphy and tsunami deposits (*see sidebar on next page about records of earthquakes*). These different measurement methods translate to long-term-average ground shaking estimates that differ by 40 percent, which affects many parameters used for earthquake planning, such as seismic building design criteria.

Frontier research.—Acquisition and analyses of offshore sediment cores and high-resolution subsurface and bathymetric imagery will provide means of testing conditions under which turbidites may be generated by great earthquakes. Earthquake chronologies from offshore sediment cores may be compared with those from onshore studies of coastal land-level changes and tsunami deposition, earthquake-triggered landslides, and geodetic and ground motion modeling.

Understanding Cycles of Volcanic Eruptions

Knowledge and capability gap.—Volcanoes have diverse eruptive styles and rates that challenge forecasts and evaluations of future activity. All volcanoes studied to date appear to have periods of frequent eruptions separated by longer quiet intervals, but the length of active and quiet periods vary from one volcano to another: active periods may last anywhere from a few years to centuries, and quiet periods may range from a few decades to thousands of years. Most subduction zone volcanoes erupt infrequently, so collecting interpretable monitoring data that span the full eruption cycle, from quiescence to the buildup to eruption, requires adequately instrumenting many potentially hazardous volcanoes.

Frontier research.—Studies that systematically sample volcanic rocks, lavas, and gasses and apply state-of-the art age-dating methods improve knowledge of eruption chronologies and reveal the causes and characteristics of eruption clustering. Improving eruption chronologies, in turn, improves the confidence and accuracy of volcano hazard assessments at high-threat volcanoes.

Forecasting Destructive Earthquake-Triggered Landslides

Knowledge and capability gap.—Hazard assessments for earthquake-shaking triggered landslides are based on highly simplified models and incomplete input data, and generally do not provide estimates of the areas likely to be covered by landslide debris; oftentimes areas forecasted to fail are over-estimated by more than a factor of two; and landslides frequently occur in locations forecast as stable.

Frontier research.—Laboratory analyses of field samples from landslide-susceptible slopes will help identify conditions affecting potential slope failure during earthquake shaking. These analyses are used to constrain models of how seismic energy is amplified along hillslopes for the range of sizes and types of subduction zone earthquakes. The model results help characterize the response of shallow Earth materials to shaking, show how the materials change as they slide, and elucidate the role of saturated soils in controlling the initiation, mobility, and run-out distance of earthquake-triggered landslides.

Anticipating Great Subduction Zone Earthquakes and Tsunamis Using Seafloor Observations

Knowledge and capability gap.—The paucity of seafloor sensors limits our ability to accurately anticipate where subduction zone earthquakes will happen, the severity of their shaking, and their propensity to generate tsunamis. The destructive potential of ground shaking during great subduction zone earthquakes depends crucially on the earthquake depth and the geometry of the tectonic plate interface (essentially giant faults), as well as on the location of locked sections of the plate interface relative to populations and critical infrastructure. Significant areas of these interfaces lie beneath the ocean, where we have few or no observations to accurately determine their configurations and whether they are locked or not.

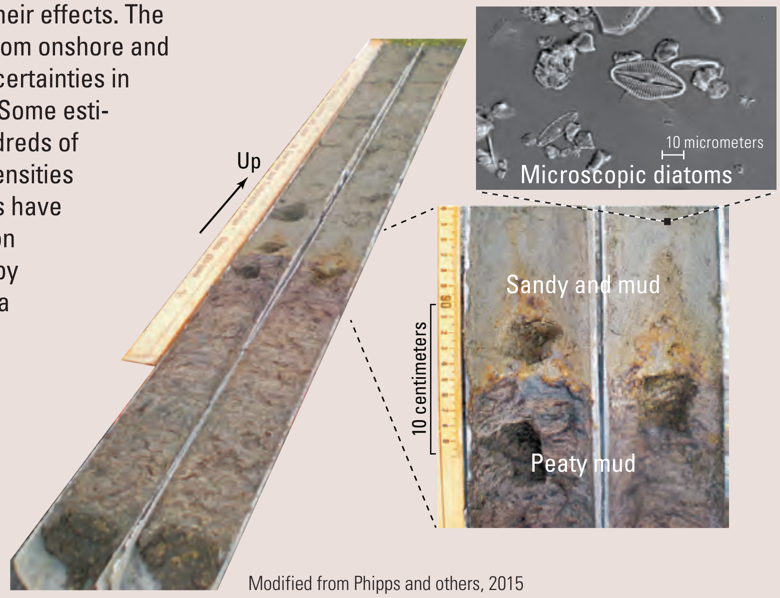
Frontier research.—Repeat temporary deployments of seafloor seismic, geodetic and other instruments provide first-order constraints on key unknown attributes of plate interfaces. Seafloor observatories operated by the Japanese government, for example, have demonstrated the practicality and value of seafloor monitoring, which illuminates the geometry, depth, and spatially variable strength of subduction zone faults. Such information leads to reduced uncertainty regarding where and why some regions of plate interfaces are stuck while others slide freely (*see sidebar about seafloor instrumentation on p. 16*). Knowledge of the temporal and spatial variability in interface behavior requires that such instrumentation be deployed permanently and record continuously. Offshore sensors must transmit data from the seafloor in real time in order to be useful for detection of activity that may be precursory to a major earthquake and tsunami, and to improve warnings of earthquake shaking and tsunami waves.

Determining the Role of Water in Subduction Zone Processes

Knowledge and capabilities gap.—Water plays a key but poorly understood role in determining where faults are stuck and ultimately slip in earthquakes, and where they slip slowly without radiating damaging seismic waves. Water also promotes magma generation below subduction zone volcanoes and controls eruption style and energetics. Water is thought to be trapped in sediments and minerals and transported to great depth during subduction, where it is released due to intense pressures and temperatures. At the land surface, elevated pore pressure from infiltrated rainfall and snowmelt affects slope stability and therefore landslide probabilities. The accuracy of earthquake, landslide, and eruption forecasts would be greatly improved by increased understanding of water entrainment

The Onshore and Offshore Records of Great Earthquakes

Scientists use reconstructed histories of past great earthquakes to estimate the likelihood of future events and their effects. The Cascadia earthquake chronologies estimated from onshore and offshore studies differ, leading to significant uncertainties in seismic hazard (ground shaking) assessments. Some estimates of earthquake repeat times differ by hundreds of years, which translates into ground shaking intensities that differ by about 40 percent; such differences have major effects on building codes and construction costs. Preserved onshore coastal deposits left by tsunami waves and sudden subsidence record a long-term history of large earthquakes, evident as abrupt changes in the subsurface layers in sediment cores. The photograph shows a core collected in Grays Harbor, Washington, after the core was split open. The abrupt color change in the core indicates that ancient tidal marshes, where peat and mud developed (the reddish-brown sediment), were suddenly inundated with sands and muds (grayish sediment)—most likely due to subsidence during a great Cascadia earthquake. Analyses of preserved microscopic organisms above and below this abrupt change in the core (the photo-micrograph shown in the top left image) and knowledge of their preferred habitat provide estimates of the amount of subsidence, which helps constrain the magnitude of the causative earthquake (images from Phipps and others, 2015). Offshore, strong earthquake shaking along steep submarine slopes may loosen massive volumes of sediments, mixing with water to become slurries that rush downslope along seafloor canyons. These turbidity currents leave deposits called turbidites, which are identifiable in sediment cores collected far offshore on the continental slope and deep seafloor. High-resolution maps of seafloor topography offshore Washington State (map modified from Goldfinger and others, 2016) show inferred flow channels that turbidity currents might follow (teal lines). By correlating similar turbidite characteristics among selected cores across the region (red dots show core locations), scientists have estimated the dates and magnitudes of large prehistoric great earthquakes. USGS scientists and university colleagues are working to understand the different onshore and offshore estimates of Cascadia earthquake recurrence.



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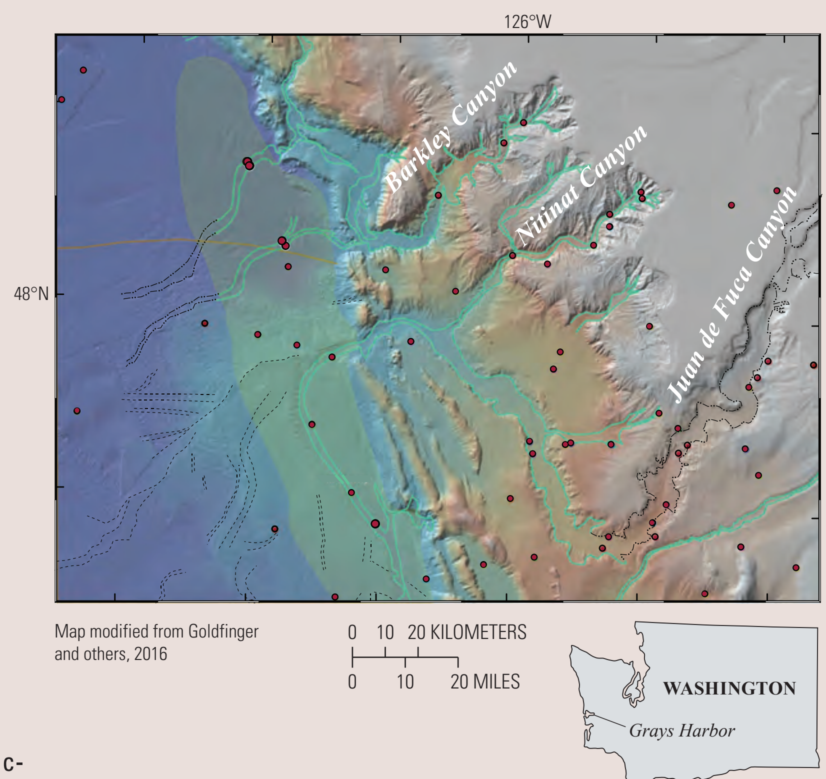
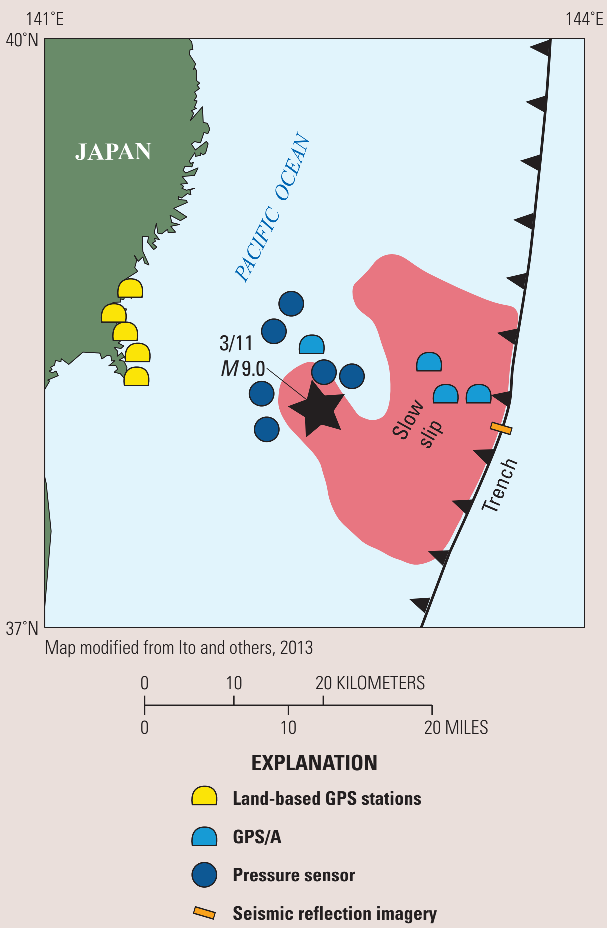
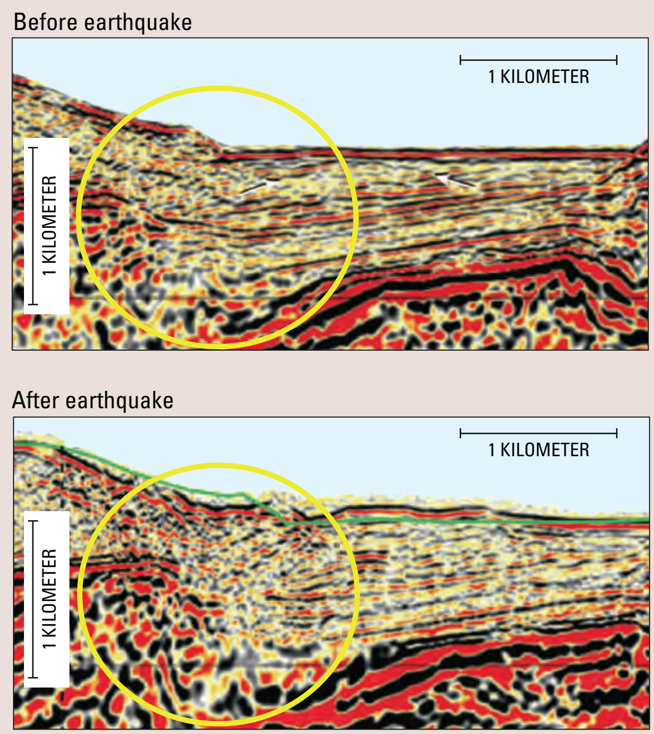


Map modified from Goldfinger and others, 2016

Seafloor Instrumentation and the 2011 Magnitude 9.0 Tōhoku, Japan, Earthquake

Following the 2011 magnitude (*M*) 9.0 Tōhoku, Japan, earthquake, scientists made important discoveries about the earthquake and tsunami because they had already mapped the topography of the seafloor (bathymetry), seismically imaged geologic units below the seafloor, and installed seafloor monitoring instruments. Continuous records of changes in the seafloor elevation and height of the water column (measured by the pressure it exerts on the seafloor), confirmed that the plate interface slipped slowly (left figure, pink area; map modified from Ito and others, 2013) during the two-day foreshock sequence prior to the *M*9.0 event (black star marks earthquake epicenter). Seafloor pressure records during the *M*9.0 earthquake, as well as measurements of seafloor position using acoustically linked global positioning system (GPS) receivers (blue symbols labeled "GPS/A") documented an enormous amount of fault slip (more than 50 meters, or 64 feet) in the shallowest part of the fault (Iinuma and others, 2012). High-resolution marine seismic-reflection images (right figure, from Kodaira and others, 2012)—effectively like sonograms of the subsurface—revealed that the *M*9.0 earthquake dramatically deformed sediments (especially within yellow circles; note how continuous layers in the "Before" image appear mangled in the "After" image). These large disturbances of the seafloor and the sediments and rocks along the fault accounted for the tremendous ensuing tsunami, and the potential for similarly large future events are now being included in tsunami inundation models worldwide. Moreover, comparison surveys of seafloor topography before and after the 2011 earthquake (see, for example, the green line in the "After" image that shows the pre-event topography) revealed evidence of a submarine landslide that may have intensified the tsunami (Tappin and others, 2014). Seafloor measurements over the nine years prior to the 2011 *M*9.0 earthquake led to more accurate estimates of how stresses are accumulating on the plate interface than can be obtained from land-based GPS data alone (yellow symbols on map; Sato and others, 2013).





and release, and how it controls the occurrence of these hazardous events.

Frontier research.—Advanced laboratory techniques that precisely measure water and other constituents of rocks that were transported to the surface by geologic processes, and new field techniques that accurately detect and measure gases emitted from active volcanoes provide key constraints on the conditions required to trap and release water. These measurements, coupled with new computer models, seismological and geodetic analyses, and laboratory studies will lead to new insights into the mechanical and chemical effects of fluids in landslides, faulting, and volcanism.

