The SZ4D Initiative

Understanding the Processes that Underlie Subduction Zone Hazards in 4D

A Vision Document Submitted to the National Science Foundation

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Executive Summary

The devastating tsunamis resulting from the 2004 Sumatra and 2011 Tōhoku earthquakes are vivid examples of global disasters that result from subduction, the process by which oceanic plates sink into the mantle and generate Earth's largest earthquakes and volcanic eruptions. The 2004 and 2011 disasters could be a preview of what may happen if a large subduction earthquake were to shake the Pacific Northwest. The next major eruption of Mt. Rainier has the potential to devastate major urban centers in the state of Washington. Large landslides such as the 2014 event near Oso, Washington, are a common occurrence in the Pacific Northwest, Alaska, and Puerto Rico. Despite the enormous social significance of these hazards to society, many of the basic physical and chemical processes controlling the occurrence and magnitude of these natural events remain poorly understood. Almost all hazardous subduction zone events are poorly forecast or occur with no apparent warning at all.

Subducting plates descend into Earth at different speeds, ingesting sediment, water, and carbon dioxide into Earth's mantle. How are these materials recycled in explosive volcanic eruptions? What processes control fault slip on subduction megathrusts, which ranges from rapid earthquake rupture over seconds to slow steady slip lasting years? How do spatial variations in the initial subduction conditions lead to the cascade of seismic, fluid, magmatic, and landscape responses? What subduction processes control the pulse of continental growth, and how do tectonic and climate processes interact to create and modify our landscape?

Advances in offshore and satellite observations now offer opportunities to record the run-up to earthquakes and eruptions. New high rate data sets near faults and on volcanoes provide geochemical, hydrological, geophysical, and geological observations that, when assimilated, will lead to new dynamic, predictive models. The predictability of eruptions has been shown to improve dramatically with only a handful of instrumentation. Laboratory experiments are now able to measure the behavior of material in faults and under volcanoes, and new chemical timekeepers are constraining rates of processes from minutes to millions of years. These technological advances, combined with new observations collected over a broad range of spatial and temporal scales, provide the impetus for a new, interdisciplinary, coordinated program to understand the fundamental physical processes that underpin subduction phenomena. We need to accelerate the pace of subduction zone research to ultimately improve the resilience of the societies that live in these dynamic regions.

The current energy and optimism to understand fundamental subduction processes and hazards motivated the U.S. scientific community to convene a workshop in September 2016 to discuss the potential for Subduction Zone Observatories. More than 250 scientists from 22 countries attended. The scope of the subduction zone problem is intellectually, geographically, and temporally wide-ranging, and the workshop attempted to cover all of these perspectives. Here, we present the views discussed at the workshop on the high-priority science targets, the critical gaps that are holding back subduction zone science, the need for interdisciplinary in-reach and capacity-building outreach, and the paths forward that the academic, national agency, and international communities could pursue to transform subduction zone science.

The workshop produced a vision of capturing the four-dimensional (4D) evolution, in space and time, of subduction processes that create geohazards and drive the evolution of the solid Earth and its surface. The ***SZ4D Initiative*** seeks to move subduction science from describing static snapshots to fully capturing and modeling key phenomena as they evolve both in real time and through geological time. ***SZ4D*** will enable frontier activities that are impossible or difficult to do now. For instance, we need to instrument offshore seismic gaps to capture large ruptures well enough to derive the frictional, hydrological, and thermal behavior before and during slip and in the excitation of a tsunami. We need to track the motions of magma beneath the surface and relate them to the array of currently unrelated events in the run-up to eruptions. We need to quantify the fluxes of mass, stress, and fluid between the plate boundary and the shallow crustal faults that pose the greatest hazard to coastal cities. We need new multidisciplinary data sets in the United States and globally.

Three key components—a modeling collaboratory, an interdisciplinary science program, and a community infrastructure program—in combination over 10 years would lead to a new understanding of subduction phenomena and in so doing, advance our ability to forecast earthquakes, tsunamis, and volcanic eruptions. There are extensive existing programs run by multiple U.S. agencies, including NSF, USGS, NASA, and NOAA, and numerous international organizations that already provide a strong foundation. The ***SZ4D Initiative*** will present a new opportunity to coordinate efforts across agencies and with international partners. In this report, we develop the scientific motivations and present a vision for the frontier opportunities and key ingredients of the ***SZ4D Initiative***.

1. Introduction

Subduction Zones Generate Our Planet's Greatest Geohazards

By focusing vast amounts of mechanical energy into narrow coastal belts, subduction zones are responsible for the enormous risks associated with the array of geohazards in these densely populated regions, including earthquakes, tsunamis, volcanic eruptions, and landslides. Subduction, the underthrusting of an oceanic plate into the mantle, occurs along a continuous fault that can extend for thousands of kilometers along the shoreline and can reach hundreds of kilometers inland. The largest earthquakes on Earth occur where large segments of the plate boundary can store energy for centuries and then release it in minutes. Energy release from the largest subduction zone earthquakes (2011 Tōhoku, 2004 Sumatra, 1964 Alaska, and 1960 Chile) dwarfs that of all other earthquakes over the last century. Within the United States, the Cascadia subduction zone in the Pacific Northwest has been storing energy for over 300 years that must inevitably be released. We have witnessed this process repeatedly around the globe in the form of powerful earthquakes, and many regions are currently expected to experience such catastrophic ruptures in the coming decades. Yet, we don't understand the fundamental physical and chemical processes that govern the release and recharge of stress on these faults well enough to anticipate the spatial and temporal patterns of future ruptures.

Tsunamis, which provide an even greater additional threat to coastal communities, are caused by vertical motion of the seafloor during such ruptures (**Figure 1.1**). Their wave trains cross oceans at speeds comparable to those of airplanes and impact coastlines at heights of tens of meters. As demonstrated in the 2004 M9.2 Sumatra earthquake, with over 250,000 deaths spread across 15 countries, tsunamis can produce truly international catastrophes. The 2011 M9.0 Tōhoku earthquake and tsunami in Japan showed that even the most prepared countries can suffer significant economic damage (>$300 billion in direct losses) and loss of life (>10,000) due to tsunami inundation. The true impact of these events is difficult to measure and lasts for decades. What unanticipated features of fault physics allowed the 2011 rupture to propagate all the way to the seafloor trench and hence generate such a historic tsunami? We need to instrumentally capture such events in order to answer this basic question.

The most devastating historic volcanic eruptions have also occurred at subduction zones, with global climate effects resulting from the 1815 Tambora, Indonesia, 1982 El Chichón, Mexico, and 1991 Pinatubo, Philippines, eruptions. Tens of thousands of people were killed by pyroclastic and volcanic mud flows in the 1902 Pelée, Martinique, and 1985 Nevado del Ruiz, Colombia, eruptions (**Figure 1.2**). Currently, more than 30,000 people a day fly over the remote Aleutian and Kuril volcanic arcs, where the 1989 eruption of Mt. Redoubt, Alaska, led to $80 million of damage to a single aircraft that experienced complete engine failure while flying through its ash plume. Such eruptions are fueled by volatile-rich magmas that derive their water and CO_2 from hydrated oceanic crust and sediments carried into the subduction zone. The fluids are subsequently driven out of the subducting plate at depth

FIGURE 1.1. The March 11, 2011, Tōhoku tsunami washes ashore near Natori, Miyagi Prefecture, Japan. *Credit: AP/Kyodo News*

FIGURE 1.2. Explosion at Calbuco volcano, Chile, on April 22, 2015, taken from Puerto Montt, about 30 km southwest of the volcano. *Photo by Keraunos ob, posted on the Earth of Fire blog by Bernard Duyck. From Global Volcanism Program, Smithsonian Institution.*

and fuel melting in the overlying mantle. The resulting magma migrates upward and is focused into the chains of volcanoes that give the Ring of Fire its name. How do the feedbacks between crustal stress, melt viscosity, and magma flux control the ascent path and rate from the mantle to the eruption? At any given time, globally there are about 10–20 subduction zone volcanoes in a state of eruption or unrest. To improve our ability to predict how these volcanoes will evolve in time, we need to capture the events that lead to states of unrest, repose, and eruption, and link them to deeper processes occurring in crust, mantle, and subduction zone.

Lastly, what goes up via tectonic uplift or volcanic edifice-building must come down again—often in the form of landslides (**Figure 1.3**) or lahars. Subduction zones are particularly prone to landslides because of the interplay among earthquakes, volcanoes, submarine conditions, and climatic events. For example, in 1970, the M7.9 Ancash subduction earthquake in Peru triggered a massive debris avalanche from Nevados Huascaran Volcano that wiped out an entire village of ~18,000 people. The unstable terrain created by volcanoes and tectonic uplift in subduction zones also makes these areas more prone to widespread landsliding from climatic triggers. Hurricane Mitch triggered over 500,000 landslides in Honduras in 1998, including large debris flows off Casitas Volcano. Closer to home, the forearc of the Cascadia subduction zone in the Pacific Northwest experiences over 10,000 landslides a year, and a submarine landslide that was triggered by the 1964 Good Friday Earthquake, in Seward, Alaska, then initiated a tsunami that destroyed much of that town. Can we quantify the range of geologic conditions that create the observed variability in ground failure and improve our models of how slopes respond to rainfall events and seismic shaking?

Many of the physical processes controlling the occurrence, timing, and magnitude of subduction hazards are poorly understood and require focused research efforts. For example, even basic questions—such as why great megathrust earthquakes occur in some subduction segments but not others—remain elusive. In addition, there is a great need to study interconnections within the entire system (**Figure 1.4**). Earthquakes trigger landslides, particularly in steep slopes of volcanic ash deposits or areas undergoing rapid uplift and erosion. Eruptions trigger lahars, and eruptions themselves can be triggered by the shifting loads of water and ice responding to climate cycles, which may be perturbed by large volcanic eruptions. Climate and tectonic forcing compete to drive erosion, which ultimately produces the sediments that subduct and affect the mode of slip along the plate interface and the supply of volatiles that erupt at volcanoes. The interrelated processes require research into subduction zones as a system using a dedicated interdisciplinary effort.

FIGURE 1.3. On March 22, 2014, the Oso landslide in Washington State sent 18 million tons of sediment racing downhill at speeds averaging 65 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. Settlements paid to survivors total $60 million. *Photo credit Mark Reid (USGS)*

Subduction Zones Govern the Evolution of the Solid and Fluid Earth

The recycling of oceanic plates into the mantle is perhaps the most important geological process on Earth, providing the gravitational energy change that drives tectonic motions as well as controlling the mixing of surficial materials with those deep in Earth. Subduction therefore determines the vigor of mantle convection, which in turn drives the pace of plate tectonics, the assembly and dispersal of continents, sea level rise and fall, and ocean chemistry. This tectonic engine is the cause for nearly all geological deformation. Subduction zones also create the deepest seafloor trenches and the highest mountains on Earth.

The dynamics of slab descent and convection (e.g., flat vs. steep slab subduction) lead to different styles of mountain building. Furthermore, this topography then evolves from the interplay of erosion and isostasy; it is modulated by regional climate that is itself determined in part by the subduction zone's topography. The overriding plate will deform differently depending on the effectiveness of erosion and sediment burial, closing the loop from tectonics to climate. It is therefore not just the deep mass transport that matters for subduction, but also the redistribution of mass at the surface.

Volcanoes located above subducting zones not only generate hazards, but also create the land we live on, fertilize the soil in which we grow our food, and supply metal resources in the form of ore deposits. Volcanism also offers the potential for geothermal energy. The growth of continental crust via magmatic intrusion and its destruction via erosion are both regulated by the subduction system. The secular cooling of the mantle and subducting slabs has driven the evolution of continental composition and mass over billions of years. Subduction zones thus imprint a record of past tectonics onto the continental plates.

Subduction zones also regulate the flux of volatiles to our atmosphere and ocean. These include water, carbon dioxide (CO_2), and sulfur species—powerful agents of climate change—which are cycled from the rocks in the subducting plate through the volcanic arc. The last decade of research has provided evidence that much of Earth's deep water cycle may be controlled by faulting and hydration as subducting plates bend and dilate en route to a trench. The efficiency of volatile cycling has been affecting Earth's climate and habitability throughout the geologic past. For instance, how much CO_2 gets taken down into the mantle, and how much of it is returned to the atmosphere, is one of the major open questions in the Earth sciences.

Subduction Research in the 21st Century

In this century, the devastation brought about by natural hazards highlights the urgent need to understand the physical processes that underlie plate subduction. New observational capabilities often lead to rapid and unexpected advances. For example, this century began with a revolution in our understanding of how faults rupture, revealing unexpected variability. In some places faults creep stably, requiring no earthquakes to release stored energy; in other places, they lurch suddenly in major earthquakes. And in still other places, the faults slide episodically, starting and stopping over the course of days, weeks, or months in "slow slip" events. This

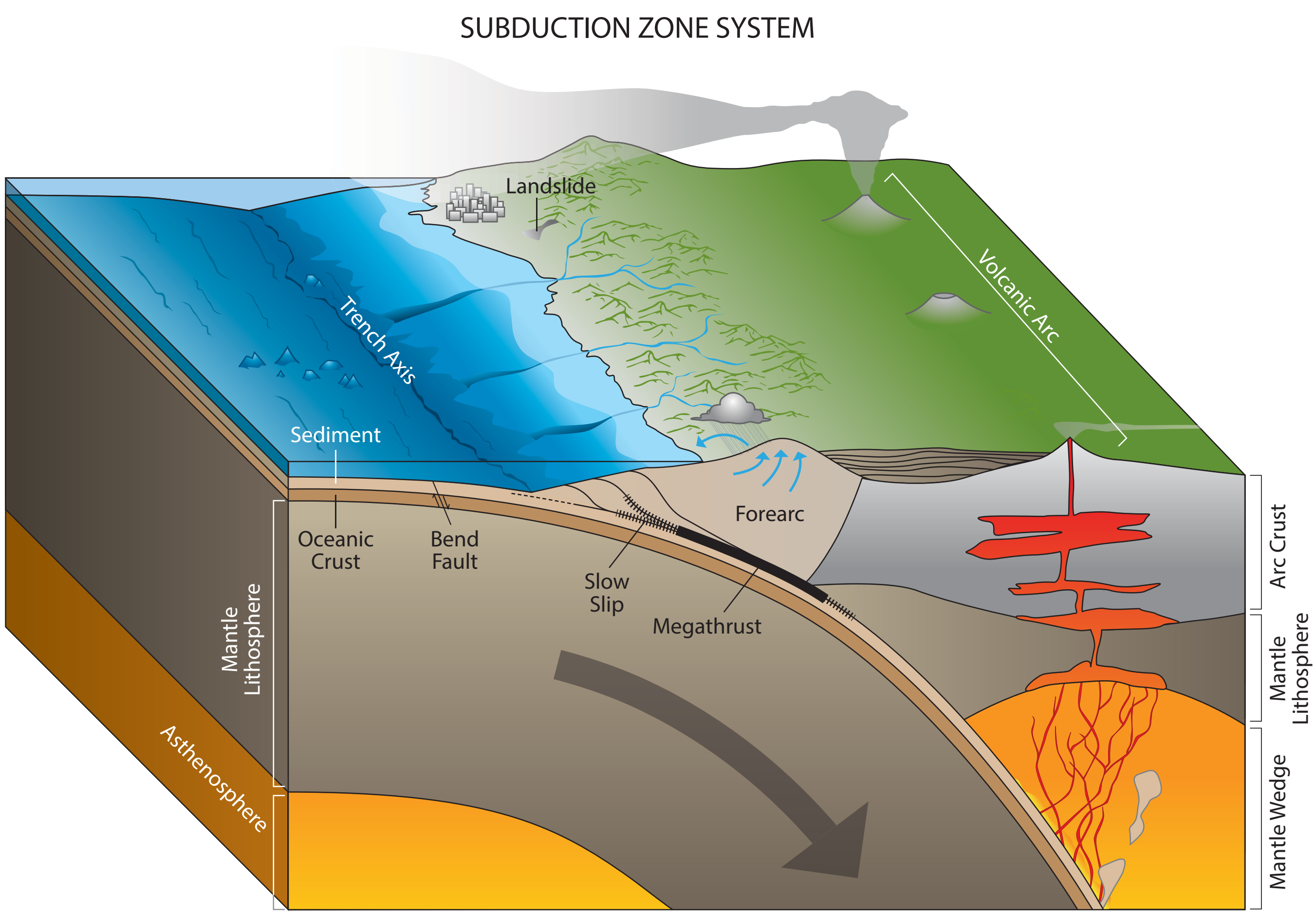


FIGURE 1.4. Representation of a subduction system, identifying many of the components discussed in this document. A subduction zone is created where two plates converge, with one sinking into the mantle. Subduction connects features on the incoming plate to dynamics along the plate interface that create earthquakes: magma generation above the sinking slab to explosive eruptions, and creation of topography in the upper plate to landslides and sediments that feed back into the subduction zone. Figures in the remainder of the report are drawn largely from the published literature and typically address specific regions and processes within this overall subduction system.

last behavior was unknown prior to the installation of dense onshore instrumentation in the Pacific Northwest and Japan in the late 1990s.

Most recently, in a span of a little over 10 years (2004–2016), Earth's subduction zones produced 18 great (magnitude 8+) earthquakes, many of which generated devastating tsunamis (**Figure 1.5**). These great earthquakes provide a few lessons. First, they remind us that much is still to be learned about the Earth system, that subduction zones in particular are ripe for discovery, and that research on these margins is deeply societally relevant. Even in Japan, with the best instrumentation and preparation on the planet, the scientific community did not foresee that the largest fault motion, over 50 m of slip, would occur at the subduction trench. Clearly, there is much to be learned about the physical processes that govern rupture evolution and tsunami generation. Second, these great events highlighted the immense scientific importance, yet current sparseness, of offshore continuous geophysical, geochemical, or hydrological instrumentation near the trench and above the region where rupture occurred. Lastly, these events exemplify the link between increasing scientific understanding and reducing the risks of natural hazards such that these goals cannot be viewed as disjoint activities. The need to develop an improved understanding of basic processes in subduction zones and effectively translate that understanding into risk reduction is urgent even in the most developed countries.

Similarly, the great eruptions of the latter part of the last century revealed an array of phenomena in the run-up to eruptions that changed our thinking of how volcanic systems work. Deep seismic events occurred in the mantle beneath Mt. Pinatubo in 1991, in the week prior to one of the largest eruptions of the last century. Indeed, new methods to date crystals have shown evidence for input of fresh magma in the months and weeks prior to eruption. New satellite and ground-based sensors have recorded a wide range in sulfur gas emission globally at subduction zones, yet there is no theory linking gas and subducted fluxes. Lastly, increases in CO_2 appear to precede some eruptions by days to weeks. Such signs of unrest are as yet unmeasured comprehensively prior to most eruptions, which prevents us from combing the insights gained through the use of different techniques to more fully elucidate the underlying processes. These potential gas precursors are of more than academic interest to the large populations in the United States and globally living under the

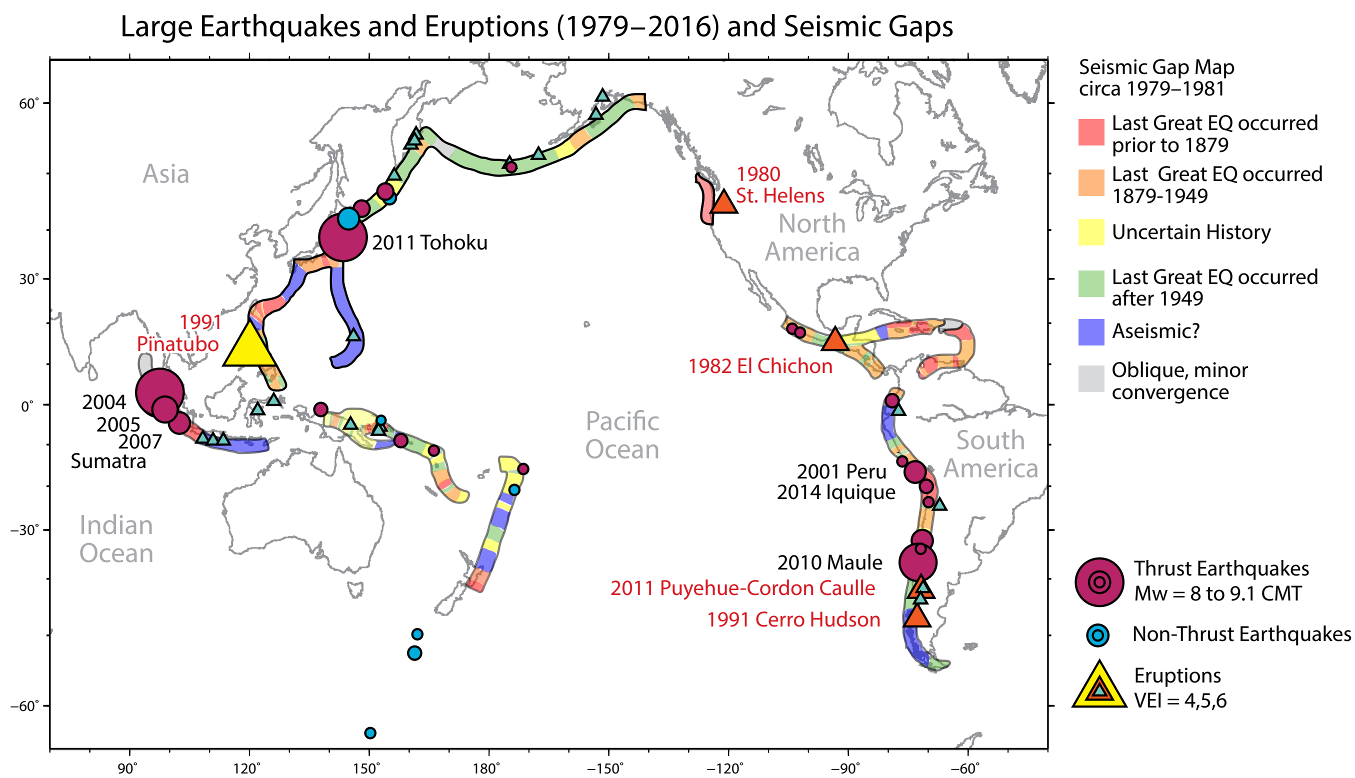


FIGURE 1.5. Major earthquakes (circles) and volcanic eruptions (triangles) that have occurred over the past 40 years at subduction zones. Symbol size scales with magnitude. Colored strips along trenches mark the time since the last great earthquake (M ≥8.0). Red and orange patches may be considered "seismic gaps," potentially overdue for large earthquakes, and regions for future focus (see Boxes 7.2, 7.3). Earthquakes with magnitude ≥8.0 are from the USGS Earthquake Catalog, accessed December 20, 2016. The earthquake data set was culled to show only events at subduction zones shallower than 60 km depth, and with an updated magnitude for the 1979 Colombia event. Eruptions with Volcanic Explosivity Index ≥4 are from Smithsonian's Global Volcanism Program VOTW, accessed January 4, 2017. Seismic gaps are identified according to McCann et al. (1979). The map was created in GeoMapApp and Adobe Illustrator using the Contininent_ln shapefile from UCLA Institute for Digital Research and Education as a base map.

shadow of volcanoes or flying over them.

The field of quantitative landscape characterization and modeling is advancing rapidly and focusing on the dynamic adjustment between tectonic uplift and surface erosion that regulates topography of the overriding plate in subduction zones. The topography provides a natural observational constraint on subduction dynamics at intermediate time scales of thousands to millions of years. Two key technological advances, the quantitative and systematic measuring of topography at high resolution via LiDAR and the dating of surfaces and determination of denudation rates via cosmogenic nuclides, have combined in recent years to provide data on the dynamic evolution of landscapes as well as to characterize the hazards associated with landslides. While these techniques are most commonly deployed on the scale of individual studies, if they were deployed on the scale of an entire forearc they could help quantify the temporal and spatial variations in accretion, uplift, and erosion rates along the margin as well as help understand the connections between permanent strain in the upper plate and megathrust behavior.

During the first part of the twenty-first century, rapid technological advances have enabled us to capture subduction zone phenomena in four dimensions with unprecedented temporal and spatial resolution. From the locking of the plate boundary fault, to the gases expelled from volcanoes prior to eruption, to the surface mass transport between forearc mountains and the trench, to geological records of past ruptures spanning back thousands of years, new, continuous (as opposed to previously captured static snapshots), observational time series are revealing Earth properties and processes. Observatory-based seismic and geodetic studies (e.g., EarthScope and similar-scale deployments in Japan, Chile, New Zealand, and China) have illuminated nearly the full spectrum of fault motion, from aseismic creep, to episodic earthquakes, to nonvolcanic tremors and slow earthquakes on time scales of months to years. Offshore seismic and electromagnetic surveys have imaged fault systems and fluid and magma pathways in unprecedented detail. Scientific drilling and the study of deeply exhumed rocks have provided precious samples of actual materials that exist deep within faults and control physical properties from the kilometer to the pore scale.

Arguably, many of the recent technological advances arose from increasing the resolution of observation and focusing community efforts on individual subduction zones of concern. In order to examine the entirety of subduction zone events and cycles from trench to arc—including precursors to great earthquakes and eruptions, and the role of volatiles and magma fluxes in seismic and volcanic hazards—we need to construct coordinated subduction zone observatories that make multiscale and multidisciplinary measurements in four dimensions.

The distinction between sensors deployed for practical hazards evaluation and for basic research is breaking down. Earthquake and tsunami early warning, eruption warnings based on geophysical unrest, and warnings of incipient landslides based on satellite observations all rely on sensor suites that now serve the dual purpose of increasing scientific understanding and reducing the risks related to natural hazards. The potential technological capabilities for observing subduction zones is expanding in many ways, but new innovations and investments remain necessary in order to implement on large scales and to interpret and translate the results in ways that can best accelerate scientific discovery while improving warning systems.

Subduction Zone Science is an International Opportunity

Investment in research into the physical and chemical processes that drive subduction zones is essential to mitigating the risk of these hazards to society. Because individual subduction zones are up to thousands of kilometers long, and contain multiple earthquake rupture zones and volcanic centers that operate on time scales from seconds to millions of years, studying them is challenging. To address these challenges, the community needs to focus on specific margins that represent the highest likelihood of testing key hypotheses in subduction zone dynamics. Currently, some convergent margins are densely instrumented (e.g., Nankai Trough, Japan Trench, Hikurangi margin) while many others are not (e.g., Alaska-Aleutian Trench, Izu-Bonin-Mariana Trench, Java-Sumatra-Andaman system).

As a community we have learned tremendously by transferring knowledge of one subduction zone to others. For example, the importance of out-of-sequence thrusts or splay faults for tsunami hazards was first recognized in the Nankai Trough, then shown to be critical to understanding parts of the Chile and Alaska margins, and elsewhere. Similarly, the discovery of ubiquitous slow slip and seismic tremor was first recognized in Japan and quickly spread around the globe. The discovery of plate-bending faulting as a major new hydration path in the Cocos Plate subsequently led to its recognition at the Chile, Mariana, Japan, and Alaska margins. The massively instrumented Etna and Stromboli Volcanoes in Italy have revealed a suite of precursory gas, petrological, and seismic signals now being sought elsewhere. Thus, there is an imperative for partnerships to study subduction zone processes and hazards by leveraging resources internationally and sharing data and results within the science community and stakeholders across the globe. While many scientists collaborate internationally on particular projects, we lack an overarching structure that can effectively translate and integrate advances between regions, promote open access to data, train a diverse workforce, rapidly respond to events, and facilitate collaborations that will accelerate progress.

The Subduction Zone Observatory Workshop, Boise, Idaho, September 2016

New scientific insights and technological advances that characterized the first decade and a half of the twenty-first century reinvigorated our optimism that major scientific and societally relevant advances in our understanding of subduction zones are within our grasp. Observational networks and scientific communities are growing, yet are hamstrung by key structural and conceptual gaps, as well as resource shortages to advance diverse scientific and geographic fronts simultaneously. Many of these discussions, often with hundreds of scientists from around the world, have identified the need for greater international coordination, stronger interdisciplinary integration, and an ability to rapidly push new technological advances out to a scale that can conquer the observational frontiers.

In response to the current energy and optimism for a major push for scientific advancement and risk reduction in subduction zones, the U.S. scientific community convened a workshop in September 2016 to discuss potential Subduction Zone Observatories. The community interest was overwhelming. We received over 350 applications, and with support from seven different programs at the National Science Foundation (NSF), the United States Geological Survey (USGS), and the Earth Observatory of Singapore, over 250 scientists from the United states and 22 foreign countries were able to attend. More than 25% of the attendees were early career scientists or graduate students. This document details the many ideas discussed during the workshop for how best to advance subduction zone science in the coming decade.

The scope of subduction zone science is extremely broad intellectually, geographically, and temporally, and the workshop attempted to cover this diverse range of perspectives. Here, we present a range of views discussed at the workshop on the high-priority science targets, the critical gaps that are holding back subduction zone science, the need for interdisciplinary in-reach and capacity-building outreach, and the promising paths forward that the academic, national agency, and international communities could pursue in the coming years to transform subduction zone science. Taken together, these views lead to a vision for a new ***SZ4D Initiative*** to capture and model the 4D evolution of subduction zones.

2. Big Science Questions Motivating a Subduction Initiative

2.1 When and Where Do Large Earthquakes Happen?

Anticipating the timing and location of major earthquakes has long been a challenge, as it requires a fundamental understanding of the physics controlling earthquake generation and fault creep, and their underlying connection to plate motion (see **White Paper 20**; hereafter, each White Paper is labeled as **WP** and a number, corresponding to the list in **Appendix 1**). Subduction zones are particularly important natural laboratories for studying these processes in part because subduction zones have a distinct plate boundary, measurable chemical inputs, and well-defined changes in temperature and pressure that make it possible to disentangle the factors that contribute to fault motion. Recent observations of subduction zones have shown that faults can fail slowly, in addition to generating great earthquakes. The interplay between creep episodes and earthquakes in absorbing plate motion is most clearly seen in subduction zones where sufficient instrumentation has already been deployed. With sufficient direct measurements of fault movement, we can place the earthquake cycle in its tectonic setting.

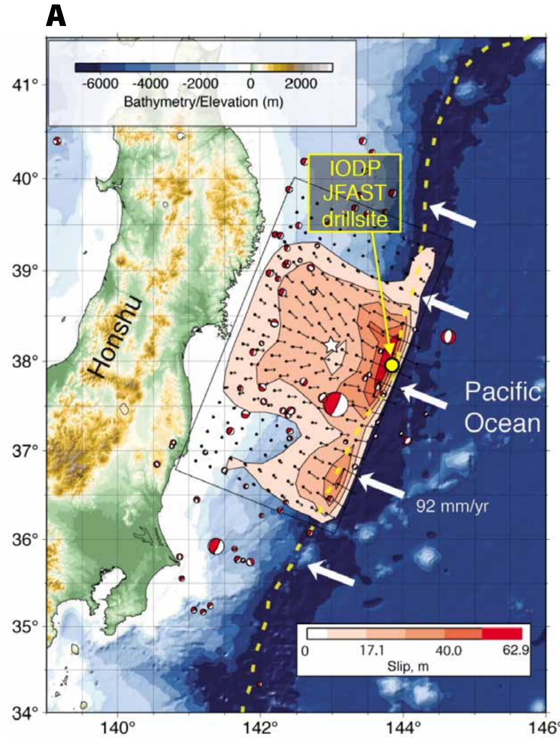
Which subduction zone segments are more likely to produce big earthquakes and what properties govern that likelihood? Both the 2004 9M.2 Indian Ocean and 2011 M9.0 Japan trench tsunami earthquakes produced massive damage in part because they occurred in places where such extreme events were unexpected. Some seismologists hold the view that any subduction zone is capable of producing an M9 earthquake, contrary to the more orthodox view that different subduction zones have different properties that lead to different seismic outcomes. Some creep slowly, some fail in small earthquakes, and still other are capable of catastrophic large earthquakes. Segment boundaries appear to be persistent in some cases, yet at other times ruptures proceed right across apparent segment boundaries, even for the same subduction systems. For example, the Sumatra, Nankai, and Japan Trenches have all exhibited varying amounts of cross-segment rupture in historic repeated events, and the paleoseismic record from Cascadia indicates both regionally limited and full-strike length ruptures. Determining the controls on earthquake size is limited in part by the availability of high-resolution imaging data that would allow us to connect fault structure with the paleo-earthquake histories. Refining and extending our paleoseismic records of past earthquakes as well as capturing future events in high resolution are critical for improving our understanding of the controls on rupture segmentation.