Addressing Multidisciplinary Questions About Sediment Transport

Knowledge and capabilities gap.—Sediment discharged from the small, high-sediment-yield watersheds typical of subduction zones is eventually deposited in the deepest seafloor basins and represents the majority of sediment reaching the world's oceans. This sediment plays a key role in subduction zone geologic processes, yet the interactions among the many natural systems that affect and are affected by sediment transport processes are poorly constrained. For example, earthquake-generated land-level changes undoubtedly alter the paths of sediment-laden streams and rivers and thereby modify flooding hazards and ecosystem habitats, but the models do not exist to predict the magnitude and precise nature of these changes.

Frontier research.—Questions about sediment transport and subduction zone processes are best addressed by collaborations amongst hydrologists, oceanographers, and geologists across USGS programs. For subduction zone hazard assessments, scientists supported by the Natural Hazards Mission Area study how sediment transport affects coastal erosion, submarine landslides, and the creation of seafloor turbidite deposits from which dates and magnitudes of past strong earthquakes can be deduced. Scientists supported by the Climate and Land Use Change and Water Mission Areas, as well as the Pacific Coastal and Marine Science Center, are addressing complementary questions about sediment transport; for example, geologic trenching and landscape studies examine the deposition and erosion associated with past extreme storms, sea level changes, or dam construction.

Mapping Bathymetry and Topography from the Deepest Seafloor to Continental Interiors

Knowledge and capabilities gap.—In subduction zones, high-resolution, regional, cross-shoreline topographic data have numerous applications, yet are lacking in many places. Bathymetric and topographic data are the foundation of products like assessments of inundation and earthquake hazards, geologic maps, and comprehensive sediment transport models. For example, cross-shoreline topographic data are needed to determine if faults mapped onshore to the coast extend offshore, and to constrain models of tsunami impacts, which depend strongly on the topography offshore and onshore. In addition to addressing geologic needs, such data also contribute to understanding of forest wetland ecology, benthic habitat structure, and ecosystem interactions (for example, the high topography built by subduction zone processes can create rain shadows and deserts).

Frontier research.—Data collection designed and accomplished through collaborations among the many users of topographic data will most effectively address all their needs. Such an effort will build on the USGS Coastal National Elevation Database Project (CoNED; http://topotools.cr.usgs.gov/coned/index.php), which is creating seamless elevation models for the U.S. coastal zone in collaboration with the USGS's National Geospatial and 3-D Elevation (3DEP) and Coastal and Marine Geology Programs, the U.S. Army Corps of Engineers, and NOAA.

Key Questions, Investments, and Products

This theme, "Advancing Observations and Models of Subduction Zone Processes," addresses fundamental science questions using predictive models. The following list summarizes the previous section, noting the outstanding gaps recast as science questions, the investments needed to make major leaps forward toward answers to them, and potential products that an enacted Subduction Zone Science Plan could deliver. The relevant products in table 1 and investments in its accompanying list are noted in abbreviated form.

1. How well do past events foretell the future? This question summarizes the gaps and investments needed to characterize past subduction zone events. For earthquakes, chronologies of past events will reveal whether characteristics of large hazardous earthquakes may be accurately anticipated from studies of more frequent smaller earthquakes. For landslides, chronologies coupled with knowledge of historic and paleo-climatic conditions and regional geology will answer questions about what initiates slippage of landslide masses. For volcanoes, chronologies of eruptions from volcanoes in different settings will show what, if any, predictable patterns in eruptive behaviors exist and how those patterns vary among volcanoes.

    Investments: offshore sediment-core samples, images of subsurface geologic structures, temporary geophysical deployments; high-resolution multibeam bathymetry offshore, airborne and space-based topographic imagery onshore; expanded geologic field programs; and laboratory capabilities for dating and analyzing the physical properties of rock samples (D, E, G, H in table 1's list).

Products: Hazard and risk assessments, scenarios, forecasts (table 1).

2. Are *M* 8–9 earthquakes preceded by precursory processes (such as foreshocks or slow fault slip)?

   Investments: denser onshore seismic and geodetic monitoring; permanent and temporary seafloor seismic and geodetic monitoring instrumentation; and offshore sediment-core samples, images of subsurface geologic structures, temporary geophysical deployments (A–D in table 1's list).

   Products: hazard and risk assessments, warning systems, new types of forecasts (table 1).

3. What processes generate and consume water during subduction, and how does water control magma generation, fault movements, and landslides?

   Investments: denser onshore seismic and geodetic monitoring; permanent seafloor seismic and geodetic monitoring instrumentation; offshore sediment-core samples, images of subsurface geologic structures, temporary geophysical deployments; geologic field programs and laboratory capabilities for dating and analyzing the physical properties of rock samples (A, C, D, G, H in table 1's list).

   Products: high-resolution hazard and risk assessments, cascading event assessments (table 1).

4. How are sediments redistributed from their source on land to the seafloor?

   Investments: offshore sediment-core samples; images of subsurface geologic structures, temporary geophysical deployments; high-resolution, multibeam bathymetry offshore, adjacent to airborne and space-based topographic imagery onshore; geologic field programs; multidisciplinary models of geologic and sediment transport processes (D, E, G, and I in table 1's list).

   Products: assessments of cascading subduction zone events (table 1), new knowledge of how sediments are redistributed from continental interior to the deep seafloor.

Theme 2: Quantifying Natural Hazards and Risk

Natural hazard assessments are estimates of the characteristics of a given event type (for example, past rates of occurrence, future probability, magnitude, duration, speed of onset, and spatial extent) and are typically either scenario-based or probabilistic. Scenario-based assessments seek to estimate the impact of a specific hypothetical natural event, constrained by historical information, by geologic field and laboratory data, or by deterministic computer modeling. Probabilistic hazard assessments combine multiple scenarios with information about recurrence times of hazardous events. They convey probabilities of experiencing certain levels of effects over a specified period of time by accounting for the likelihoods of all the scenarios. This section considers both types of assessments: both are needed for planning for natural hazards over time scales of years to decades.

Risk is the likelihood that a natural hazard event or events will cause a human, economic, or ecosystem loss and is calculated by combining the hazard probability with exposure and vulnerability of populations, economies, infrastructure, and ecosystems. Estimating risk requires a multidisciplinary approach, involving both scientific data and methods developed in social and behavioral sciences, as well as collaborations with engineers, land-use planners, and insurance entities. The knowledge and capabilities gaps and frontier research areas identified in this theme address not only the potential for a particular subduction zone event to occur, but also how that event may affect subsequent natural events, the built environment, or human activities. These are ordered roughly from the broadest to most focused in scope, and are followed by a summary of the key outstanding questions, investments and products.

A Foundation of Accomplishments and Capabilities

The USGS produces probabilistic earthquake ground-shaking hazard assessments for the Nation, including our subduction zones, in the National Seismic Hazard Maps (NSHM; available at https://earthquake.usgs.gov/hazards/hazmaps/). These maps are the basis for the seismic codes for buildings, highway bridges, landfills, dams, and other infrastructure. These earthquake hazard assessments incorporate the best data available about fault characteristics that can be inferred from chronologies of past earthquakes and tsunamis recorded in geologic, historic, and instrumental data. Higher-resolution maps that account for the complex three-dimensional effects that local geologic structures have on ground shaking exist for several urban areas (*see sidebar on about neighborhood-scale maps p. 11*). The USGS is also a leader in the computer simulation of earthquake ground motions for a variety of plausible earthquake models, particularly those in subduction zones.

USGS scenario ground-shaking maps (called "ShakeMaps;" https://earthquake.usgs.gov/earthquakes/shakemap/) serve as input to the FEMA Hazus vulnerability and risk assessment tool (available at https://www.fema.gov/hazus) and, together, ShakeMaps and Hazus are key resources for emergency management, loss estimation, and emergency response exercises. For example, ShakeMaps for 20 hypothetical earthquakes provide the foundation for a scenario catalog hosted by the Washington State Emergency Management

Division and Department of Natural Resources to assist cities and counties in their mitigation plan development (https://fortress.wa.gov/dnr/protectiongis/seismicscenarios/). ShakeMaps for great subduction zone earthquakes were input to Hazus to serve as the foundation of the Oregon Resilience Plan (https://www.oregon.gov/OMD/OEM/Pages/osspac/osspac.aspx#Oregon_Resilience_Plan) and the 2014 and 2016 FEMA-led Alaska Shield (https://www.fema.gov/media-library/assets/videos/93182) and Cascadia Rising (https://www.fema.gov/media-library/assets/documents/116120) national level exercises, which test the effectiveness of response and recovery within Federal, State, and local governments, and private entities individually and collectively.

The USGS has released hazards information for every high-threat subduction zone volcano in the Nation. For many of the volcanoes posing the greatest threat, the USGS has mapped the potential for ground-based volcanic impacts—lava, mud and pyroclastic flows, avalanches, and landslides—and more far-reaching hazards such as volcanic gases and ash falls. Long-term assessments are based upon detailed geologic mapping and dating of volcanic deposits, which provide a record of past eruptions, integrated with high-resolution topographic mapping and computer models to forecast the effects of these eruptions.

The USGS National Volcano Early Warning System (NVEWS, https://volcanoes.usgs.gov/vhp/nvews.html) is a proposed national-scale system to assess the threat posed by each volcano in the Nation, to prioritize study and monitoring of volcanoes according to their risk, with the primary goal of providing timely warning of an eruption to potentially affected areas and communities. U.S. volcanoes have been grouped into five threat categories (very high, high, moderate, low, and very low) based on a combination of volcanic hazards and exposure of population and property. The 2005 NVEWS assessment of volcanic threat and level of instrumentation identified 37 volcanoes in Alaska and the Mariana Islands that have either inadequate or no monitoring networks in place, and 21 additional volcanoes that have some deficiencies in their monitoring (Ewert and others, 2005). Since the 2005 report, progress towards NVEWS's goals has included instrumentation upgrades on six volcanoes, design and permitting of comprehensive networks for three volcanoes, upgrading of data telemetry from analog to digital where feasible, development and installation of infrasound (acoustic) monitoring instruments in Alaska and the Pacific Northwest, and repair of numerous failed remote instruments in Alaska. Together, USGS scientists and stakeholders have developed volcano emergency response plans at more than 88 volcanoes nationwide.

USGS scientists have identified conditions that facilitate landslides triggered by rainfall and earthquakes and have developed multiple approaches to regional mapping to depict landslide-prone areas. Some of these approaches have been developed for and applied to earthquake- and rainfall-induced landslides in Oregon, Washington, and Alaska. Subduction-zone-related uplift, the inevitability of future earthquakes, and wet winter climates make large parts of these States highly susceptible to landslides. For example, the USGS has produced maps that show where landslides are likely to initiate in Seattle, Washington (fig. 2).

USGS scientists have developed a probabilistic tsunami hazard assessment (PTHA) framework that has been used in engineering and flood insurance applications, following the same probabilistic approach that underlies the National Seismic Hazard Maps. Unlike the seismic hazard maps, though, the tsunami hazard assessment has the added challenge of needing to include probable earthquake sources throughout the ocean basins, because tsunami amplitude attenuates much more gradually with distance than earthquake-induced ground shaking. Products from PTHA range from estimates of tsunami runup (the highest elevation a tsunami reaches on land)

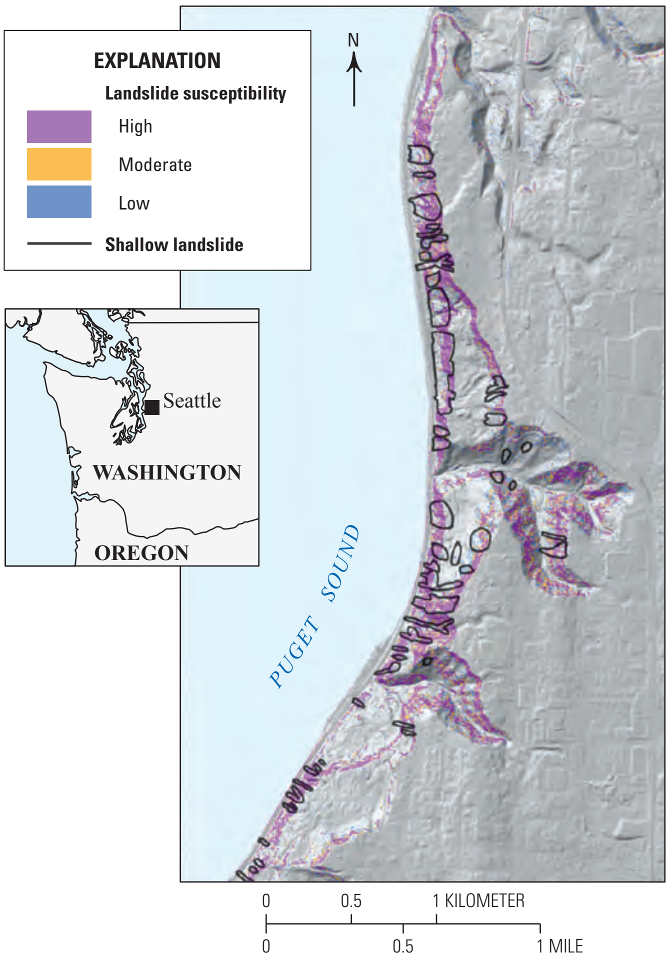


Figure 2. Example of a landslide susceptibility map after a period of heavy rainfall (2 inches, or 52 millimeters, in 1.5 days). This assessment, along a key railroad corridor about 9 miles (15 kilometers) north of Seattle, Washington, shows which areas would be most susceptible to shallow landslides (purple areas have high susceptibility). From Godt and others (2008).

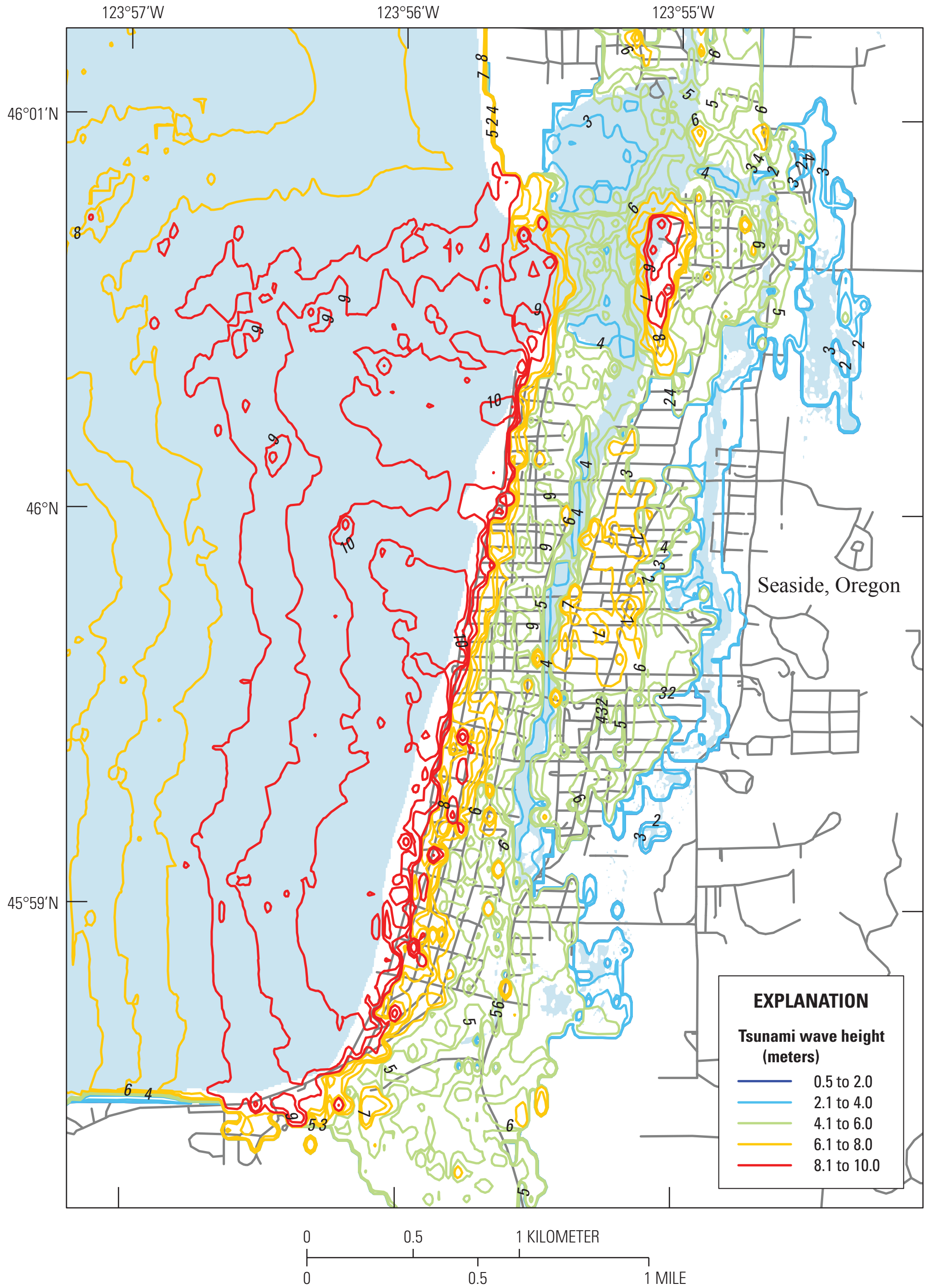


Figure 3. Tsunami wave height estimates for Seaside, Oregon, calculated for a range of likely earthquake sources of magnitude 8–9. Contours are drawn at 1 meter (~3 feet) intervals. At the beach, for example, waves could be 8, 9, or 10 meters tall (red contours), while the more inland parts of town might see waves of 2, 3, or 4 meters (light blue contours). These wave height estimates are used for conservative, long-term planning and design. Land areas in white and the Pacific Ocean in blue; roads are thin gray lines. Image modified from Tsunami Pilot Study Working Group, 2006.

to probabilistic inundation maps that show how far inland a tsunami is likely to reach at a particular coastal location. A variety of PTHA products have been created for a pilot project involving USGS, NOAA, and FEMA to update FEMA's Flood Hazard Maps in Seaside, Oregon; an example is shown in figure 3. With support from the U.S. Nuclear Regulatory Commission, the USGS also completed an assessment of the tsunami hazard along the U.S. East Coast (ten Brink and others, 2014).

USGS researchers have used population characteristics within tsunami hazard zones to improve tsunami evacuation protocols in coastal communities. These studies take into account tourist and non-residential populations who may be more vulnerable because of a lack of situational awareness during a hazardous event, as well as populations with limited mobility or health issues who might be unable to evacuate without assistance. Using these analyses, for example, researchers determined pedestrian evacuation times within the Cascadia Subduction Zone (Wood and others, 2016).

Gaps in Knowledge and Capabilities and Frontiers of Scientific Research

Communicating Hazard and Risk to Communities

Knowledge and capabilities gap.—There is a dearth of knowledge about how to best tailor hazard communications to target diverse at-risk communities. While USGS researchers have studied vulnerable populations (Wood and others, 2016), little is known about how historical, cultural, and economic factors may influence the ability or willingness of a population to utilize USGS tools to prepare for, respond to, and recover from a hazardous event.

A technician installs lahar monitoring equipment in Washington State. U.S. Geological Survey photograph by Elizabeth Faust.

Frontier research.—USGS scientists will seek collaborations with behavioral psychologists, sociologists, user-centered designers, communications experts, and other Federal, State, and local agencies to understand when and how to release information in order to ensure effective and appropriate response. Such research is especially important for implementing new warning systems and in communicating preparedness messages that help subduction zone residents to prepare for and react to a complex cascade of events and consequences following a major earthquake, tsunami, widespread landslides, or a volcanic eruption.

Discriminating Between Causes and Effects of Subduction Zone Processes and Climate Change

Knowledge and capabilities gap.—Subduction zone science relies on understanding climate change, because short-term events that occur in subduction zones can affect, or be affected by, longer-term climate changes. These interactions have been quantified poorly at best, but examples of some qualitatively understood interactions include climate-change-driven sea-level rise that affects the extent of seawater inundation by tsunamis and by earthquake-induced coastal subsidence; changes in rainfall and the thinning and retreat of tidewater glaciers that affect submarine and subaerial landslide susceptibility, size, and frequency; and ash clouds from large volcanic eruptions that temporarily alter the rate of average global temperature rise. These interactions need to be considered not only through the science underlying hazard assessments, but also to assess the exposure, vulnerability, and risk from both subduction zone and climate-change processes (which is a goal also noted explicitly in the USGS Climate and Land Use Change Science Strategy).

Frontier research.—Accurate interpretation of both the geologic record of subduction zone processes and of climate change requires forefront studies of the interplay between them, which will improve interpretations of geologic evidence of past subduction zone events and forecasts of future ones. Studies of tsunami inundation and the deposits they leave in the geologic record, earthquake-generated coastal land-level changes, and landslide occurrence in areas affected by sea-level and glacial changes will engage scientists from the USGS Climate and Land Use Change Mission Area, the Natural Hazards Mission Area, the National Cooperative Geologic Mapping Program, and partners at State geological surveys.

Assessing the Nation's Energy and Mineral Resources

Knowledge and capabilities gap.—The economic consequences of steady geologic processes and of damaging events in subduction zones have only begun to be quantified. The former produce geothermal energy and mineral resources, but latter may disrupt their production. The abundant volcanism along subduction zones makes geothermal energy a key resource in global subduction zones (for example, in the Republics of the Philippines and Indonesia, Japan, and New Zealand). The majority of the world's copper is produced from shallow granitic intrusions that formed beneath subduction zone volcanoes, and gold, silver, tungsten, and tin may form as direct mineral deposits in subduction settings. A preliminary USGS study (Menzie and others, 2011) provides an example of the effects of a great subduction zone earthquake on the availability of mineral resources; in this study USGS scientists concluded that the 2011 *M*9.0 Tōhoku, Japan, earthquake and tsunami disrupted Japan's mineral and mining industries, which supply the world with 25 percent of its iodine, 10 percent of its titanium, and smaller but significant fractions of other nonfuel minerals.

Frontier research.—Advanced USGS subduction zone science will focus on both the economic benefits and the hazards of subduction zone processes, particularly geothermal power and mineral assessments. USGS studies of the geothermal potential of the Cascades volcanoes indicate their potential is relatively modest (Guffanti and Muffler, 1995; Muffler and Temanyu, 1995), but many Alaskan volcanoes erupt more frequently and may have greater geothermal potential (for example, Makushin Volcano, Akutan Peak, Mount Spurr, Augustine Volcano, Mount Okmok, and Korovin Volcano). Studies of subduction zone processes also may address the energy-producing potential of volcanic sources, their effects on mineral resources, and the potential of subduction zone events to disrupt supply chains that depend on energy and mineral resources from subduction zones.

Assessing the Potential for Submarine Landslides

Knowledge and capabilities gap.—The ability to assess the potential for submarine landslide occurrence is almost entirely lacking, even though such slides may generate locally hazardous tsunamis and can damage offshore infrastructure (*see sidebar on next page about using bathymetric data to identify tsunami hazards*). It is unknown if existing slope stability models, developed for terrestrial landslides, can be used for submarine slopes, given the significant differences in sediment mechanical properties and hydrodynamics of sediment/fluid mixtures between onshore and offshore environments. Existing bathymetric data lack adequate resolution and submarine slope materials are sparsely sampled in most regions.

Frontier research.—Collection of samples of slope materials and high-resolution bathymetric data, determination of ages and stability-affecting properties, and development of physical models at a regional scale will identify the distribution and characteristics of submarine landslides. Results from these activities can help determine the applicability of existing slope-stability models and contribute to new ones as needed.

Accounting for Locally Hazardous Tsunamis

Knowledge and capabilities gap.—Probabilistic tsunami hazard assessments consider only earthquakes that occur on the plate interface, neglecting tsunami-generating landslides, volcanic events, and earthquakes on shallow intraplate faults, particularly those close to shore (which may locally be more hazardous than trans-oceanic tsunamis). For example, of the tsunami-related losses that followed the 1964 *M*9.2 1964 Alaska earthquake, most of the damage and 76 percent of the fatalities were generated by localized, subaerial and submarine landslides (Suleimani and others, 2009). Ninety tsunamis of volcanic origin have been produced in the world's ocean basins in the past 250 years (Beget, 2000), but the majority of submarine volcanism occurs undetected. Information is lacking about the frequencies of submarine volcanic activity, offshore landslides, shallow intraplate fault earthquakes, and about how these events displace seawater to generate tsunami waves (*see sidebar about using bathymetric data to identify tsunami hazards on next page*).

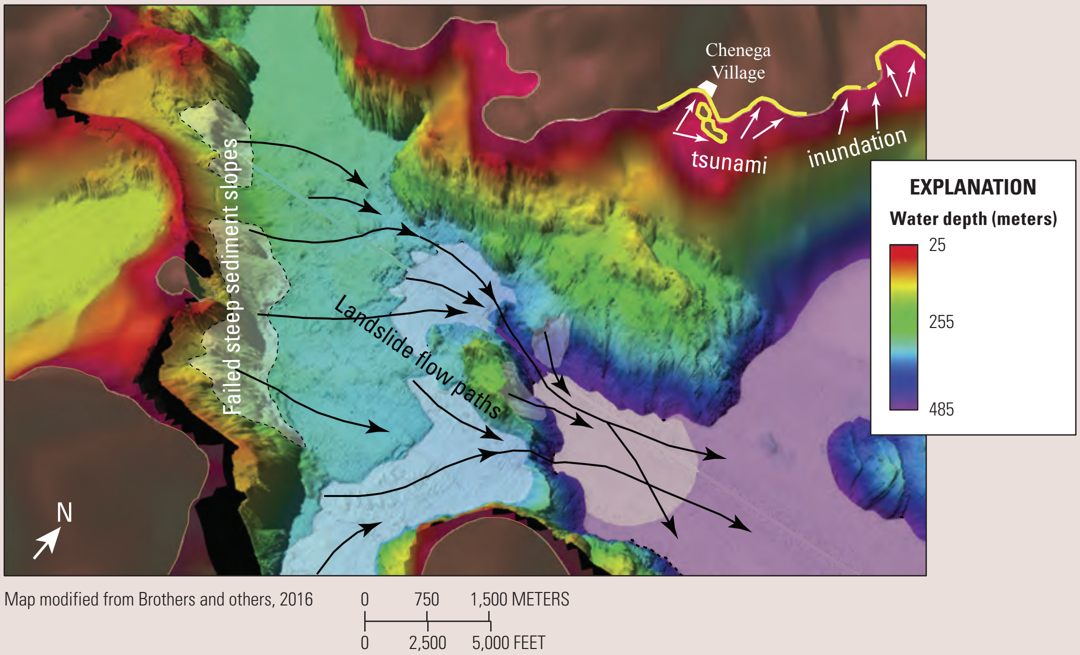
Frontier research.—Understanding frequencies and mechanisms of submarine volcanic activity, offshore landslides, shallow intra-plate fault earthquakes, and how these events displace sea water to generate tsunami waves relies on the development of new instruments that can make long-term measurements on the seafloor. Accurately measuring slow displacements and earthquakes (with geodetic and seismic sensors), and volcanic activity (with hydro-acoustic arrays), in concert with acquisition of seafloor bathymetry data and other types of imagery, would reduce the uncertainty in estimates of shallow, intraplate slip rates and will identify potential submarine landslides and volcanic sources.

Predicting How the Built Environment Will Respond to Strong Earthquake Shaking

Knowledge and capabilities gap.—The duration and oscillation periods of shaking resulting from great (M>8) subduction zone earthquakes are significantly longer than for other types of earthquakes—and can be particularly damaging to tall buildings and other large structures—but these factors are not accounted for in most earthquake risk assessments and structural design codes. Both computer simulations of time variations in ground motion and empirical characterizations (such as ground-motion prediction equations) are needed so that scientists and stakeholders can accurately predict the shaking created by great earthquakes. These simulations and empirical characterizations are particularly important because they include the seismic amplification by the sedimentary basins that underlie cities like Seattle and Tacoma, Washington, Portland, Oregon, and Anchorage, Alaska. These products may be combined with exposure (for example, building inventories) and fragility data for risk modeling.

Using Bathymetric and Topographic Data to Identify Local Tsunami Hazards

In March 1964, a tsunami engulfed Chenega, a small fishing village on Chenega Island in Prince William Sound, Alaska, killing 23 people and a significant fraction of the fish population. Recently acquired high-resolution, shaded-relief bathymetric and topographic images reveal the probable cause of the tsunami: failure of the steep submarine slopes bordering the coastline was initiated by the magnitude 9.2 Alaska earthquake that occurred the same day, spawning massive sediment flows and tsunami waves. Many of the other destructive tsunamis that followed this earthquake were likely caused by similar submarine landslides. Data like these help scientists understand the sources of these local tsunamis so that the impacts of future events may be mitigated.



Map modified from Brothers and others, 2016

Frontier research.—New collaborative studies that engage both engineers and scientists will employ recorded and simulated ground motions to assess the vulnerabilities of the built environment to strong shaking from great subduction zone earthquakes at the neighborhood scale. Simulations would benefit from investments in high-performance computing tools, development of observationally constrained three-dimensional models of the subsurface, and validation against earthquake ground motions recorded during large earthquakes.

Key Questions, Investments, and Products

The questions below summarize the outstanding gaps in knowledge and capabilities relevant to theme 2 of this Subduction Zone Science Plan, “Quantifying Natural Hazards and Risk,” the investments needed to make major progress towards answering them, and potential products that an enacted plan could deliver. The investments and products are noted in abbreviated format and by reference to table 1 (on p. 2).

1. How do subduction zone events affect climate and vice versa?

    Investments: geologic field programs that constrain land- and sea-level changes on timescales of millennia and those caused by major instantaneous events; multidisciplinary models that include simulation of both climatic and geologic processes (G and I in table 1’s list).

    Products: high-resolution hazard and risk assessments; models of cascading events (table 1); climate change assessments that more accurately account for feedbacks between geologic and climatic processes.

2. How do long-term processes and major events in a subduction zone affect energy and mineral resource distributions and supplies?

    Investments: three-dimensional subsurface models of processes affecting mineral and gas deposits; geologic field mapping, coring and subsurface imaging programs; laboratory capabilities; multidisciplinary models (F, G, H, I in table 1's list); and assessments of the impacts of subduction zone hazards and risks on geothermal power production and mineral resources.

    Products: high-resolution hazard and risk maps, databases, and tables conveying information about the distributions of faults, heat flow, rocks, fluids and other parameters relevant to energy and mineral resources; assessments of the probabilities of cascading geologic events (table 1), and their effects on the potential and resilience of geothermal power and mineral resource production.

3. What are the hazards and risks from submarine landslides?

    Investments: multidisciplinary (for example, seismic and geodetic) onshore and offshore monitoring; offshore sediment-core samples, images of subsurface geologic structures, temporary geophysical deployments; high-resolution, multibeam bathymetry offshore, adjacent to airborne and space-based topographic imagery onshore; laboratory capabilities for dating and analyzing physical properties of rock and sediment samples (B, C, D, E, H in table 1's list).

    Products: high-resolution hazard and risk assessments and event scenarios extending from offshore to the continental interior (table 1).

4. What are the hazards and risks from locally generated tsunamis?

    Investments: offshore structural characterizations and high-resolution elevation data (D, E in table 1's list).