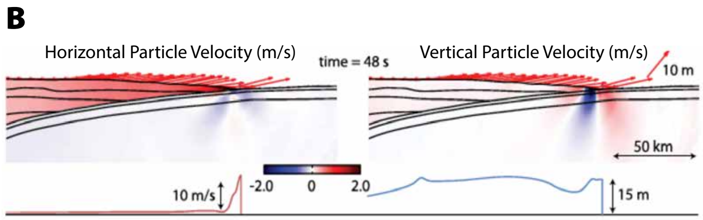
How does stress accumulate over the course of a seismic cycle? Paleoseismic studies have demonstrated that great earthquakes on a particular subduction zone segment are typically separated by time intervals of centuries and are often quasi-periodic (**Box 7.3**). This suggests that the slow and steady accumulation of stress resulting from plate tectonic loading, as observed by modern geodetic networks, plays a dominant role in regulating the timing of large earthquakes. Recent large earthquakes have filled in some previously identified seismic gaps, supporting this renewal model (**Figure 1.5**). How important are finer-scale variations in stress accumulation and release? Slow slip events regularly relieve stress on some parts of the megathrust and load others. Postseismic deformation is often a first-order and time-variable factor in subduction zone stress evolution. Even the locking distribution late in the cycle appears time dependent (**Box 6.2**). Moreover, fault zone drilling data have suggested that major earthquakes relieve all or most of the stress that was accumulated on at least the shallow portion of the fault (**Box 2.1**). We need sufficient observations of fault properties combined with long-term seismic and geodetic data at a suite of subduction zones to piece together a full understanding of the evolution of the stress state over the seismic cycle.

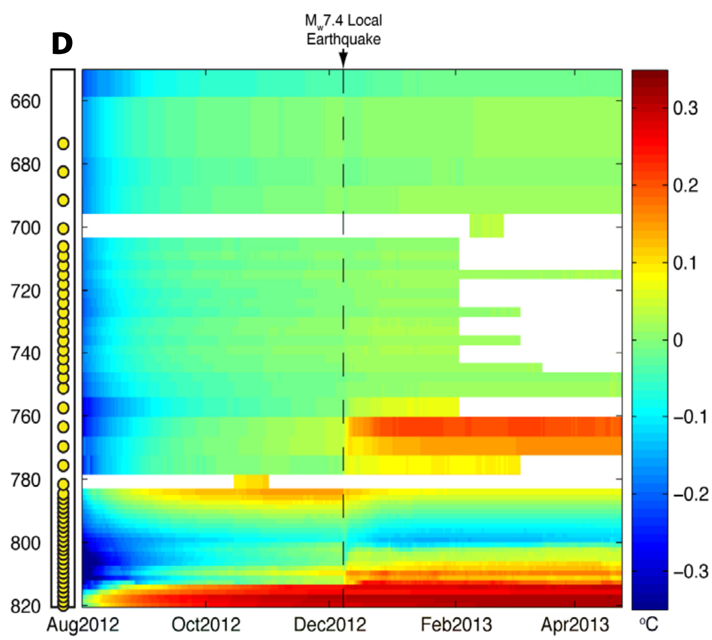
What is the role of slow slip events in relieving tectonic stress or promoting earthquakes? One of the major advances of Earth science in the twenty-first century was the discovery that slow-motion earthquakes can take place over weeks or months in subduction zones. The slow slip can be accompanied by a flurry of small earthquakes or tremor (**Figures 2.1 and 2.2**). These transient motions complicate our understanding of the earthquake cycle (**Box 2.2**, **WP29**). It seems that a fraction of plate motion is accommodated at times and in places by these nondestructive events. Slow slip can also load adjacent locked sections, potentially triggering

Box 2.1. Investigations of the Tōhoku 2011 Earthquake

Very large amounts of shallow slip were detected during the 2011 M9.0 Tōhoku earthquake and have been the subject of intensive investigation. (A) Inversions of seismic slip (Lay et al., 2011, shown, and many others) suggest megathrust slip exceeded 50 m and ran to very shallow portions of the fault, perhaps to the trench. (B) Dynamic rupture simulations (example from Kozdon and Dunham, 2013) showed that this can occur even in velocity-strengthening fault materials for such large slip events. The International Ocean Discovery Program Japan Trench Fast Earthquake Drilling Project investigated the physical properties of the fault zone itself, located in cores (C; photo credit: Jim Mori) through geological and laboratory study of the fault materials (Chester et al., 2013; Ujiie et al., 2013) and downhole observations of a residual temperature anomaly (D) created by frictional heating during the earthquake (Fulton et al., 2013). Panel D depicts the array of temperature sensors (yellow circles on left side) and the time series they measured, showing initial recovery of drilling thermal disturbance and the high-T anomaly at ~820 m depth along the fault.







larger earthquakes. We need to understand under what circumstances each of these scenarios can occur and which scenario is more likely in key regions (**Box 2.1**, **Figure 2.2**). Long-term measurements of fault slip from the seafloor have the best chance of resolving the activity on the fault, and need to be coupled with new laboratory measurements and detailed observations of exhumed fault rocks to develop an integrative model.

What causes foreshocks, and do they indicate a preparatory process for large earthquakes? It is now clear that migrating foreshock sequences precede some major earthquakes, but these sequences are difficult to distinguish in real time from normal earthquake behavior. The 2011 M9 Tōhoku and 2014 M8.3 Iquique earthquakes were both preceded by similar increased rates of earthquakes that migrated toward the eventual mainshock hypocenter in the weeks prior to the mainshocks (see **Box 4.1**). Models suggest that foreshocks might be generated through either a cascade of triggering or gradual creep on the fault. The different models have strong implications for predictability. If the cascade model is correct, the predictive value of foreshocks is limited, but if the creep model is correct, foreshocks may be diagnostic of a distinct, preparatory process prior to large earthquakes. In situ, continuous observations prior to magnitude 8 earthquakes would be required to resolve whether creep and foreshocks are diagnostic of an impending event.

Under what physical conditions will rapid slip during an earthquake displace the seafloor and increase the likelihood of generating a significant tsunami? The large amount of shallow slip that occurred during the 2011 Tōhoku earthquake was unexpected, and new networks in New Zealand (**Figure 2.2**) and Japan (**Box 2.1**) are showing a rich set of phenomena that focus interest shallower than the conventionally defined seismogenic zone, where the megathrust reaches the trench. Locking, fault geometry, splay faults, material properties, dynamic stress concentrations, seafloor roughness, and rupture history may all affect fault behavior in this shallow region, and some of these conditions are detectable or mappable in advance (**WP28**). Moreover, many are key ingredients in rupture dynamics models that predict enhanced tsunami generation from shallow ruptures. Illuminating the behavior of the shallow, updip region of the subduction plate boundary fault system is currently limited by a lack of appropriate structural images and long-term seafloor instrumentation required to understand the time evolution and slip history of this region for most of the world's subduction zones. The shallow fault system is a particularly strategic target because it is not only the most accessible to drilling, direct sampling, in situ instrumentation, and high-resolution imaging, but it is also the most critical region for understanding the generation of tsunamis.

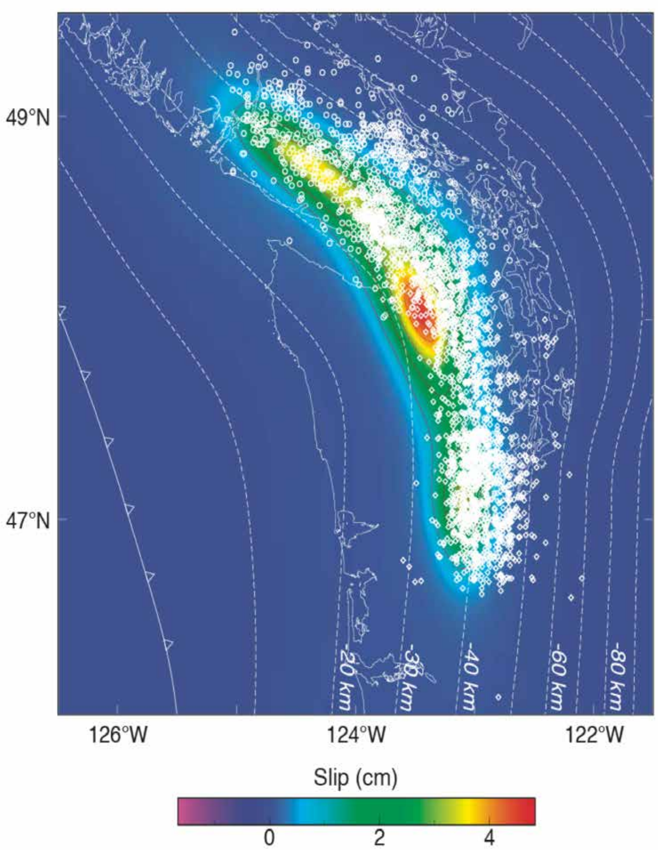


FIGURE 2.1. Spontaneous (deep, M6–7) aseismic slip transients and telltale seismic tremor. The plate-interface slipped slowly (displacements colored) over several weeks in 2008, evident in GPS and strainmeter signals. This slow slip was accompanied by rapid slip on tiny patches (white diamonds) that radiate seismic waves, observed on seismograms as low-amplitude tremor signals. *Credit: Gomberg et al. (2010)*

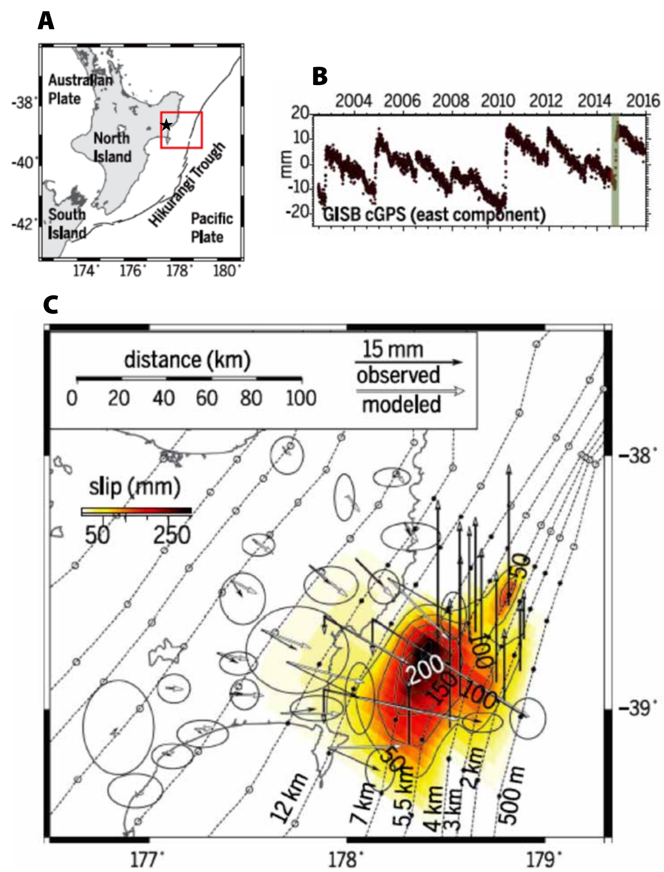


FIGURE 2.2. Shallow, episodic slow slip transients at the Hikurangi subduction zone extend all the way to the trench, as detected on a combined onshore and offshore geodetic network (Wallace et al., 2016). (A) Location of the northern Hikurangi margin and network, including station GISB (star). (B) Time series of example continuous GPS easting component from GISB showing background westward strain punctuated by several SSE events, including a September to October 2014 event marked with green bar. (C) Inversion of all onshore-offshore data for the September to October 2014 event, with colors and contours showing displacement in millimeters, with equivalent magnitude $M_w = 6.8$. Uplift of near trench sites indicates that the slip continues to the shallowest portions of the subduction interface and possibly all the way to the trench itself.

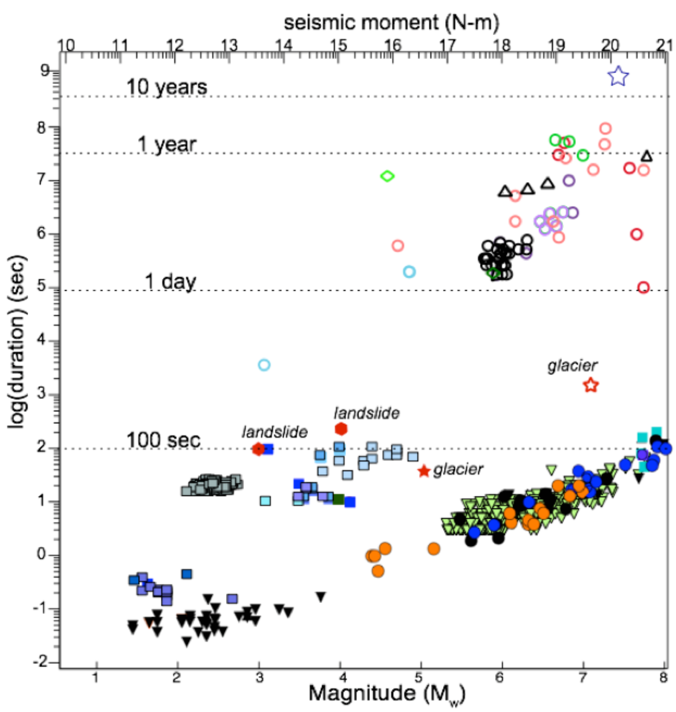
What processes control the downdip transition from earthquake slip to aseismic creep along the subduction megathrust? Knowledge of the downdip depth limit of unstable slip is very important because this transition controls the landward extent of destructive ground shaking. In addition, most episodic tremor and slip occurs near this rheological transition; there are competing hypotheses to explain this phenomenon. To what extent do different rock types (e.g., serpentine, and clay-rich, siliciclastic, or carbonate lithologies), different fluid transport processes, and different deformation processes affect this transition? How does this transition evolve during the earthquake cycle? Specific challenges that have limited our understanding of this plate boundary region include acquisition of laboratory measurements of the complex rheology of the relevant rock type at appropriate pressures, temperatures, and strain rates, and development of constitutive models that transcend traditional domains of "brittle" (earthquake generating) and "ductile" (smoothly sliding or flowing) deformation.

What governs the occurrence, scale, and seafloor displacement of earthquakes in a subduction zone away from the plate boundary? Devastating earthquakes >M8 in Japan (Sanriku 1933) and Samoa (2009) have also occurred seaward of the trench in normal faults that form as a result of bending of the downgoing plate. Little is known about the conditions that lead to the frequency and slip of bend faulting, and the relationships to plate geometry, convergence rate, age, temperature, and hydration state of the incoming plate. Capturing the full sequence of events that leads to the events, combined with modeling approaches, will stimulate progress.

Box 2.2. Sampling the Complete Slip Spectrum

The observations we make fundamentally determine the scope of our understanding. They allow us to tune and test models, but also motivate hypotheses about what underlying physical processes might be relevant. Thus, it is essential to fully understand what we can and cannot yet observe. The evolution in our understanding of how faults slip provides a vivid example. As geodetic observations have grown in number and quality, so has the recognition that significant fractions of slip on faults occur aseismically, rather than the previous paradigm in which almost all faults were thought to be perfectly stuck until they slipped seismically. We have now sampled a sufficient variety of slip modes to begin to see patterns emerge, and to make inferences about how slip characteristics scale with size, what environmental conditions may be controlling, and how they vary temporally and spatially. This applies not only to faults but also to interfaces bounding and within landslides and glaciers, and at the microscale in laboratory samples of geologic materials.

Subduction zone plate interfaces appear to exhibit all modes of slip in an abundance not found in other environments, making them ideal locations for sampling the complete spectrum of slip. However, a major gap remains in relevant observations from the offshore regions. For example, the major slipping surfaces offshore separate thick accretionary prism sediments from oceanic crustal rocks, a setting with little observational, theoretical, or laboratory information to draw upon. Fortunately, new relevant measurement technologies and techniques (for submarine faults and landslides) are being developed, at least for temporal and spatial scales equivalent to those on shore. Development and deployment of new instrumentation for continuous and sustained seafloor network-style seismic and geodetic monitoring will fill in temporal gaps. Additionally, just as differential imaging (e.g., with InSAR, LiDAR) has proven very powerful to achieve spatial-scale sampling over previously inaccessible regions and resolution onshore, repeat high-resolution bathymetric imaging should be considered offshore. Finally, to fill in gaps at very long time scales, greater investment needs to be made in geologic studies that sample multiple fault slip event cycles, at many more locations, and in continued development of precision dating methods and laboratories.



Published estimates of transient slip event durations versus sizes. Empirical relationships between duration and size have been interpreted in terms of various source physics, but measurement limitations also affect the apparent relationships. The absence of measurements in the lower right corner reflects true physical limits, but demonstrable observational limitations explain the absence in upper left corner and the gap between durations of ~100 seconds to 1 day. However, the reason for other gaps remains uncertain. All measurements are for faults except for those labeled, and come from many different locations globally. Colors (other than blue and gray) correspond to different studies, and solid and open symbols denote seismic and geodetic measurements, respectively, except for the star at the top that was derived from uplifted corals. Different symbol types indicate types of slip events; geodetically measured events include spontaneous slow slip, afterslip, and preslip. *Figure courtesy of J. Gomberg*

2.2 How is Mantle Magma Production Connected Through the Crust to Volcanoes?

Recent seismic and magnetotelluric imaging studies have identified regions of melt and fluid in the mantle wedge that underlie subduction-generated volcanoes (**Figure 2.3**). At the same time, magma pathways in the crust have been observed "lighting up" with increases in seismic events between, prior to, and during eruptions (see **Figure 3.4**), and some magma storage regions "breathe" geodetically between eruptions (see **Box 4.3**). However, the connections between these two systems—the crustal magmatic plumbing and the mantle melting region—are poorly understood. We currently have no unifying models that allow us to understand the connections among magma generation, storage, transport, and eruption from the hydration of the mantle wedge above the slab to the volcano at the surface. By considering the mantle melting region as a part of the volcanic system, ***SZ4D*** could provide a fundamentally new way to interrogate and develop long-term forecasts of volcanic system behavior**.**

How do magma production and crustal construction vary between arcs, and what parameters control production rate? The Cascade volcanic arc has long been regarded as magmatically feeble, presumably due to slow subduction of a relatively young and hot plate that dehydrates early into shallow mantle that is too cool to melt significantly. However, whether magma production rates are actually lower in the Cascades compared to the Aleutians and Andes is a subject of debate (**WP2**). Accurate estimates of arc-scale production rates require large-scale geophysical constraints on crustal volumes and extensive geologic and geochronologic investigations (**WP9**). To identify the controls on magmatic productivity at arcs, which in turn set the pace of continental growth, we need to explore a range of convergence rates and plate ages, and their control on the locations and flux of fluid that ultimately drive mantle melting (**WP44**). Identifying the factors that control magma productivity in the mantle wedge requires a new generation of geophysical images and models to infer the volume and distribution of melt in it (**Figure 2.3**), coupled with arc-scale mapping of plutonic and volcanic volumes and determination of their ages.

How fast do magmas traverse the uppermost mantle and crust, and what controls the location of storage regions beneath volcanoes? New petrological studies involving crystal clocks have constrained relatively rapid time scales for magma ascent from the mantle to eruption—less than a year for some arc volcanoes (**Box 2.3**). Thus, the rate of magma production from the mantle may be a key variable governing magma ascent vs. stalling, in its control on the thermal structure of the surrounding crust and the buoyancy flux of the magma. Also recognized in the months preceding eruption are deep, long-period seismic events suggestive of fluid transfer at the crust-mantle interface, and magmatic gas emissions high in CO_2 (**Box 2.3**). The location and volume of magma storage regions are beginning to take shape with geophysical imaging (**Figure 2.4**) and are being coupled with complementary geodetic studies to infer inflation regions. However, petrological tools to constrain magma stalling depths are lagging behind and require development of geobarometers. Such petrological and geophysical studies have rarely been performed together, and are necessary to understand the rates and controls on magma delivery, stalling, and storage.

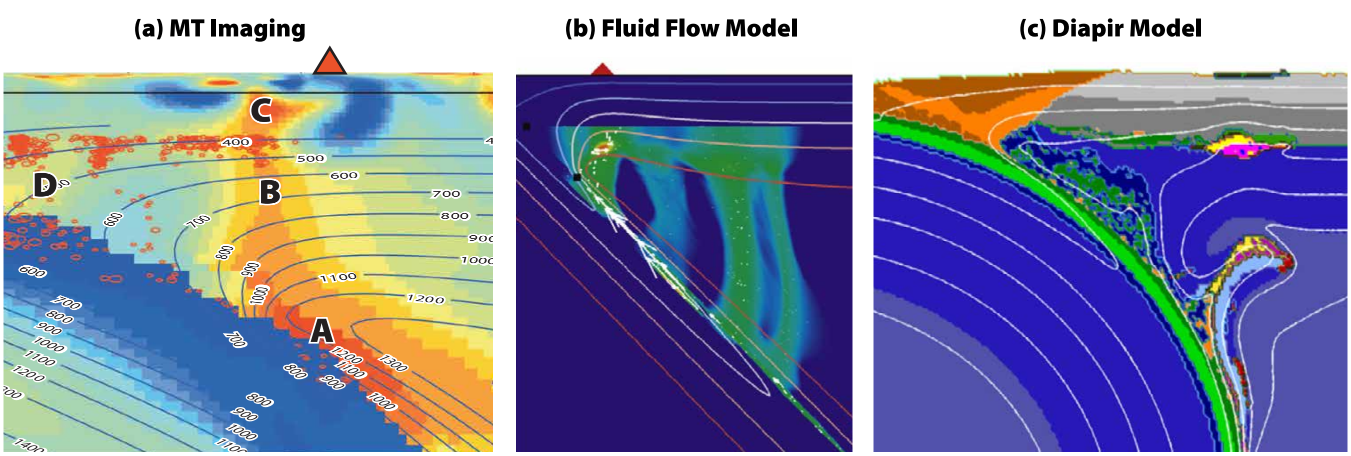


FIGURE 2.3. Probing the melt production region beneath arcs with imaging and models. (a) Image of crustal and mantle melt and fluid pathways (yellow-to-orange) region beneath Mt. Rainier, Washington (red triangle), from a magnetotelluric (MT) study. *From McGary et al. (2014)* (b) Numerical model of fluid flow up the slab, through the mantle wedge and into the upper plate lithosphere (green regions and white arrows). *From Wilson et al. (2014)* (c) Numerical model of "cold plumes" of buoyant material separating from the slab and ascending into the mantle beneath arcs. *From Vogt et al. (2013)*

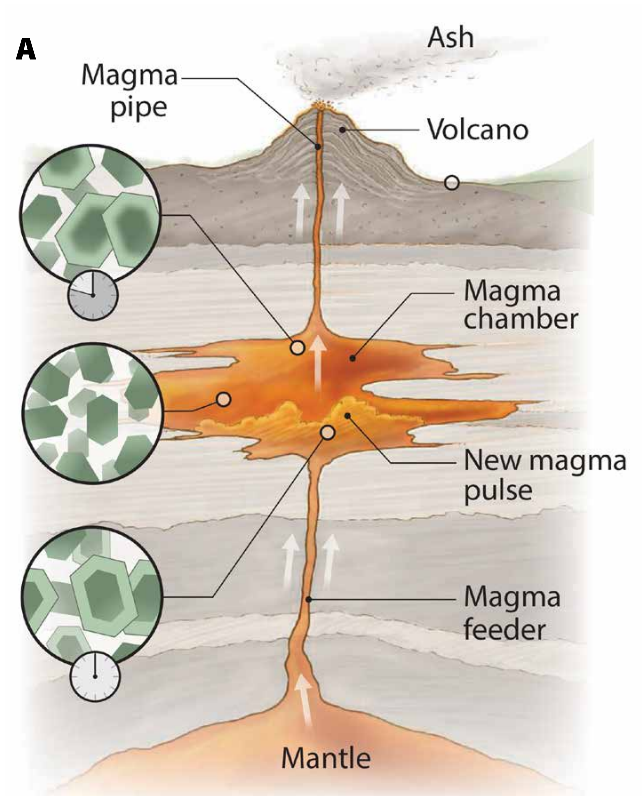
What are the physical processes that drive pre-eruptive phenomena and which events are eruptive precursors? Volcanoes display a range of pre-eruptive phenomena, including changes in seismicity, gas composition, and surface displacement. The time elapsed between the onset of unrest, as interpreted from these observables, and the eruption is called the run-up time, which varies from days to years (**Figure 2.5**). Recent studies have shown how crystals may record similar time scales of magma mixing prior to eruption, potentially linking pre-eruptive events directly to magma recharge (**Box 2.3**). These kinds of observations have led to the hypothesis that eruptions can be triggered by injection of basaltic magma, which provides both the heat to thaw existing mush bodies and the volatiles to fuel eruptive ascent. Alternatively, crystallization can increase the volatile concentration within the melt phase, potentially leading to increasing

Box 2.3. The Timing of Magma Recharge Prior to Eruption

Observations from seismology, gas chemistry, and petrology are providing complementary views of the events leading up to eruption

Crystals record in their chemical zonation profiles time scales of magmatic events prior to eruption. These "crystal clocks" are providing new views of the magmatic system, from the mantle through the crust to the volcano, and the timing of magma movement and mixing. (A) The cartoon shows how a new magma pulse can create chemical zonation in crystals (shown as color), and the smearing of these initially sharp zones reflects the duration of time between the new pulse and the eruption. (B) An X-ray map of Mg concentration in an olivine from Etna Volcano, Italy, showing an Mg-rich zone (red) on the rim, reflecting a new pulse of hotter (higher Mg) magma. (C) Ni zonation in a primitive olivine from Irazu Volcano, Costa Rica. The preservation of Ni gradients (red dots) requires rapid transport from the mantle to the eruption, on the order of months to a year, to prevent diffusive homogenization.

Figure D shows combined data sets that sense magma recharge in the run-up to eruption. One month prior to the June 2006 eruption at Mt. Etna, an increase in CO_2/SO_2 heralds magma movement at depth while crystal clocks (as above) recorded intrusive events. At the same time, seismic events were recorded in the mid-upper crust (6–15 km depth). Such combined data sets, including ground deformation, ambient noise tomography, and stress field studies, exist for few eruptive events, but could be a component of ***SZ4D*** that leads to a new understanding of the physical processes that underlie phenomena precursory to volcanic eruptions.



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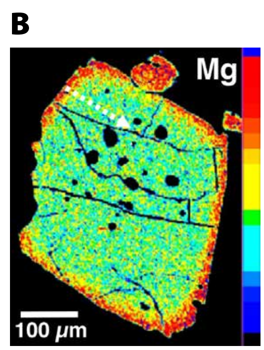
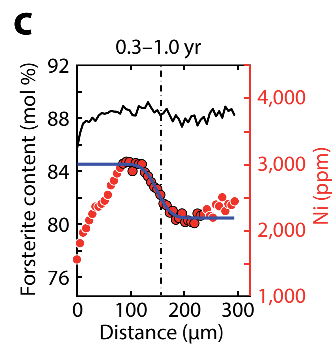


Kahl et al. (2011)



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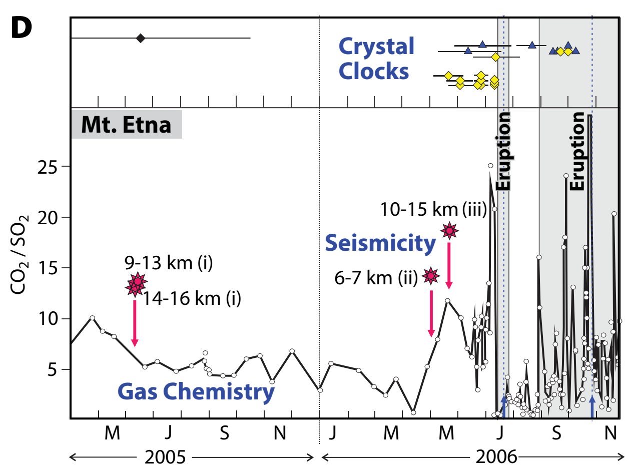

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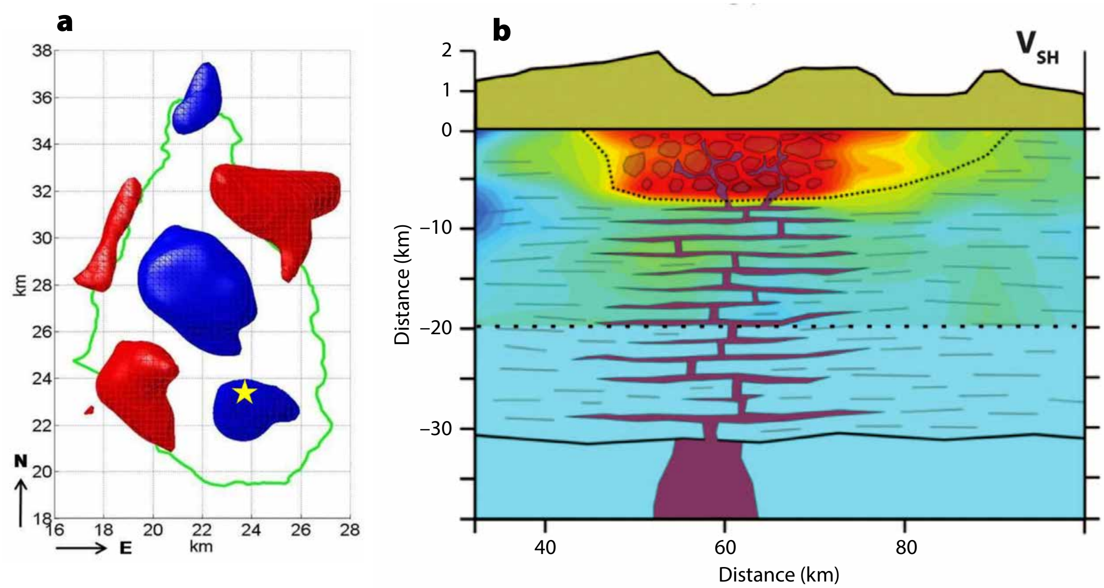


FIGURE 2.4. Tomographic images of volcanic plumbing systems. (a) Results from the SEA-CALIPSO offshore/onshore active source tomographic experiment centered on Soufrière Hills Volcano, Montserrat, which erupted from 1995 to 2010. The green line outlines Montserrat, with the Soufrière Hills vent marked by the yellow star. The blue and red blobs represent three-dimensional isosurfaces of velocity anomalies. The blue surfaces define anomalies that are >6% faster than average. The red surfaces represent anomalies that are >6% slower than average. The blobs are located between 1 km and 4 km below sea level. Note that Soufrière Hills Volcano is underlain by an abnormally fast region, which likely represents dense, crystallized rock formed by solidified dikes, sills, and other intrusions. *Figure is after Shalev et al. (2010)* (b) Schematic interpretation of velocity structure beneath the Toba caldera, Indonesia, superimposed on the distribution of the shear wave velocity (V_{SH}) (shown only above 20 km depth) obtained from ambient noise seismic tomography. Directly below the caldera (red region outlined by dotted line) is a low-velocity area that might have been affected by a Volcanic Explosivity Index 8 super-eruption ~74,000 years ago. In contrast, the anisotropy below 7 km in depth appears to be due to a layered magmatic intrusion dominated by horizontally oriented sills. *From Jaxybulatov et al. (2014)*,

volatile pressure and eruption ("second boiling"). This process may explain the lack of magma recharge events prior to other eruptions. Other models involve a vertically extensive mush system that compacts, segregates, exsolves vapor, and pressurizes chambers with no new magma flux. Discriminating between these models, and thus recognizing the immediate triggers to eruption, requires a new effort to tightly couple measurement and interpretation of deformation, seismic, gas, and petrological signals at volcano observatories (see **Boxes 4.3 and 7.1**, **WP57**).