    Products: hazard and risk assessments, databases, event scenarios, and simulations conveying information about offshore faults and potential submarine landslides, their potential to generate tsunamis, and their effects on coastal natural and built environments (table 1).

5. How will the built environment respond to strong shaking, particularly from a great (*M* 8–9) subduction zone earthquake?

    Investments: dense onshore seismic monitoring and three-dimensional subsurface models (A, F in table 1's list).

    Products: high-resolution hazard and risk assessments and scenarios (table 1), ground-motion simulations and prediction equations.

Theme 3: Forecasting and Situational Awareness

The ability to deliver accurate forecasts and warnings needs to be developed before hazardous events occur. Monitoring networks and scientific observations provide critical baseline information, which is best obtained by combining different measurement types made continuously in near-real time. We suggest that scientists continue to collaborate closely with emergency managers and others responsible for disseminating information and making actionable decisions. Building on a solid foundation of existing capabilities and recent scientific and technologic advances, major improvements to existing tools are being made and entirely new forecasting ones are becoming available. These new tools are described in the sections "Gaps in Knowledge and Capabilities and Frontiers of Scientific Research" and "Key Investments and Products." Topics are ordered roughly from broadest to most narrow in scope.

A Foundation of Accomplishments and Capabilities

Earthquake monitoring is a fundamental component of the USGS's mission. The USGS's National Earthquake Information Center delivers authoritative products (like ShakeMaps) about significant earthquakes; these information products have grown in sophistication and provide the basis for decisions that affect thousands of lives and billions of dollars in economic activity. As part of the Advanced National Seismic System and in collaboration with universities, the USGS operates extensive earthquake monitoring networks in California, Oregon, Washington, and Alaska. The USGS and its partners also monitor the Nation's volcanoes, and in both cases monitoring data are used for research, hazard assessments, and public/agency awareness and emergency response. Also, the USGS-led National Strong Motion Project operates instruments throughout the U.S. in high-hazard areas that detect strong ground motion, building response, and potential structural damage during earthquakes. The most recent monitoring development is the ShakeAlert system for earthquake early warning (EEW), which, when completed, will detect an earthquake and provide warnings of the impending arrival of destructive seismic waves within seconds to minutes. These warnings are sufficient to automatically send alerts to people to seek cover, stop trains, open elevator doors, safely close off flows through utility and other pipelines, and shut down equipment in operation. Developing an earthquake early warning system for Cascadia presents unique challenges and provides lessons for instrument deployments in other subduction zones, given their unique potential for earthquakes that take hundreds of seconds to rupture faults thousands of kilometers long, the diversity of earthquake types, and location of major faults beneath the ocean. For example, the initial estimate of the earthquake's size is completed just a few seconds after the fault begins to slip, while the earthquake is still developing, and uses measurements made at onshore instruments far from the rupturing fault. These factors introduce serious uncertainties in estimates of magnitude, location, mechanism and, thus, expected ground shaking. The earthquake early warning effort in the Pacific Northwest will benefit from lessons learned during collaborations between the USGS and Japanese colleagues, who are already operating earthquake and tsunami early warning systems, and with Chilean colleagues who are currently developing these systems.

The USGS is building on its experience forecasting aftershocks in California and is expanding this capability to all parts of the Nation, including subduction zones. Forecasts include the probability of an aftershock that is larger than the mainshock. Expansion of routine aftershock forecasting to include subduction zone earthquakes requires both the geological understanding of the complexity of earthquake types in subduction zones, and a social science understanding of how best to deliver forecasts (Wein and others, 2016), particularly in communities that are less aware of and prepared for earthquakes than in California.

The USGS issues timely warnings of a variety of potential volcanic hazards to the public, land managers, emergency responders, and to other government agencies, including reports on the location and altitude of volcanic ash in the atmosphere and potential for volcanic mudflows (lahars). In 1982 and 1989, fully loaded passenger jets flying above Indonesia and Alaska inadvertently flew into ash clouds from erupting volcanoes and lost power in all engines. Although their pilots were able to restart some engines and neither jet crashed, the planes suffered serious and costly damage. This prompted the USGS to develop the capabilities to forecast ash cloud locations and ash concentrations, and to provide this information to officials responsible for aviation safety. Ash cloud warnings are issued for the aviation industry in partnership with the National Weather Service Volcanic Ash Advisory Centers, which enables airplanes to avoid hazardous ash clouds and minimizes economic losses caused by cancelled flights. At the more local scale, user-friendly maps convey the likely paths of lahars during a volcanic eruption. For example, the USGS, together with the Washington State and Pierce County Emergency Management Departments, operates a lahar detection system designed and installed by the USGS in the 1990s that can issue warnings to residents in the paths of lahars from the northwest drainages of Mount Rainier (fig. 4).

The USGS has developed approaches for forecasting rainfall- and earthquake-induced landslides and has applied these approaches to produce landslide-hazard maps for average rainfall conditions for some regions. In southern California, USGS estimates of rainfall thresholds above which landslides are expected to occur are combined with real-time precipitation observations and forecasts to produce landslide watches and warnings issued by the National Weather Service for wildfire-burned areas. The USGS also provides near-real-time information about rainfall and landslide potential in Seattle, where landslides of various types are a significant natural hazard (fig. 5); for example, in 1997 more than 100 landslides and accompanying snow caused $100 million in damages and killed a family of four. (See http://landslides.usgs.gov/monitoring/seattle/). For earthquake-induced landslides, the USGS has produced scenario-based hazard maps for several regions (for example, Anchorage, Alaska; see Jibson and Michael, 2009) and is developing the ability to forecast such landslides in near-real-time using shaking estimates from ShakeMap.

The USGS supports multiple projects that focus on analyzing effects of an event, often conveyed as scenarios, that consider cascading social, economic, and environmental consequences. The National Earthquake Information Center and partner seismic networks of the Advanced National Seismic System produce real and hypothetical (scenario) ground-motions, or ShakeMaps, which feed directly into rapid impact assessments (PAGER alerts) used by FEMA and other institutions. The Science Application for Risk Reduction Project (SAFRR; https://www2.usgs.gov/natural_hazards/safrr/) collaborates with external stakeholders including local, State, and Federal partners to examine hypothetical yet plausible seismic, tsunami, and storm events whose physical damages may lead to social, environmental, and economic consequences (*see sidebar about the SAFRR workshop on p. 28*). The Department of the Interior's Strategic Sciences Group (https://www.doi.gov/strategicsciences) is designed to support decision making during response to actual events. When deployed, the Strategic Sciences Group convenes experts from across multiple disciplines to map out the possible cascading consequences of an event and identify interventions to support decision making.

Gaps in Knowledge and Capabilities and Frontiers of Scientific Research

Developing Tools for Cascading Hazards

Knowledge and capabilities gap.—In the real world, one event may trigger another, yet currently most hazard forecasts consider only a single geologic event. In subduction zones, earthquake shaking can destabilize slopes that ultimately fail and become landslides or submarine sediment flows; rapid seafloor faults slipping, submarine landslides, or volcanic events can all spawn tsunami waves. The ability to build models that include the interaction of multiple, linked phenomena

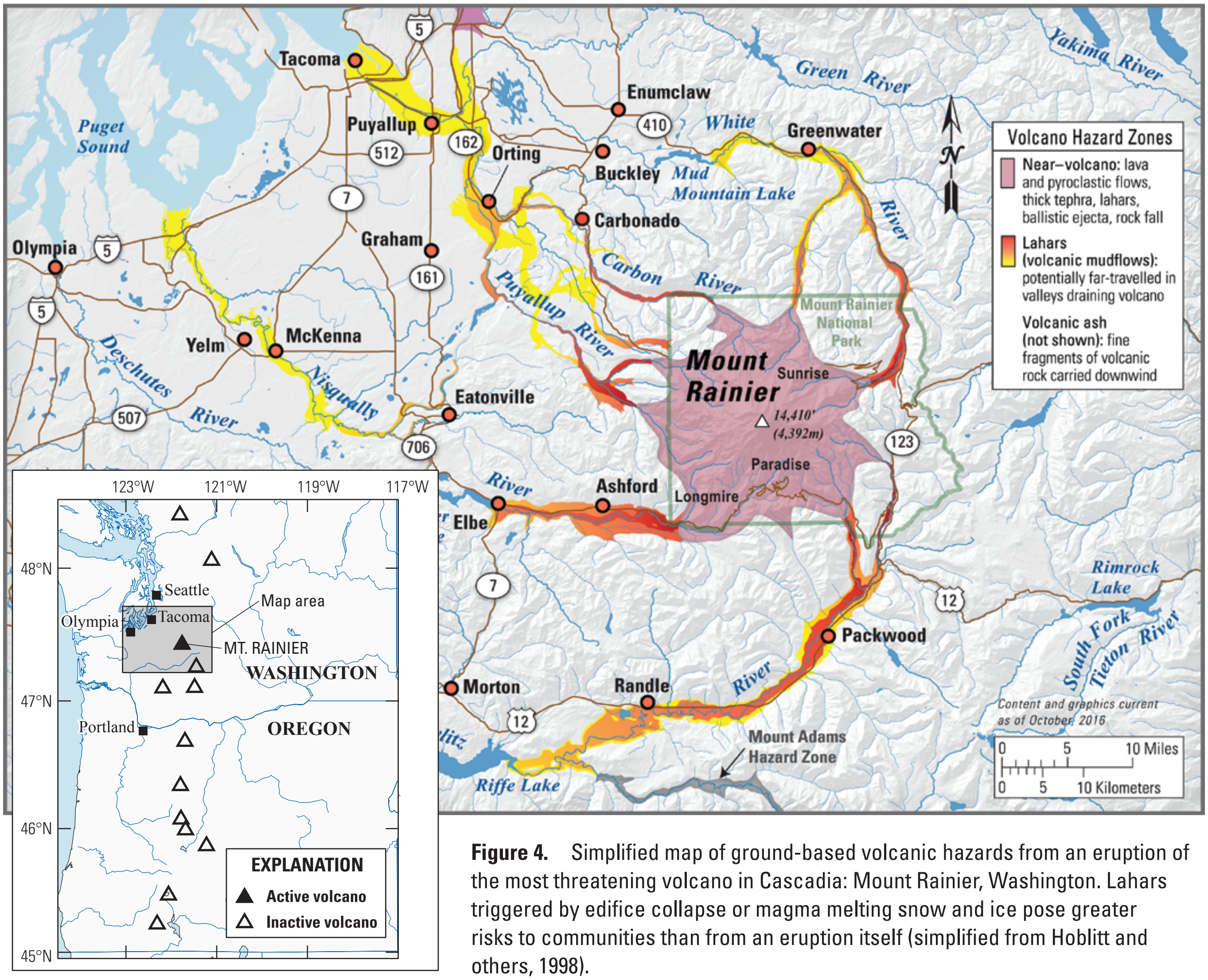


Figure 4. Simplified map of ground-based volcanic hazards from an eruption of the most threatening volcano in Cascadia: Mount Rainier, Washington. Lahars triggered by edifice collapse or magma melting snow and ice pose greater risks to communities than from an eruption itself (simplified from Hoblitt and others, 1998).

would more accurately predict the outcomes of major subduction zone events.

Frontier research.—Multidisciplinary monitoring systems and integrative computer models would provide forecasts of cascading geologic events and their impacts. An example of multidisciplinary monitoring might include the next generation of lahar warning systems, which could monitor multiple drainages simultaneously, detect initiating events like landslides farther upstream to gain more warning time, and provide estimates of the size of detected events. Such a system would employ available high-resolution topography, predictive flow models, new instrumentation, and recent improvements in seismic algorithms. Systems like this will be built not only with consideration of which natural hazards may occur as a cascade of events, but also their potential effects on communities and infrastructure. For example, methods permitting quick estimates of the probable fatalities and economic losses from earthquake shaking in the PAGER product are being extended to include possible effects of landslides and liquefaction (Allstadt and others, 2016). This capability to provide loss estimates and other new tools could be further developed to account more completely for linkages between earthquakes, tsunamis, earthquake-generated land-level changes, and volcanic eruptions through partnerships with Federal, State, and local emergency management agencies, as well as other groups that have experience in modeling losses following natural disasters.

Forecasting Coastal Land-Level Changes

Knowledge and capabilities gap.—A major earthquake may cause subsidence along hundreds of kilometers of coastline with consequent inundation equivalent to hundreds of years of sea level rise, and the land-level changes may occur quickly—in a matter of seconds—or more slowly, over a few months (*see sidebar about using satellite images to detect changes on p. 29*). Though physical models exist and may be applied to estimate these land-level changes, no tools have been developed to forecast these changes or guide recovery decisions.

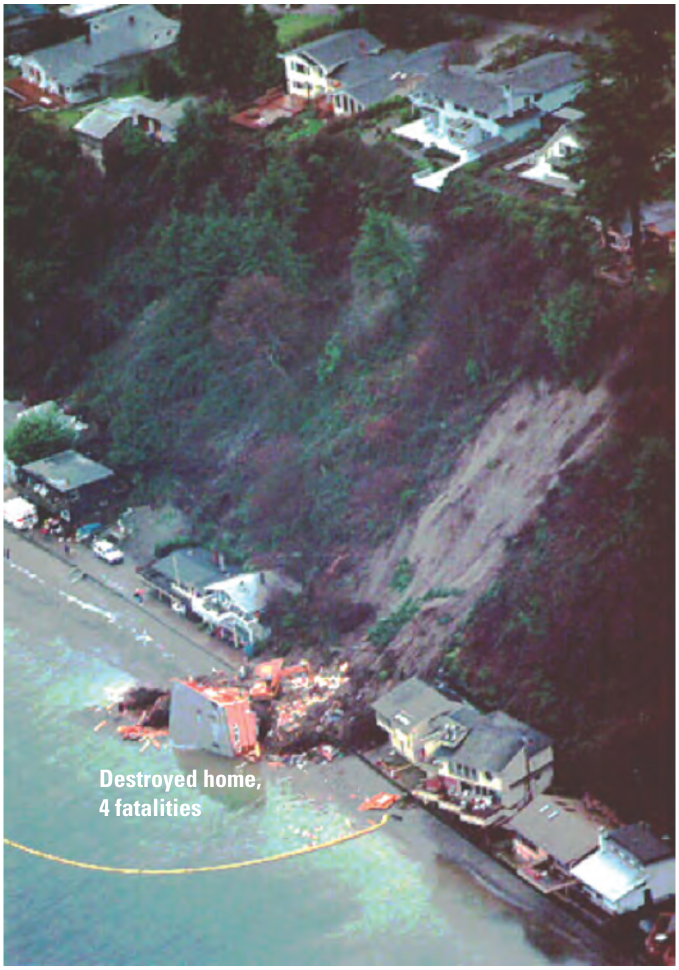


Figure 5. Landslides in Seattle, Washington. These photos of typical landslides along Seattle's coastal bluffs illustrate that subduction zone hazards don't only manifest as infrequent, major catastrophes to entire communities; they also impact lives, property, and infrastructure regularly in smaller, but still locally significant, events. Deep-seated slides, like the one shown in the left photograph, involve movement of large masses originally rooted in bedrock or relatively old sediments (photograph by L. Palmer, Federal Emergency Management Agency). In shallow slides, like the one shown in the right photograph, soils and younger sediments often rapidly flow downhill (photograph copyright 1997, T. Tamura, Seattle Times).

Frontier research.—Forecasts of land-level changes are possible using available earthquake scenarios constrained by quantitative paleo-ecological studies of past events (for example, by dating microorganisms that drowned when land sank during an earthquake and were preserved in the soil). These predictions could then be updated with measurements of land-level changes following a major event, using real-time global positioning system (GPS) measurements (relatively dense networks exist in Cascadia and parts of Alaska) and satellite imagery (including interferometric synthetic aperture radar, or InSAR). The existing web-based Coastal Storm Modeling System (https://walrus.wr.usgs.gov/coastal_processes/cosmos/), developed by the USGS to predict storm-induced coastal flooding, erosion, and cliff failures, could be leveraged by adding capabilities to convey potential subduction-earthquake-induced coastal change.

Assessing the Effects of Subduction Zone Events on Ecosystems

Knowledge and capabilities gap.—In subduction zones, ecosystems vary in space and time because of gradual environmental changes, and also because of earthquakes, tsunamis, volcanic eruptions, and landslides—events that may cause habitat fragmentation or shifts in species abundance and composition. For example, a landslide can affect habitats by changing river channel dynamics, availability of food sources, and microclimates. However, quantitative assessments of the likely effects of subduction zone events on ecosystems do not exist.

Frontier research.—Assessing the effects of subduction zone events on ecosystems requires collaborations between scientists supported by the USGS's Natural Hazards Mission Area programs and the Inland Fisheries and Aquatic Gap Programs in the Ecosystems and Core Science Systems Mission Areas. For example, an illustrative collaboration is the recent collection of high-resolution, multibeam bathymetry data in Prince William Sound, Alaska. The Alaska Department of Fish and Game, which is interested in characterizing the environment inhabited by fish populations, provided a ship, and the USGS, which is interested in identifying submarine faults and unstable slopes, contributed surveying equipment. Bathymetry data collected filled needs of each agency: to characterize fish habitats and to identify submarine faults, respectively.

Regional Workshop to Develop the SAFRR Tsunami Scenario

The U.S. Geological Survey Science Application for Risk Reduction (SAFRR) project develops and delivers products with and for stakeholders to help communities prepare for and be more resilient in the wake of natural disasters. The SAFRR product most relevant to subduction zone hazards is a hypothetical scenario examining the expected impacts to California from a tsunami generated by a magnitude 9.1 earthquake located offshore of the Alaska Peninsula (Ross and others, 2013). The results of the Tsunami Scenario will help risk and emergency managers understand the context and consequences of their decisions about how to most effectively improve preparedness and response to tsunamis. The Tsunami Scenario exercise involved collaboration between the U.S. Geological Survey (USGS), the California Geological Survey, the California Governor's Office of Emergency Services (Cal OES), the National Oceanic and Atmospheric Administration (NOAA), other Federal, State, County, and local agencies, private companies, and academic and other institutions. The scenario builds on sound science to estimate many aspects of the event's consequences: physical impacts (inundation areas, current velocities in key ports and harbors, structural damage), economic consequences, environmental and ecological impacts, social vulnerability, emergency management and evacuation challenges, and policy implications. Once completed, the SAFRR Tsunami Scenario results and products were publicly introduced in September 2013 through a series of workshops that brought together emergency managers, maritime authorities, first responders, elected officials and staffers, the business sector, State agencies, local media, scientific partners, and special districts such as utilities. SAFRR continues to assess the effectiveness of the scenario process for target stakeholders to improve similar efforts going forward.

Photograph of the SAFRR Tsunami Scenario workshop by Stephanie Ross, USGS.

Increasing the Reliability of Earthquake and Tsunami Warnings

Knowledge and capabilities gap.—Earthquake early warning systems and tsunami warnings currently employ monitoring data from seismic instruments, some of which can saturate when large ground motions exceed their recording range, rendering event size difficult or impossible to estimate. Tsunami warnings are issued from NOAA's Tsunami Warning Centers and also use data from their Deep-Ocean Assessment and Reporting of Tsunamis (DART) systems (which are buoys that measure deep-water pressures as a means of detecting unusual water-column heights associated with a tsunami wave). However, while the DART data do not saturate, they require 10 minutes or more to be received and processed, which is useful for tsunamis originating outside the affected coastline but is too long to provide sufficient warning to coastal communities closest to the source.

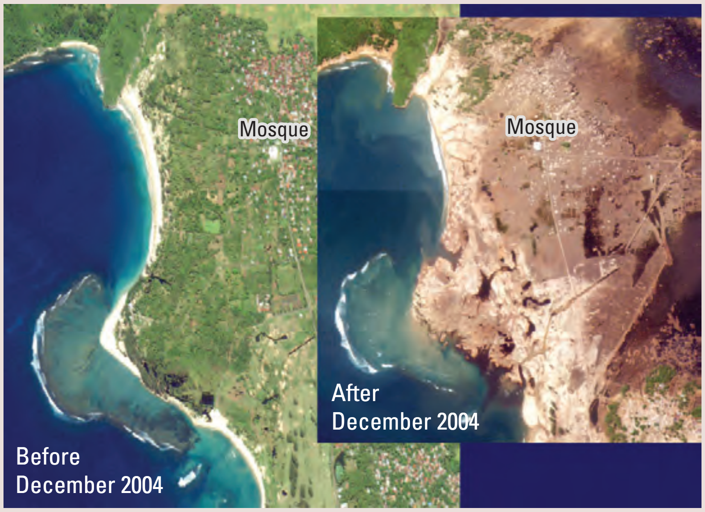
Frontier research.—A new generation of monitoring network operations will integrate real-time GPS measurements—some acoustically linked from floating GPS receivers to monuments on the seafloor—with measurements from the existing earthquake monitoring networks, which use only seismic data. Observations made on the seafloor just above the rupturing fault are particularly important for accurate and rapid characterization of the earthquake and its potential for generating strong shaking and tsunami waves.

Providing Reliable, High-Fidelity Volcano Warnings

Knowledge and capabilities gap.—Practical warning of volcanic unrest relies on detection and interpretation of changes in geologic processes that are often only measurable near or on a volcano, yet many volcanoes have few or no monitoring instruments. Volcanic eruptions are often heralded by clear precursors in the weeks to months prior, such as anomalous seismicity, low-level sound waves, elevated surface temperatures, volcanic gas emissions, and measurable ground deformation. To determine whether changes in volcano activity are due to movement of magma, of hydrothermal fluids, or both requires measurements of several of these precursors and thus multiple types of instruments. To make this assessment in time to warn and respond requires that data are transmitted in near-real-time to analysts.

Satellites Identify Areas of Tsunami Inundation

Satellite images acquired before and after the 2004 magnitude 9.2 Indian Ocean earthquake provide documentation of widespread destruction by tsunami waves. Vegetation, beaches, buildings, and roads are seen in pre-earthquake images of the Aceh district on the northwestern coast of Sumatra (left), but after the earthquake (right), virtually all of the plant life and buildings were stripped away, and much of the area is submerged (brown area) or was destroyed by the tsunami, except for a single mosque (white dot). Within hours of the initial tsunami waves' landfall, coastal subsidence resulted in significant erosion and shoreline retreat that continued for weeks and months, while elsewhere new beaches developed. All these changes affected road repair and redevelopment of coastal villages.



Satellite image acquired using Space Imaging's IKONOS satellite and processed by the Centre for Remote Imaging, Sensing and Processing (CRISP), National University of Singapore (see http://www.crisp.nus.edu.sg/tsunami/ for more information about the images).

Frontier research.—Monitoring that combines signals from multiple instrument types significantly reduces uncertainty in interpreting potential precursors and can provide automated alerts to speed the dissemination of warnings. Such monitoring would require increased numbers and new types of instruments, noting that some U.S. volcanoes have none or just a few seismometers, others have several GPS receivers as well, and only the most high-threat volcanoes have other types of instruments. For example, the data from new real-time volcanic gas emissions and infrasound (acoustic signals not audible by humans, but that travel long distances) sensors deployed near volcano summits, when combined with data from seismometers, deformation sensors, and InSAR imagery, would reduce ambiguities in the interpretation of volcanic unrest.

Projecting Ash Cloud Trajectories More Accurately

Knowledge and capabilities gap.—Uncertainties in forecasted volcanic ash cloud volumes, compositions, and trajectories still result in significant economic loss. While significant progress has been made in forecasting ash cloud trajectories, the prolonged closure of European airspace in 2010 following an eruption in Iceland illustrates how uncertainties in ash cloud dispersal estimates may lead to conservatism with resulting unnecessary inconvenience and economic losses. Challenges include learning the tolerances of aircraft to ash and accurately estimating and measuring ash concentrations in eruption plumes at various elevations and distances from the source.

Frontier research.—Predictive capabilities can be improved by integrating satellite data into dispersion and ash-grain aggregation models, the output of which is validated against measurements of ash concentrations in the field (see sidebar below about volcanic ash forecasting). Results of all these activities will guide collaborative work with the aviation industry to test how much and what types of ingested ash may damage jet engines; preliminary experiments of this kind are underway in Europe and the United States.

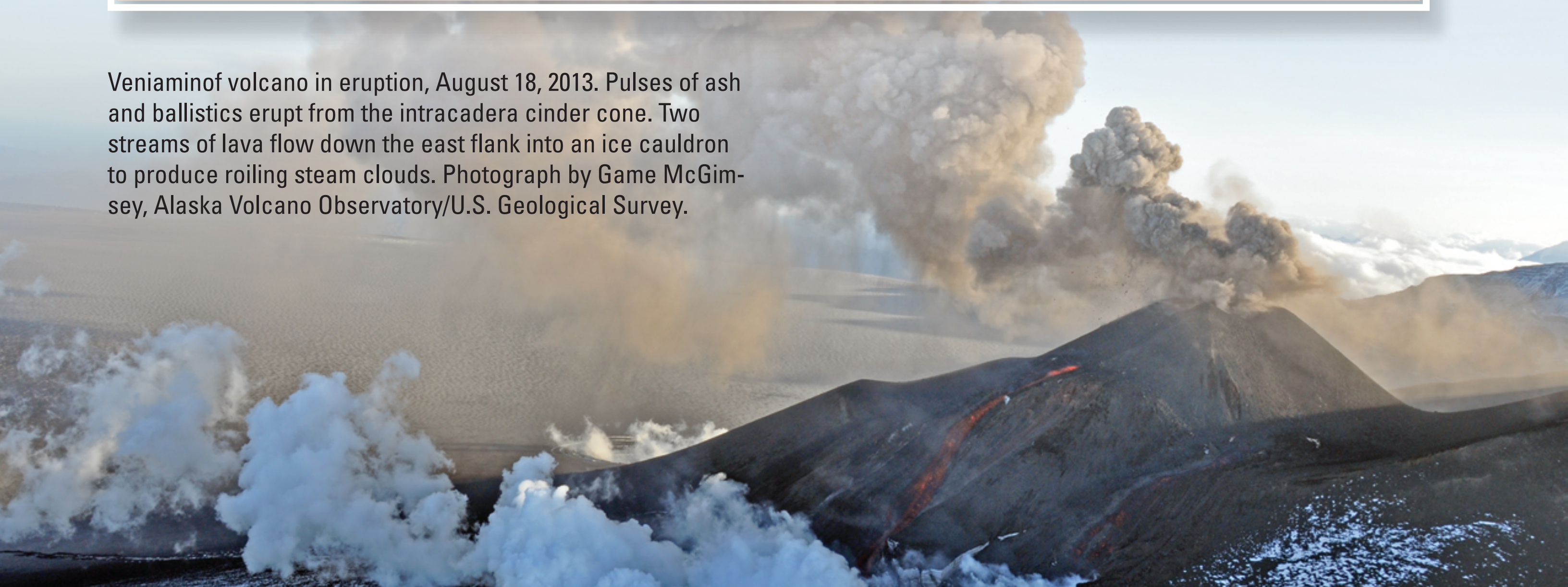
Providing Spatially Varying, Regionally Specific Aftershock Forecasts

Knowledge and capabilities gap.—Current aftershock forecasts are based on statistical analyses of past sequences from subduction zones worldwide, but sequences exhibit tremendous variability in behaviors from one geologic setting to another. The aftershock forecasts are updated only using rates of aftershocks in the ongoing sequence and do not provide any information about the likely locations of aftershocks; this lack of spatial information is particularly problematic for large subduction earthquakes, where faults may span hundreds of miles.

Frontier research.—Forecasts that employ new real-time GPS data, satellite imagery, and knowledge of fault systems,

Volcanic Ash Forecasting

Volcanic ash hazards are far reaching and disruptive, affecting more people, infrastructure, and daily activities than any other eruptive phenomena. The U.S. Geological Survey (USGS) provides forecasts of expected ash dispersal and deposition using an atmospheric transport model called Ash3D. When observations warrant an elevated alert level for a particular volcano, USGS scientists use Ash3D to simulate the outcome for a reasonable eruption scenario. This example Google Earth view of Ash3D output from a Mount St. Helens simulation shows cloud concentration (pink and purple area labeled 1); affected airports (red dots, labeled 2); the model boundary (white box, 3); and an animation tool (horizontal bar at top of the image, 4). If an eruption occurs, the forecast is updated with observations as they become available, and results are posted online and provided to the National Weather Service for use in its public ashfall advisories. Real-time information also goes to the National Oceanic and Atmospheric Administration's Aviation Weather Center, which issues volcanic ash advisories to the Federal Aviation Administration so aircraft can be safely diverted around the affected area. This information also is shared with officials in other countries, including the Kamchatkan Volcanic Eruption Response Team in the Russian Federation and the Tokyo Volcanic Ash Advisory Center in Japan.



Veniaminof volcano in eruption, August 18, 2013. Pulses of ash and ballistics erupt from the intracadera cinder cone. Two streams of lava flow down the east flank into an ice cauldron to produce roiling steam clouds. Photograph by Game McGimsey, Alaska Volcano Observatory/U.S. Geological Survey.

and that integrate slip distributions and physical mechanisms controlling interactions between earthquake sources, would provide spatially varying probabilities of aftershocks in particular time intervals, tailored for specific regions. Acquisition and integration of GPS, satellite, and fault-interaction data will also improve the temporal accuracy of aftershock forecasts.

Key Investments and Products

The key investments and products outlined below for theme 3, "Forecasting and Situational Awareness" will enable the USGS, in collaboration with its partners, to deliver short-term forecasts and warnings with the spatial resolution needed by stakeholders to plan for, and respond to, evolving subduction zone events. Advances of existing capabilities would reduce false or inaccurate alarms and missed events, and provide more precise notifications. More specifically, new capabilities would include high confidence in offshore earthquake and tsunami warnings, warnings of activity at volcanoes that are currently unmonitored or poorly monitored, more accurate ash cloud trajectories, and spatially varying and regionally specific aftershock forecasts (see "Warning systems" in table 1 on p. 2). Additionally, new tools can provide forecasts that are updated as individual and cascading events evolve. Examples include updated forecasts of ash falls and lahars during volcanic eruptions and of aftershocks following great earthquakes; forecasts of changes in coastal land levels, ecosystems, flooding and erosion (see "New types of forecasts" in table 1). These would require investments in dense and multidisciplinary onshore monitoring; offshore seismic and geodetic monitoring; high-resolution multibeam bathymetry offshore, adjacent to airborne and space-based topographic imagery onshore; and models that link understanding of and simulate multiple phenomena (key investments A, B, C, E, I in table 1's list).

U.S. Geological Survey field engineer Lynn Simmons installs new equipment at a former temporary seismic monitoring station in Marblemount, Washington, that was part of the National Science Foundation's Transportable Array project. The upgraded site will be a permanent earthquake monitoring station in the Pacific Northwest Seismic Network, which is operated as a partnership between the USGS and the University of Washington. Photograph by Maia ten Brink, IRIS.