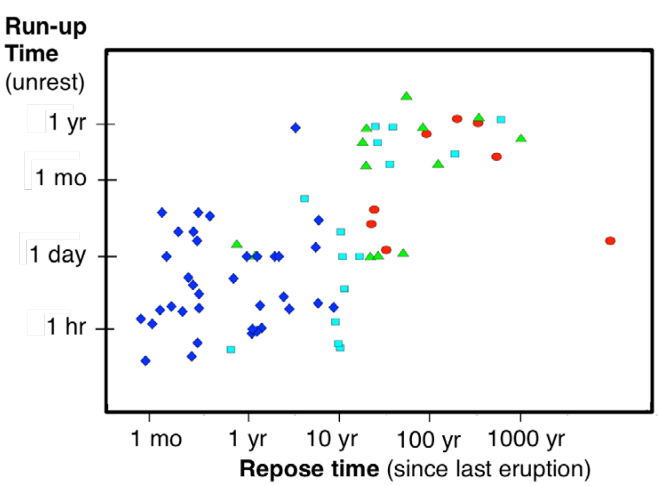


FIGURE 2.5. Duration of run-up vs. repose for instrumented volcanic eruptions (from Passarelli and Brodsky, 2012). Why is the run-up to different eruptions days vs years? Colors reflect low silica (blue, basalts) to high silica (red, dacites) content, which relates to viscosity. Other physical parameters have yet to be explored, however, and neither gas nor petrological data have been included to constrain the origin of the unrest. This is an opportunity linking ***SZ4D*** science and hazards.

Can eruption forecasts be guided by in-depth understanding of the physical and chemical processes occurring beneath volcanoes, akin to state-of-the-art weather forecasts? Although presently most eruptions at well-monitored volcanoes can be forecast based on a variety of geophysical and geochemical precursors, these forecasts are empirical and based on patterns recognized during previous eruptive episodes. Such an approach is limited by poorly documented eruptive histories, as the same volcano may cycle between different eruptive behaviors and intensity on time scales of decades to millennia. The longer-term goal is to move past forecasts based on past behavior, and develop ones based on near-real-time measurements and physical models (**Box 7.7**), as for weather forecasting. ***SZ4D*** can provide a framework within which to develop such models for well-instrumented volcanoes along arc segments that capture transitions in driving parameters such as convergence rate, crustal structure, slab depth, and/or upper plate stress regimes.

2.3 How do Spatial Variations in Subduction Inputs Affect Seismicity and Magmatism?

Sediments, oceanic crust, and mantle lithosphere descend into the subduction zone, carrying water and carbon within them (**Box 2.4**). The composition and strength of the input material are likely to profoundly affect seismic and volcanic behavior, but we are faced with challenges in quantifying these effects. Different models relate the sliding behavior of subduction faults to the type of subducting sediment on the one hand, and to pore fluid pressure on the other. Water- and carbon-rich fluids released from the input material weaken faults and drive melting, but few relationships have been found thus far that

Box 2.4. Extent of Hydration of the Incoming Plate

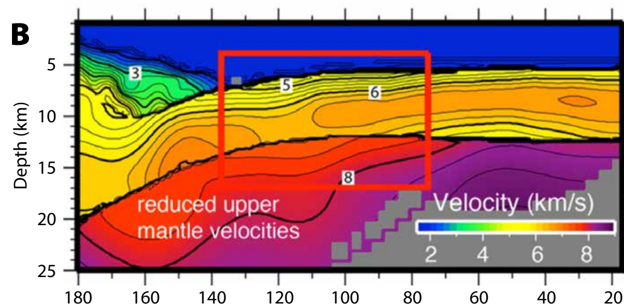
To what extent is the incoming plate hydrated, and how does water supply affect slip, earthquakes, slab dehydration, melting, and volcanism?

The incoming plate fractures as its bends into the trench, and such faults are pathways for water to hydrate the plate just prior to subduction. Such hydration was first recognized in seismic images, and a new active source electromagnetic survey finds low resistivity hydration channels that doubles previous estimates for water bound in the incoming oceanic crust (A). Seismic refraction is also finding evidence for hydration deep into the mantle section of the incoming plate (at subseafloor depths >5 km), seen as reduced seismic velocities as the plate approaches the trench (B).

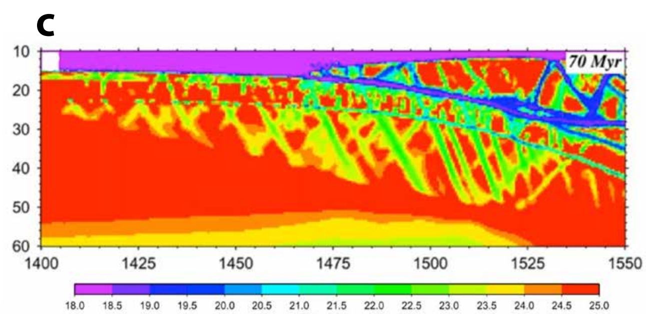
It is still unclear how much hydration accompanies plate bending, and how this varies for different subduction zones. In some regions like the eastern Aleutians, a thick sediment cover appears to shut down deep plate hydration, as does trench-normal abyssal hill topography (Shillington et al., 2015). Numerical models illustrate the importance of plate age, velocity, interface coupling, and slab pull on the depth and extent of incoming plate faulting and hydration (illustrated in the viscosity structure of a model 70 million year old plate; C).

The hydration flux associated with plate bending is a major source of water to the subduction zone, potentially dwarfing all other sources (sediments, pore fluids, oceanic crust altered at the mid-ocean ridge). It is unclear where this water is released, and its potential effect on slip, intermediate depth earthquakes, melting, magma composition, and eruption. If this water is not returned to Earth's surface, water should be accumulating in the mantle transition zone, and the entire ocean would disappear down the subduction zone in one or two billion years.

Material properties, mineralogy, and textures of hydrated rocks are key to interpreting seismic and electromagnetic images of hydrated input. The photo (D) shows the microscopic network of serpentine, brucite, and magnetite that forms during hydration of olivine. Tracking the extent of hydration of the incoming plate and its subsequent dehydration is central to processes occurring across the subduction zone and over Earth history.



Shillington et al. (2015)



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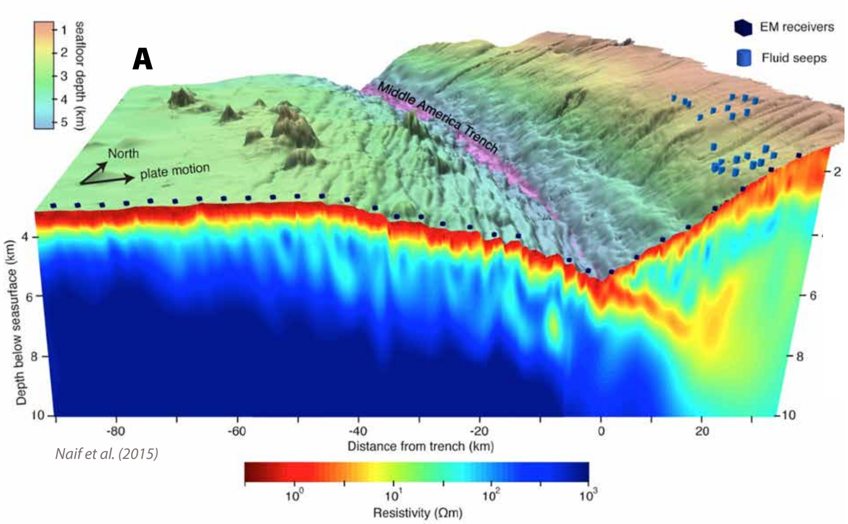

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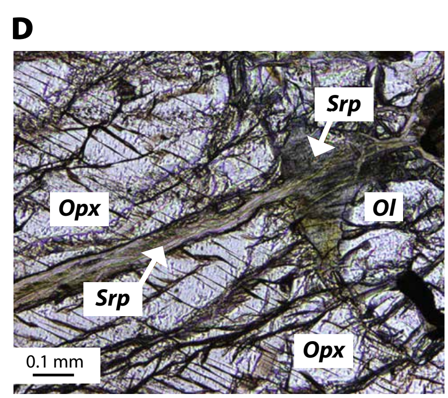


Schwarzenbach et al. (2016)

relate different water and carbon inputs to fault behavior. Existing weak layers within the incoming oceanic plate may influence the ratio of accreted to subducted material, thus affecting the topographic response of the forearc. One fruitful approach to exploring the effects of inputs involves making observations in regions where spatial variations in subduction inputs exist, such as changes in seafloor fabric and/or sediment thickness, as observed along the Alaska-Aleutian and Central American subduction systems.

How does the extent of hydration of the incoming plate vary laterally? One discovery of the past decade has come from seismic and electromagnetic imaging of the incoming plate, which have found evidence for hydration of the lower crust and mantle section due to fracturing as the plate bends into the trench (**Box 2.4**). This water flux may dwarf the other sources of water in the incoming sediments and oceanic crust. It is unclear, however, what subduction parameters control the depth extent and magnitude of plate hydration. Recent work along the Alaska-Aleutian margin finds a greater degree of plate hydration in a region where the incoming seafloor hosts a thin sediment cover and develops trench-normal faulting. This region appears to be spatially associated with a seismic gap. These regions appear to be spatially associated with megathrust events and volcanism. Is this true elsewhere? Along-strike studies of the incoming plate that target regions with transitions in the sediment cover and seafloor fabric are an efficient way to prospect for variations in plate hydration.

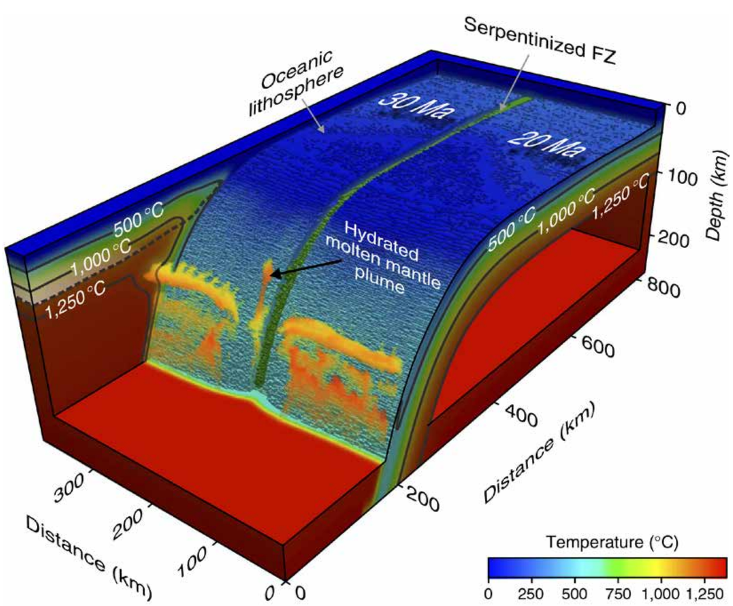


FIGURE 2.6. This numerical experiment incorporates the effects of along-margin variation in slab age and subduction of a partially serpentinized fracture zone (green strip) in the middle of the subducting plate. Color indicates the distributions of temperature; partially molten mantle above the slab is colored according to the temperature. The dashed line represents the base of the continental lithosphere. *From Manea et al. (2014)*

Arc-system-wide studies are necessary to track the potential downstream effects of plate hydration on seismicity, fluid generation, plate strength, mantle melting, magma composition, and eruptive style (**WP5**, **WP21**).

How do lithological and geological features in the subducting input affect seismicity and volcanism? Rapid-response drilling during the Japan Trench Fast Drilling Project (JFAST) provided evidence that the fault that slipped during the 2011 Tōhoku earthquake may have occupied a <1 m layer of particularly weak brown clay (see **Box 2.1**). At the other end of the length-scale spectrum, regions along Alaska, Central and South America, and Hikurangi margins are colliding with igneous plateaus and/or ridges 100–1000 km in width. Fracture zones may provide loci for greater fluxes of sediment or extents of hydration that could lead to local melting anomalies and arc magmas enriched in certain chemical tracers (**Figure 2.6**). Drilling and imaging are necessary to define the different material properties, fluid contents, and mechanical obstacles presented by incoming features.

How do subduction inputs affect subduction zone thermal structure and volatile budgets? Subduction parameters such as slab age and subduction rate control advective heat transfer and thus slab thermal structure. Many subduction parameters and slab geometries have been determined through geophysical observations and are used to construct thermo-petrologic models that have been successful in mapping specific mineral reactions to zones of intermediate depth seismicity (**Figure 2.7**). However, there remain large uncertainties in the thermal structure and depths of volatile release due to the effects of frictional heating along the plate interface, fluid and material transport within the slab and along the plate interface, and slab-mantle viscous coupling that induces mantle wedge flow. Some studies have hypothesized a possible link between intraslab earthquakes and rehydration reactions driven by migrating slab-derived fluids. Indeed, recent models that incorporate more realistic dynamics and physical properties, such as mantle matrix compaction and grain size variation, show both updip fluid flow along the plate interface and focusing of fluids beneath the volcanic arc (**Figure 2.3**, **WP48**). However, these studies are primarily in two dimensions. A frontier area is the development of dynamical, thermochemical numerical models in four dimensions, over time scales from arc-plate evolution (tens of millions of years) to seismic cycle time scales (tens to thousands of years). Rocks that are exhumed from paleosubduction zones can provide material to better constrain models for dehydration reactions,

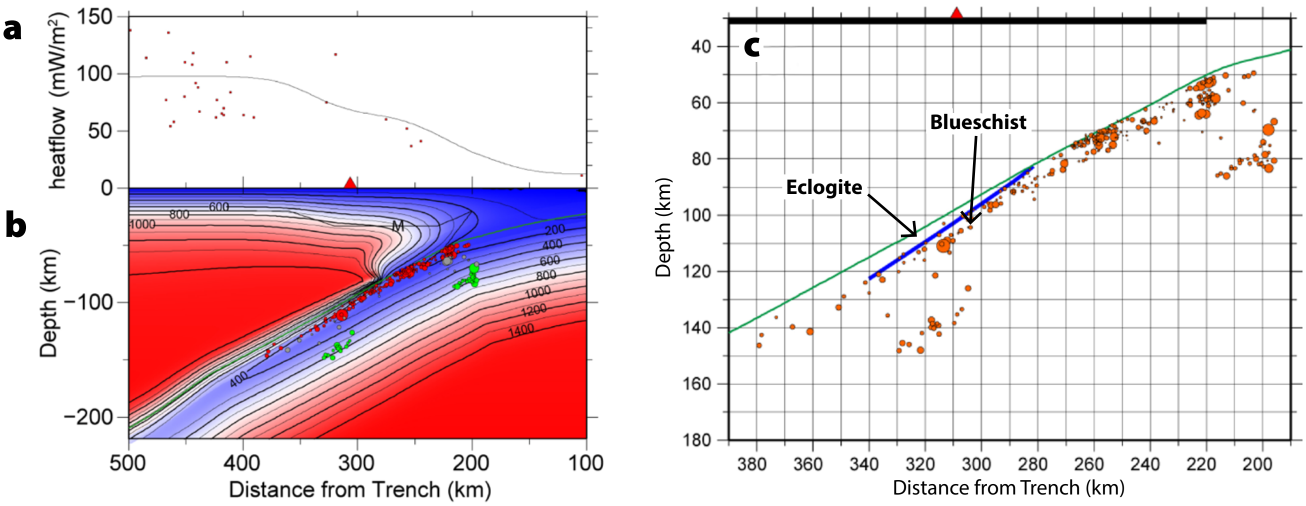


FIGURE 2.7. Two-dimensional thermal modeling results for northern Tōhoku, Northeast Japan. (a) Surface heat flow data (red circles) and model-predicted surface heat flow (black line). (b) Calculated thermal structure overlain by intraslab seismicity (red and green circles for the upper and lower planes, respectively, of the double Wadati-Benioff zone). (c) Location of the blueschist-eclogite transition (blue line) in the subducting crust calculated from the thermal model shown in (b) overlain by intraslab seismicity (orange circles), which occurs in the subducting slab that has not undergone blueschist-eclogite transition. Green lines in (b) and (c) indicate the slab surface. *From van Keken et al. (2012)*

fluid migration, faulting, and melting (**WP45**, **WP47**, **WP62**). High-resolution seismic and electromagnetic imaging in three dimensions are also required to constrain the thermo-petrologic structures and fluid distributions in subduction zones. The sum of chemical reactions and fluid migration during subduction fundamentally controls the balance of H_2O and CO_2 between Earth's surface and interior, which is currently uncertain to the degree that we do not know if our planet is net ingassing or outgassing CO_2 with respect to H_2O.

2.4 How do Surface Processes Link to Subduction?

The surface expression of subduction zones and the associated uplifted topography are where people live, and are also the sites of some of Earth's greatest natural hazards. The topography reflects a dynamic adjustment between uplift and surface erosion. It provides a natural observational constraint on subduction dynamics at time scales of thousands to millions of years. Sediment fluxes to the subduction zone may be linked with climatic variations, magmatic flux, seismic magnitude, patterns of deformation, and particle exhumation path and timing (**WP55**). How is convergent margin physiography developed and maintained in space and time? The field of quantitative landscape characterization and modeling is advancing rapidly and provides an opportunity to address basic questions about the subduction system with new tools and viewpoints.

What are the relative roles of mass transfer, crustal deformation, and mantle dynamics in modifying topography? Decades after plate tectonics has been accepted, we still do not understand the processes and timing associated with the creation of topography above subduction zones. Most models for mountain building accept plate convergence and dip as the drivers of crustal shortening and thickening. However, to what extent are there feedbacks between crustal thickening and driving forces in the mantle? Massive crustal thickening requires forces that may only be possible once whole-mantle convection is established. The time required for mountain belts to form above subduction zones is an active area of research. Does it relate simply to the age of the subducting slab, or to the time it takes the slab to sink through the entire mantle (**Figure 2.8**)? Does the topography represent accretion and dynamic forces in the mantle at play—or is there external forcing that affects the mass flux and the creation of topography? How is this mass flux budget modulated by rock strength, climate, weathering, and tectonic uplift?

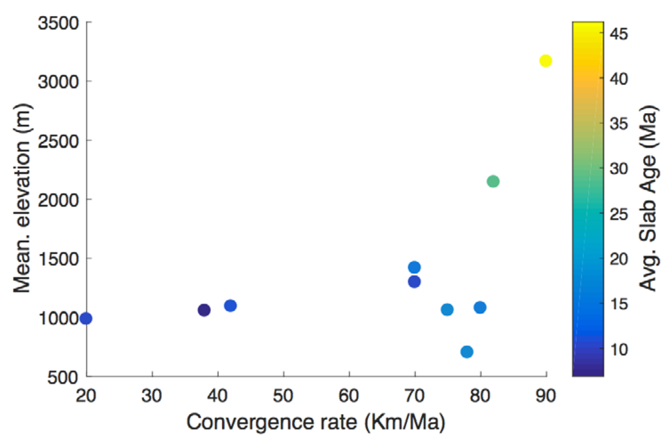


FIGURE 2.8. Correlations between mean elevation of the topography above the subduction zones along the western margin of North and South America and the observed convergence rate and slab age point to potential subduction mechanisms for drivers of topographic change. *Figure from Val et al. (in prep); data from Schellart (2008) and Clift et al. (2009)*

How does bedrock strength influence mass flux? Erosional gradients from rock strength along and across a mountain belt modify the topography and may even affect the mass balance and crustal thickness. Fracture density, rock uplift rates, exhumation rates, landslide frequency, precipitation patterns, glacial erosion, and temporal denudation records have been established as important metrics in understanding mass loss via erosional processes. Do the along- and across-strike patterns of erosion correlate with fracture density, bedrock strength, and sediment caliper? If bedrock strength controls the median sediment caliper, which in turn can govern river incision, is there a positive feedback between tectonics and itself, forming a self-sustaining process that is only weakly modified by glacial processes or precipitation rate? Given the currently available data, these questions cannot be addressed unless supplemented with along- and across-strike data sets of denudation (on one hundred to million year time scales), complementary fracture density and grain-size data, pressure-temperature (time-depth) paths of key lithologies that now outcrop along-strike, and analysis of modern geodetic data sets.

How do subsurface hydrology and basal rheology interact to govern landslide failure? Subduction zones are particularly prone to landslides because of the interplay between earthquakes, volcanoes, submarine conditions, and climatic events. The key question is how to assess slope strength and subsurface hydrology at the outcrop scale to understand landslide susceptibility at a particular site. Observatories that combine borehole measurements with various surface-based imaging techniques would facilitate both the modeling of landslide physics and the understanding of how to survey potential sites for hazard estimation. Particularly important is understanding the role transient stress fields that result from earthquakes and other sources such as rainfall play in landslide initiation. While local studies focused on particular sites will provide more insight into basic processes, a significant challenge exists in scaling up. To improve landslide assessment at a regional scale, we need open databases of landslides triggered by earthquakes and rainfall events, detailed slope maps from LiDAR (land) and sonar (seafloor), and the development of methods to identify slope strength characteristics at these scales.

In what way does the interplay between subduction and climate control topography and erosion of the orogenic wedge? The crustal geometry underneath a mountain range is commonly depicted as a double-sided wedge, or a sideways diamond (i.e., the orogenic wedge). The width of this wedge, from the boundary of the collision zone on one side to the edge of the deformational zone on the other side, with the ridgeline positioned in between, can vary as a function of these mass trade-offs (**Figure 2.9**). In fact, modeled strain partitioning in the orogen and P-T paths of particles moving through the wedge and orogen are critically dependent on the mass flux from both sides of the range. Depending on how fast mass is added by compressive forces due to subduction and how fast mass is removed at the surface due to erosion, the wedge is thought to widen or narrow, respectively. Erosion may vary through time, and the amount of time between uplift and erosion could be millions of years (see **Box 4.2**). Because mountain ranges can grow tall enough to block atmospheric circulation, the windward side of the mountains focus precipitation while the leeward side is situated in a quasi-rain shadow. One end-member scenario predicts that the windward sides of mountain ranges

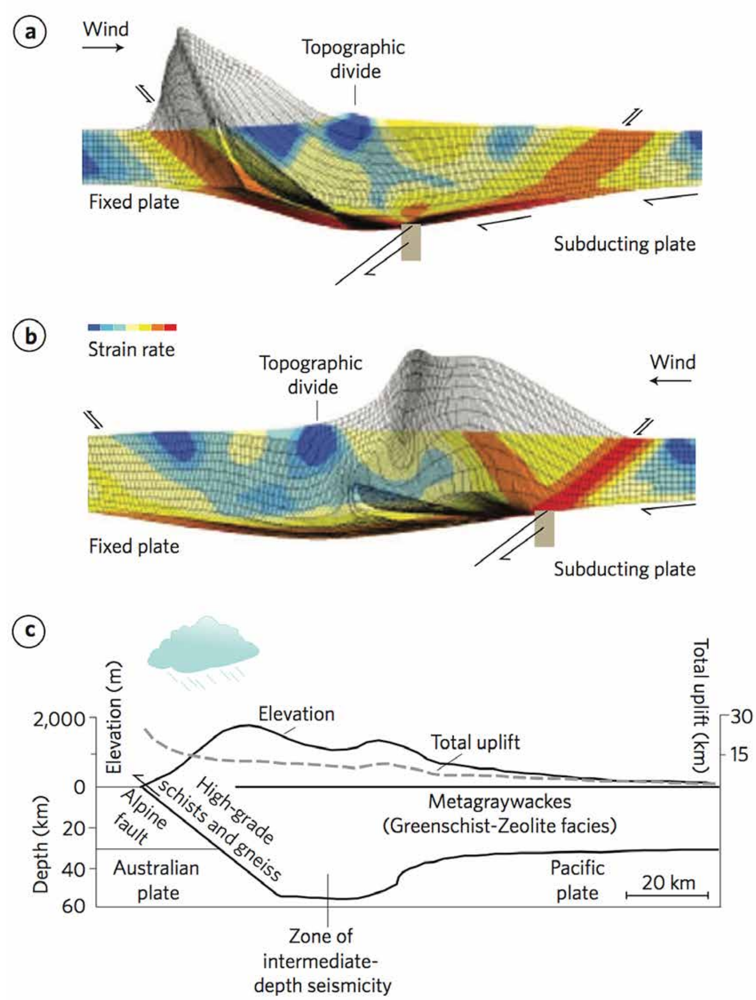


FIGURE 2.9. Moisture flux and mountain-belt evolution. (a,b) Results of numerical models aimed at understanding the exhumational and structural response of mountain belts to unidirectional moisture flux. Tectonic convergence velocity and subduction direction in the models match conditions for the Southern Alps of New Zealand. (c) Observed Southern Alps topography. *From Whipple (2009)*

undergo a disproportional amount of erosion compared to the leeward side, which causes the formation of an asymmetrical orogenic wedge and increased material influx into the subduction zone. However, these correlations are not straightforward due to climate oscillations like glacial-interglacial cycles through the last two million years and an incomplete understanding of how increased precipitation rates affect erosion rates. Enhanced erosion in the last two million years may have strongly influenced the patterns and magnitudes of erosion for different surface processes, such as fluvial and glacial erosion. Taking this approach and measuring rates on both sides of the ranges will allow tests of these predictions. Are glacier equilibrium line altitudes and the thermal regime of the glacier bed controlling the maximum heights of the peaks or is there a tectonic cause?

Do subducted sediment and arc magmatic fluxes affect the height of mountain ranges? The history of the topography may also play a role in the creation of relief and setting of the maximum elevations on mountain peaks. One hypothesis is that the internal waxing and waning of dense crustal roots affects the elevation of the subduction-related topography. The oscillatory model of topography (**Figure 2.10**) includes arc magma flux and isotopic composition covarying with surface elevation in the subduction zones. If surface elevation and slope are related to erosion, and sediment delivery to the subduction zone is coupled with magmatic production, then is the time scale of geomorphic adjustment to a new slope or mountain height setting the pace of lithospheric compositional evolution? Or, is the causality reversed? Does the sediment delivered to the trench affect subduction itself and the magmatic flux (see **Box 4.2**)? Assessing these questions requires geomorphic and paleoseismic data sets on deformation processes occurring on intermediate (10^3–10^5 yr) time scales. A systems-level approach is necessary for understanding the dynamic linkages described here.

How is permanent strain in the forearc accommodated, and does it influence the earthquake cycle? Many subduction zones partition plate motion into a trench-normal component accommodated via shortening of the overriding plate and an along-strike component accompanied by strike-slip faults in the forearc crust. The rotation of the Pacific Northwest (**Figure 5.1**) and the Great Sumatran Fault (**Box 6.3**) are classic examples of the variety of ways this strain is accommodated. These structures create considerable seismic hazard owing to their proximity to population centers. To understand the role of these structures in the geodynamics of subduction zones, we need to move from site-specific studies to quantifying the 4D mass flux in the entire forearc. How do the pre-existing geologic terranes of the upper plate affect strain accommodation and megathrust locking and rupture behavior? Are there connections between these upper-plate structures and the locations that generate seismic tremor on the deep plate interface? Many techniques, from continuous GPS, to LiDAR, to paleoseismology could be combined to develop community-scale models of the deformation of entire forearcs.

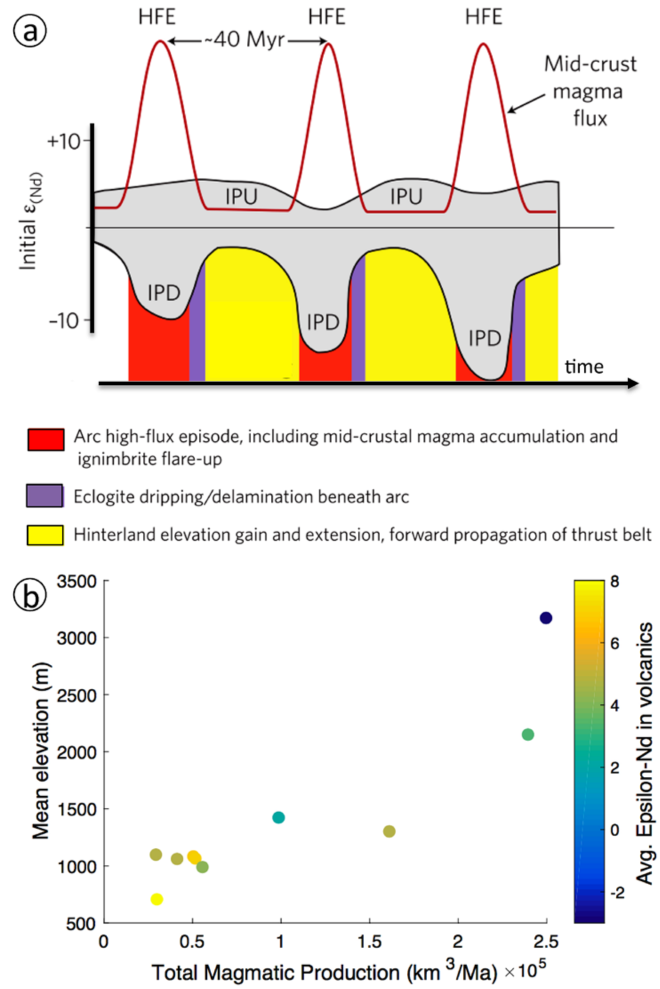


FIGURE 2.10. (a) DeCelles et al. (2009) model of oscillatory topography. Arc magma flux plotted against the backdrop of isotopic composition in terms of the initial εNd value (gray band) showing a hypothesized covariation of isotope pull-downs (IPD) and pull-ups (IPU) with high magmatic flux and low magmatic flux events, respectively. (b) Surface elevation in the subduction zones in North and South America appears to follow this pattern. *(a) Adapted from DeCelles et al. (2009). (b) Figure courtesy of Jane Willenbring*

The product of the ***SZ4D Initiative*** will be a framework for interpretation that will link different Earth subsystems (mantle-lithosphere-surface), integrating them into a 4D model based on global subduction zones as natural laboratories.

3. The 4D Approach

The unifying theme of the ***SZ4D Initiative*** will be the integration of data sets and models that capture the four-dimensional evolution of key subduction processes (**WP16**). Earthquakes, tsunamis, volcanic eruptions, and landslides as well as the cycling of water, carbon, and key elements through the system (**WP46**) are controlled by processes that span spatial and temporal scales ranging from nanometers to kilometers and seconds to millions of years. The ***SZ4D Initiative*** seeks to move subduction science from describing disparate snapshots over limited spatial and temporal scales to fully measuring, integrating, and modeling processes across disciplinary boundaries. Acquiring, analyzing, and interpreting data across these scales will require a collaborative infrastructure and implementation of a full range of techniques by ***SZ4D*** (**Figure 3.1**). Grappling with problems on this scale needs sustained and robust interactions over the full suite of disciplinary expertise.