National and Global Partnerships

Current and Future Domestic Institutional Partners

The range of partners that the USGS engages in subduction zone science is already very broad, both nationally and internationally. For example, within the NSF, the EarthScope and GeoPRISMS programs, as well as core programs within the Divisions of Earth and Ocean Sciences, have provided both facility and research support for efforts to better monitor and understand subduction zones. The EarthScope Plate Boundary Observatory includes extensive geodetic monitoring of the Cascadia and Alaska Subduction Zones, and the GeoPRISMS effort has enabled important research in the offshore areas of subduction zones. USGS has benefitted from, and co-supported, both of these ongoing NSF efforts.

Looking forward, an expanded effort in subduction zone science could include additional partners in a number of Federal agencies, State and territorial agencies and interest groups, and several scientific and engineering consortia. We highlight current and potential collaborative activities with key Federal, State, and territorial governments, professional organizations, and private sector partners in appendix 1.

The USGS's partnership with the NSF warrants a special mention, because of its past and present strength; the leveraging of expertise and resources of both the NSF and the USGS has contributed substantially to the success of the NSF's EarthScope and GeoPRISMS programs. Widespread enthusiasm and significant momentum exist within Earth science communities to undertake a subduction zone initiative, envisioned as a multidisciplinary program of monitoring systems and scientific studies of one or more subduction zones as an integrated system, with significant potential support from the NSF. In September of 2016, a workshop convened 250 Earth scientists from 21 countries to gather input and start to define what an initiative focused on fundamental scientific research of subduction zone processes might look like, with a goal of preparing a proposal to the NSF (see https://www.iris.edu/hq/workshops/2016/09/szo_16 for workshop overview and report). Earthquake, tsunami, landslide, and volcano hazards were highlighted in the workshop and report, and scientists described many opportunities for collaborating on the complementary activities described in this science plan and within an NSF-supported initiative.

Shared Scientific Infrastructure

Our understanding of subduction zones would benefit from shared scientific data centers, laboratories, field instruments, and computational facilities, which would extend observations at minimal cost, maximize efficiencies, and facilitate the exchange of data and knowledge. Here we outline existing and potential shared onshore and offshore instrumentation and facilities, which demonstrate that the goals laid out in this science plan are technologically and logistically feasible.

Onshore Monitoring and Laboratories

The temporal and spatial scales over which subduction zone processes evolve necessitates monitoring networks that are operated collaboratively for years to decades. Such a sustained activity requires leadership by a Federal agency like the USGS with the support of its partners. Examples are the Global Seismographic Network, the ANSS (including new instrumentation in support of ShakeAlert), and the developing NVEWS. These and other monitoring networks and the diverse organizations that operate them are further detailed in appendix 1.

Laboratories critical for studying subduction processes are used to measure the eruption ages of volcanic rocks by radiometric methods, the chemical and isotopic compositions of volcanic products for the study of the origin, storage, and ascent of magmas, the failure behaviors of rocks during deformation and faulting, the evolution of rock permeability and other rock properties over time at elevated temperatures, and the conditions of fluid release during subduction. Some of the key laboratories capable of making these measurements are operated by the USGS and shared with collaborators, and in other cases contractor or collaborator laboratories are used to make these measurements.

The Offshore Frontier

Significant fractions of all active U.S. subduction zones lie beneath the ocean, so marine research is essential and exciting, but also is challenging. Because the oceans are a global resource and their exploration is so costly, international and national collaborations are already well established. Several existing programs provide research ships, cabled seafloor observatories, and fund research in new technologies to observe the oceans; some of these are described in appendix 1. Examples of recent offshore community endeavors focused on subduction zones include the NSF-sponsored 2011–2015 Cascadia Initiative, which deployed a temporary array of seafloor seismometers and pressure and temperature sensors from northern California to southernmost British Columbia. The USGS has led and participated in cruises (funded by the USGS, NOAA, and international partners) throughout the northeast Caribbean to map bathymetry, image and sample the subsurface, and record earthquakes that illuminate active faults (*see sidebar about Caribbean earthquakes on next page*); such work contributes directly to assessments of tsunami hazards along the U.S. East Coast.

Recovery of data from most ocean-bottom instruments traditionally requires laborious and expensive shipboard cruises, and data are recovered and analyzed long after the measured events occurred. Real-time data, however, are provided through the NSF's Ocean Observatories Initiative using fiber-optic cables that extend from the Oregon seashore to the Juan de Fuca Ridge's Axial Seamount volcano, as well as Ocean Network Canada's NEPTUNE fiber-optic cable from Vancouver Island to the northern Juan de Fuca Ridge. Complementing these efforts, the USGS is partnering with universities and other institutions to explore other methods than cables to transmit data from remote seafloor sensors and that are significantly less expensive and may be more geographically distributed. For example, the USGS is helping to develop wave gliders that perform as self-powered underwater drones that enable acquisition of scientific data using acoustic or optical telemetry from seafloor monitoring stations (*see sidebar about real-time monitoring from the seafloor on p. 34*).

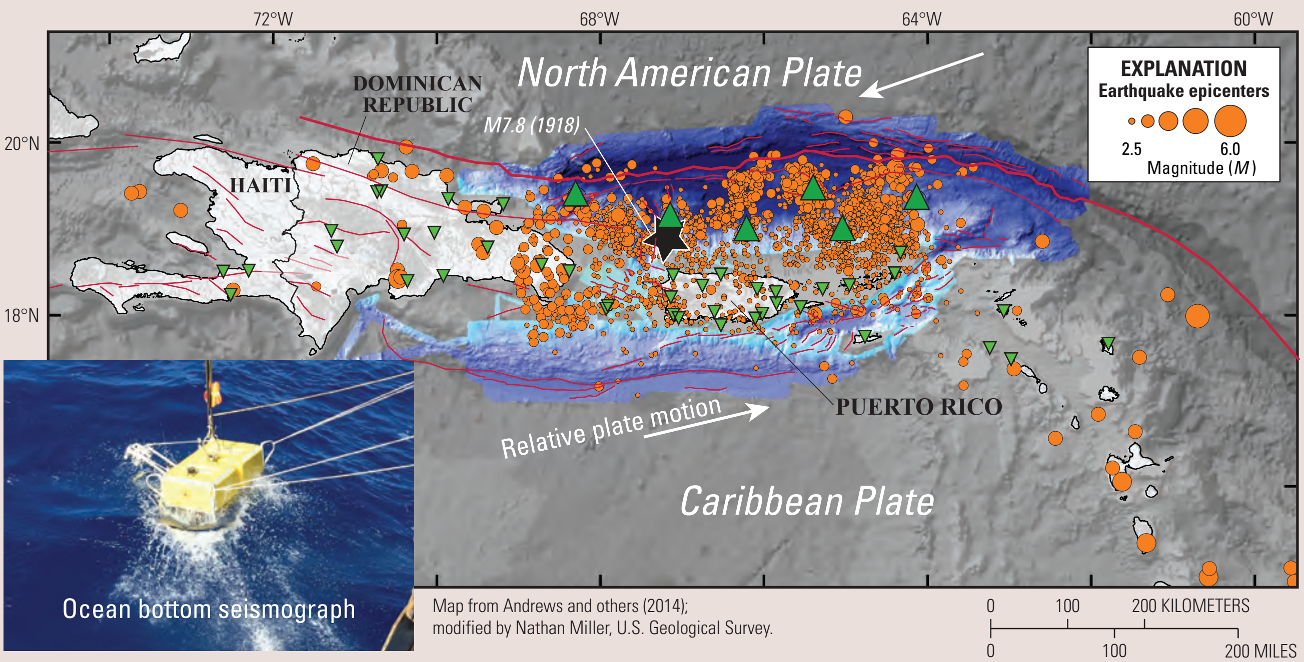
Although advances have been made in seafloor seismology, comparable efforts have not yet been made to measure slow deformation of the seafloor. GPS signals cannot be transmitted to or from the seafloor, so a variety of approaches are being explored to measure slow displacements in the marine environment. One promising approach combines GPS at the sea surface with acoustic ranging to seafloor transponders, serviced by self-propelling wave-gliders and optical data transmission. Testing of new seafloor pressure sensors that provide continuous measurements of vertical displacements is also underway.

Information Technology and Management

Large monitoring networks and remote sensing systems produce high volumes of data that must be transferred, stored, analyzed, and shared efficiently. Institutions dedicated to the archiving and serving of geophysical and image data include the USGS's Earth Resources Observation and Science (EROS) Data Center, the NSF-supported IRIS Data Management Center for seismic data, and UNAVCO (originally the University NAVSTAR Consortium, now an independent nonprofit organization) for Global Navigation Satellite System (GNSS) and other geodetic data. Besides storing and sharing data, these institutions develop data standards and transfer protocols used worldwide. Similar community information technology exists for the archiving and sharing of the chemical compositions and ages of igneous rocks (for example, NAVDAT [North American Volcanic and Intrusive Rock Database], GEOROC [Geochemistry of Rocks of the Oceans and Continents], IEDA [Interdisciplinary Earth Data Alliance], and PetDB [Petrologic Database]).

Offshore/Onshore Earthquake Hazard Experiment in the Caribbean

The relative motion of the North American and Caribbean Plates (white arrows) at is an oblique angle to the plate boundary, which is a complex zone of faults (red lines). This oblique motion means the plates are both colliding and sliding past one another. The colliding results in subduction, but in combination with other types of faulting and geologic processes, and in ways that have changed over geologic time. Scientists are only beginning to unravel how this complex system works, but knowledge of which faults are currently active and moving is revealed in the characteristics of recent earthquakes. Methods for locating earthquakes use triangulation (signals from at least three seismic stations), and are far more accurate when instruments are close to and surround earthquakes; however, more than half of this complex and poorly understood region lies offshore. There are no instruments deployed on the seafloor in this area on a permanent basis, but the USGS and Woods Hole Oceanographic Institution installed six ocean-bottom seismographs (inset photograph and large green triangles on map) from May 2015 to March 2016. During this experiment, earthquake activity near the Puerto Rico Trench (orange circles) was much more accurately characterized; hundreds of earthquakes were detected, helping to understand fault motions at this subduction zone. The data collected from the temporary offshore seismographs complement those from the onshore permanent seismic network stations (small inverted green triangles). The last significant plate-interface earthquake in this region was the magnitude 7.1 Mona Passage event in 1918 (black star on map, which generated a tsunami that inundated the northwestern coast of Puerto Rico as far as 100 meters (328 feet) inland and resulted in 116 fatalities.



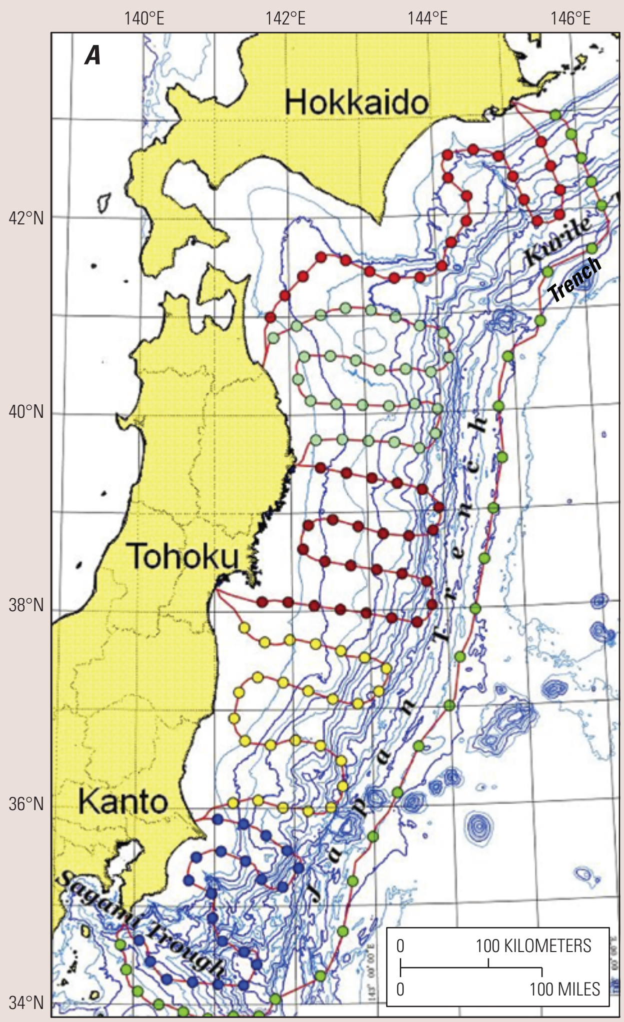
Map from Andrews and others (2014); modified by Nathan Miller, U.S. Geological Survey.

This stray coral boulder, which was transported by a tsunami from offshore to 230 meters inland on Anegada, British Virgin Islands, and other debris from past tsunamis are used to assess earthquake and tsunami hazards of the subduction zone and the adjoining outer rise along the Puerto Rico trench. U.S. Geological Survey photograph by Brian Atwater.

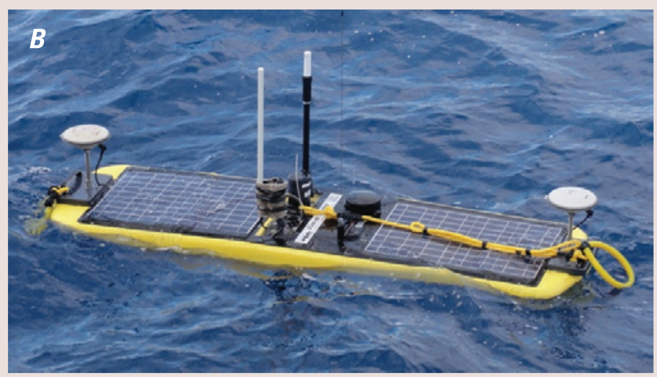
Seafloor Real-Time Monitoring

Motivated by the disastrous magnitude 9.0 Tōhoku, Japan, earthquake and tsunami and the ensuing loss of life and damage to its national economy, Japanese scientists have recently installed a new seafloor network of 150 earthquake and tsunami detectors (circles on map, colors denote different cable segments) that transmit data to land in real time using fiber-optic cables. This network, called the Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (called S-net for short) should provide an extra 20–30 seconds of warning of an earthquake and an extra 10 minutes of warning of a tsunami.

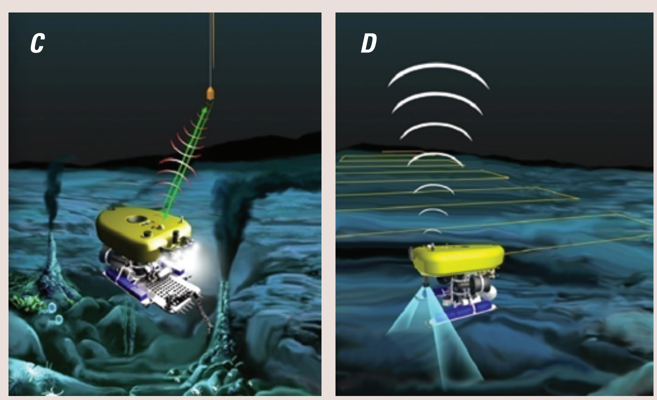
In Cascadia, the offshore instrument network that transmits data using seafloor cables is too sparse and slow to contribute to early warning systems, and no appropriately instrumented cables exist in the other U.S. subduction zones. However, a variety of new technologies under development, shown in images *B*, *C*, and *D*, below, offer alternatives for real-time seafloor monitoring that are far less costly and more versatile than cabled systems. For example, wave gliders (*B*) are self-powered underwater drones that can collect data in the ocean and send them from the surface for analysis via satellites or radio. They operate without environmental impact, cost hundreds of times less to operate than traditionally deployed ships, and for some applications provide higher-fidelity data. For transmitting data from seafloor instruments to wave gliders or ships, new optical modems (*C*) can transmit at high sample rates (for example, for seismic signals) over distances of hundreds of feet, acoustic modems (*D*) can work over thousands of feet but at lower rates, and both eliminate the need for expensive and difficult-to-access physical connections.