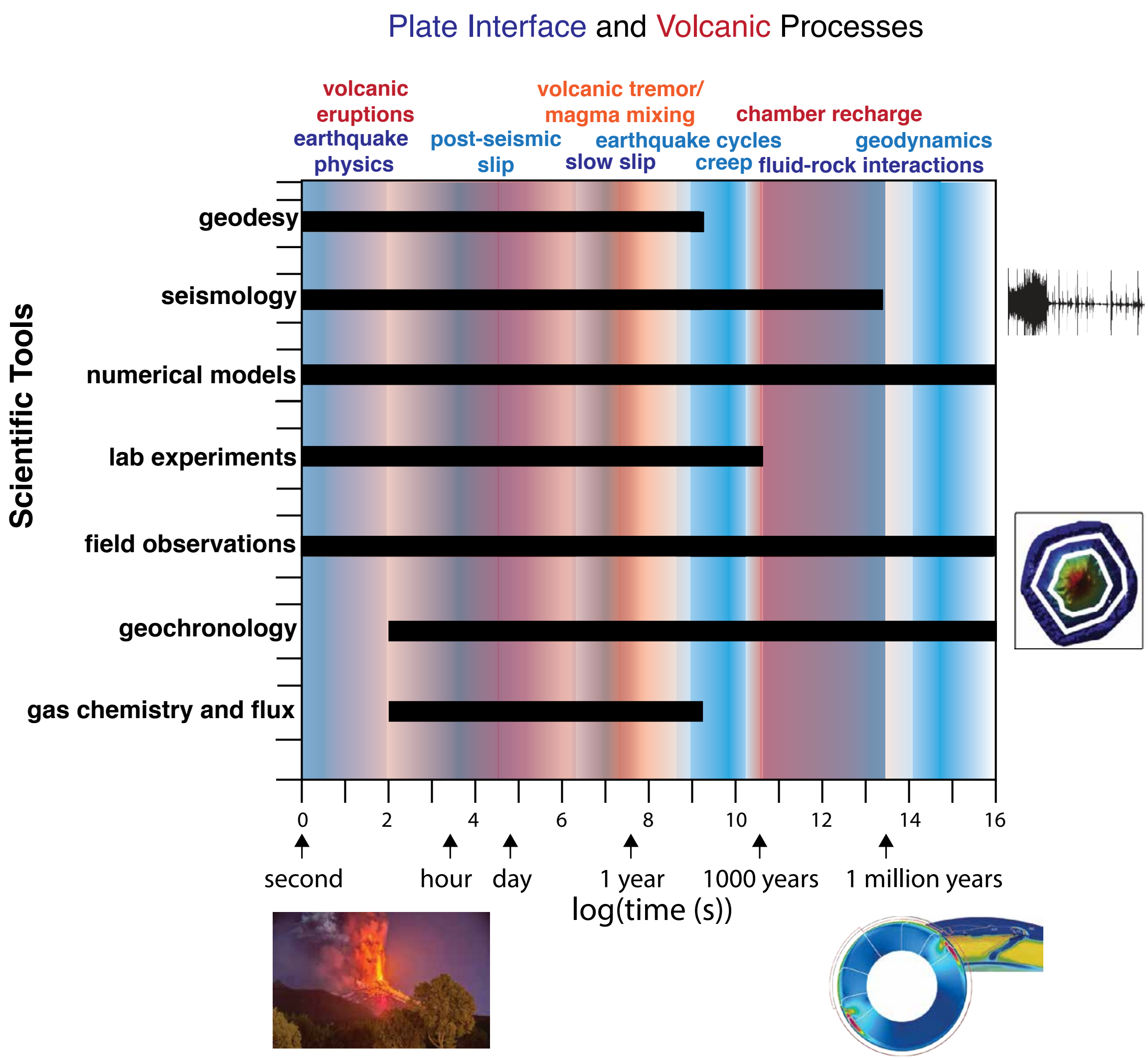


FIGURE 3.1. Processes that control the dynamics of subduction systems (top x-axis) occur on time scales that span 16 orders of magnitude (bottom x-axis). The time scales of volcanic processes are indicated in red and orange colors and those of plate boundary fault processes are indicated in shades of blue. There is significant overlap in the time scales of processes, as shown by the blending of colors. To understand the physics and chemistry of the processes that control plate boundary deformation and volcanism requires a suite of methods (y-axis) that are each informative over a range of time scales indicated with a black bar. The ***SZ4D Initiative*** will facilitate the integration of data and models across temporal scales using these diverse scientific tools. Graphics show examples of tools used to study volcanic and plate boundary processes. Clockwise from the top right: an earthquake seismogram (Brudzinski, 2011), a garnet crystal (~1 mm diameter) drilled (white) for geochronology (Dragovic et al., 2012, 2015), a geodynamic model (Stadler et al., 2010; Alisic et al., 2010), and a volcanic eruption (photo credit: A. Aiuppa). *Figure courtesy of M. French*

The ***SZ4D Initiative*** seeks to invest in multidisciplinary observatories where data from evolving systems can be captured in sufficient resolution to observe their fundamental physics and chemistry. Maximizing our understanding of these 4D data sets will require developing system-scale quantitative models of subduction zone behavior. At the largest scale, tectonic, volcanic, surficial, and climate cycles will be linked in space and time through mass and volatile fluxes. Subduction zone models of lithospheric deformation will bridge the seismic and tectonic time scales and will incorporate structural information from seismic reflection imaging, geologic sampling, and laboratory simulations in order to inform earthquake forecasts with physical models (**Figure 3.2**). Diatom assemblages can be used to reconstruct land level to determine cycles of earthquakes, surface deformation, and associated tsunamis (**Box 3.1**). We will build on models of static geology to consider structural and lithologic evolution and their roles in the evolving distribution of megathrust locking over decades to millennia. Several nested models can be used to bridge magmatic production and volcanic eruption, and deformation and landscape response. In addition, the cycles of magma reservoirs can be treated as evolving multiphase mixtures that reside at multiple depths and are replenished, degassed, and experience freeze-thaw cycles prior to eruption.

Recent technological and scientific advancements indicate that now is the time to collect and integrate data on scales that have never before been possible. For instance, dense, high-quality, long-term seismologic and geodetic data are needed to capture both the diversity of conditions and deformation processes in subduction zones, as well as the statistically significant number of measurements necessary to understand earthquake cycles and precursory signals to eruptions (**Figure 3.3**). Similarly, continuous, multidecadal observations of volcanoes that record an entire eruptive cycle are extremely rare, but provide important glimpses into how volcanoes work (**Figure 3.4**). Finally, at the margin-wide scale, understanding landscape evolution requires systematic quantification of mass flux potentially driven by tectonic-climate interactions.

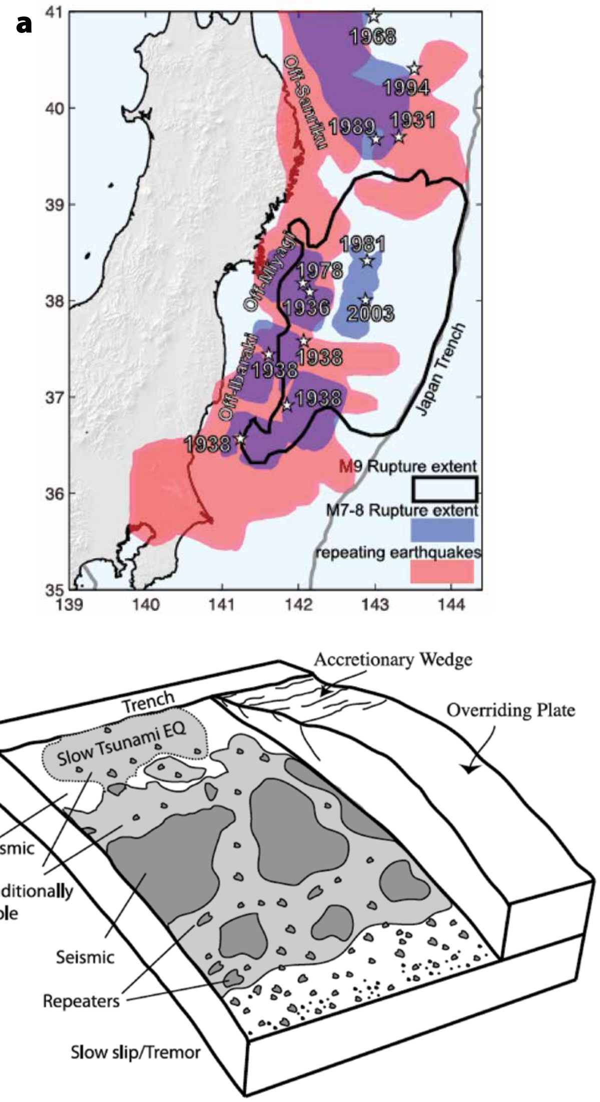
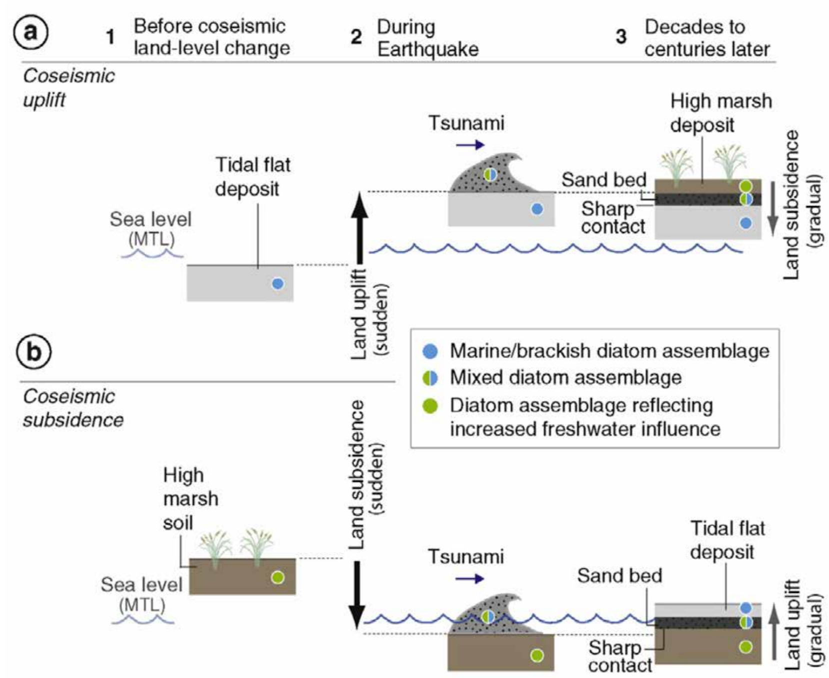


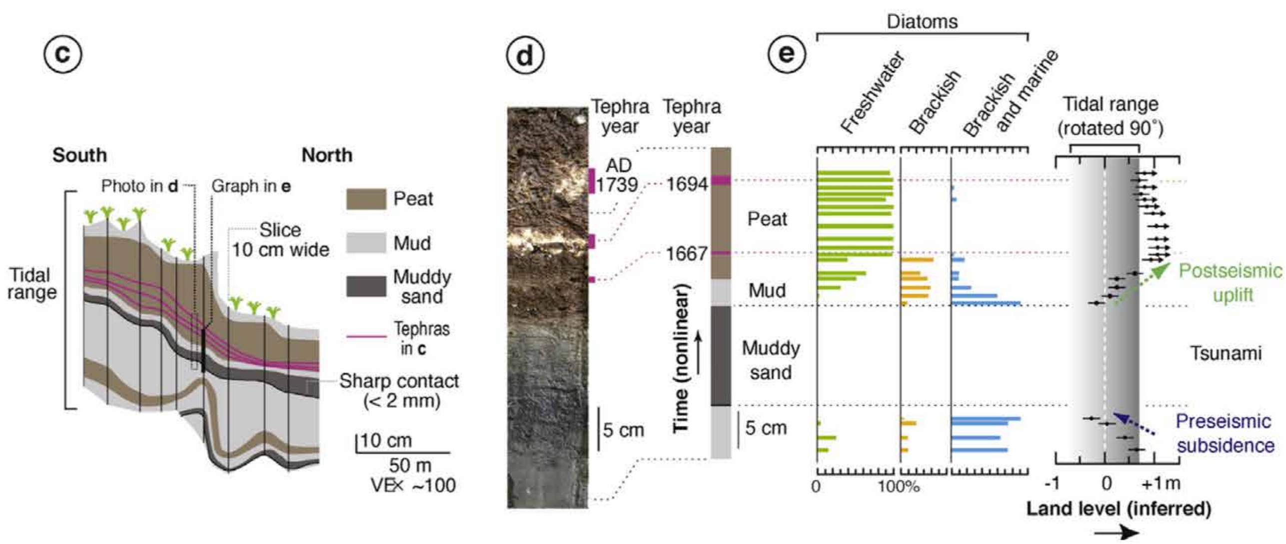
FIGURE 3.2. There is evidence that fault slip patterns are controlled in part by geologic heterogeneity that occurs from the millimeter to hundreds of kilometer scale and evolves over time. (a) A map view shows patches of seismic (blue and empty) and aseismic (red) fault deformation in northern Japan (from Johnson et al., 2016; data from Kiser and Ishii, 2012, and Uchida and Matsuzawa, 2011). (b) A cut-away view for a conceptual model of lithological heterogeneity distribution along the subduction plate boundary (from Lay et al., 2012). Light gray regions promote stable slip, while dark gray areas promote earthquakes. Currently, this model has not been directly linked with regional geology or evaluated in conjunction with dynamic rupture effects, but this could be pursued through an interdisciplinary effort to integrate lithological, structural, geodetic, and seismological data sets in dynamic rupture models.

Box 3.1. History of Subduction Zone Earthquakes and Tsunamis from Microfossils

Diatoms and forams can be used to reconstruct the likelihood of subduction zone earthquakes and the recurrence time between them. This record can also be used to identify surface elevation changes through time.

Schematic drawing of coseismic uplift (a) and subsidence (b) and accompanying tsunami inundation. (c–e) Example of land-level reconstructions using diatoms from in Hokkaido, northern Japan. (c) Stratigraphic cross section. (d) Photograph of a core and log of stratigraphy. The core is an example of the change from tidal-flat mud to lowland-forest peat, punctuated by a tsunami deposit and by volcanic ash layers. (e) Diagram showing the schematic stratigraphy, changes in diatom assemblages, and the results of transfer functions for a seventeenth-century large earthquake. Error bars for height estimates span two standard deviations. *Figures a–b are from Dura et al. (2016); Figures c–e are modified and reprinted from Sawai et al. (2006)*





Are volcanic eruptions predictable?

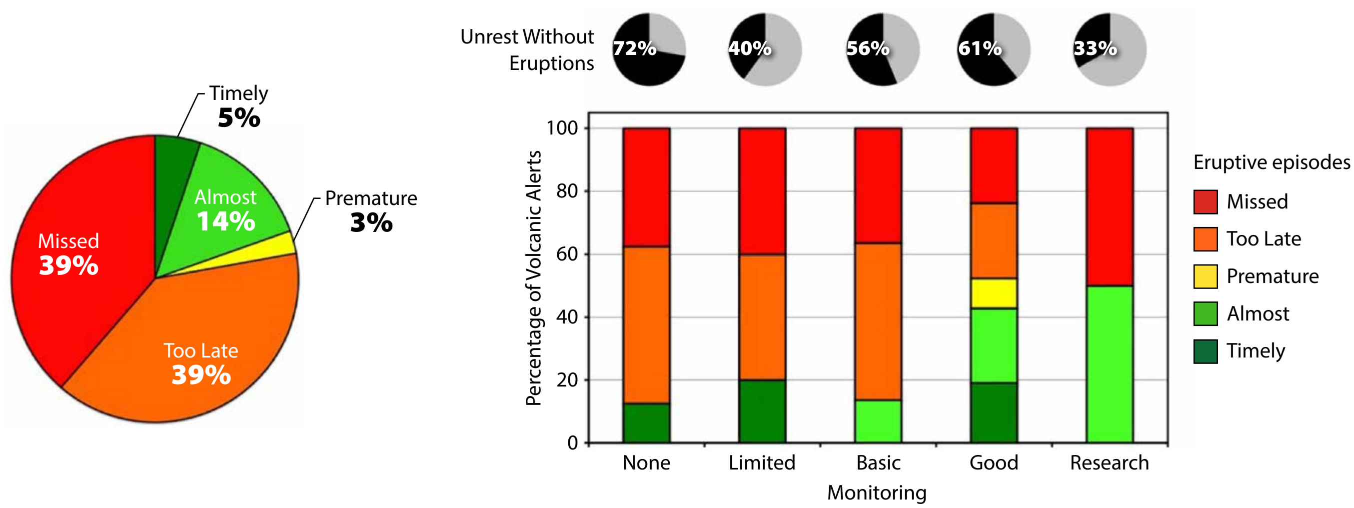


FIGURE 3.3. Volcanic eruptions are preceded by a greater variety of observable phenomena than any other major natural hazards; however, less than 20% of eruptions are predicted accurately (here defined as an alert that is Timely or Almost timely). Winson et al. (2014) showed that predictive accuracy went up significantly with the quality of the volcano monitoring network. They defined a Good network as one with six seismometers or continuous GPS instruments on the volcano or continuous gas monitoring. The success rate doubled for volcanoes instrumented at this level. The number of false alarms (Unrest Without Eruptions) also decreases significantly with increased monitoring. The study illustrates there can be dramatic improvements in predicting volcanic eruptions with modest investments in instrumentation, a clear opportunity for the ***SZ4D Initiative***. *Adapted from Winson et al. (2014)*

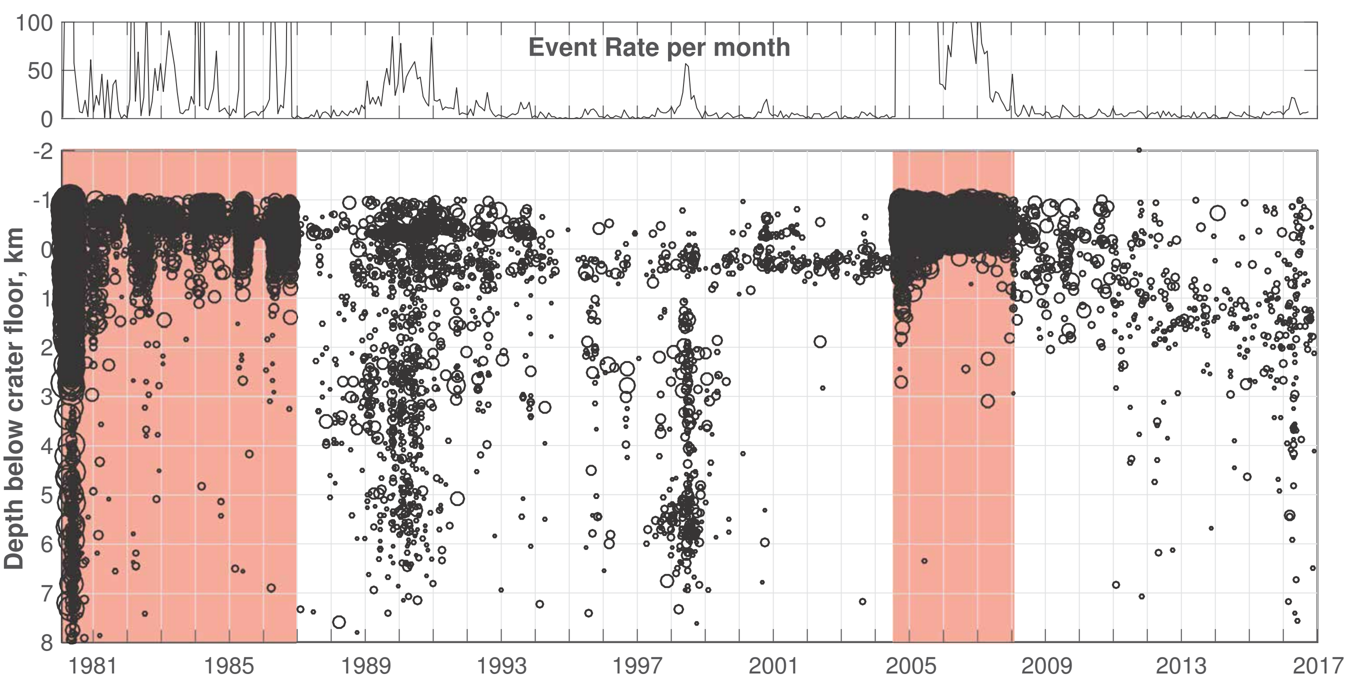


FIGURE 3.4. Time-depth plot of volcanic earthquakes (open circles: size of circle scales to earthquake magnitude) beneath Mt. St. Helens, Washington, from 1980 to 2017. Red regions are periods of eruption. Green regions are inter- or post-eruptive periods. It appears that recharging of the shallow magma chamber that fed the 2004 eruption of Mt. St. Helens began almost immediately after the previous eruption was over, starting with the crustal earthquake swarms in 1989–1992 and including the big swarm in 1998. *Figure courtesy of Wes Thelen, USGS*

4. Frontiers

The ***SZ4D Initiative*** will pursue frontier observational activities that have not been previously attempted (outlined in **Boxes 4.1–4.7**). The defining feature of these efforts will be measurement of critical and understudied geological events and processes. For instance, the frontier in understanding the nucleation and propagation of great megathrust earthquake ruptures is in deploying a new generation of marine instrumentation, in sufficient density, to capture high-resolution geophysical signals under the continental shelf and slope prior to, during, and subsequent to the rupture, including the tsunami generation that follows (**Box 4.1**). Similarly, a frontier in volcanology is capturing the long- and short-range run-up to eruptions, the eruption, and its aftermath with a dense, multidisciplinary suite of sensors and samples (**Box 4.1**). For understanding the connections between tectonics and surface processes, the frontier is quantifying the 4D evolution of mass flux in the forearc via high-resolution topographic, geophysical, and geochronological techniques (**Box 4.2**).

To achieve the vision of a 4D collaboratory that successfully addresses these frontier science problems requires using

Box 4.1. Time Series in the Run-up to Events

Continuous time series preceding earthquakes and eruptions are revealing emergent phenomena, potential precursory signals, and constraints on the physical conditions that lead to hazardous events

Both the 2011 M9.0 Tōhoku earthquakes in Japan and the 2014 M8.2 Iquique earthquake in Chile were preceded by unusually large and robust migrating sequences of earthquakes (top figure). These foreshocks might, or might not, be indicative of slow slip that presaged the major earthquakes.

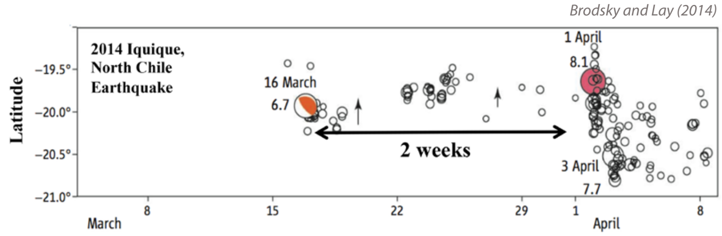
For both Tōhoku and Iquique, some geodetic data suggest that creep occurred. For Tōhoku, a few temporary stations on the seafloor appear to have captured motion prior to the mainshock, but their short time series is noisy and difficult to interpret. For Iquique, continuous onshore stations seem to indicate precursory, offshore motion in the weeks preceding the 8.1 main shock (middle figure showing east component). The great distance between the onshore instruments and the fault makes it difficult to determine if the motion is simply the slip during the foreshocks or contains some extra creep.

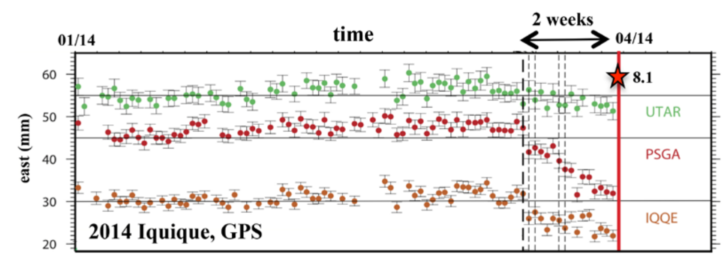
Long-term geodetic instruments on the seafloor near the megafaults need to be in place prior to the next M8 subduction zone earthquakes. With such instruments, we can ascertain whether or not giant megathrust earthquakes slide slowly for weeks prior to their rupture, as the current data suggest.

The bottom figure shows a continuous time series of CO_2 to total sulfur (S_T) and SO_2 flux measurements preceding the 2014 eruption of Turrialba volcano in Costa Rica. Approximately three weeks prior to the Oct 29, 2014, eruption, the CO_2/S_T ratio in gas emissions rose dramatically, consistent with magma rising at depth.

Such signals are ripe for integrating with geodetic and seismic detection of dike intrusion, migrating seismicity beneath the volcano, and eruptive samples that provide crystal clocks and thermobarometers that date and constrain the magmatic conditions prior to eruption (see figure in Box 2.3 for another example of a recharge event prior to the 2006 eruption of Mt. Etna). These integrated data sets are necessary to relate precursory signals to the physical conditions under the ground that lead to eruption. Very few other volcanoes are currently instrumented in this way.

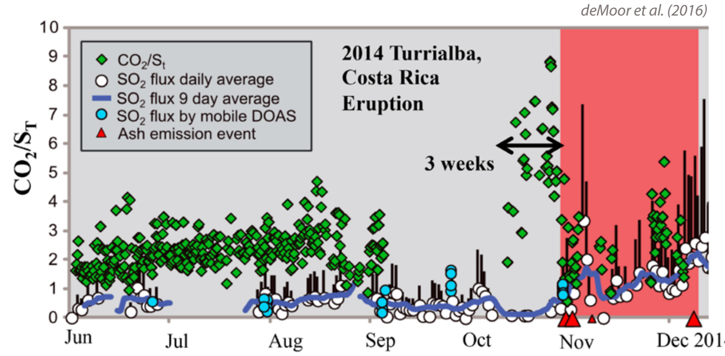
Brodsky and Lay (2014)





Ruiz et al. (2014)

deMoor et al. (2016)



techniques for scaling processes developed at the individual PI level and integrating them with community-scale experiments. Significant progress on the range of frontier problems is likely achievable on the time scale of ***SZ4D*** because a number of new technologies are available. The NASA-ISRO Synthetic Aperture Radar (NISAR) satellite will revolutionize 4D studies of ground deformation with its coverage of most points on the globe every week (**Box 4.3**). Seafloor and subseafloor seismic, geodetic, and fluid flow observatories are expanding rapidly in Japan and elsewhere (**Box 4.4**). Active source imaging studies can be proposed to coincide with or precede installation of sensors to identify fault geometries related to megathrust ruptures and tsunamigenic possibilities (**Box 4.5**); such studies, in combination with allied efforts for chronology (e.g., International Ocean Discovery Program, or IODP), could define the mass flux within the forearc by mapping sediment volumes. The chemical precursors to volcanic eruptions are starting to be detected by continuous sensor arrays and microanalysis of crystal clocks. The key to maximizing the impact of ***SZ4D*** will be having the right sensors in the right places at the right time through a combination of continuous measurements (**Box 4.6**) and rapid response facilities (**Box 7.3**).

In addition to capturing geological events, ***SZ4D*** will enable robust development of apparent links between phenomena that are at this time only tantalizing suggestions. For example, hydration of the incoming plate as it bends into the trench has been observed by new seismic reflection and electromagnetic experiments (**Box 2.4**). Although it is expected that this hydration front could affect seismicity in the downgoing plate as well as volcanic arc melting processes, we still do not know if and how it does (**Box 4.7**). Serpentinization of the mantle wedge is observed to occupy a "nose" region in the mantle

Box 4.2. Temporal Evolution of Subduction Zones and Topography

How and when do landscapes respond to tectonic perturbations from subduction, and how does erosion feed back into the subduction zone properties?

Relationships between total sediment subducted and magmatic productivity show that an arc-wide sediment flux of ~0.5×10^5 km^3 My^{-1} can create conditions optimal for magmatic productivity. However, not enough sediment and too much sediment seem to shut off magmatic productivity (figure, top).

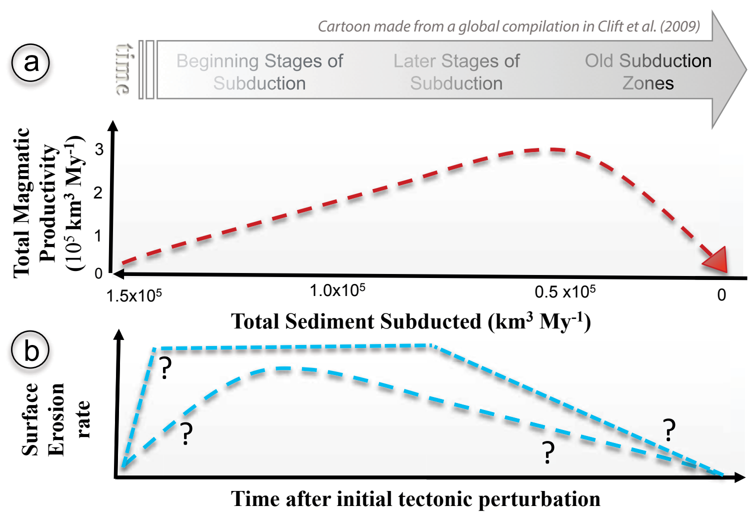
The amount of sediment subducted can be thought of as a temporal journey through a subduction zone (gray arrow in top figure). At the beginning of subduction, sediment input can be plentiful and can decrease over time as the erosion cannot keep pace with subduction of sediment into the trench.

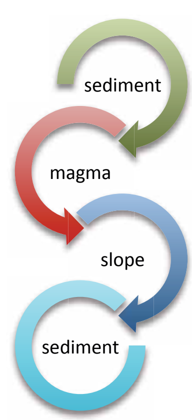
Currently, it is unknown how quickly the geomorphic system takes to respond, and in what manner, to tectonic perturbation. Panel b in the top figure shows this process, hypothesized in Willenbring et al. (2013). Is the erosion response to tectonic perturbation relatively rapid and sustained? Or, is the erosion slow to respond and peaks late?

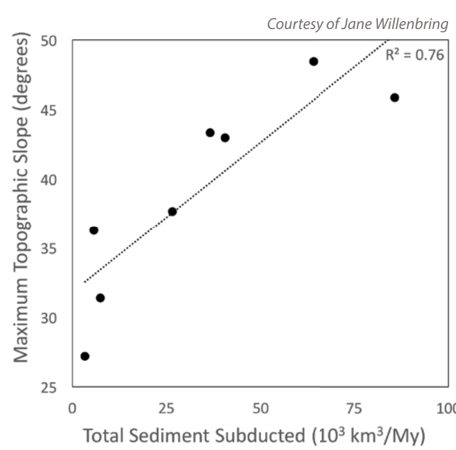
These questions relate directly to feedbacks now recognized in the subduction zone system. The plot in the bottom figure shows a significant, linear correlation between the total amount of sediment subducted and the maximum topographic slope from the subduction zones in Cascadia and the Andes.

We currently have a limited understanding of the direction of the forcing for this striking, empirical relationship. Does an increase in slope of the topography increase the sediment supply to the subduction zone? Does the amount of sediment in the subduction zone impact the friction, and hence plate locking, along the slab interface, raising the topography and thus the slope? Either direction of causality implies that there could be tight coupling between the surface and internal subduction forces.

Geodynamic models of subduction zones currently do not link the dynamics of the slab and the evolution of Earth's surface. Geomorphological research on these processes and integrated data sets are necessary to understand the temporal evolution of these enigmatic areas on Earth's surface.





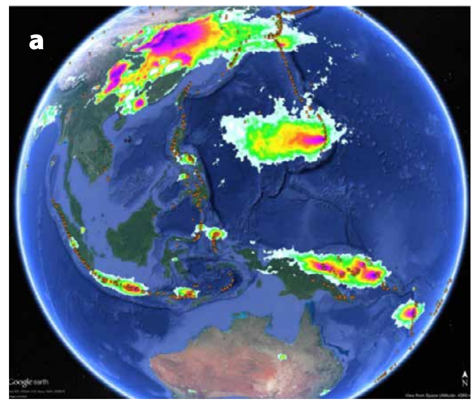


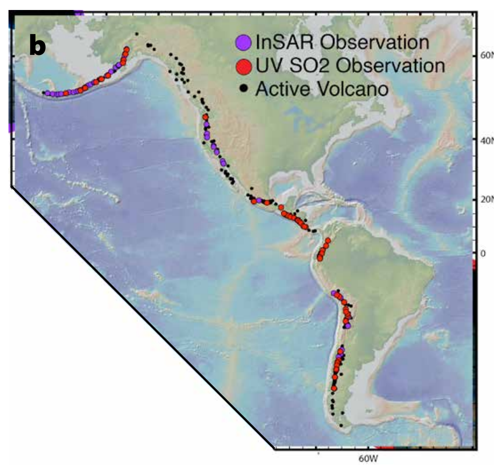
wedge, which may in turn affect the transitions to slow slip, decouple the plate thermally from the mantle, or intrude the overlying plate. Volcanoes have shallow magma storage regions in the crust, but are rooted in the mantle. Experiments have attempted to connect the magma production region in the mantle with the plutonic incubators in the crust, as well as the type, volume, and vigor of eruptions. Some volcanic eruptions may be triggered by earthquakes, but the conditions for triggering are poorly understood. All of these topics are at the frontier of each discipline, and the observations are at the edge of where one discipline meets another. ***SZ4D*** can provide the mechanism to make observations across the subduction system, to discover connections that would otherwise not be seen and yet may be fundamental to processes that drive earthquakes, eruptions, surface deformation, erosion, and climate.