Map modified from Detweiler, S., and Ellsworth, W., eds., 2015



Waveglider photo from Chadwell and others, 2016



Modem photos from Farr and others, 2010

A, Ocean bottom cabled observation network composed of seismometers and tsunami meters. ***B,*** Wave glider for data acquisition and transmission. ***C,*** Optical data transmission modem. ***D,*** Acoustic data transmission modem.

Analyses of massive datasets and state-of-the-art modeling also requires high-performance computing capabilities. The USGS's Advanced Research Computing Program facilitates the fulfillment of these needs. USGS researchers have benefitted from supercomputing facilities at the NASA Ames Research Center, Department of Energy's (DOE) Pacific Northwest and Oak Ridge National Laboratories, and the joint USGS-NSF supported Southern California Earthquake Center.

International Activities

Globally, major subduction earthquakes, tsunamis, large landslides, and major eruptions take place at intervals of several years. Major events and ongoing research activities related to subduction zone geologic processes abroad often affect U.S. domestic affairs and can be invaluable learning opportunities. On an ongoing basis, the USGS is a major player in global hazard monitoring, disaster assessment, response, and in assisting other countries to build internal capabilities for these activities; examples include Volcano Disaster Assistance Project (VDAP) (*see sidebar on next page about VDAP and USAID efforts*) and Earthquake Disaster Response Teams (EDAT) staffed by USGS scientists with support from the U.S. Agency of International Development's Office of Foreign Disaster Assistance (OFDA) program. Many of these international activities, and the partnering international programs, are described in appendix 2. Ongoing USGS research collaborations with scientists in countries facing subduction zone hazards are facilitated by formal agreements with Japan, New Zealand, Russia, Canada, China, Italy, and Chile.

New Community Resources and Engagement

The USGS seeks to deliver products in ways that meet stakeholder needs and to ensure the most current science is available to inform decision making in subduction zone regions. This section summarizes an envisioned package of linked, innovative products and activities meant to address stakeholder needs, many of which also have application to a broader array of societal needs.

Products

- Systematically acquired high-resolution bathymetry and topographic mapping data and subsurface imagery will be community resources. A precedent exists in the Pacific Northwest, where consortia for the Puget Sound region and the States of Oregon and Idaho bring together State, Tribal, Federal, private, and academic institutions to coordinate acquisition and distribution of light detection and ranging imagery (called lidar, which is remotely sensed, digital topographic data) to be used for urban and county planning, forest and habitat management, and geological studies. The exceptional spatial resolution provided by airborne lidar imagery has dramatically improved the USGS's ability to map a broad suite of natural hazards, including recent and prehistoric fault scarps left by earthquakes, lava flows, magma domes, debris flows, lahars, and landslides. The combination of lidar and multibeam echo-sounder bathymetry data would allow detailed, seamless mapping of both the land and the seafloor, which would have wide-ranging applications for hazards studies, fish and wildlife management, siting and safety of seafloor cables and infrastructure, national defense, and coastal erosion studies.

  The USGS's 3DEP (three-dimensional elevation program), programs in the Natural Hazards Mission Area and others have partnered with many agencies to acquire lidar and bathymetric data, including NASA, NOAA, Bureau of Ocean Energy Management, U.S. Department of Agriculture (USDA) Forest Service, U.S. Army Corps of Engineers, Bureau of Reclamation, the Alaska Department of Fish and Game, Oregon Department of Geology and Mineral Industries, Washington State Department of Natural Resources, and numerous other State, county, and city governments. The USGS also partners with international governments (such as the Canadian Geological Survey), public utility districts, private industry, and academic groups, further demonstrating the universal value of high-resolution topographic and bathymetric data (*see sidebar about how to identify local tsunami hazards on p. 23*).

- A comprehensive, public database of active faults near areas with dense population and critical infrastructure, both on land and offshore, builds on USGS expertise and existing products. For example, recent mapping suggests numerous faults in these densely populated areas may be active, but for many known faults there is insufficient information to determine past rates of movement and likely future ruptures. Studies to gather this information are needed—the USGS Quaternary Fault and Fold Database (http://earthquake.usgs.gov/hazards/qfaults/) is very incomplete. Great subduction zone earthquakes occur along the interface between colliding plates, but experience and research show that local earthquakes on shallow crustal faults may be more hazardous if located near urban areas and critical infrastructure.

- Accurate community-accepted models of geologic structures, regional-scale fault systems, and tectonic

Partnering with USAID for Science and Humanity

The Volcano Disaster Assistance Program (VDAP) is the international arm of the U.S. Geological Survey (USGS) Volcano Hazards Program, which is partly funded by the U.S. Agency for International Development's Office of Foreign Disaster Assistance (USAID/OFDA). For the past 30 years, VDAP has strived to reduce loss of life and property by enhancing volcano monitoring and eruption response capabilities of nations around the world. In addition to building in-country capacity for host nations, VDAP maintains a team of experienced volcano-disaster scientists ready to respond to volcanic unrest with the latest tools and methods. In this photograph (by Chistoph Kern, USGS), USGS and Indonesian scientists install monitoring equipment at Sinabung volcano in 2016. USAID/OFDA also partners with USGS on an Earthquake Disaster Assistance Team (EDAT) of USGS scientists who work with local and national governments in countries affected by damaging earthquakes to improve understanding of seismic hazards and develop appropriate building codes and land-use plans. To date, EDAT has collaborated with scientists in China, Comoros, Haiti, Indonesia, Malawi, Nepal, and Turkey. Following the 2015 magnitude 7.8 earthquake in Nepal, for example, a six-person EDAT-supported team installed low-cost seismic monitoring instruments, conducted instrument training sessions, assisted with data analysis, documented earthquake-induced landslides and liquefaction, and helped assess ongoing landslide hazard in preparation for the 2015 monsoon season.

Monitoring equipment being installed at Sinabung volcano in Indonesia on August 14, 2016. Photograph from Christoph Kern, USGS.

Damaged shoreline at Lhoknga, Indonesia, following the December 2004 Indian Ocean tsunami. U.S. Geological Survey photograph by Guy Gelfenbaum.

motions have proven to be valuable resources for research, engineering, and outreach products in southern California (https://www.scec.org/research/usr); development of similar such community models for the Nation's subduction zones will provide shared frameworks that enable integration of results from a diversity of studies, and serve as common foundations for more detailed explorations.

- A seamless onshore/offshore subduction zone series of digital maps (of topography, faults, geologic structures, rock and sediment types, and so on) and an interactive mapping application will serve as a platform for integration of research, resource management, hazards mitigation and response, and public education. The USGS-led California Seafloor and Coastal Mapping Program (https://walrus.wr.usgs.gov/mapping/csmp/) provides an example of an innovative framework for scientific research, coastal planning, and public engagement through the online release of all project data, including a user-friendly video and photograph portal and interactive web services for visualizing and analyzing large geospatial datasets. The application could be linked to an enhanced fault database with fault information that is digital, understandable and useful to both technical and non-technical users, and easily integrated into other applications, such as insurance risk models, and new development planning by city engineers and private developers. (The existing USGS Quaternary Fault and Fold Database contains only textual, technical descriptions.)

- Web-enabled three-dimensional visualizations have the potential to convey the complexities of subduction zone processes so they are understandable and interesting, both for the general public and scientific researchers. Together with partners from NASA, the USGS can leverage their experience making the mysteries of outer space accessible and exciting to the public through use of computer visualization tools (such as NASA's World Wind interface, at https://worldwind.arc.nasa.gov/) that could be adapted to do the same for subduction zones. These interactive tools also help scientists to visualize the information contained in large datasets, to integrate multiple datasets, and to understand them in the context of complex, intertwined physical processes. For example, new insights about how faulting and earthquakes evolve over millennia have resulted from the ability to visualize the predictive models of how faults relieve stresses in complex, three-dimensional fault networks. Visualization tools also allow model-predicted parameters to be compared with real measurements.

- Experience with the scenarios noted throughout this plan indicates the potential for regionally focused, publicly available libraries of risk-based scenarios for the full range of subduction zone events, and perhaps even cascades of events, that would be widely used in engineering design, emergency management plans and exercises, insurance projections, and infrastructure planning.

Outreach and Education

Workshops with user groups, webinars and online courses, surveys, and participation in professional society activities engage users and evaluate the efficacy of our products. Activities and products described in this Subduction Zone Science Plan will follow guidelines on how to effectively communicate scientific information to others developed by a diverse group of risk communication experts from the USGS and universities (Perry and others, 2016). Experts in hazard and risk communications with stakeholders from the USGS's SAFRR project also would be engaged to ensure the application of scientific discoveries and products fills stakeholders' needs (*see sidebar story on p. 26*).

The inevitability of great earthquakes, tsunamis, volcanic eruptions, coupled with the potential for scientific discovery and the development of new exploration tools, particularly in the offshore reaches of subduction zones, provide tremendous opportunity to capture the public's imagination and educate communities about the hazards they face. For example, engaging and educational imagery may be conveyed to the public via webcam and (or) through easy-to-use online geospatial viewers like the USGS Video and Photograph Portal for the Coastal and Marine Geology program (http://cmgvideo.usgsportals.net/). Additionally, the USGS's established presence on various social media platforms such as Facebook, Google Plus, Twitter, and others may be expanded to educate the public about subduction zone science discoveries, and to both gather and distribute hazard information.

Ensuring continued development of effective products requires the training of students in the science of hazard and risk assessment. Training includes topics from the social sciences, such as user-centered design and risk messaging. Example topics from the physical sciences include statistical methods for incorporating field observations of ash flow deposits into probabilities of future eruptions, and application of computer simulations of earthquakes on complex fault networks. The varied and significant potential hazards associated with subduction zone processes make related research and activities ideal opportunities for hands-on learning, through USGS internships, post-doctoral and volunteer programs, and through teaching at partner universities.

Finally, the USGS will continue its strong tradition of educating the public through individual scientist participation in and institutional support of professional societies and consortia, particularly those concerned directly or indirectly with subduction zone geologic processes.

Geologists drive a core into marsh sediment to document interbedded peat and silt that records sudden vertical land movements associated with fault slip during large subduction-zone earthquakes. U.S. Geological Survey photograph by Rich Briggs.

Data Management Plan

To achieve the USGS mission of providing scientific data that serves the Nation, the data and science products described herein will be peer reviewed, made widely available, and managed for long-term storage. Under the authority of the USGS Community for Data Integration, all data and products from the Subduction Zone Science Plan will be made available to the public for posterity through a suite of web applications, spatial data tools, and archival resources.

Acknowledgments

This report was supported by the U.S. Geological Survey Natural Hazards Mission Area. The Subduction Zone Science Plan reflects the ideas of Annemarie Baltay, Nicholas Beeler, Scott Bennett, Michael Blanpied, Amy East, Eileen Evans, Carol Finn, Jonathan Hagstrum, Anna Kelbert, Jared Kluesner, Nicolas Luco, John Lyons, Nathaniel Miller, Alan Nelson, Jared Peacock, Jonathan Perkins, Mark Petersen, Geoffrey Phelps, Cyrus Read, Bruce Richmond, Daniel Scheirer, Kevin Schmidt, David Scholl, Lydia Staisch, Weston Thelan, Roland von Huene, Aaron Wech, Robert Witter, and William Yeck. The writing team thanks Kate Allstadt, David Applegate, Brian Atwater, Susan Benjamin, Jonathan Godt, Gavin Hayes, Stephen Hickman, Jill McCarthy, Seth Moran, Alice Pennaz, John Power, Jane Reid, Stephanie Ross, Uri ten Brink, Greg Shelton, Colin Williams, and Nate Wood for their valuable reviews.

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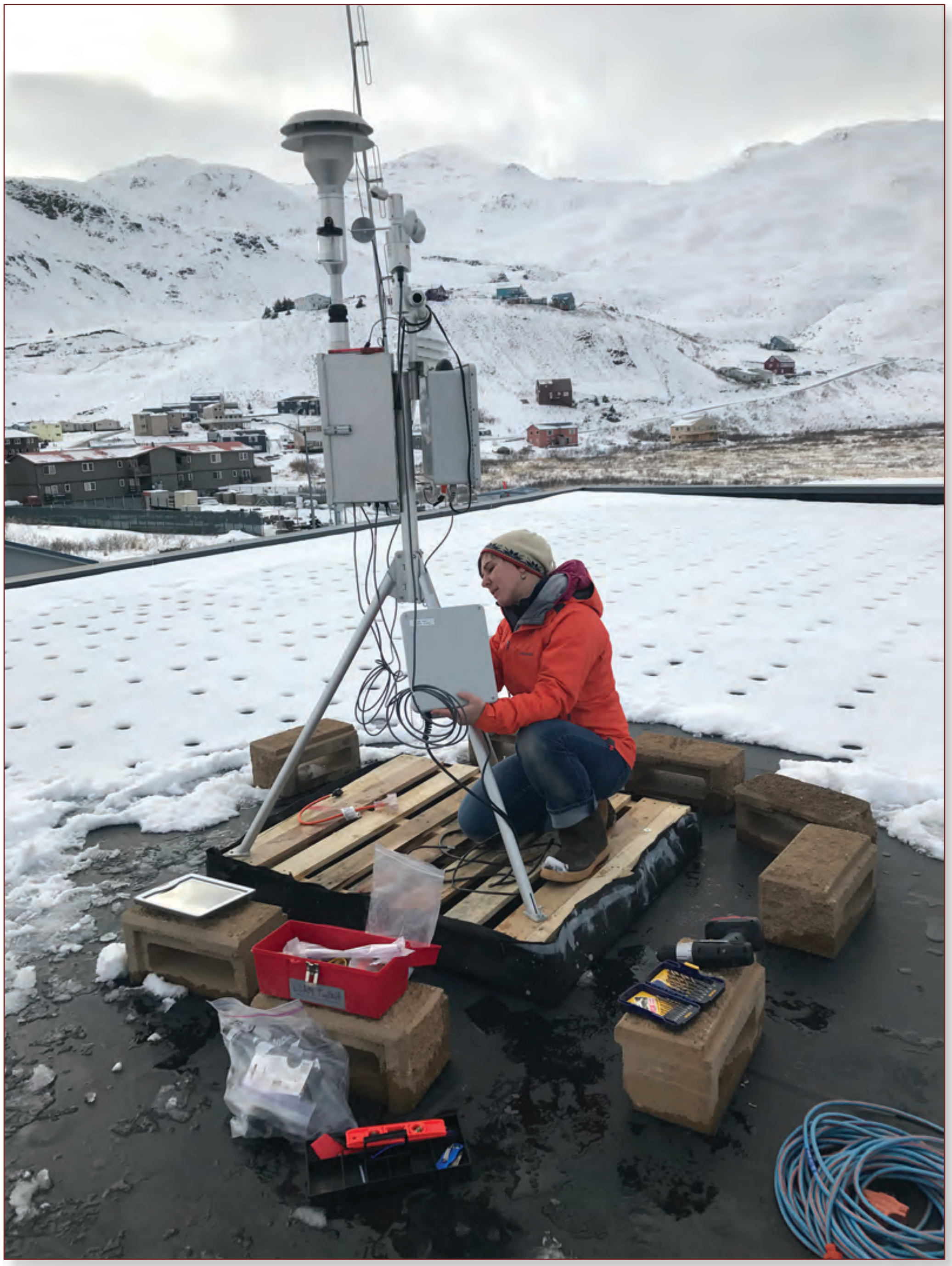
Appendixes



A U.S. Geological Survey scientist installs an air-quality monitor in Unalaska, Alaska, during the eruption of Bogoslof Volcano in February 2017. Alaska Volcano Observatory/U.S. Geological Survey photograph by Janet Schaefer.