Box 4.3. Satellite Volcano Observation

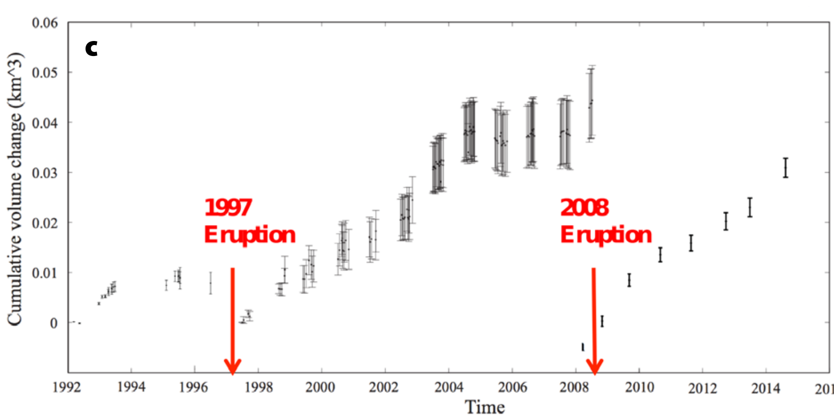
Remote-sensing tools enable global 4D observations of volcanic activity

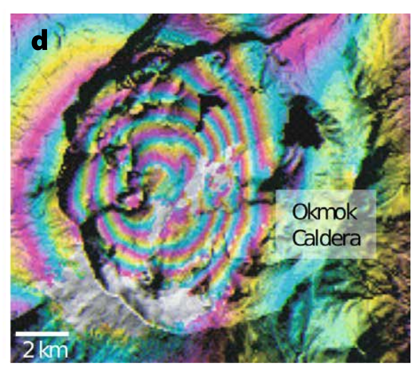
Satellite-borne instruments capable of detecting emission of gases such as SO_2, thermal anomalies, and rapid ground deformation are complementary and crucial tools for studying processes of magma recharge prior to eruptions, including volatile input rates and rates of magma supply from depth. Satellite-borne gas sensors are useful for providing data on "open vent" volcanoes that are relatively open to the atmosphere and thus do not build significant below-ground pressure before eruptions. Satellite-borne deformation sensors, in contrast, are sensitive to closed-vent volcanoes that retain most gases underground until eruption. These sensors are useful for detecting and analyzing precursory unrest, while satellite-borne thermal and visual sensors are useful for tracking gases and ash once an eruption has begun. Satellite-borne instruments provide global coverage at the cost of resolution and sampling frequency (relative to equivalent ground-based instruments). However, planned launches of next-generation gas- and deformation-sensing satellites is expected to increase the repeat time of observations, allowing for the development of robust 4D data sets spanning much of the globe.





(a) Map of anthropogenic and volcanic SO_2 sources in East Asia and the western Pacific region based on Ozone Monitoring Instrument satellite data collected in 2005–2007. SO_2 detected over East Asia is mostly anthropogenic SO_2 emissions from China; the other SO_2 sources are mostly due to passive volcanic degassing. Significant volcanic SO_2 emissions can be seen in Japan, the Mariana Islands, the Philippines, Indonesia, Papua New Guinea, and Vanuatu. *Figure by Simon Carn, based on data from Fioletov et al. (2016)* (b) Map of the East Pacific margin showing all volcanoes that have been observed by SAR (purple dots are deformation) or satellite UV (for SO_2 gas emissions (red dots) instruments. *Based on data from the Smithsonian Institution Global Volcanism Program* (c) The inflation-deflation cycle at Okmok Volcano. Volume change in the magma reservoir is calculated from deformation recorded as in (a). The increase in volume after the 1997 eruption is interpreted as an influx of magma. The ground surface then rapidly subsided during the 2008 eruption and the reservoir is inflating now again. (d) InSAR image showing inflation of Okmok Volcano, Alaska, in 2002–2003, where each interference fringe represents 2.83 cm of change in distance between satellite and ground. *After Lu and Dzurisin (2014)*





Box 4.4. Seafloor Geodesy and Seismology

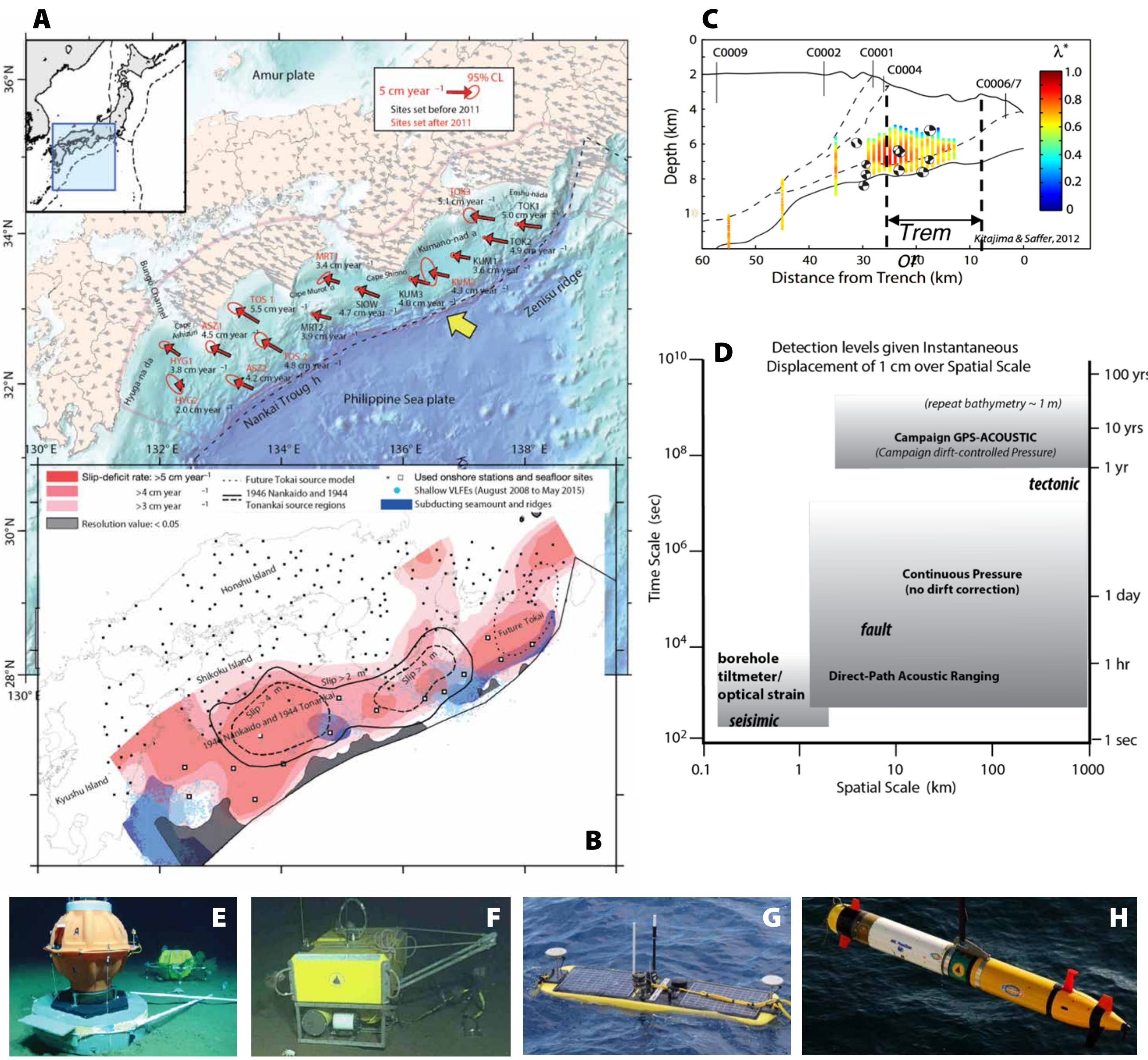
Evolving toward long-term flexible observatories

Campaign seafloor geodetic and seismic deployments are now routine. The acoustic-GPS method is used in Japan and elsewhere to measure the crustal velocity field (A), infer the locking distribution of the thrust interface (B), and capture coseismic offsets from large earthquakes. Seafloor seismic arrays routinely improve earthquake detection thresholds by two orders of magnitude over land arrays. They reveal the connections between material properties, tremor, and slow slip (C) in the updip region of megathrusts (Kitajima and Saffer, 2012).

Panels A and B show results from systematic surveying in Japan using the acoustic-GPS technique (Yokota et al., 2016). The interseismic velocity field is characterized both onshore (GEONET GPS) and offshore (A), and used to infer the locking distribution on the plate interface (B).

Ideally, ***SZ4D*** will record seafloor deformation continuously. New techniques could supplement acoustic-GPS to achieve this temporal resolution in different observational bands (D).

Improving the flexibility, data latency, and cost effectiveness of seafloor deployments is necessary to realize the ***SZ4D*** goals. Array locations will evolve over time and operational costs could prevent ***SZ4D*** from achieving a useful scale. A number of promising technology developments will help make locked zone observatories realizable. Power requirements are dropping; geodetic benchmarks (E) can be deployed for many years and seismic instruments for up to two years. Advances in atomic clocks (F) mean that longer deployments can return sufficient data quality for state of the art seismology. Additional cost savings will likely come from marine robotics. Wave Glider systems (G) are now being used to survey geodetic benchmarks without a ship, and autonomous underwater vehicles (H) could be used to offload data from entire seismic networks without a ship.



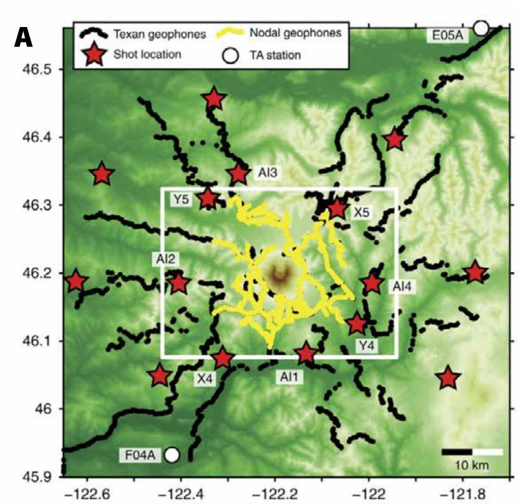
Box 4.5. High-Resolution Seismic Imaging

High-resolution seismic imaging is rapidly evolving both onshore and offshore. A new generation of short period sensors that are easily deployable in large numbers is illuminating the deep structure of volcanoes such as Mt. St. Helens. The dense iMUSH deployment (A) identified rapid spatial variations on the scale of a few kilometers in Moho reflectivity beneath the volcano (B), likely imaging the eastward boundary of the cold, serpentinized portion of the mantle wedge. These new data suggest that the magma supply from the mantle is from the east rather than directly under the volcano.

Similarly, offshore, ever better resolution of plate interface architecture and physical properties from 3D seismic data are being achieved. For example, multichannel seismic data acquired with R/V *Langseth* off Costa Rica (C) show down-dip variations in reflectivity of the plate boundary that correlate with changes in seismicity. These variations are interpreted as related to changes in fluid content.

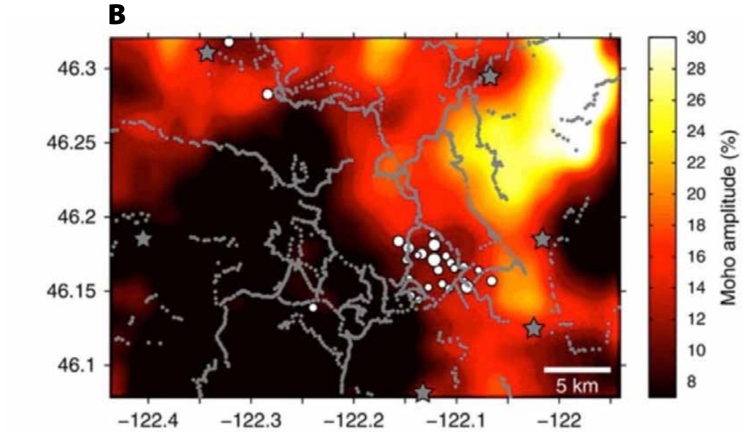
An 8 km long seismic streamer and R/V *Langseth*'s large source array allowed the ALEUT experiment to image the plate boundary interface in the Semidi segment of the Alaska-Aleutian megathrust to a depth of about 60 km. Image (D) shows the along-dip variation in reflections, from a narrow set along the interface to a thicker band of multiple reflections at deeper depth.

A



Hansen et al. (2016)

B



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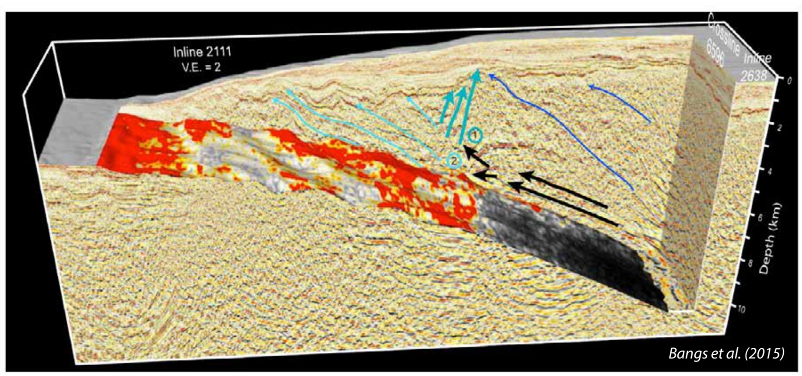
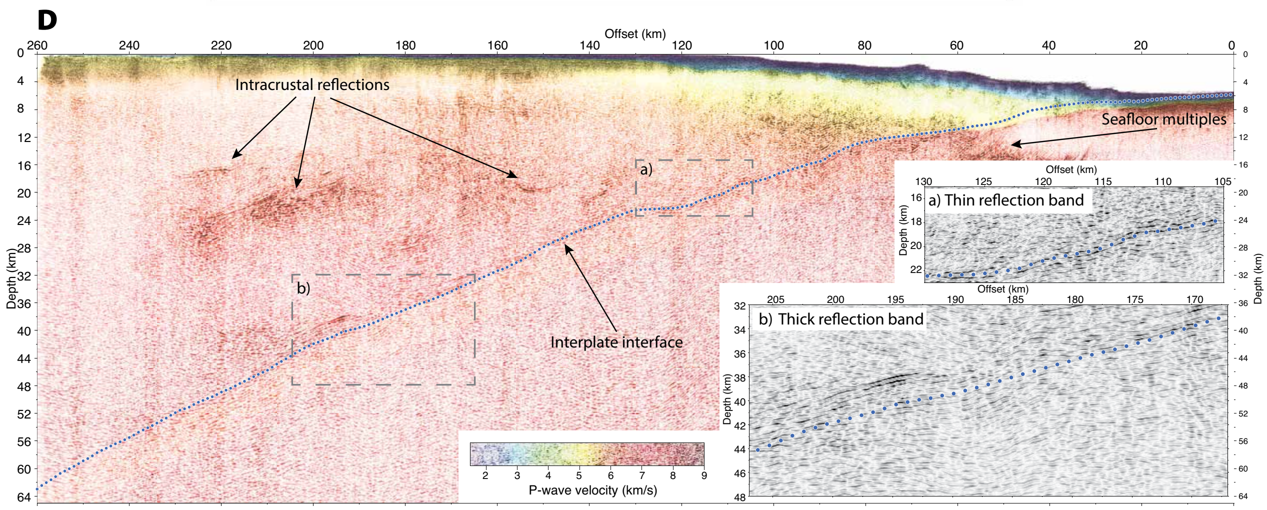


Bangs et al. (2015)

D



Kuehn et al. (2016)

Box 4.6. Continuous Seafloor Observation

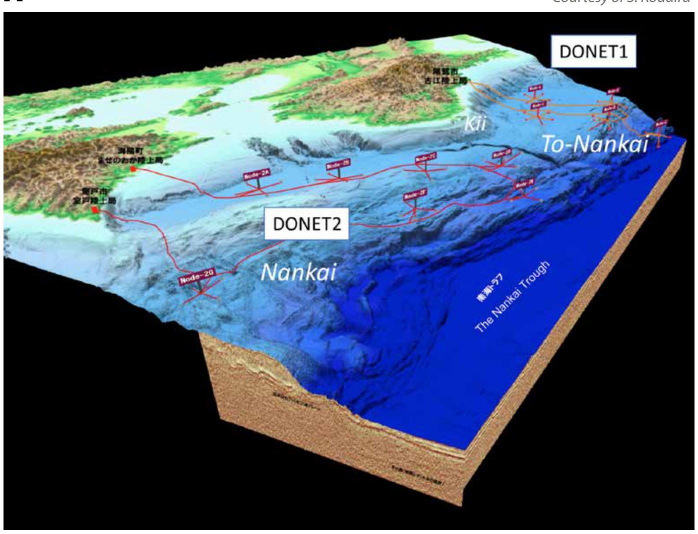
The frontier of earthquake and tsunami observation is offshore, where the slip in great earthquakes actually happens but is almost never recorded. A key data gap thus lies in the region directly above and in the near field of zones of high strain accumulation and slip, where major tsunamis are generated, and where transitions in megathrust behavior likely give rise to slow earthquake phenomena and complex heterogeneous patterns of locking and slip. In this region, material properties and fluid state likely evolve rapidly due to progressive heating, compaction, lithification, and shearing. Thus, there is a critical need for continuous seafloor observation to capture the evolving state of the megathrust in 4D.

Thus far, Japan has led the way in observatories offshore for both fundamental research and early warning. The Dense Ocean floor Network for Earthquakes and Tsunamis (DONET) 1 and DONET2 observatories in southwest Japan (A) cover the Nankai Trough subduction zone and telemeter data from dozens of seafloor seismic, geodetic, and oceanographic instruments. DONET1 is also connected to the NanTroSeize borehole observatories that measure subseafloor fluid pressure, seismic, and geodetic signals, and are among the most sensitive instruments we have for monitoring the plate boundary. In northern Japan, the Ocean Bottom Seismic and Tsunami Network is being deployed with over 150 sites along the Japan Trench (B).

Off Costa Rica's Nicoya Peninsula, two CORK (circulation obviation retrofit kit) borehole observatories were established near the trench by the Ocean Drilling Program in 2002 (C) and have been recording hydrogeology and deformation associated with subduction for over 15 years. Over this time, the pair of boreholes have recorded several formation pressure anomalies that typically occur weeks after episodic tremor and slip events occur onshore, demonstrating a previously undocumented connection between slip of the megathrust and coseismic dilatation in the outermost prism and incoming plate.

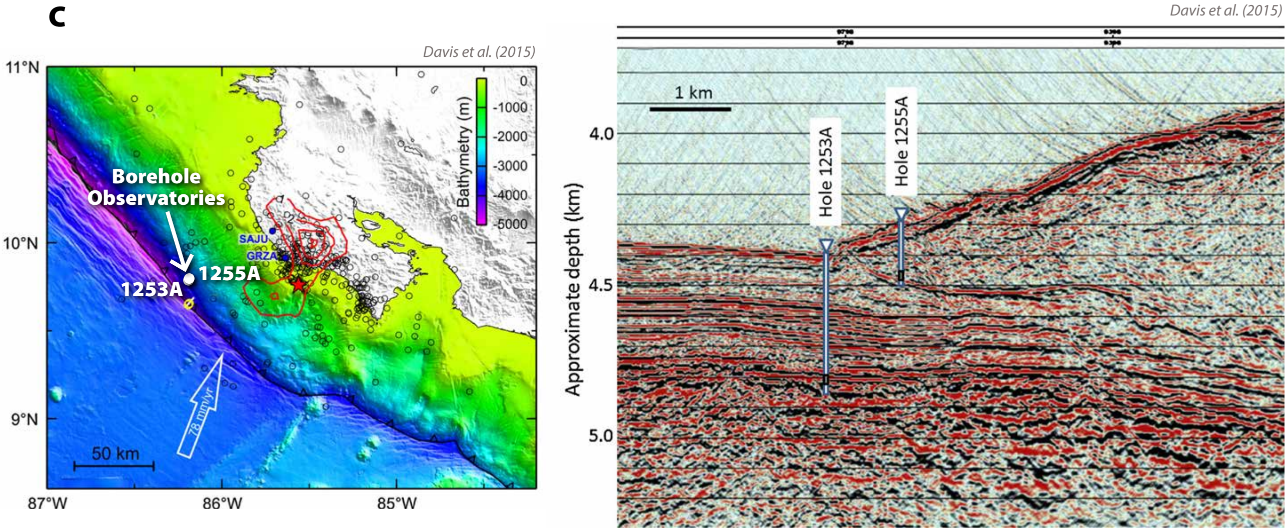
Building from the existing cabled network off Cascadia, a much more ambitious cabled array could serve the dual purpose of forming a major regionally concentrated dense observatory on this megathrust, as well as being a key element of an earthquake early warning system for the region (Figure 5.1). The rate and spatial extent of strain accumulation could be defined and so test whether the Cascadia megathrust, eerily quiet today, indicates either complete locking or aseismic creep (Figure 5.2).

A *Courtesy of S. Kodaira*



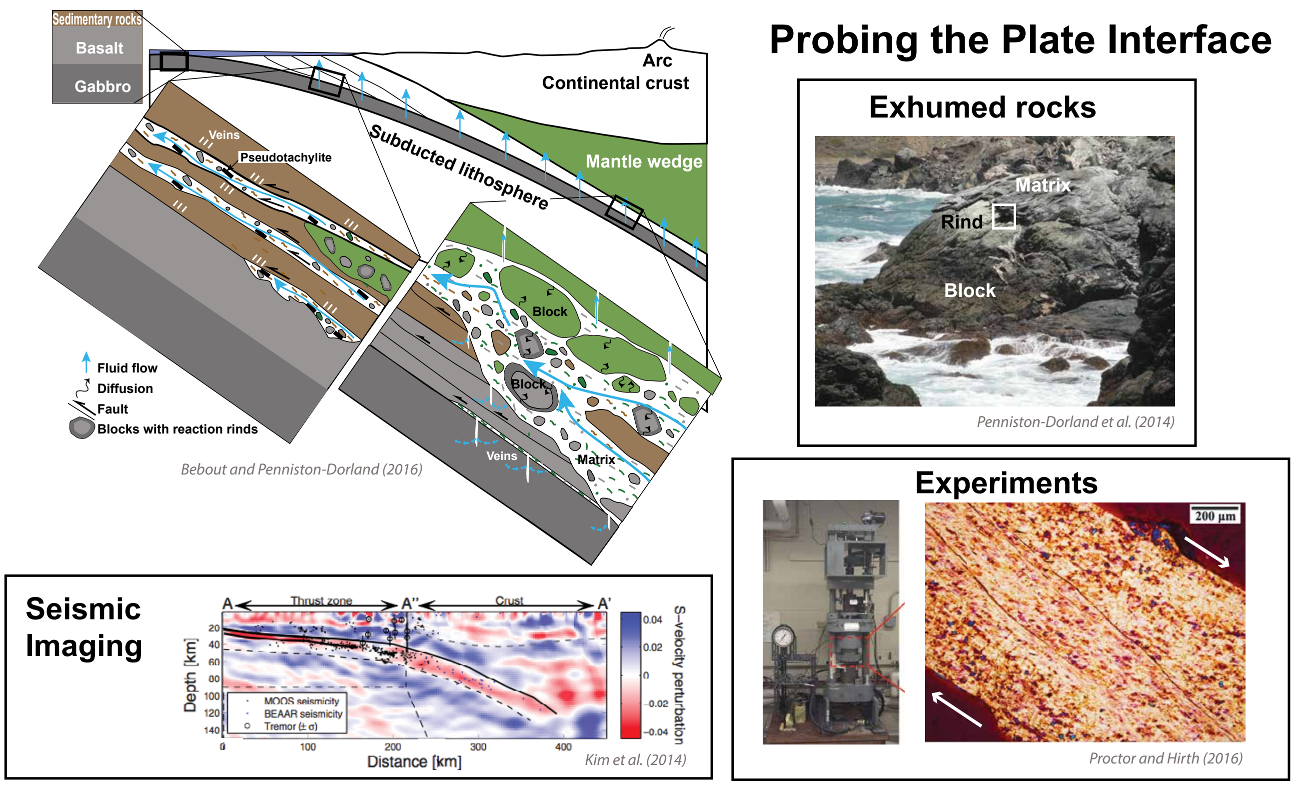
B *Monastersky (2012)*

C *Davis et al. (2015)* *Davis et al. (2015)*



Box 4.7. Probing the Plate Interface from the Megathrust to the Mantle Wedge

In subduction zones, the extent of earthquake nucleation and the depth of rupture propagation along the megathrust are controlled by changes in the microphysics of rock deformation that are reflected in spatial transitions between seismogenic and aseismic deformation. Specific challenges that have limited our understanding include: (1) determining the lithology or lithologies that control this transition; (2) measuring the rheology of the relevant lithologies at the relevant pressure, temperature, and strain rate conditions; and (3) integrating constitutive models across traditional "brittle" and "ductile" disciplines. There is also geophysical evidence that pore fluid pressures are very high near the brittle-ductile transition, and it is unknown what first- or second-order effects fluid pressures have on deformation at these conditions, largely because experimental apparatus have not been designed to achieve this set of conditions. Illuminating these micromechanical processes requires samples of the types of material that occur along the thrust interface, whether they are retrieved from drill cores or ancient exhumed subduction zones, as well as studies of the field relations, mineralogy, and chemistry of exhumed rocks. For example, block and rind structures in a matrix reveal mixing processes that occur at the plate interface. In addition to laboratory experiments and studies of exhumed rocks, seismic imaging is providing sharper views of plate interface structure and properties. Scattered waves illuminate the megathrust at 30–40 km depth as a thin layer (3–5 km) with low seismic velocity, consistent with thick sediments with high pore fluid pressure. The way forward involves integration of observations of exhumed rocks, laboratory experiments, and geodynamic and hydromechanical models with seismic imaging to reveal active processes along the plate interface.



5. The Link Between Hazards and Fundamental Science

Subduction zone hazards are substantial, and the devastation resulting from events related to them can have long-lasting effects on society. The vision of the ***SZ4D Initiative*** is to use fundamental science to better understand and forecast geohazards. Thus, the social context of mitigating the risk of subduction hazards would clearly benefit from the ***SZ4D*** research enterprise. On the other hand, applied science is a powerful motivator that can lead to fundamental breakthroughs, with applications far past the original project goals. In the case of the ***SZ4D Initiative***, the benefits of advancing our knowledge on subduction zone processes can reach beyond hazard mitigation. Our understanding of the foundations of the Earth system will be improved, and through this understanding we foresee further applications to the geothermal energy and mineral exploration industries. While natural hazards are a high-level driver of the ***SZ4D Initiative***, the science program should be guided by basic research questions developed by the scientific community. The knowledge gained will be impactful and lead to interdisciplinary interactions with the social sciences and engineering communities, and close coordination with USGS programs focused on risk mitigation and resiliency.

Hazard, Vulnerability, Exposure, and Risk

Natural hazards, in the context of subduction zones, are geologic phenomena such as earthquakes, volcanic eruptions, landslides, and tsunamis that threaten human life and the natural and built environments. *Vulnerability* describes the characteristics and circumstances of a community that make it susceptible to a hazard, such as a building's resistance to strong shaking. The intersection of the geographic distribution of vulnerability and the severity of hazard is the *exposure*, and its combination with a hazard produces the *risk*, which can also be understood as the likelihood that a hazard will lead to loss of life, property, or critical resources.

In this context, as population centers and infrastructure continue to grow in and around subduction zones, so does their risk related to earthquakes, volcanic eruptions, landslides, and tsunamis (UNISDR, 2015). While knowledge of the hazard, vulnerability, exposure, and risk are each distinct building blocks of resilient communities, all must be built on a foundation of fundamental understanding of each hazardous phenomenon. Thus, investments in basic scientific research will lead to more accurate and timely hazard assessments, forecasts, situational awareness, and ultimately more resilient societies.

Subduction zones host an extraordinary diversity of earthquakes. There are intermediate depth, intraplate events that can produce strong shaking, shallow outer-rise earthquakes that yield little strong shaking but generate large tsunamis, and megathrust earthquakes in excess of magnitude 9 with catastrophic consequences for societies within thousands of kilometers of the epicenter. These largest events are unique in their ability to generate ocean-basin-wide hazardous tsunamis. Significant events at subduction zones also lead to a cascade of other phenomena. For example, strong shaking can produce subaerial and submarine landslides that generate local hazardous tsunamis.

Subduction zone volcanoes also exhibit a great diversity in eruptive processes, from caldera-forming super-eruptions to small Strombolian displays, from basaltic to rhyolitic compositions, from water-rich (>6 wt%) to water-poor (2 wt%) magmas, from volcanoes that erupt every year to those that have not erupted in millennia. This variety of eruptive behavior also leads to great uncertainty in the hazard potential, which can take the form of deadly pyroclastic flows and lahars, slow-moving lava flows, or aircraft-crippling ash plumes. Arc volcanoes can have devastating impacts not only on the local environment, but also on infrastructure and climate regionally and globally.

Furthermore, long-term impacts from large subduction earthquakes, volcanic eruptions, and associated geohazards have important consequences. The widespread distribution and magnitude of coastal subsidence and uplift that may follow great earthquakes within minutes to days can result in permanent local or regional sea level changes equivalent to hundreds of years of climate change-related sea level rise. Subduction creates dramatic topographic relief that in wet coastal climates sets the stage for widespread landslides. All of these hazards alter long-term erosion, flooding patterns, and biological habitats.

Science Requirements for Reducing the Risk of Subduction Zone Hazards

Basic research related to subduction zone phenomena can impact risk mitigation in multiple ways: (1) by better understanding hazardous phenomena such that their potential impact can be anticipated and mitigated, (2) by leading to the creation of warning systems that issue alerts ahead of the occurrence of hazardous phenomena (**Figure 5.1**), and (3) by providing post-event situational awareness. To achieve scientific understanding needed for robust forecasts of behavior or events, the ***SZ4D Initiative*** must meet four major goals.

First, ***SZ4D*** must take a holistic systems approach, in which research addresses the linkages between intertwined events (e.g., the role of fluids in fault slip and volcanism). For this reason, observations will have to be interdisciplinary. For study of earthquake hazards, this includes high-resolution bathymetric surveys, geophysical imaging, coring/drilling, fluid geochemistry, and geodetic and seismic arrays. For volcano research, this requires measuring deformation, seismicity, gas, and the eruptive products themselves, in order to develop the ability to recognize phenomena that are truly precursory. These suites of measurements are seldom taken at the same time and in the same place.

Second, ***SZ4D*** facilities and research must extend into the offshore frontier (**WP1**). An example of the critical importance of offshore measurements comes from the Cascadia subduction zone. Without seafloor geodetic measurements of deformation in the shallowest part of the megathrust, it is currently impossible to identify whether it is freely slipping or fully locked (**Figure 5.2**). This has major implications for understanding the details of the tsunamigenic potential of the next large Cascadia earthquake. Japan has already demonstrated the viability of these technologies by deploying both research-oriented and hazards warning networks offshore. These data are even more critical in regions where paleoseismic studies are more difficult like Java.

Third, ***SZ4D*** infrastructure must be in place long enough and in enough regions to measure the subduction system before large earthquakes, tsunamis, or volcanic eruptions occur, but also as they unfold, and as they build to the next event. Hazard assessments are most robust when based on long-term (many cycles) chronologies of earthquakes, eruptions, and landslides, including smaller events that are not well preserved in the geologic record but are more frequent than catastrophic events. These studies must also investigate different regions in order to reveal the more complete range of complex behaviors. Theoretical and numerical models that predict the recurrence patterns over many cycles serve as guides to integrate physical principles and different types of observations. The typical recurrence times of larger, hazardous

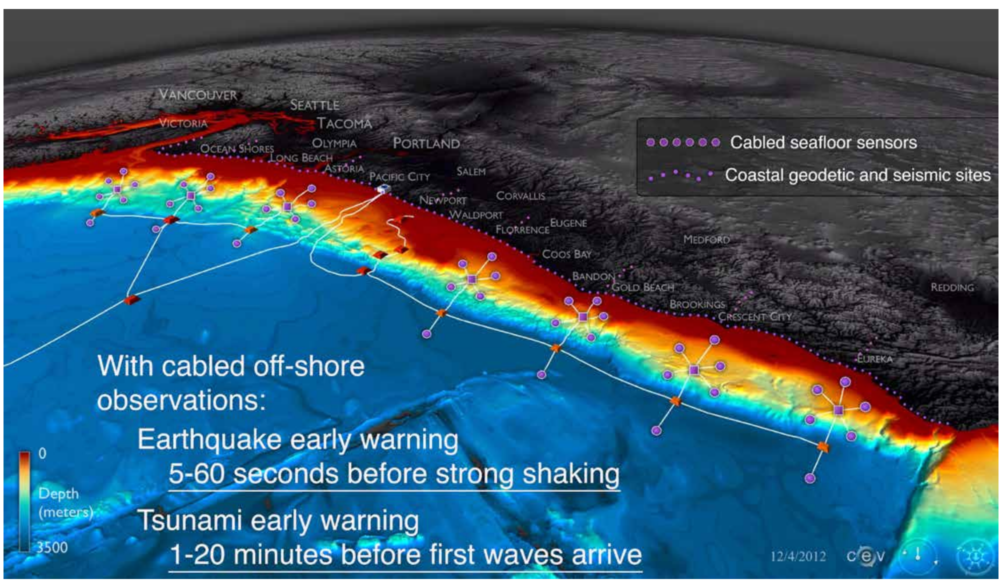


FIGURE 5.1. Conceptual diagram of a potential offshore cabled earthquake early warning (EEW) and observatory network for the Cascadia subduction zone, modeled on the existing Japanese systems (Box 4.6). Offshore measurements would complement existing onshore networks and can have a significant impact on both earthquake and tsunami early warning. EEW in Cascadia is already being implemented as part of the ShakeAlert project using existing onshore sites exclusively. Should the next Cascadia earthquake nucleate offshore, warnings will be delayed by virtue of the onshore sites being far away from the hypocenter. Offshore seismic sensors would allow complete coverage of the megathrust, detecting the event sooner and providing far better characterization of key source parameters such as the magnitude and geographic extent of faulting in real time. This will lead to not just faster, but more accurate, alerts. For a large Cascadia event, the first tsunami waves will reach the near-source coastline within 5–15 minutes of the earthquake's initiation. Currently, local warning relies exclusively on onshore measurements from seismic and geodetic sensors that cannot properly characterize an offshore tsunamigenic displacement. Seafloor pressure gauges or tsunameters can measure the initial sea surface disturbance produced by the earthquake as soon as it happens and dramatically reduce the time taken to make an accurate assessment of the unfolding event, enabling much better warning to coastal communities well in advance of the arrival of large destructive waves. *Figure from Wilcock et al. (2016)*

events range from years to millennia, and thus necessitate geological studies to provide in situ evidence of single, and certainly multiple, events at a single fault, volcano, or landslide-prone area. Geological studies are the "ground truth" of hazards science, and continued development of techniques and facilities aimed at improving the accuracy and resolution of geochronological and paleontological dating techniques translates directly into more certain associations of geologic observations with distinct paleo-events, and thus, more accurate hazard assessment. In volcano hazard assessment, there is a need to shift from forecasts currently based on recognizing patterns in data, to quantitative physical models (**Box 7.7**) that use near-real-time observations to forecast the size, duration, and hazard of eruptions.

Fourth, successfully capturing major events requires ***SZ4D*** to take a portfolio approach. Gambling that a single system will produce the key observation is unwise. However, recent history shows that major events occur frequently enough that suites of faults, volcanoes, and terranes can be assembled where there is a high likelihood of making key observations. In the 50 years since the development of plate tectonic theory, sufficient information has accumulated that we now have the ability to plan strategically and build observational portfolios that capitalize on the experience of previous forecasts (see **Figure 1.5**).

Short-term forecasting and early warning systems require real-time, or at the very least, low-latency telemetry **(Figure 5.1)**. This is a particular challenge for events happening offshore. In addition to cabled networks (**WP35**), recent developments in new technologies, such as Wave Gliders and smart cables (**WP19**), are promising and applicable to a wide range of disciplines and measuring sensors. Both warning and short-term forecasting also require fundamental scientific research. Development of more accurate and faster algorithms hinges on improved understanding of the underlying physical processes.

The accuracy of predictions and forecasts depends on understanding the underlying physical and chemical processes that lead to hazards, collecting high-quality field observations before and after events, and having a quantitative knowledge of the properties of Earth materials. For society to better manage the risks associated with hazards, the ***SZ4D Initiative*** needs to support an intellectual infrastructure that unites modeling, field, and laboratory efforts in new and innovative ways.

The Nature of the Link Between Hazards Science and Society

Fundamental knowledge gained about the science underlying hazardous natural phenomena can be used to mitigate risk in three ways. The first is to communicate this knowledge to those needing to act on it, from the general public to policymakers, as knowledge is motivating and informed decisions are sure to be most effective. For example, the *New Yorker*

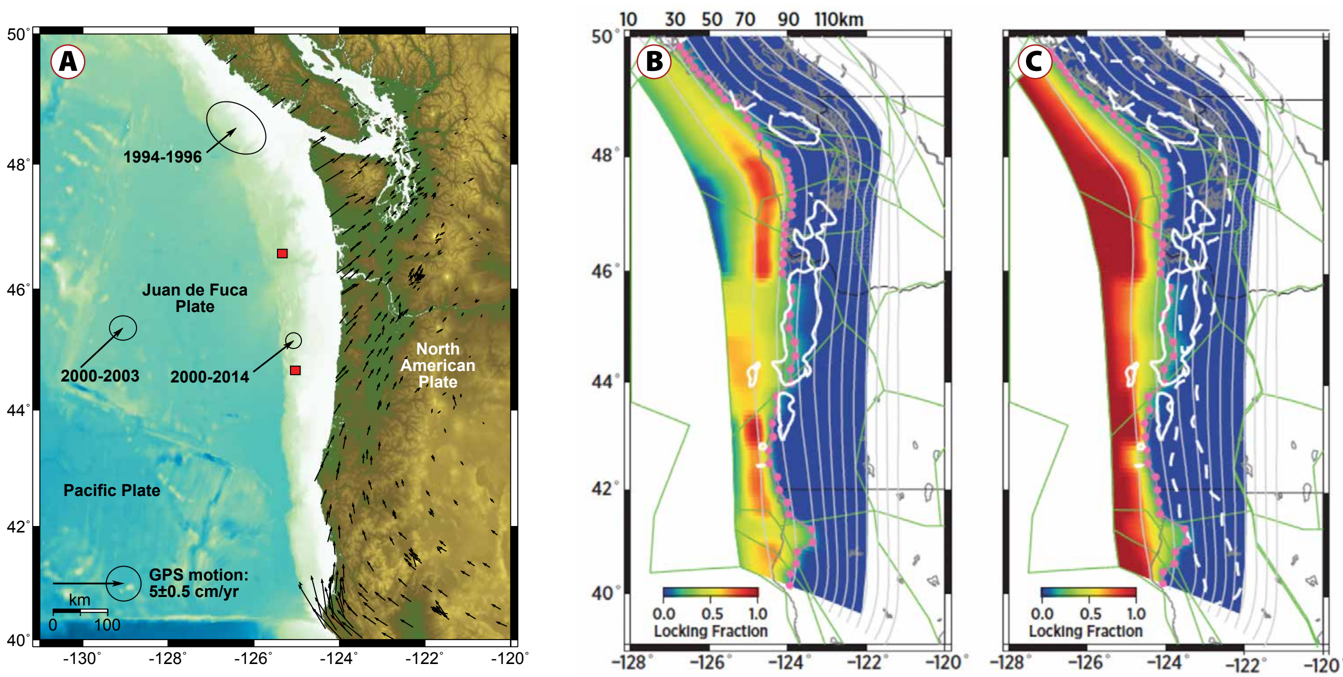


FIGURE 5.2. Models of the interseismic stress accumulation in the Cascadia megathrust based on existing GPS coverage (A) cannot distinguish between a mostly creeping shallow zone (B) and a mostly locked shallow zone (C). GPS-acoustic measurements above the unresolved section will be needed to discriminate between these end member models. Two GPS-A sites (solid red squares in (A)) on the continental slope are presently being measured annually to help resolve this issue. Panel A shows GPS velocities (black) onshore from the EarthScope Plate Boundary Observatory and offshore from GPS-acoustics. *Panel A from Chadwell et al. (2015). Panels B and C from Schmalzle et al. (2014)*

article, “The Really Big One” (Schulz, 2015), masterfully communicated the science, hazard, and risk of an M9 Cascadia earthquake and engendered unprecedented interest and action. The second way by which basic research can mitigate risk is by direct incorporation into the normative aspects of human endeavors. This requires interaction with the engineering and social sciences communities. For example, an understanding of ground motion hazards has led to the creation of building codes that directly guide earthquake-resistant building designs, outlining best practices in regions where strong shaking is expected. This effort has been very successful in many countries that routinely experience earthquakes. Notably, during the M9 2011 Tōhoku-oki event, building or shaking-related casualties were modest, with the bulk of the fatalities attributed to the large tsunami that ensued. This has also been a subject of much attention. During the Tōhoku-oki events, why, if strong shaking and a large tsunami were forecast in a matter of minutes, were people slow to mobilize and evacuate? Studies have shown that a slow social response led to increased casualties. This highlights potential interactions between fundamental hazards research and social science. The third way by which basic research can mitigate risk is through early warning systems that respond quickly to an unfolding event and alert the population. These warnings can be automated and integrated into transportation, utilities, and infrastructure systems. Such systems can and have provided alerts seconds before strong shaking, minutes before a large tsunami, and days before large eruptions, and are also the subject matter of the engineering and social sciences communities.

There was much discussion at the September 2016 Subduction Zone Observatory (SZO) workshop about the right balance between fundamental and societally driven research. In one end-member approach, knowledge for the sake of knowledge is the main driver. Practical outcomes, such as risk mitigation, may be a motivating factor for the research, and a positive broader impact, but fundamental understanding of Earth processes is the dominant goal. However, there are recent examples of the societally driven end-member being used to justify scientific and technological research. One such notable example is the deployment in Japan of a costly and technically advanced cabled, real-time seafloor network (S-net). While the observations collected there will undoubtedly further knowledge of subduction zone processes, funding for that endeavor was only possible because of a vocal societal demand for better earthquake and tsunami warning and short-term forecasting. Another example is the International Monitoring System (IMS) of seismic, hydroacoustic, infrasound, and radionuclide detectors used for ensuring compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT) and the resulting scientific advances from the network. A new USGS National Volcano Early Warning System (NVEWS), targeting 57 undermonitored volcanoes in the United States and its Commonwealths, has recently been introduced as a bill to Congress. While the goal is to ensure that the most hazardous volcanoes are properly monitored well in advance of the onset of activity, such data will be of obvious benefit to understanding the processes that occur in run-up to eruption (**Boxes 2.3 and 4.1**). The NVEWS program envisions partnerships between the USGS, local governments, emergency responders, and the academic community, motivated by many of the linkages outlined here.

Thus, to be successful, the ***SZ4D Initiative*** must articulate its place within the spectrum of hazards-related research, on the one end acquiring fundamental scientific knowledge related to subduction zone hazards and, on the other end, contributing to the demands of society for mitigating the risks from hazards. This is especially important in the context of multi-agency and multinational collaborations, where different entities pursue subduction research from different perspectives and prioritize efforts along different parts of the knowledge-risk mitigation continuum.

6. International Opportunities

Due to the societal impact associated with their geologic hazards, there is strong international interest in subduction zones. There is also a strong and growing interest in greatly expanding the limits of our understanding of the fundamental processes involved in their dynamic behavior. At the 2016 SZO workshop, 47 of the 241 participants represented 22 foreign countries (**Table 6.1**). Pre-workshop webinars highlighted the scientific and collaborative opportunities for studies in Central America, South America, Indonesia, South Asia, Japan, New Zealand, Cascadia, and Alaska, and in total have continued to garner over 1500 views (https://www.iris.edu/hq/workshops/2016/09/szo_16). Many white papers have also put a spotlight on specific regions that have had targeted experiments, such as Chile (**WP8**, **WP31**, **WP33**), Alaska (**WP13**, **WP22**, **WP49**, **WP60**), Mexico (**WP17**, **WP59**), Izu-Ogasawara (**WP24**), Indonesia (**WP30**), Central America (**WP32**, **WP34**, **WP54**), New Zealand (**WP26**), South America (**WP39**, **WP54**), Myanmar (**WP40**), Canada (**WP50**, **WP51**), Korea (**WP53**), and Tonga-Kermadec (**WP61**).

In many of these countries, there is already a strong intellectual and infrastructure investment into subduction zone science. Through collaboration, community-building, and investment in innovative observational and analytical techniques, the United States has the opportunity to leverage the existing resources, and be a leader in advancing subduction zone science on a global scale.

For example, the two primary subduction zones within U.S. borders, Cascadia and Aleutian-Alaska, offer many scientific and logistical opportunities for advancing subduction zone science, but a complete 4D model of subduction zone processes also requires focused study in parts of the world where the data to measure these processes are more readily accessible, or that display behavior not found in the continental United States (see **Box 7.2**). A full understanding of megathrust earthquake cycles requires detailed observations of the seismogenic zone, which is more easily accomplished when this part of the system can be monitored with onshore instrumentation or directly accessed through drilling and field studies, as is the case for the Osa or Nicoya peninsulas of Costa Rica (**WP4**) and the Hikurangi plateau of New Zealand, as opposed to being offshore as it is in Cascadia and the Aleutian-Alaska system. In another example, the frequency of eruptions has been low in the Cascades over the last decades, and while dozens of eruptions have occurred over the same time period in the Aleutian arc, most of these volcanoes are remote and difficult to access. Furthermore, many potential international partners have existing monitoring networks and data sets. These resources are a valuable means for extending the time scale of measurements of subduction zone processes. Formal collaboration will facilitate access to these resources, which may not be available to U.S. researchers through informal channels. Lastly, international partnerships can leverage worldwide social demands for hazard reduction, leading to additional options for funding, opportunities for USGS engagement, and motivation for E&O activities. Thus, there is significant consensus that achieving the goals of the ***SZ4D Initiative*** requires an international effort focused on targeted subduction zones around the globe as well as international partners to support this effort.

There are many examples of current large-scale subduction zone efforts that may offer opportunities for strategic partnering. Examples from which a program could perhaps emulate or build upon include those in Indonesia, Japan, and Chile (**Boxes 6.1–6.3**). In Indonesia, the Earth Observatory of Singapore at Nanyang Technological University is leading a multidisciplinary effort to investigate the seismic and volcanic activity of the Sunda subduction zone. These efforts include paleogeodetic studies, geophysical and tide-gauge monitoring networks, satellite interferometry, and strong collaborations with local Indonesian agencies and research institutions (**Box 6.1**). In Japan, an impressive base of scientific knowledge has been amassed by a strong research community from many different academic and government institutions, governmental investment in geophysical and geologic measurements, monitoring both onshore and offshore, and through international partnerships such as IODP (**Box 6.2**). In

TABLE 6.1. Countries with scientific institutions represented at the 2016 Boise SZO Workshop

North America	South America	Europe	Asia	Oceania
United States of America	Argentina	France	Bangladesh	Australia
Canada	Chile	Germany	China	New Zealand
Costa Rica	Colombia	United Kingdom	Indonesia	
Mexico	Ecuador		Japan	
Honduras	Peru		Korea	
	Venezuela		Myanmar	
			Singapore	

Box 6.1. Spotlight on the Sunda Subduction Zone

The Sunda subduction zone offshore Indonesia has been the source of some of the largest and deadliest historical earthquakes and eruptions, including four M>8 earthquakes since 2004 and the eruptions of Tambora in 1815 and Krakatau in 1883. Together these disasters have claimed hundreds of thousands of lives around the world. Currently, tens of millions of people live along this dangerous subduction zone.

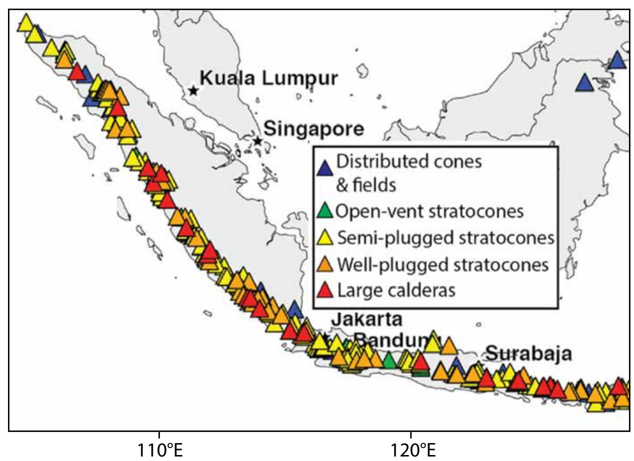
Extending for more than 3500 km, the Sunda system exhibits great contrasts along strike. Ancient Mesozoic oceanic lithosphere and pelagic sediments subduct beneath densely populated Java and Bali, where great earthquakes are absent from the historical record. In contrast, offshore Sumatra Cenozoic lithosphere subducts obliquely with a great load of turbidite sediments creating complex structures, including backthrusts, distributed deformation in the Wharton Basin, and a great strike-slip fault. Sumatra has a robust history and prehistory of major earthquakes. Paleogeodetic and GPS data collected on the chain of forearc islands indicate temporally and spatially variable coupling patterns, with great earthquakes bounded by persistent barriers to rupture that appear to coincide with subducting fracture zones. Despite these contrasts, moderate-magnitude, shallow tsunami earthquakes occur offshore both Java and Sumatra.

Volcanic activity varies greatly along the arc. The Java arc consists of two volcanic fronts, while Sumatra has a single front that lies along the Sumatran transform fault (A). Java hosts about twice the number of Holocene volcanoes per kilometer and twice the number of eruptions per volcano in the last 500 years compared to Sumatra. Large volcanic calderas are much more abundant in Sumatra than Java (B).

The reasons for such significant differences in earthquake and volcano behavior for Sumatra and Java remain elusive. Are they due to different convergence rates, differences in the obliquity of subduction, the presence of fracture zones, the age or dip or sediment load of the subducting plate, or the presence of fluids? Why is rupture segmented along Sumatra? Is the megathrust offshore Java locked or creeping? Both Java and Sumatra thus provide strategic targets for the ***SZ4D Initiative***. The Mentawai segment off Sumatra has been identified as a seismic gap, forecast for one or more large earthquakes in the coming decades (C and Box 7.3). Java lacks forearc islands from which to gather paleogeodetic information, but offshore measurements could test the locking vs creeping hypothesis (as in Figure 5.2). Seven volcanoes on or adjacent to Java have been identified from space as active sulfur emitters; all of these volcanoes have erupted in the past 10 years and are strategic targets for capturing events prior to eruption.

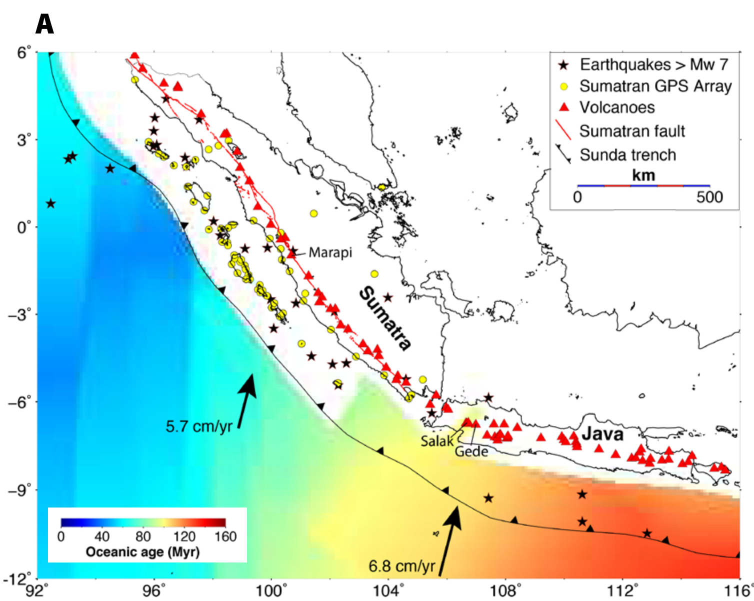
The Earth Observatory of Singapore (EOS) at Nanyang Technological University is currently carrying out geological, geochronological, geophysical, and geodetic studies of the seismic and volcanic activity of the Sunda region (WP30). EOS together with CVGHM (Center for Volcanic and Geologic Hazards Mitigation, Indonesia) have focused investigations on volcanoes closest to the capital Jakarta (Gede and Salak) and the most active volcano in Sumatra (Marapi; see A). The monitoring network includes more than 10 broadband seismometers, seven GPS stations, and soon two multigas stations. In collaboration with the Indonesian Institute of Sciences (ILPI), EOS has also operated a 50-station GPS array in Sumatra (figure, bottom left). Future efforts require strong collaboration with Indonesian agencies such as BMKG (which operates seismic networks) and BIG (which operates additional GPS and tide-gauge networks), in addition to ILPI and CVGHM.

B



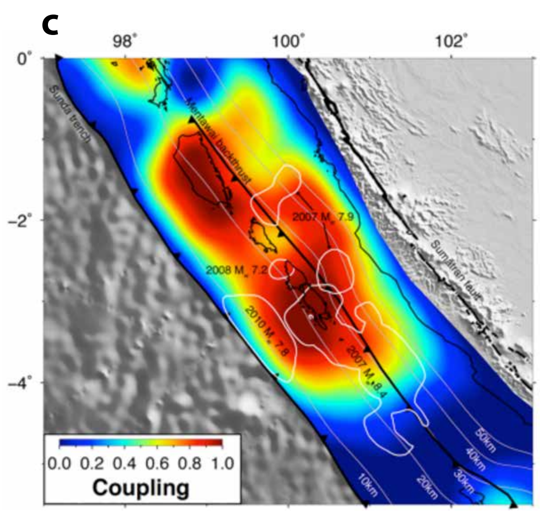
Young volcanoes of Sumatra and Java. Javan volcanoes are more closely spaced and have been more active than Sumatran volcanoes. More large calderas occur on Sumatra. *Credit: Kerry Sieh*

A



Major faults and volcanoes of the Sunda subduction zone. Continuous GPS stations from the Sumatran GPS Array (SuGAr) are marked in yellow. *Figure by Rino Salman*

C

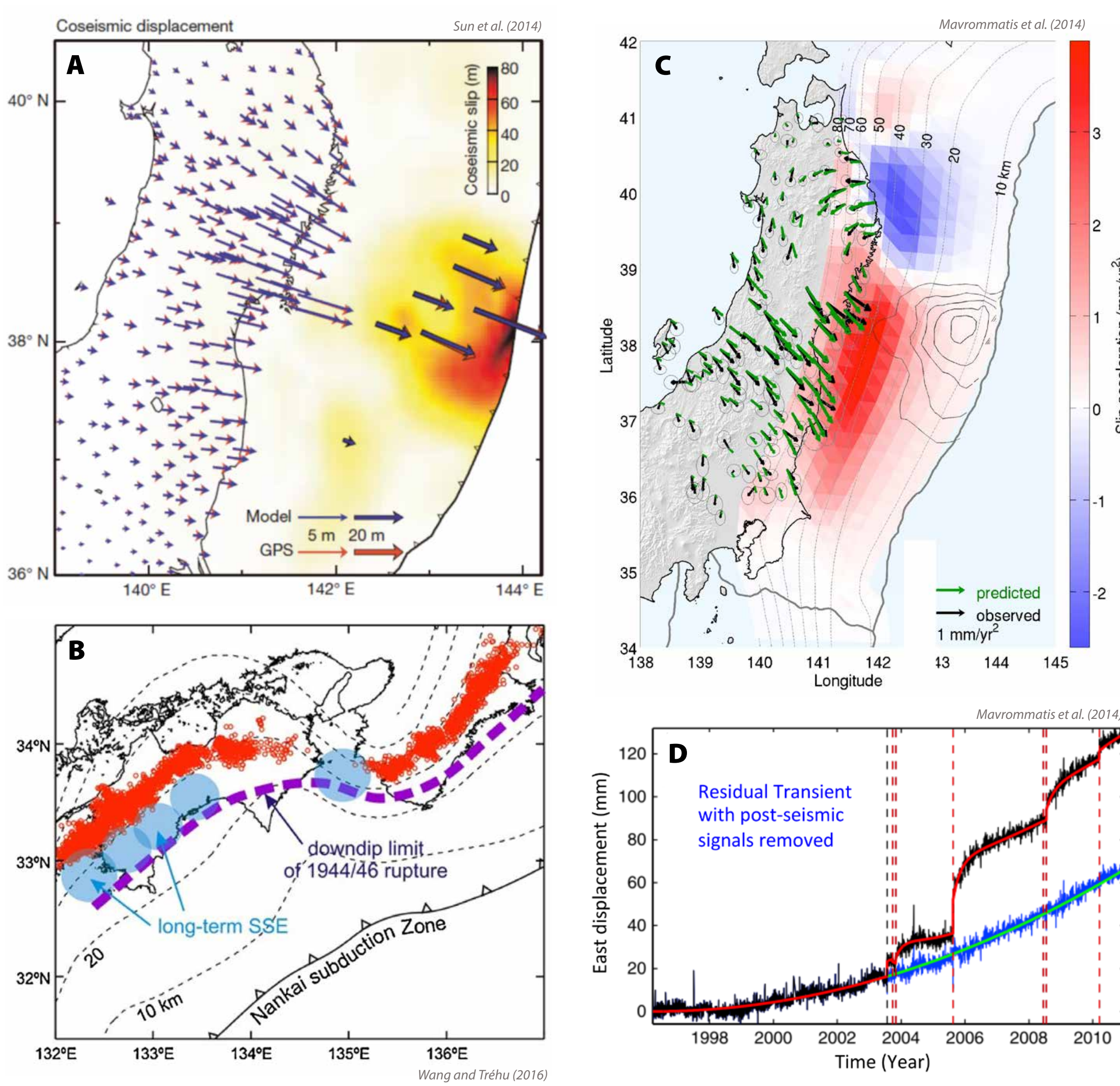


Estimated coupling ratio for the Mentawai patch (from Chlieh et al., 2008), and locations of recent rupture patches (outlined by white contours). *Figure by Rino Salman*

Box 6.2. The Japanese Subduction Zone Observatories

High-resolution, multidisciplinary, onshore-offshore, multidecadal

Following the devastating 1995 Kobe earthquake, Japan committed to a major investment in its geophysical monitoring networks covering the entire country. The combination of the GEONET GPS, the HINET borehole seismic and tilt, and the Knet and Kiki net strong motion arrays, each with over 1000 sites, has lead to an unequaled ability to capture earthquakes such as the GPS displacement field from the 2011 M9 Tōhoku earthquake (A). They also led to the discovery of widespread slow slip and seismic tremor in subduction zones (B; see also Box 2.2). The scientific value of these networks is growing ever greater. For instance, analysis of the ~15+ years of GEONET GPS data has revealed that the distribution of plate locking was not static, but instead was evolving rapidly in the decade before the M9 Tōhoku earthquake as the slip rate accelerated on the deep part of the fault (C and D). This fundamental quantity for understanding fault mechanics and seismic hazard has now been shown to dynamically evolve. More recently, Japan expanded their observatories offshore (see Box 7.5). The Japanese scientists at the SZO workshop stressed that their approach considered the demands of society first (e.g., hazard estimation, warning, risk reduction) in designing the observatories but that cutting-edge science experiments were devised to contribute to these goals, and new discoveries resulted from this investment.



Chile, a series of geophysical observatory networks have been developed through strong international collaborations, particularly with German and French research partners and with other partnerships supported by the Chilean government and U.S. National Science Foundation funds awarded through IRIS (**Box 6.3**). These networks have enabled characterization of the subduction zone and have integrated well with many other local and internationally led studies within the region. No global organization currently exists to coordinate these different activities. The ***SZ4D Initiative*** is thus poised to lead the coordination of existing observational efforts as well as plan new targeted ones with international partners.

There are clearly many different models for developing successful collaborations and international partnerships. Given the specific scientific objectives of ***SZ4D***, there is potential to develop several new productive partnerships. Success in previous and existing programs has come largely from leveraging social demands for hazard reduction. In identifying potential international partners, it may be advantageous to focus on the science-society connections associated with subduction-related processes.

The keys to establishing successful international partnerships under the auspices of ***SZ4D*** include careful planning for coordination of data collection efforts, integration of analytical results and interpretations, and dissemination of results to various stakeholders. International partnerships should be mutually beneficial, involve significant capacity building as needed (see **Section 8.4**), and support the efforts led by key partner institutions. Additionally, data sharing must be balanced (reciprocated) and open. Formal international consortia, such as the IODP and InterRidge, are good models for effective international coordination, including identifying multinational funding sources (e.g., USAID, the World Bank, private foundations), providing guidance and coordination, and organizing local facilities and resources. Memoranda of Understanding will be vitally important for standardizing policy on data and sample collection logistics, data and sample sharing and analysis, study authorship, training and knowledge/technology transfer, capacity building, and rapid event response. Such agreements can exist on multiple levels made at different stages in an international partnership as appropriate, from the national, to the institutional, to individual PI levels.

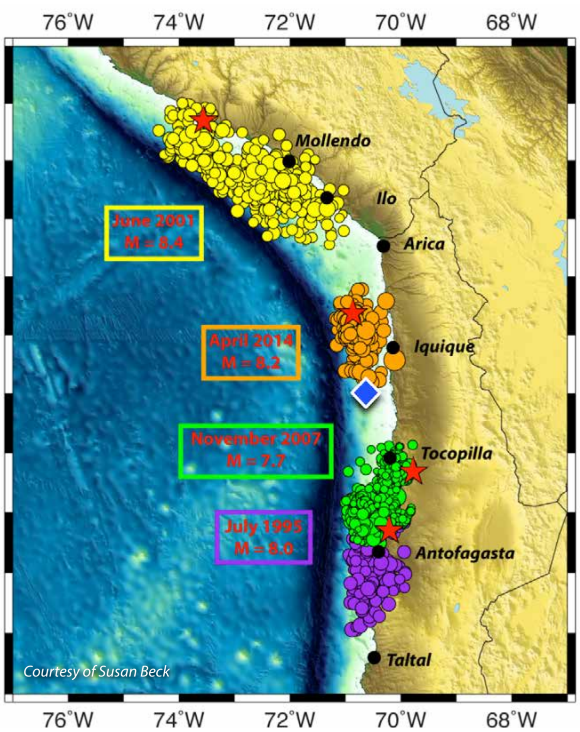
Box 6.3. The Chilean Subduction Zone Observatories

Enabling rapid response, capturing great earthquakes through international cooperation, and producing breakthrough science

Subduction of the Nazca Plate regularly produces great earthquakes along the Peru-Chile Trench (A), including four earthquakes with magnitudes >7.5 in the last three years. These events have been locally recorded by an unprecedented number of strong motion, broadband, and geodetic instruments, allowing detailed characterization of the source properties at their pre-, co-, and postseismic stages. This capability is the result of a combination of efforts: (1) the decision by the government to invest in a state-of-the-art standardized network composed of 65 multiparametric stations (broadband and strong motion sensors), 130 Global Navigation Satellite System (GNSS) devices, all of them to be connected in real time, complemented by 297 accelerographs (for site assessment), together with the communications and processing systems; (2) strong international collaboration, evidenced by the initiatives of the Integrated Plate Boundary Observatory Chile (IPOC), an effort conducted in northern Chile by GeoForschungZentrum (GFZ) Potsdam with 16 multiparametric stations and the Institute de Physique du Globe de Paris with additional four stations, and Geophysical Research Observatories (GRO) with 10 multiparametric stations (effort funded by IRIS-NSF and installed in Chile with the financial help of the government); and (3) the operation of these facilities by a well-developed, capable local group of seismologists and engineers, together with the implementation of procedures, protocols, and metrics for network operations and maintenance. The resulting scientific studies have captured large earthquakes and tsunami excitation in great detail (D).