Appendix 1. Selected Current and Potential Partnerships

The USGS has a strong tradition of leveraging its assets by partnering with a wide range of public and private-sector institutions. Advancing subduction zone science in the significant ways described in this plan will require nurturing existing partnerships and developing new ones. This appendix summarizes many of these collaborations in order to demonstrate that, indeed, this type of cooperative science can be done and can give rise to new discoveries, technologies, and capabilities that save lives and property.

U.S. Governmental, Professional, and Private Entities

Federal Agencies

- The National Science Foundation's (NSF) Division of Earth Sciences (EAR) currently supports the EarthScope facility and research program; the Plate Boundary Observatory and Transportable Array, operated by the EarthScope program, have direct applicability to subduction zone science. EAR also supports the Global Seismographic Network and the Continuously Operating Caribbean GPS Observational Network (COCOnet). The Division of Ocean Sciences (OCE) supports the International Ocean Discovery Program (IODP) and the Ocean Observatory Initiative (OOI). The cross-division initiatives at NSF that are directly related to subduction zone science include GeoPRISMS, the Cascadia Initiative, and the Trans-boundary, Land and Atmosphere Long-Term Observational and Collaborative Network (TLALOC) in Mexico. Other relevant NSF initiatives include the Prediction of and Resilience against Extreme Events (PREEVENTS) research initiative. NSF also supports high-performance computing that could be integrated into various subduction zone modeling efforts. In October 2016, the NSF sponsored a scientific community workshop in support of possible development of a proposal for a new initiative focused on subduction zones. USGS would closely coordinate its plans and activities with such a proposal and program, so that they maximally complement one another.

- The National Oceanographic and Atmospheric Administration (NOAA) already partners with the USGS for tsunami monitoring, warning and hazard assessment. Activities related to bathymetric mapping and tsunami source modeling are coordinated through the National Tsunami Hazard Mitigation Program, which includes participants from all U.S. tsunami-vulnerable States, territories, and regions. The USGS's National Earthquake Information Center (NEIC) routinely provides seismic data and derived information to the NOAA's Tsunami Warning Centers. This collaboration could be extended through new USGS investments in geodetic networks, lidar imagery collection, and other mapping efforts. NOAA is also responsible for atmospheric monitoring, including the presence of volcanic ash clouds, and issues volcanic ash advisories through its Volcanic Ash Advisory Centers (VAAC) in Anchorage, Alaska; Washington, D.C.; and seven other cities outside the United States. The basis for these warnings comes from information provided by USGS Volcano Observatories.

- The National Aeronautics and Space Administration (NASA) currently partners with the USGS, NOAA, and NSF to compile hazard-related data, conduct research, and deliver post-disaster products. NASA co-supports UNAVCO, a nonprofit organization that helps scientists collect geodetic data, which operates data acquisition form the Global Navigation Satellite System (GNSS). NASA is currently working with NOAA to integrate real-time, GNSS-derived displacements to the NOAA Tsunami Warning Centers. NASA is also planning to launch a radar satellite (operated jointly by the United States and India, called NISAR), which will provide a wealth of imagery data that will transform research on the Earth's surface —in subduction zones and elsewhere. NASA's Disasters Applications project supports research and other activities to improve the prediction, preparation, response and recovery to natural disasters. Combining the unique capabilities of NASA to acquire and analyze data from space with the USGS's terrestrial monitoring and geologic studies would strengthen the research and products of both agencies.

- The Office of Foreign Disaster Assistance (OFDA) of the U.S. Agency for International Development currently supports the USGS to engage internationally in volcanic eruption response and scientific capacity building (through the Volcano Disaster Assistance Project, or VDAP), and earthquake disaster response (through the Earthquake Disaster Assistance Team, or EDAT), both of which are described in the "International Activities" section of this plan and in the sidebar "Partnering with USAID for Science and Humanity." OFDA also supports USGS development of an earthquake and tsunami early warning system in Chile and an operational aftershock forecasting system in Mexico (which will also be applied in other countries). The longstanding cooperation with OFDA has engaged USGS scientists countless times to provide expertise and training, typically in developing countries, many of which sit atop the world's subduction zones.

- The Nuclear Regulatory Commission (NRC) coordinates with the International Atomic Energy Agency to oversee the safety of nuclear plants and to engage in response and assessment activities following a nuclear incident (such as the meltdown of the Fukushima Nuclear Power Station reactors following the 2011 Tōhoku earthquake and tsunami). Although there are no longer U.S. nuclear power plants operating atop the most active portion of U.S. subduction zones (the Columbia Generating Station in eastern Washington is inboard of the Cascade volcanic arc, in the "back-arc" region), nuclear power plants along the coasts of the Atlantic Ocean, Gulf of Mexico, and California could be impacted by tsunami waves generated in subduction zones. The NRC recently supported USGS efforts to assess the likelihood of tsunamis striking the eastern seaboard of the U.S., as a result of local landslide sources or earthquakes in the Caribbean (ten Brink and others, 2014).

- The Federal Aviation Administration (FAA), within the U.S. Department of Transportation, has responsibility to issue and disseminate Notices to Airmen (NOTAM) when informed of precursory volcanic unrest by USGS Volcano Observatories, eruptive activity, or volcanic ash in the national air space.

- The Federal Emergency Management Agency (FEMA) is a partner agency with the USGS in the National Earthquake Hazard Reduction Program (http://www.nehrp.gov/). USGS earthquake and tsunami products feed directly into FEMA's software package Hazus (https://www.fema.gov/hazus), which estimates potential building and infrastructure losses from earthquakes and floods. USGS earthquake data also contribute to FEMA's local hazard mitigation planning tools that help communities reduce long-term risk (https://www.fema.gov/hazard-mitigation-planning-process). Other FEMA products, such as flood insurance rate maps for the tsunami-vulnerable town of Seaside, Oregon (https://catalog.data.gov/dataset/f4100300001d-tif-fema-flood-insurance-rate-maps-for-the-seaside-gearhart-oregon-area-gearhart), are built collaboratively with USGS and NOAA. Earthquake scenarios and subject matter expertise for local to national exercises also exemplify the collaboration between the USGS and FEMA.

- Other Federal agencies that collaborate with the USGS on subduction zone science include the National Institute of Standards and Technology (another partner in the National Earthquake Hazard Reduction Program), the General Services Administration, the Department of Defense, the Department of Energy (DOE), and several other Federal agencies that own land, ports, buildings, and other structures that are at risk from the natural hazards present in subduction zones. For example, in a recent assessment, the Government Accountability Office mapped the locations of Federal buildings in earthquake-prone areas in the Pacific Northwest as part of a Congress-requested assessment of Federal building risk. The DOE operates the Hanford Site in Washington, which is the focus of the Nation's largest environmental cleanup project and home to the commercially operated Columbia Generating Station nuclear power plant; the USGS and its partners operate a seismic monitoring network on and around the Hanford Site and conducts geologic field studies to assess the seismic hazard associated with the multiple faults in the area.

State, Commonwealth, Territorial

State geological surveys, emergency management agencies, insurance organizations, airport authorities, departments of transportation, and numerous tribal governing bodies are just some examples of State agencies that USGS already partners with to assess hazards and distribute information. USGS also partners with various entities in the U.S. territories of Puerto Rico and the Virgin Islands, Guam, the Mariana Islands, and American Samoa.

Professional and Academic Organizations and Private Companies

The USGS has a strong tradition of educating and learning through participation in professional societies and consortia concerned with subduction zone geologic processes; for example, in the Pacific Northwest these include the Cascadia Regional Earthquake Workgroup (http://www.crew.org/), the Pacific Northwest Economic Region organization (http://www.pnwer.org/), and the Western States Seismic Policy Council (http://www.wsspc.org/). By working with engineers in academia, private companies, and professional organizations (such as the Applied Technology Council, Earthquake Engineering Research Institute, Structural Engineers Association of Washington, Pacific Earthquake Engineering Research Center, Center for Disaster and Risk Analysis), USGS scientists ensure that its products are useful to as many communities as possible.

Monitoring Networks

Large-scale, permanent monitoring networks are often operated as partnerships between the USGS and other institutions and data are publicly shared. Seismic networks on U.S. subduction zones include the Northern California Seismic Network (jointly operated by the USGS and the University of California, Berkeley), the Pacific Northwest Seismic Network and Cascade Chain Volcano Monitoring Network (with the University of Washington), the Alaska Earthquake Information Center and the Alaska Volcano Observatory (with the University of Alaska, Fairbanks), the Puerto Rico Seismic Network (with the University of Puerto Rico), and the Canadian National Seismograph Network (with Natural Resources Canada). For monitoring slower deformation, mainly using GPS, networks operated by the USGS and partners include the Pacific Northwest Geodetic Array (with Central Washington University) and volcano-specific sites operated by the California, Cascades, and Alaska Volcano Observatories (which are mainly maintained by the USGS). These and other GPS networks contribute data to the much larger Plate Boundary Observatory (PBO, which has 1,100 sites), a major component of NSF's EarthScope Program; data from EarthScope have contributed to many USGS subduction zone studies and will be employed in the USGS's earthquake early warning system. Currently, the PBO has a scheduled termination date in 2018, but NSF is considering a follow-on National Geophysical Observatory for Geoscience. Such an observatory would allow for continued operation of the current Seismological Facilities for the Advancement of Geosciences (SAGE) and Geodesy Advancing Geosciences and EarthScope (GAGE) facilities. The USGS also uses data from satellites, including radar instruments operated cooperatively by several governments, including the European Union, South Korea, and Japan.

Offshore Facilities

For U.S. oceanographic vessels and instrumentation, the University-National Oceanographic Laboratory System (UNOLS) coordinates U.S. ship schedules and the NSF-supported Ocean Bottom Seismograph Pool (OBSIP), which is a distributed oceanographic instrument pool; the USGS has collaborated with both of these groups to carry out experiments in multiple subduction zones. The International Ocean Discovery Program (IODP) organizes scientific drilling expeditions in ocean basins to acquire samples and measurements that address a wide range scientific questions. IODP experiments are planned years in advance; recent and upcoming expeditions relevant to subduction zone science include cruises to Sumatra (2016), the Mariana subduction zone (2016–2017), and New Zealand (2017 and 2018). A recent major IODP effort has been to drill into and instrument the earthquake-generating fault of the Nankai Trough subduction zone offshore Japan (NanTroSEIZE); future IODP cruises may include similar efforts in the U.S subduction zones of Cascadia, the Alaska-Aleutian Trench, and the Mariana Islands.

The U.S. Geological Survey and the University of Alaska, Fairbanks, partner to monitor earthquakes on and around significant infrastructure, such as at this dam at Bradley Lake, which is the largest hydropower project in Alaska. Photograph by Ian Dickson, Alaska Earthquake Center, University of Alaska, Fairbanks.

Appendix 2. International Monitoring, Disaster Mitigation and Response, and Capacity Building

As a global leader in Earth science research, the USGS has a long history of collaboration with foreign scientists, agencies, and governments to provide information and guide best practices before, during, and after natural disasters, particularly in subduction zones. In this appendix we summarize some of these international collaborations.

The U.S. Geological Survey (USGS) National Earthquake Information Center (NEIC) determines, as rapidly and accurately as possible, characteristics and potential effects of earthquakes that occur worldwide. It disseminates this information within minutes to National and international agencies, scientists, critical facilities, and the general public. The Global Seismograph Network (GSN; https://www.iris.edu/hq/programs/gsn) is a cooperative partnership involving the Incorporated Research Institute for Seismology (IRIS), the National Science Foundation and the USGS. It provides free, real-time, open-access seismological data from more than 150 stations worldwide. Since the early 1990s, Japan, New Zealand, and Canada have been monitoring portions of their subduction zones and many of their hazardous volcanoes using both onshore and offshore geophysical instruments. Geodetic instrumentation to track plate motion in Chile, Mexico, and the Caribbean is being deployed with the aid of funding from government agencies in other nations, including the United States.

Through a multinantional agreement called the International Charter: Space and Major Disasters, the USGS and other member agencies contribute satellite imagery in support of disaster response. The Volcano Disaster Assistance Program (VDAP) is a global volcanic risk mitigation activity that is co-funded by the U.S. Agency for International Development (USAID) and the USGS. The more recently established USGS/USAID Earthquake Disaster Assistance Team (EDAT) provides technical assistance to establish monitoring capabilities, collect relevant geologic field data, conduct geophysical surveys, and more, collaborating with local scientists shortly after large earthquakes occur in foreign countries so that they can “build back better” after events. EDAT has supported activities in a number of countries with subduction zone settings.

USGS scientists contribute research results to a wide range of international organizations focused on mitigating tsunami hazards. The Intergovernmental Oceanographic Commission (IOC) Tsunami Programme (http://www.ioc-tsunami.org/index.php?option=com_content&view=article&id=1&Itemid=2&lang=en) supports member States in assessing tsunami risk, implementing tsunami early warning systems, and educating communities at risk about preparedness measures. These missions are addressed by the IOC through actions of the International Tsunami Information Centre (ITIC), which it oversees. The ITIC is a professional interchange, supported by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the National Oceanic and Atmospheric Administration (NOAA), that maintains relationships with scientific organizations, civil defense agencies, and the general public. The NOAA Pacific Tsunami Warning Center (http://ptwc.weather.gov/ptwc/responsibilities.php) provides warnings for Pacific Ocean tsunamis to the countries around the Pacific Rim and the Pacific island states with U.S. interests, under the auspices of UNESCO. NOAA also operates the National Tsunami Warning Center (http://wcatwc.arh.noaa.gov/), which serves the continental United States, Alaska, Puerto Rico, the Virgin Islands, and Canada.

The International Civil Aviation Organization (ICAO) has established nine Volcanic Ash Advisory Centers (VAACs, http://vaac.arh.noaa.gov) across the world to keep aviators informed of volcanic hazards. The USGS hosts the website for the Volcanic Ashfall Impacts Working Group, an international consortium of multidisciplinary geoscientists focused on ash-cloud forecasting and understanding and mitigating the effects of ashfall.

USGS partnerships with the private sector include the many corporations that have facilities, financial institutions that have investments, and insurers that have clients in subduction zones globally. Additionally, private, non-profit, and governmental international aid organizations, such as the International Red Cross, Oxfam, and various assistance arms of the United Nations, require information about subduction zone hazard and risk. The Global Earthquake Model (GEM; https://www.globalquakemodel.org) is a public-private partnership that guides and funds work such as urban risk scenario development and experimental risk reduction initiatives. The Global Volcano Model (GVM; http://globalvolcanomodel.org) is an international effort to create an accessible information platform that models volcanic hazard and risk on global and regional scales, and to support volcano observatories at a local scale. Both GEM and GVM count risk-modeling and reinsurance companies among their sponsors. A more nascent, comparable effort to develop a Global Tsunami Model also is underway.

Publishing support provided by:
Menlo Park, California, and Rolla, Missouri, Publishing Service Centers
Manuscript approved for publication March 24, 2017
Edited by Claire M. Landowski
Layout and design by Suzanne Roberts

For more information concerning this publication, contact:
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Back cover. GPS (Global Positioning System) data, such as from a station near Iniskin Bay, Alaska, provide key constraints on the characteristics of individual earthquakes and their impacts. This station contributed important information following the damaging magnitude 7.1 Iniskin earthquake near Anchorage, Alaska, in 2016. Maintenance of these remote sites require support from ships and helicopters, as shown here. Photograph by Heidi Willoughby, UNAVCO.

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Gomberg and others—**Reducing Risk Where Tectonic Plates Collide—A Plan to Advance Subduction Zone Science**—Circular 1428

ISBN 978-1-4113-4150-0

ISSN 1067-084X (print)
ISSN 2330-5703 (online)
https://doi.org/10.3133/cir1428