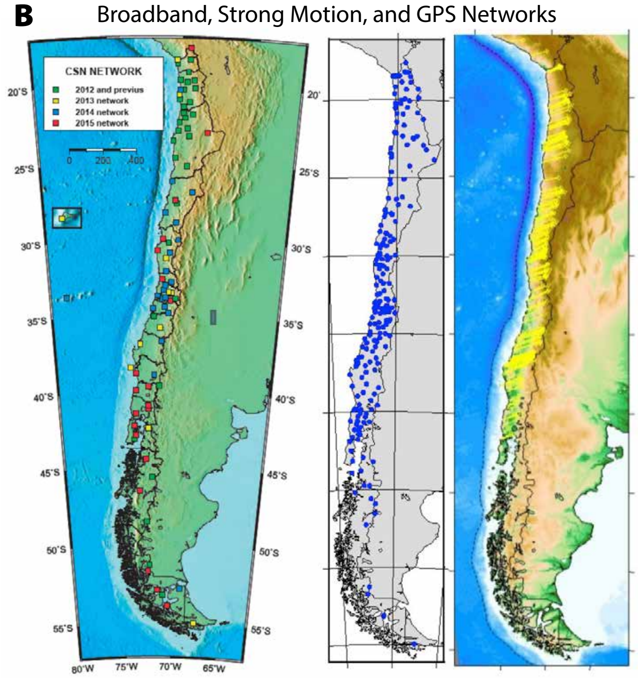
Most of rupture regions of large earthquakes in Chile are located offshore, up to 100–150 km away from the coast (A, D); therefore, almost the whole observation system lies on one side of the object of study. Better characterization of seismic sources, of their tsunamigenic potential, as well as detection of possible preseismic deformation requires augmentation of the seismic and geodetic observation system to the seafloor, directly above the seismic sources (C). The GEOSEA geodesy array off Iquique led by GEOMAR (blue diamond in A) represents an initial effort in this direction. Future efforts should be focused along these lines and, if the system provides data in real time, it will be able to provide improved early warning of events.

A



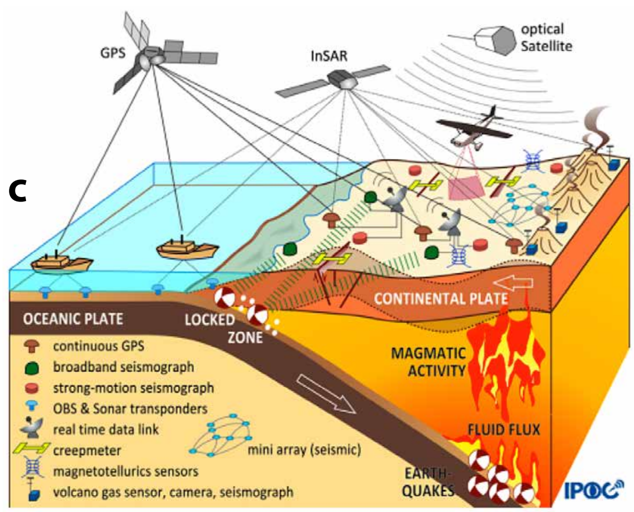
Courtesy of Susan Beck

B Broadband, Strong Motion, and GPS Networks



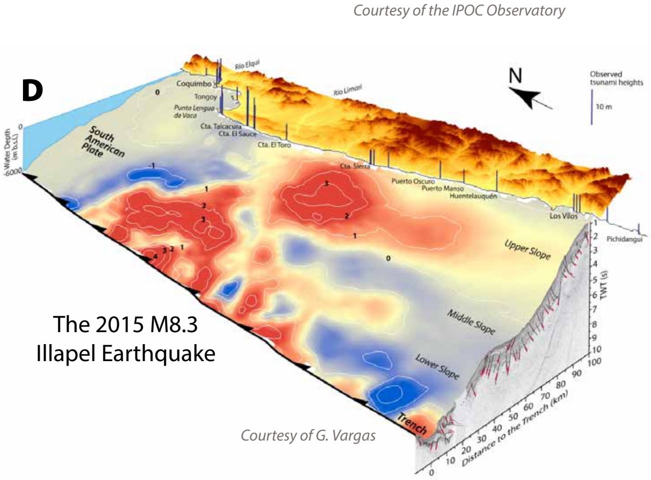
Courtesy of Sergio Barrientos

C



Courtesy of the IPOC Observatory

D



Courtesy of G. Vargas

7. Community Infrastructure and Implementation Strategies

7.1 Overarching Infrastructure Strategies

Fundamentally, the ***SZ4D Initiative*** needs both a *physical* infrastructure and an *intellectual* infrastructure. A viable ***SZ4D*** will require a number of key ingredients:

- A consensus on the **key problems** to be attacked and the means of attacking them, developed by the community of researchers
- A network of **in situ observational technologies** with freely accessible and suitably packaged data streams
- A capability to support **focused field experiments** and/or campaigns
- Access to and support for **laboratory facilities** for geochemical and geochronological analyses as well as mechanical experiments
- A **modeling effort** to integrate data with cross-scale, process models for improved understanding of the entire system dynamics
- A **data infrastructure** to ensure the availability, accessibility, and open distribution of the products of the entire effort

In developing an adaptable and multifaceted ***SZ4D*** plan, no matter what shape it takes, the following principles will need to be considered. First, the plan should include a balance between **broad vs. focused** experiments and networks of observatory instruments. Broad swaths of subduction zone geography can be addressed though development of "**backbone**" suites of observations and deployment of tools (e.g., see **Box 6.2**), allowing a wide spectrum of geological/geophysical variability to be captured, with **concentrated and/or rapid response efforts** targeting specific focus regions or corridors (or even non-geographically localized themes). This will permit the broadest possible buy-in and scientific interest; enhance the likelihood of capturing important events such as an eruption, megathrust earthquake, or major landslide; and get dense enough, multidisciplinary information from the focus areas to intensively zero in on specific key questions from the borehole or outcrop up to the regional level.

Second, the array of both broad and focused activities should be designed in a fundamentally inclusive, **interdisciplinary** way. Geophysical instrumentation networks for seismology and geodesy are an important element; equally so are geochemical sampling, geomorphologic and surface process experiments and networks, geological and geophysical field-based studies, and integrative modeling efforts. An implementation plan should be developed to optimize across all of these needs to ensure versatility. **Focus sites** in particular should be selected to create compelling scientific opportunity across the range of interested disciplines.

Third, infrastructure for ***SZ4D*** will involve a mix of activities in a nested timeline, from ones that are critical for **immediate technique development** to others that build for **future major infrastructure**. One immediate focus should be on critically needed technical development, examples of which include new and more cost-effective seafloor geodetic systems and standardized volcano networks. It was clear from workshop discussions that consensus is already strong that such instrumentation should be a major element of ***SZ4D***, and that the community is poised to rapidly advance both of them. Such development efforts, already underway, can be incorporated as "kickstarter" first activities of a nascent ***SZ4D Initiative***.

Finally, over the decade or longer duration envisioned for the ***SZ4D Initiative***, a key element will be a **community leadership structure** that ensures that the relationship between the intellectual and physical infrastructure is flexible and efficient in producing the community-scale efforts that are most scientifically fruitful.

Specifying the implementation plans for the ***SZ4D Initiative*** will require considerable planning and oversight efforts that must remain transparent and community driven. While the SZO workshop was not intended to produce an implementation plan, it provided numerous examples of the scale and types of efforts that could advance our understanding. In the rest of this section, we describe a number of these potential classes of efforts.

7.2 Physical Infrastructure

Although detailed implementation strategies for physical infrastructure will need to be developed, strong consensus was apparent during the workshop on some of the key elements. Inspired by the success of EarthScope, there was considerable support for a program that provides (1) community-scale, open, quasi-permanent backbone observatories and (2) the opportunity to access tools and instruments for specific, PI-level, targeted data collection.

Backbones. From trenches to volcanoes, a suite of field-deployed, quasi-permanent sensing systems will be needed to collect time-series data on active processes. The backbone may include, for example, seafloor geodetic (acoustic-GPS and pressure) and seismometry elements in a network (e.g., see **Figure 2.1** and **Box 6.2**), ideally with real-time (or at least minimal-latency) data transmission capability and potentially including borehole-based observatories, to be used to detect elastic strain accumulation and its release on a wide range of spatial and temporal scales (e.g., locking, slow slip, and tremor events). Onshore, existing geodetic and seismic networks aimed at capturing deformation related to the earthquake cycle (e.g., EarthScope Plate Boundary Observatory) could be enhanced and expanded to other countries, similar to the efforts already taking place in Chile (see **Box 6.3**, **WP6**). At the volcano scale, new SAR missions such as NISAR with weekly coverage will greatly enhance deformation measurements, and should be supplemented with a suite of multidisciplinary ground-based instrumentation described below.

The gold standard today for backbone instrumentation of the offshore forearc region is in Japan's two major subduction zones (see **Box 6.2**). The S-net cabled array in the Japan Trench and the DONET arrays in the Nankai Trough (see **Box 4.6**) represent an investment of hundreds of millions of dollars and are even now transforming how we understand strain accumulation, locking, and coseismic tsunamigenic displacement during megathrust earthquakes. Because every subduction zone presents a unique set of physical conditions, these two deployments are not enough. They do not even come close to sampling the range of possible subduction megathrust fault systems, nor do they meet the requirements for a geographically distributed portfolio to ensure the recording of major events. By deploying an advanced offshore array in one or more additional complementary subduction zones, ***SZ4D*** can leverage and be informed by the pioneering Japanese efforts (**WP16**, **WP19**, **WP25**, **WP27**, **WP31**, **WP33**, **WP38**, **WP58**). DONET, S-net, and related systems in Japan provide ***SZ4D*** with major points of comparison *and* an excellent head start.

Campaign Efforts. Complementing the backbone observatories would be a mechanism to support focused campaign efforts to conduct more detailed or targeted investigations. Examples could include a dense array geophysical deployment on a volcanic system like the imaging Magma Under St. Helens (iMUSH) experiment, 2D and/or 3D seismic reflection and magnetotelluric (MT) surveys, and a sampling and mapping effort for the volcanic geology, gas emission, and deformation like ongoing work at Okmok Volcano (see **Box 7.1**). Partnership campaign efforts are also envisioned, such as IODP expedition(s) to obtain samples, measure critical in situ properties, and install long-term borehole instrumentation and observatories. Campaign efforts will require a funding mechanism for PI-driven projects rooted in an overarching framework of scientific goals, as exemplified by GeoPRISMS and the Flexible Array arm of EarthScope's USArray.

Access to certain facilities, even if they're not necessarily dedicated solely to ***SZ4D***, will be critical to enable these envisioned campaign efforts. In the marine setting, the program will need to have access to surface vessels for instrument deployment, retrieval, and seafloor observation (including deep submergence, autonomous underwater vehicle [AUV] and/or remotely operated vehicle [ROV] access, **WP41**). A pool of modern broadband ocean bottom seismometer/ocean bottom pressure (OBS/OBP) instruments will need to be available to the program, along with other emerging seismic and geodetic technologies. Equally critical is a capability for high-resolution seabed (bathymetry and backscatter) and subsurface (seismic reflection and refraction, and electromagnetic) imaging (**Box 4.5**, **WP15**). We also need assured continued access to a seafloor deep drilling capability as well as vessels and tools that can flexibly and/or autonomously download data from seafloor instruments, likely including AUVs/ROVs and autonomous gliders (**Box 4.4**, **WP11**).

7.3 Examples of Implementation

A wide range of specific examples of physical infrastructure implementation strategies were discussed at the SZO workshop as a means to attack big science questions with new approaches.

Seafloor Observations. There is widespread recognition of the need to improve offshore observations, especially geodetic ones. Continuous, long-term measurements close to the plate boundary are required to resolve some of the most fundamental problems presented in **Section 2.1**. For instance, the physical mechanisms driving foreshock swarms and their hypothesized precursory significance could be addressed using a hemisphere-scale backbone (**Box 7.2**), while understanding megathrust late-stage interseismic behavior, rupture, and tsunami generation could be studied by targeting seismic gaps (**Box 7.3**).

A Rapid Response Facility. The workshop discussions emphasized flexibility and the ability to respond to events of opportunity, whether to collect volcanic ash, monitor and map a landslide, study earthquake triggering, immediately observe post-seismic geodetic/seismic signals, or detect geomorphic stress, fluid flow, or other temporal changes associated with major earthquakes and tsunamis (**WP7**). In light of the reality that many of the best opportunities could occur anywhere around the globe, there was considerable support for a formal

7.1. Arc-Scale Volcano Observatories

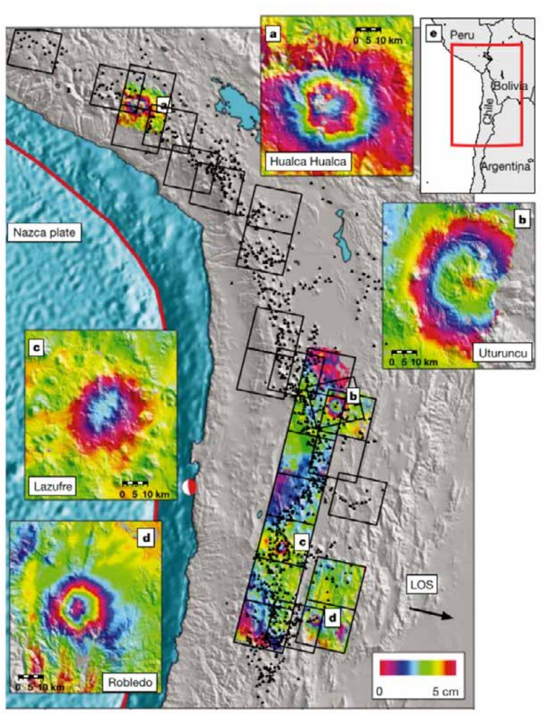
For fundamental understanding of magma transport rates and volcanic eruptions

Arc magmatic systems connect mantle melt production regions above subducting slabs to volcanoes at the surface. Few studies capture the dynamics of arc magmatic systems in four dimensions, on a whole-arc scale, from beneath the Moho to gas plumes in the atmosphere, and over minutes to millennia. Ground deformation detected by remote sensing (A) and seismicity in the lower crust and mantle (B) reflect magma movement in the upper mantle and crust. Coupled with information on gas (C) and groundwater chemistry, seismic and magnetotelluric tomographic images (Figure 2.2), and chronologies and chemistries of erupted products (D), these observations can constrain transport rates and the character of recharge events in the run-up to eruption. Such coupled data sets exist for very few volcanoes worldwide, and nowhere currently at the scale of an arc or segment, where there is an opportunity to connect magmatic and eruptive processes to along-strike variations of the subduction zone.

Arc-scale observations could be made by a sparse backbone "vanguard" network coupled with a rapid-response instrument cache (Box 7.3). Simultaneously, the most frequently active volcanoes within the arc could be observed with dense networks of modern seismic, geodetic, magnetotelluric, groundwater, and gas-detection instrumentation. Continuous ash collection and development of volcanic-plutonic chronologies would then connect instrumental measurements to magmatic products through time.

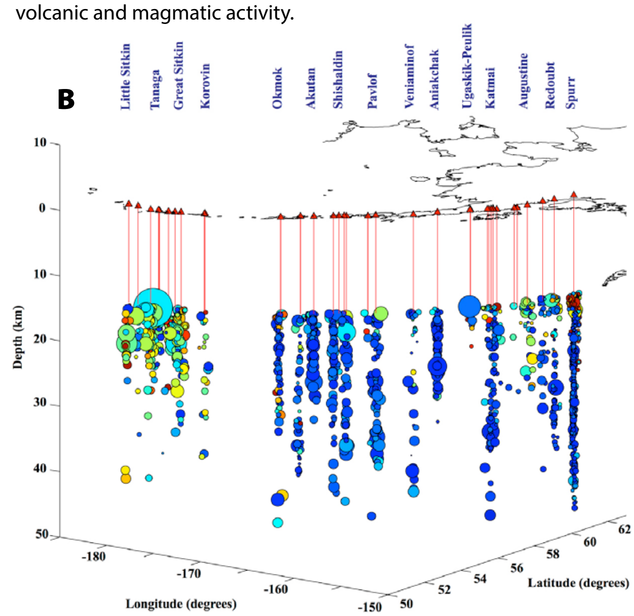
There is substantial opportunity for ***SZ4D*** to couple with existing volcano observing efforts by national volcano monitoring agencies such as the USGS or by private consortia such as the Deep Carbon Observatory's Deep Earth Carbon Degassing (DECADE) initiative (C) to develop research-grade arc-scale volcano observatories capable of providing high-fidelity observations of the complete spectrum of volcanic and magmatic activity.

A



(A) Arc-scale detection of volcanic deformation in the central Andes from 1992–2000 using satellite-based synthetic aperture radar interferometry. Black triangles show 1,113 volcanic edifices, four of which (insets a–d) were found to be actively deforming. *From Pritchard and Simons (2002)*

B

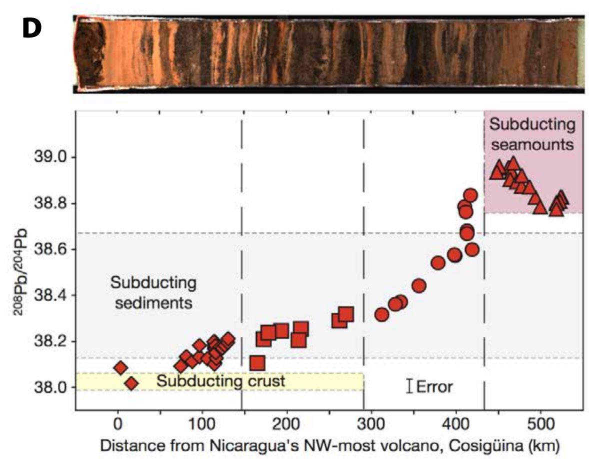


(B) Lower crustal and upper mantle seismicity beneath volcanoes along the Aleutian arc. The history of these sequences suggests a link between volcanic unrest and deep magmatic processes that occurs on time scales of weeks to months. *From Power et al. (2013)*

C

(C) Deployment of a multi-gas sensor at Masaya Volcano, Nicaragua, as part of the Deep Carbon Observatory's DECADE initiative. *Photo credit: Alessandro Aiuppa and Marco Liuzzo (INGV)*

D



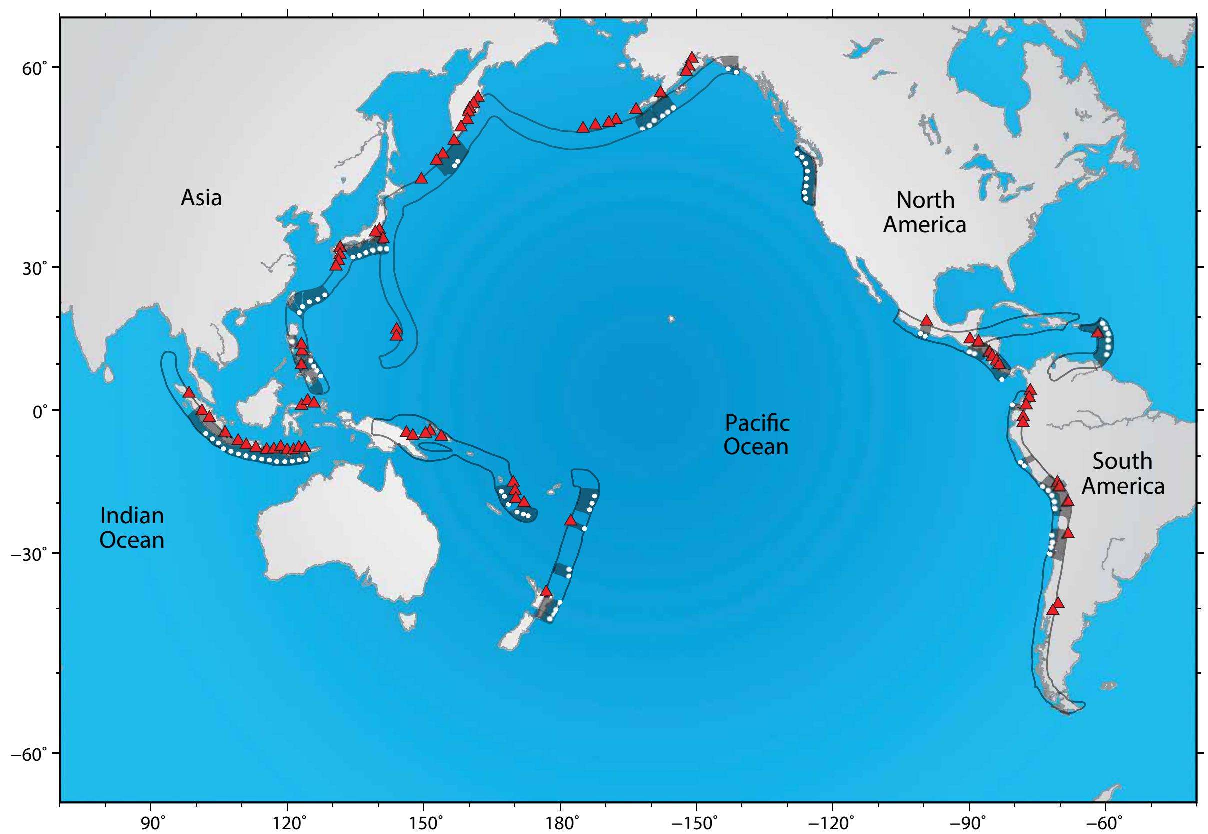
(D) Lake core (0.5 m) of last ~1500 years of explosive eruptions (dark layers) at Akutan Volcano, Aleutians. Pb isotope variations in Nicaragua-Costa Rica lavas observed 500 km along strike. *From Hoernle et al. (2008)*

Box 7.2. Measuring Deformation Offshore and Volcanic Degassing at Many Subduction Zones

Measuring Deformation Offshore Prior to Large Earthquakes. Does the plate begin to move weeks before a very large subduction zone earthquake as recent observations in Japan and Chile suggest? The only definitive answer to this question will come from measuring deformation and recording seismicity offshore prior to a magnitude 8 earthquake. Knowing which plate boundary will next have a magnitude 8 earthquake is difficult, if not impossible, given our current knowledge. Thus, instrumenting a single subduction zone in the hope of capturing such a large earthquake has a low probability of success. In addition, to ensure that we understand the significance of any apparently precursory signals, offshore recordings of multiple earthquakes are needed. Measuring a sufficiently large number of subduction zones increases the odds of collecting key data.

The Pacific Rim encompasses nearly 20,000 km of arc length. Over this zone, 14 magnitude 8 or greater earthquakes have occurred in the first 16 years of the twenty-first century. Therefore, if the Pacific Rim arcs were instrumented in entirety for at least 10 years, the chances are very high that multiple magnitude 8 earthquakes would be captured. The study zones required can be reduced by noting that recent large earthquakes preferentially occur in defined seismic gaps (see Box 1.5). Limiting instrumentation to established seismic gaps that have not yet had major earthquakes would reduce the required arc coverage more than a factor of two. Because magnitude 8 earthquakes have rupture lengths of a few hundred kilometers, 100 km spacing may be sufficient for the task (i.e., fewer than 100 stations; see figure).

Measuring Volcanic Degassing at Persistently Restless Volcanoes. Are eruptions preceded by distinctive changes in gas chemistry that can be used to develop better forecasts? The recent deployment of near-real-time gas sensors on several volcanoes has shown increases in CO_2/S ratios weeks prior to eruption (as at Etna, Box 2.3 and Turrialba, Box 4.1), a signal of magma rise from depth. How common is this precursory signal and does the timing vary from volcano to volcano? Answering these questions within the scope of an ***SZ4D Initiative*** requires instrumenting volcanoes that will degas and erupt over the next decade. A compilation of satellite measurements from 2005–2015 identifies ~90 volcanoes worldwide that passively degas sulfur (Carn et al., 2017). All but six of these volcanoes occur at subduction zones, and the vast majority of these volcanoes have erupted in the last 10 years. These are the persistently degassing and erupting volcanoes, and most of them are minimally instrumented. Only about 15 volcanoes worldwide are currently instrumented for high-rate (~1/10 seconds) CO_2/S measurements. A decadal program could target all ~80 of the degassing volcanoes in the map below for at least daily gas measurements of CO_2/S and a seismic network of at least six instruments. This modest level of instrumentation has been shown to have a dramatic effect on the accuracy of forecasting eruptions (see Figure 3.3). When coupled with geodetic and petrological measurements, such a campaign represents not only a tremendous opportunity to learn about the fundamental questions of magma and gas fluxes at subduction zones, but also of unquestioned benefit to populations living near persistently active volcanoes.



A conceptual map of a possible deployment strategy focusing on established subduction zone gaps and degassing volcanoes. Shaded areas are high-likelihood seismic gaps from Figure 1.5 that have not yet had major earthquakes, and white dots are 80 possible stations that could potentially provide coverage should a large earthquake occur in the region. Red triangles are ~80 volcanoes that emit sulfur, as measured by satellite from 2005–2015 (Carn et al., 2017). The vast majority of these volcanoes have also erupted in the last 10 years. Modest instrumentation of these persistently active volcanoes could dramatically improve our ability to both predict eruption (Figure 3.3) and track magma movement and volatile fluxes from the subduction zone. There is no implied relationship between the seismic gaps and the degassing volcanoes, but both are strategic targets for the ***SZ4D Initiative***. *Figure courtesy of T. Lay, E. Brodsky, and T. Plank.*

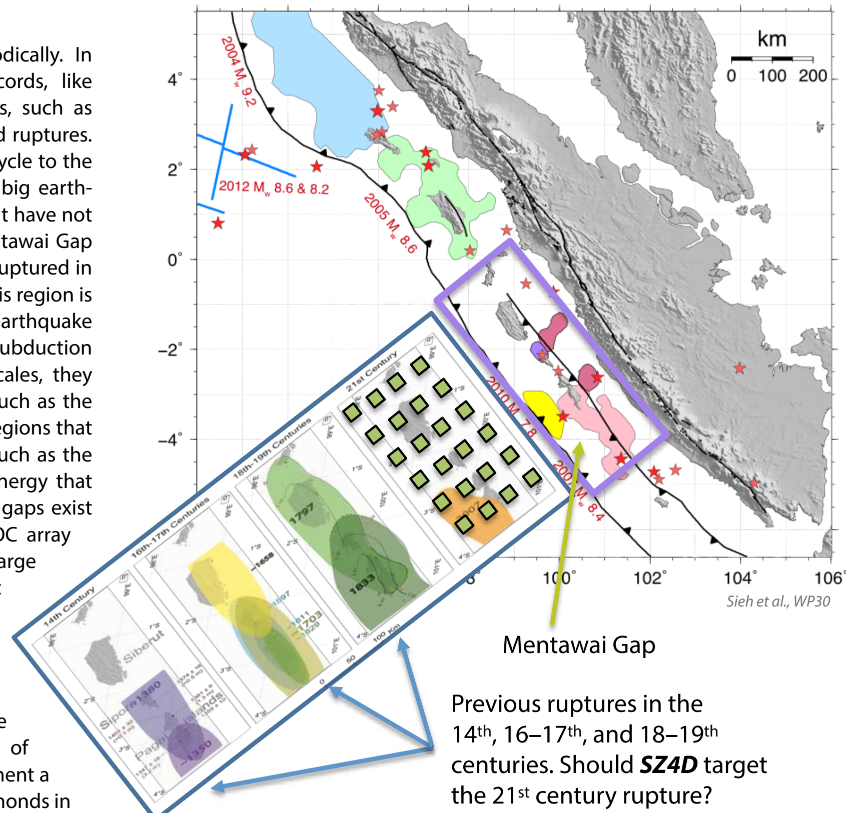
Rapid Response Facility (RRF) that could facilitate such efforts, patterned after the logistical support currently provided for deployments by such entities as the PASSCAL Instrument Center, UNAVCO, or forward deployment of resources at McMurdo Station (**Box 7.4**).

Marine Imaging. Dense survey data are central to imaging fault structure, fluid production and migration, and magma storage. Recent advances in active source electromagnetics are particularly exciting, opening new possibilities for understanding fluid/melt distribution (see **Boxes 2.3 and 2.4**, **WP52**). The new capability for long-offset (>15 km) active source seismic imaging using R/V *Langseth* promises to reveal ever sharper images of major structures to greater depths than previously possible (**Box 4.5**); seismic images of the subduction zone fault systems and stratigraphy are a requirement for placing any study of the offshore region in appropriate context and siting any allied drilling projects. High-resolution seismic

Box 7.3. Seismic Gap Observatories

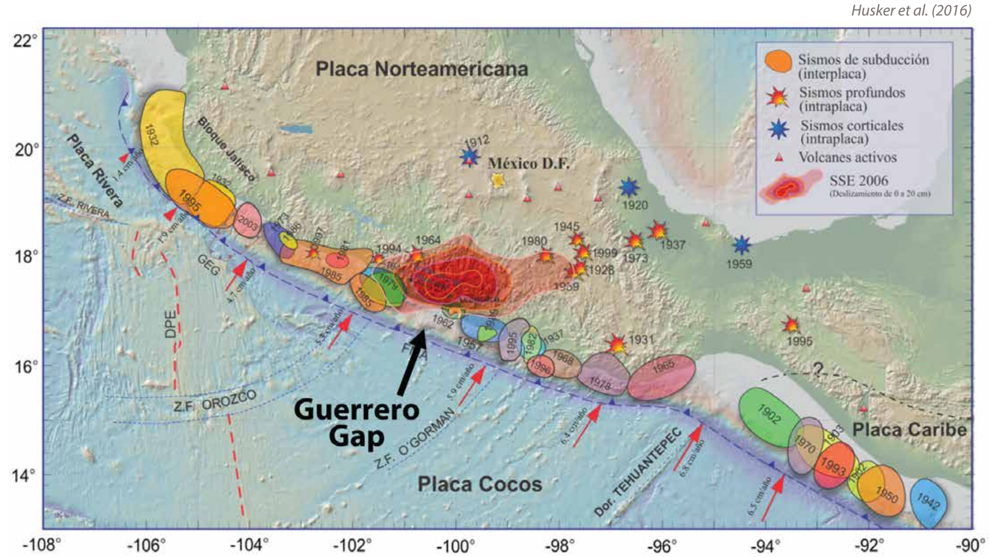
Subduction zone earthquakes occur quasi-periodically. In locations with either outstanding historical records, like Nankai, Japan, or outstanding geological records, such as Sumatra or Cascadia, there is evidence of repeated ruptures. The details of the rupture may change from one cycle to the next, but the clear implication is that to catch a big earthquake, it is best to put instruments in locations that have not had a rupture for centuries. For instance, the Mentawai Gap offshore of Sumatra (figure, right) has repeatedly ruptured in sequences of M8 earthquakes every ~200 years. This region is immediately adjacent to the 2005 M8.6 Sumatra earthquake and has not had a large event since 1833. When subduction plate boundaries are viewed on century time scales, they often appear to be "tiled" by great earthquakes, such as the last ~150 years in Mexico (see figure below). The regions that have not had a large rupture in that timeframe, such as the Guerrero Gap, have likely stored up significant energy that could be released in the coming decades. Similar gaps exist in Chile and possibly southern Cascadia. The IPOC array in Chile (Box 6.3) used this strategy to capture large earthquakes with onshore seismic and geodetic networks.

Many seismic gaps are 200–400 km long, and the expected ruptures are mostly offshore. To have a high probability of catching the next large rupture with a multidisciplinary, onshore/offshore array requires a commitment on the time scale of decades. A coordinated global approach to instrument a portfolio of these with tens of sites (e.g., green diamonds in figure, right) may be the best way to capture a large rupture and the generation of a tsunami.



Sieh et al., WP30

Husker et al. (2016)



reflection surveys can enable examination of upper plate fault slip at the resolution of individual events. High-resolution bathymetric data make possible studies of the evolution of the seafloor as a surface process, and repeat surveys as a rapid response tool can quantify tsunami sources. Surveys require appropriately equipped ships as a community infrastructure resource; ready access and international coordination are particularly important for repeat surveys to capture coseismic deformation or fluid transients.

Volcano Networks. The study of volcanoes over the life cycle of an eruption requires dense, standardized instrumentation that allows comparisons between systems. A suite of volcanoes with equivalent instrumentation, open data access, and professional data management could solve long-standing problems, including correctly identifying eruption precursors (**WP14**). A nested approach is appropriate, with a sparse backbone "vanguard" network that monitors an entire volcanic arc (**Box 7.1**) coupled with a subset of volcanoes with concentrated instrumentation (**Box 4.3**, **WP12**) and a rapid response

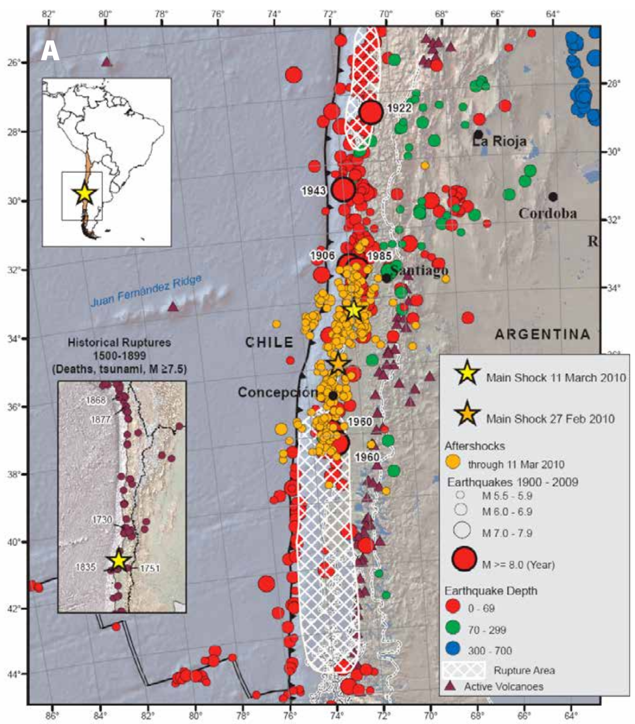
Box 7.4. Rapid Response Protocols

Planning for the collection of critical ephemeral data in subduction zones

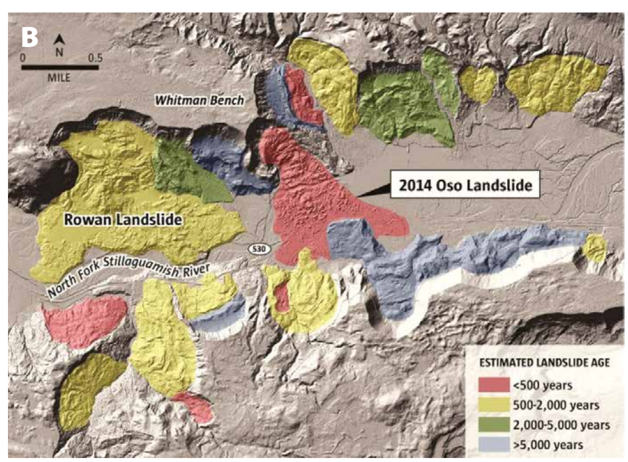
Improving understanding of many hazardous subduction zone phenomena requires extremely rapid responses to key events to collect ephemeral observations. Following major earthquakes (A), detailed study of post-seismic deformation (e.g., aftershocks, slow slip) is necessary to constrain the co- and postseismic fault slip, stress transfer processes, the response of the crust and mantle, and more. In the run-up to and aftermath of major volcanic eruptions (C), observations of precursory and syneruptive microseismicity, gas emissions, and ground deformation are necessary to understand magma storage and ascent conditions. Collection of ash samples, which often erode within days of deposition, is necessary to obtain petrological constraints on magma storage and ascent conditions. In the run-up to and aftermath of major landslides (B), assessment of evolving climatic conditions, slope morphology, and mechanical properties of geologic materials is necessary to understand failure and stabilization processes.

Challenges to the timely collection of these types of critical-yet-ephemeral observations include procurement and transport of scientific instrumentation, logistics (e.g., customs), and safe access to often hazardous and inaccessible field sites. This is particularly true offshore. Advanced planning and coordination is thus key, and can be facilitated by an ***SZ4D***. Rapid-response instrument caches can be staged in-country, and agreements can be made with in-country or local partners for their timely deployment.

There is substantial opportunity for the to develop new technologies and protocols that will make rapid response more feasible and productive (e.g., economically deployable submarine gliders). Under the auspices of ***SZ4D***, preplanned "wish lists" of observations and samples can be developed in advance so that responders have guidance for maximizing the scientific return from their efforts.



(A) 2010 Maule, Chile, M8.8 earthquake. Topographic map with earthquake source model and aftershocks. *Figure credit: USGS*



(B) Map showing the extent and age of the 2014 Oso, Washington, landslide and similar landslides in the region. *Figure credit: University of Washington*

(C) Ash from the 2016 eruption of Pavlof Volcano, Alaska, coating a vehicle in the nearby village of Nelson Lagoon. *Photo credit: Barrett Taylor* instrument cache (**Box 7.4**). This approach would permit study of topics ranging from the overall volatile cycle to the dynamics of individual eruptions.

Quantifying the Transient and Permanent Strain Budget in the Upper Plate. On land, high-resolution and repeat-acquisition topographic data from LiDAR, drones, and SAR are now making possible measurement of transient and ongoing signals (**Boxes 4.9 and 7.5**). Similarly, advances in sonar technology enable higher resolution seafloor mapping such that changes in forearc topography can be directly measured after a subduction zone event, as was shown for the Tōhoku M9 tsunamigenic earthquake. Improvements in ocean bottom pressure sensors permit analogous data to be collected offshore so that changes in bathymetry associated with tectonic strain can be detected.

Laboratory Experiments to Illuminate Subduction Processes. Allied with the field campaigns, a similar concerted laboratory effort will be required to address many of the essential processes that drive subduction phenomena. For example, drilling projects, including the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), JFAST, and San Andreas Fault Observatory at Depth (SAFOD) have provided samples and a framework for laboratory mechanical friction experiments (along with many other physical properties) that have led to breakthroughs in understanding the physics of locking, seismic slip, transients, and conditional behavior. At deeper levels on the plate interface, laboratory experiments are needed to elucidate the pressure and temperature of dehydration reactions, and the physical properties and mechanics of porous, deforming, reacting media. An experimental gap exists in the very region where slip transitions from seismic to aseismic, requiring new equipment and approaches to access this critical zone (**Box 7.6**). An outstanding challenge in experimental petrology is the development of accurate geobarometers, sorely lacking for volcanic/plutonic systems, that would constrain the depths of magma stalling and storage.

Geochronology. As a program that focuses on 4D observations, time series, and temporal evolution, ***SZ4D*** requires geochronology. A rich variety of approaches are needed to access the 4D evolution of the subduction system (**Box 3.1**), from the minutes to years of magma ascent recorded in the chemical zonation of volcanic crystals (**Box 2.3**), to multidecadal geodetic signals across earthquake cycles from coral stratigraphy, to thousands of years of tectonic denudation recorded in cosmogenic isotopes from the land surface, to arc crust construction over millions of years from radiogenic isotopes in crystals. Real-time observations must be integrated with long time series to fully capture the dynamics of tectonic and volcanic systems. Geochronological labs are distributed widely and require coordinated partnerships with ***SZ4D*** observationalists, modelers, and theorists.

7.4 Intellectual Infrastructure

Through integration of the wide range of scientific disciplines represented by ***SZ4D*** researchers and development of overarching objectives, the ***SZ4D Initiative*** will address broader scientific problems and achieve greater outcomes than individual researchers can accomplish alone. Individual research projects will benefit from integration within the larger umbrella afforded by this collaborative structure. The ***SZ4D*** should put into place a framework that makes this interdisciplinary communication and collaboration possible. There should be a sustained effort to develop consensus in the scientific community on the key questions, identify the "knowns and unknowns" of the science around any of these key questions, and agree on a path forward for making progress. A variety of program elements were endorsed at the workshop as important ways to achieve this integration, including the following key components.

Organizational Structures. Workshop participants discussed a range of ideas for the overarching organizational structure of a new program. They weighed advantages and disadvantages of several models, based in part on an understanding of what has worked well in past or existing major sustained programs such as IODP, EarthScope, GeoPRISMS, and the Southern California Earthquake Center (SCEC). Participants identified positive aspects of these programs that would foster the desired integrative efforts, balancing intellectual and physical infrastructure needs as the program initiates and evolves. Interdisciplinary communities have successfully gathered around a consensus set of scientific objectives and regional focus with a decentralized funding structure (the GeoPRISMS model), as well as a more directed community science "collaboratory" (SCEC model). Highly successful physical infrastructure has been developed within a centralized facility for operation and management (EarthScope model). The imperative for international coordination and field studies requires an international component larger than these other models, although likely less centralized than IODP. Organizational structures that have been successful entail coordinating offices hosted in universities that promote science motivation, community building, program steering, and education and outreach; PI-driven projects that compete in peer review for dedicated NSF science program funding; and facility operation and management with strong links to academic consortia. **Section 9** (Building a Program) provides a 10-year vision and timeline for the ***SZ4D Initiative***.

Box 7.5. Connecting the Megathrust to Upper Plate Deformation in Forearcs

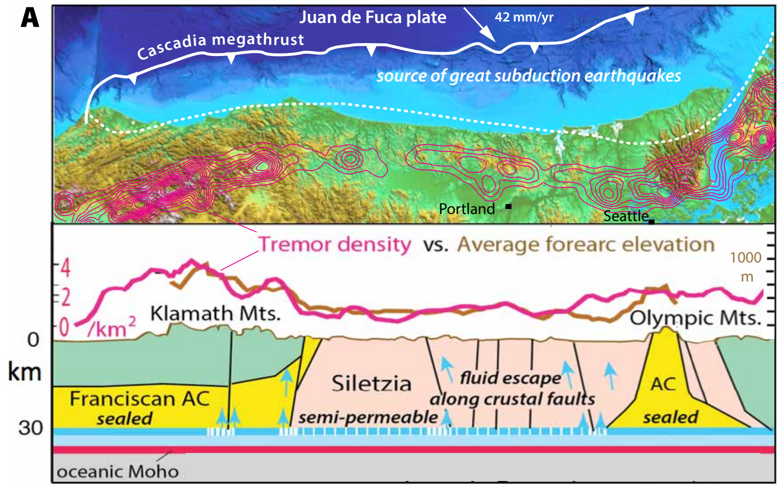
Forearc regions respond to subduction topographically and may in turn affect the dynamics of the subduction through the nature of their bedrock. In Cascadia, for example, the Olympic and Franciscan accretionary terranes of the upper plate correlate with broad forearc topographic highs and high tremor density on the megathrust, in contrast to low elevation and tremor rates in the basaltic Siletzia terrane (A). Are such relationships seen elsewhere, and how might upper-plate terranes affect the megathrust and growth of topography?

Faults break forearc crust into blocks and build short wavelength topography (B). In Cascadia, the forearc is broken into fault-bounded, northward-migrating crustal blocks that appear to segment regions of different tremor density. Do faults in the upper plate seismically segment the megathrust, and what is their role in strain partitioning?

The forearc volume is a balance between erosion and accretion (Figure 2.9). River incision, debris flows, and landslides are major forces for landscape change that mediate tectonic uplift driven by underplating and accretion. In the Olympic Mountains of Washington (C), erosion and uplift are in steady state, whereas Siletzia is exhumed at a lower rate (Batt et al., 2001; Roering et al., 2005). Is underplating along the margin (Calvert et al., 2011) the controlling factor? How important are landslides as agents of erosion, in addition to the serious hazards they pose? New LiDAR approaches can document temporal and spatial variations in accretion, uplift, and erosion rates along the margin and their relation to megathrust behavior.

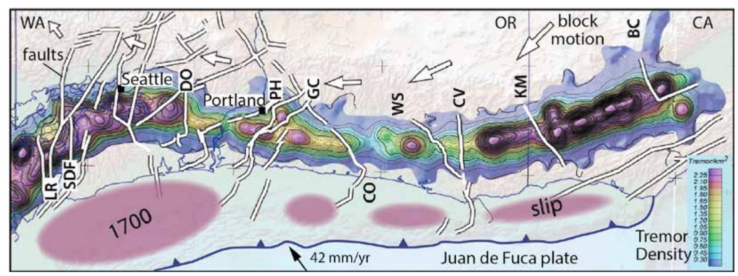
Below (D) is an example of how to integrate processes from the megathrust to the forearc landscape.

A



Wells at al. (2017)

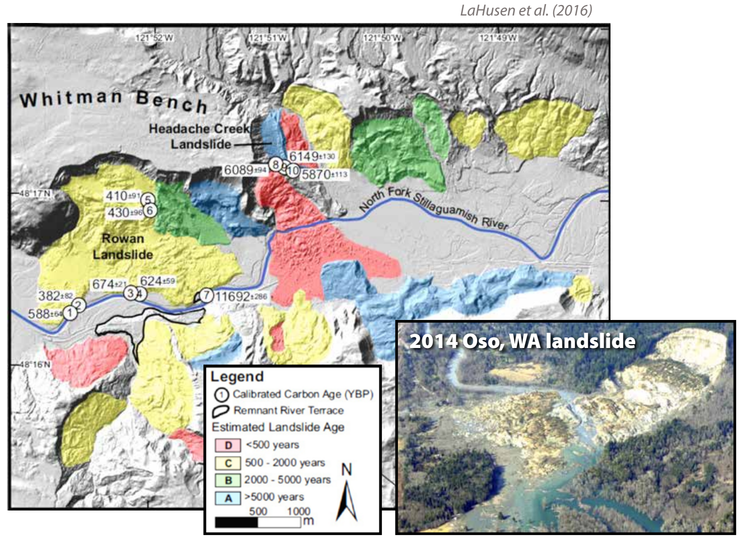
B



Wells at al. (2017)

LaHusen et al. (2016)

C



Associated Press/Ap Images

D Implementation

CAScadia Earthquake Center

Modeled after SCEC, coordinating regional, academic, federal, state, and private sector institutions to prioritize and support tasks, including:

CCFM/CCVM
Cascadia Community Fault and Velocity Model – 3D Cascadia fault geometry, linkages, history and recurrence, interactions, and crustal velocity

MOOS
Marine Offshore-Onshore Synthesis – Seamless linking of structure and process across the shoreline with GIS, potential fields, and fieldwork, establishing along strike variability and segmentation of the margin

COLE
Collaboratory for Landscape Evolution – Documentation of landscape change in space and time with quantitative geomorphology and geochronology to address tectonic vs. climate forcing and their interaction

SASS
Systematic And Synoptic Surveys for Active Faulting and Landscape Change – Coordination of LiDAR acquisition to infill LiDAR patchwork; systematic repeat acquisition leading to 4D SASS time series

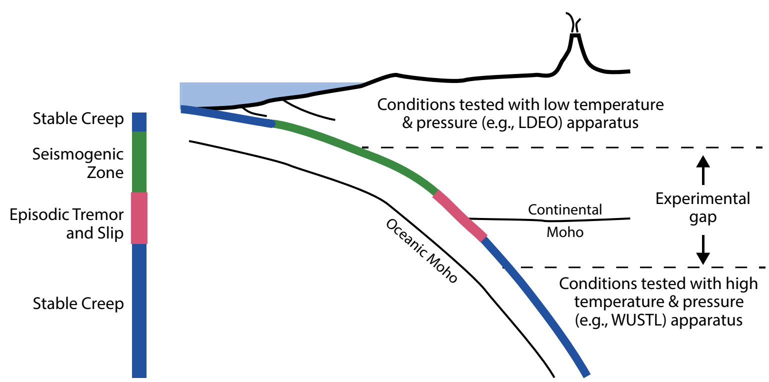
Community Models. As described in the previous sections, there is a clear need for further development of theoretical and numerical models for various subduction-related phenomena on a range of spatial and temporal scales. This need will only grow stronger as more observations become available and new hypotheses and conceptual models are put forth to be tested. ***SZ4D***, however, aims beyond the success of these theoretical and numerical models for the individual phenomena in explaining and predicting discrete observations. This new initiative seeks to provide a framework that will unify these individual models and lead to the development of integrative, 4D, system-scale models. Such integrative approaches can be applied to community models that have proven to be useful in several contexts, such as the Intergovernmental Panel on Climate Change's assessment of global climate models, and models for the San Andreas fault system developed through SCEC. A community approach does not imply that there will necessarily be a single, consensus model, but rather that a framework and integrative workflow can serve to further motivate, guide, and leverage basic science efforts to be translated into improved understanding of hazards. The process of trying to build such ambitious systems-level models is often key for identifying the highest priority knowledge gaps in both data and theory, and developing strategies to address them (**WP3**). Community models allow this process to proceed in a context larger than those produced by a particular research group.

The diverse suite of disciplinary results that characterize complex subduction zones are ready to be assimilated into

Box 7.6. Experimental Rock Deformation in a Subduction Zone Observatory

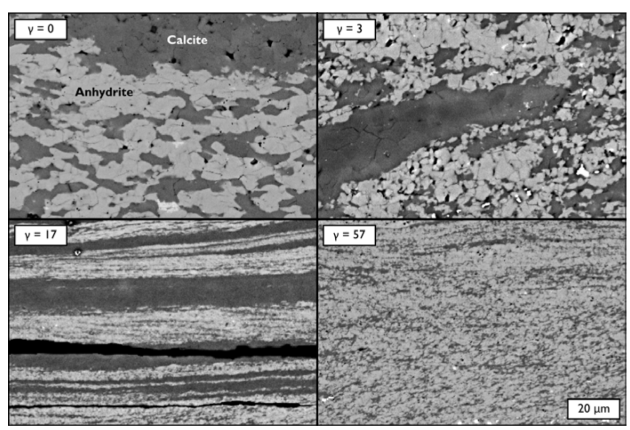
SZ4D will record geophysical data with unprecedented density and precision. However, the greatest scientific advancement will be realized by connecting these new data to the proper experimental, geologic, and theoretical framework. Rock deformation experiments are an essential complement to all geophysical disciplines, providing the context through which observations are interpreted, theory is validated, and models are parameterized.

Currently, most rock deformation apparatuses are designed for studies either far above or below the seismic-aseismic transition. Participants in the SZO workshop expressed a need for infrastructure that facilitates collaboration between scientists at different laboratories to bridge the gap across the P-T boundaries that distinguish subdisciplines of rock deformation experimentation and theory. A means of inter-laboratory comparisons of rock characterization and material behavior is also desired to aid integration across the limited range of P-T conditions that can be achieved by any single apparatus or laboratory.



The distribution of fault slip behavior in a subduction zone and the conditions that are achievable in an experimental apparatus. There is a gap in experimental capabilities between the downdip transition from seismic slip to stable creep. *Modified after Scholz (1998)*

(left) The triaxial apparatus at Lamont-Doherty Earth Observatory is used to study rheology at low pressure and temperature. (right) The large volume torsion apparatus at Washington University in St. Louis is optimized for mantle conditions. *Photo credits: (left) Philip Skemer and (right) Heather Savage*



Rock deformation experiments are used to study connections between microstructural evolution and strength over a wide range of deformation conditions, including variations in stresses, strain rates, temperatures, pressures, and fluids. The photos show a sequence of deforming calcite-anhydrite mixtures from low to high strain. *From Cross and Skemer (2017)* integrative system-scale models (**WP43**). A physics-based volcano model, a fault model that captures rupture and the seismic cycle, and a slab thermomechanical model were all identified as medium-scale modeling efforts that could help pull disparate observations together in the short term (**Box 7.7**).

Multidisciplinary Data Access. Data management and data discovery tools are crucial parts of a community infrastructure (**Box 7.8**). Interdisciplinary science can only thrive when the entire geoscience community can access and utilize data from all disciplines (**WP18**, **WP56**). This level of interoperability requires dedicated, professional data managers along with carefully designed and maintained software. Searchable data sets need to be created that include fully descriptive metadata about uncertainties and limitations. Linkages between existing data archive capabilities such as those at the IRIS Data Management Center (DMC), the Seismic Data Center, and the IODP should be seamless with ***SZ4D*** data management systems. Communication about the data sets needs to be built into the organizational structure so that potential users are aware of, understand, and can access data from multiple disciplines. For some disciplines, these data tools are mature (e.g., the IRIS DMC for seismic data), while for other disciplines, these tools require further development.

Explicit Synthesis Activities. Previous programs have achieved progress by holding virtual and actual institutes, symposia, and workshops to enable interdisciplinary synthesis. ***SZ4D*** should provide similar **opportunities for cross-disciplinary learning**, such as theoretical and experimental institutes centered on themes that cross disciplinary boundaries and focus discussion on common scientific questions. Additionally, ***SZ4D*** should promote field institutes where scientists studying different disciplines travel together to make observations in the field (e.g., of exhumed rocks, seismometer arrays, active volcanoes). At a more focused level, it would be beneficial to hold working group meetings where scientists working on different projects meet to compare results and

Box 7.7. Community Models

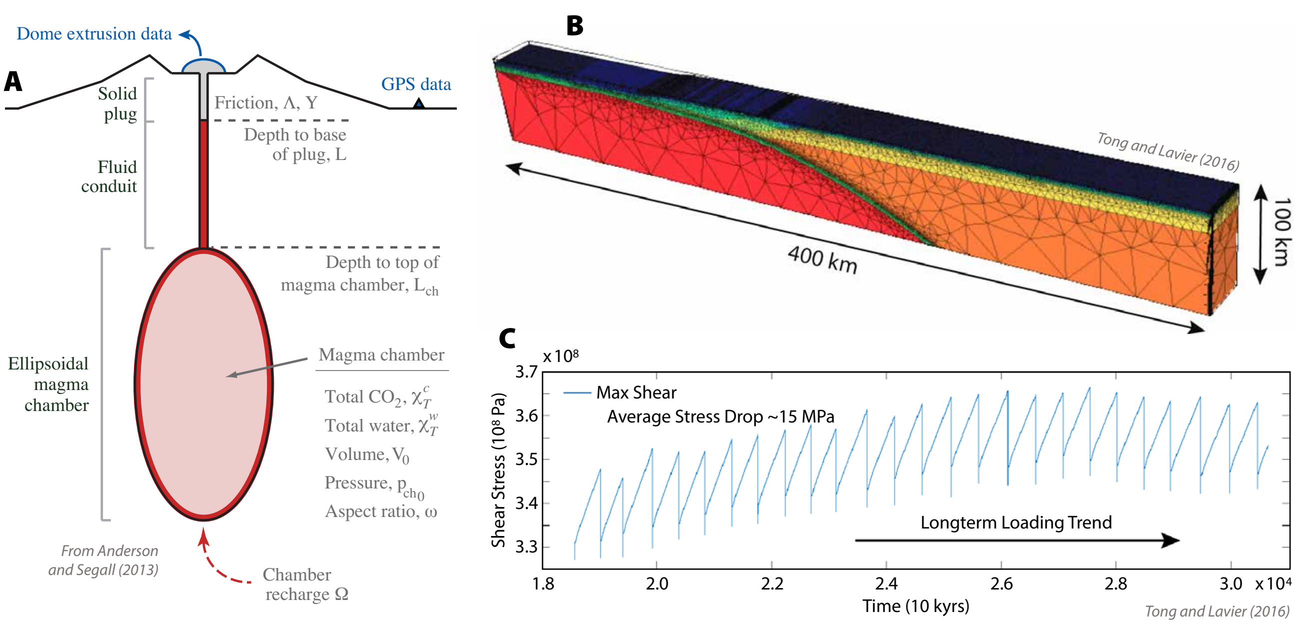
Open multiscale, and multiphysics numerical models are needed to integrate diverse geophysical, geodetic, and geological observations from subduction zone observatories to understand the driving forces for, and links between, processes from volcanic eruptions (A) to earthquakes and convective material transport over tectonic time scales. Once adapted to regional settings, such models can be used, for example, to connect the subducting and overriding plate systems, and to infer which kinds of observations are most important to constrain subduction zone behavior in terms of optimal experimental design.

Several groups are working on subduction zone models that can capture both short- (rupture to seismic cycle) and long-term (thermo-mechanical, mantle convection, and slab dynamics) effects including fluid transport.

Panel B shows an example, 3D finite element model mesh of a thrust fault. The visco-elasto-plastic material behavior incorporates rate- and state-dependent friction at the fault interface, allowing for sliding velocity variations over eight orders of magnitude.

Panel C shows how deviatoric shear stress in the fault in this model displays both the typical, sawtooth patterns of stick-slip, and a long-term trend due to reorganization of the shear zone.

The next 10 years will likely see further increases in the capability of such models, for example, including fluid and melt transport, as well as integration into larger-scale mantle convection settings in evolving plate boundary configurations.



develop a common understanding of a particular aspect of a subduction zone. At the graduate student level, several successful examples exist in the form of workshops, institutes, tutorials, short courses, and field experiments (e.g., through the Cooperative Institute for Dynamic Earth Research [CIDER], and GeoPRISMS Theoretical and Experimental Institutes and Exhumed Terranes [ExTerra]; see next section) that could be embraced by ***SZ4D***.

Box 7.8. Data and Samples for Interdisciplinary Research

SZ4D will lead community cultural change by adopting strong data, sample, and research products access policies

"Open data" refers to making publicly funded research freely accessible without restrictions (Fowler, 2016). Meaningful open data come with full access to metadata —the actual physical samples that measurements were taken on, the experiment methodology, standards, software, etc.—that allow others to reproduce scientific results. Despite pockets of outstanding community culture, field sciences lag behind. McNutt et al. (2016) reveal "cultural, financial, and technical barriers to chang[ing] the ways in which funders, publishers, scientific societies, and others are responding [to make data and samples available]." These barriers hinder discovery, synthesis, and interdisciplinary understanding of complex systems, like subduction zones.

***SZ4D* can accelerate the pace of discovery and interdisciplinary integration by insisting upon an open data culture. *SZ4D* also recognizes and will tackle the unique challenges posed by sharing data across international and institutional borders.**

Many funding entities already have data policies in place (see figure), and many data and sample repositories are available. ***SZ4D*** commits to making open data a priority when funding, evaluating, and publishing our science and when training, evaluating, and rewarding our community's scientists. Moreover, we will focus on developing tools that allow a broad range of subduction zone scientists to work with open access research products as a way to facilitate interdisciplinary research.

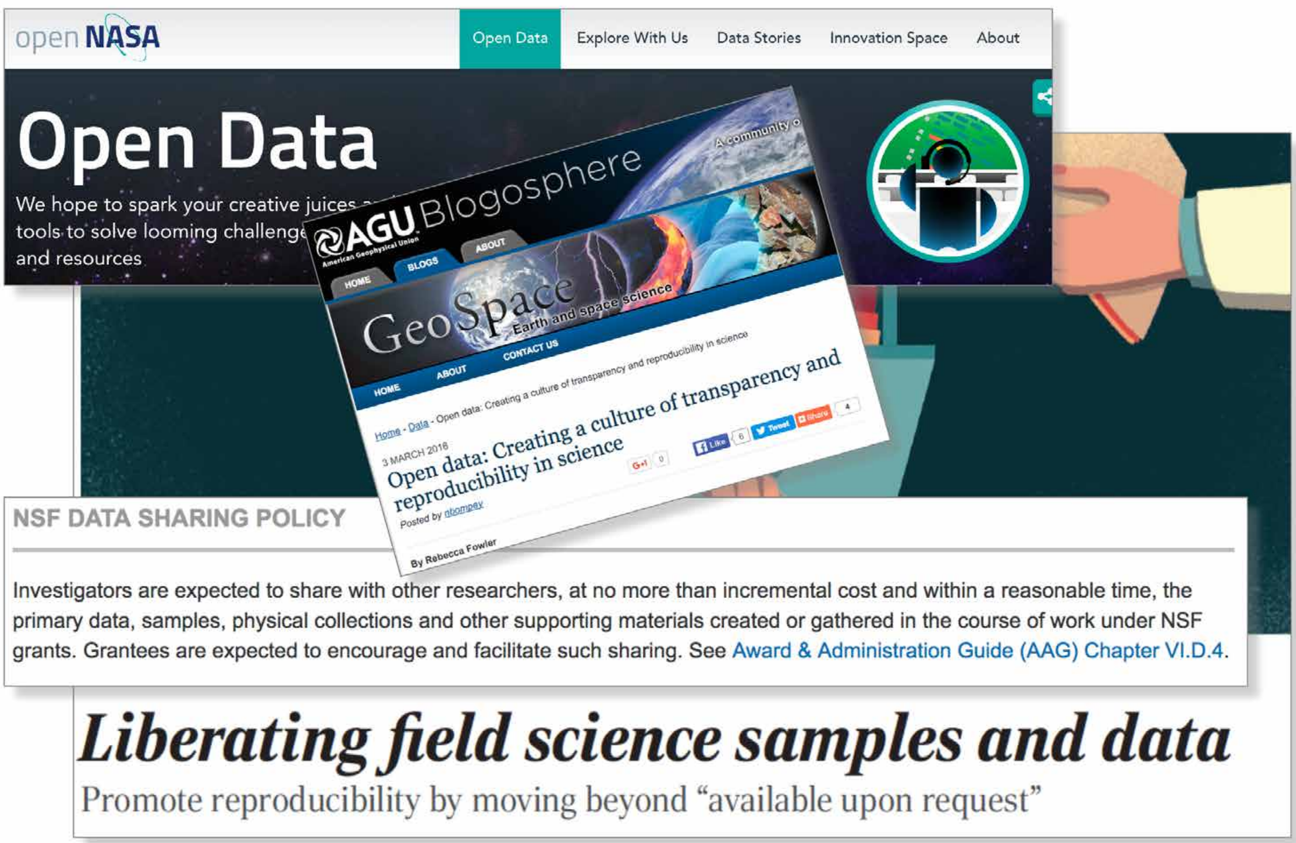


Figure 1. Collection of open data articles and policies pulled from AAAS *Science*, NASA, NSF, and AGU.

8. Framework for Education and Outreach and Capacity Building

The scientific goals of ***SZ4D*** are unique, and the vision encompasses a scale never before attempted. The education and outreach goals are similarly ambitious—to communicate the current scientific understanding of subduction zones and associated hazards to the general public and to policymakers, and to train the next generation of scientists to tackle our gaps in knowledge of subduction processes in a fundamentally interdisciplinary way (**WP10**). The international nature of ***SZ4D*** also provides an important opportunity for capacity building—developing scientific partnerships that transfer skills, data, technology, and expertise to other countries. The broader impacts of ***SZ4D*** will be aligned with the scientific goals and guided by plans for communication, implementation, and evaluation. In all the ***SZ4D*** efforts, engaging a diverse population will be an important goal. Achieving the desired impact will require sustained activity over decades.

The different ways in which ***SZ4D*** will impact different communities are outlined below.

1. **Outreach:** Bringing new content to the public domain via informal education, especially important to communities potentially affected by subduction hazards
2. **Up-Reach:** Bringing subduction zone science directly to users, such as policymakers, engineers, and sponsors
3. **In-Reach:** Supporting early career scientists and graduates students to work globally and across disciplines, while building an intellectual infrastructure within the academic community
4. **International Capacity Building:** Transferring skills, data, software, and technology to communities in emerging and developing countries where subduction zones are located

8.1 Outreach (General Public)

The ***SZ4D Initiative*** will develop programs to articulate the outcomes of subduction zone science in a way that engages and educates lay audiences across all demographics (**Figure 8.1**). Informal learning opportunities exist over an ever-increasing array of platforms, such as:

- Online content through formal media and social media
- Citizen science campaigns in target regions
- Public lectures, especially in research locations
- Museum exhibits
- "Serious games" (e.g., Budget Hero)
- Science programing (documentaries for film, TV)
- Books or popular articles

Components of this work will include a coordinated communications plan, skilled and qualified outreach coordinator, a strong online presence in digital and social media, leveraging of traditional journalism, public engagement and citizen science programs, and evaluation of outcomes and benefits. Creative use of both the location-specific nature of ***SZ4D*** and its hazards implications can provide initial entrées and connections to the general public (**WP42**). The portfolio of activities should include specific products that engage diverse audiences, including those that are non-English speaking and underrepresented in STEM.

FIGURE 8.1. Visitors learn about earthquakes at the Washington, DC, Science Festival. *Photo credit: B. Bartel*

8.2 Up-Reach (Sponsors, Policymakers, Engineers)

The public safety component of ***SZ4D*** also provides a natural conduit to policymakers and other decision-makers and stakeholders outside of the research realm. The science and hazards to be addressed in ***SZ4D*** are complex and multifaceted and have far reaching implications beyond pure science, into other areas such as economic growth, human health, and national security. The aim of a coordinated up-reach effort is to ensure policy decisions and hazard assessment are informed by science. ***SZ4D*** will engage with professional organizations and utilize established avenues that link policy and science, and link science to risk mitigation. Specific up-reach strategies might include:

Governmental Briefings. Professional development in communicating to policymakers will be available to all ***SZ4D*** scientists to help them to get started in engagement activities and arm them with the skills necessary to be effective communicators to nontechnical audiences. Increased personal contact and connections between scientists and policymakers is critical to reaching science-informed decisions (**Figure 8.2**).

Coordinating with Government Agencies Tasked with Hazard Assessment and Warning. ***SZ4D*** should strengthen ties to the governmental bodies that are tasked with official assessment, warning, and forecasting of subduction zone hazards. Several examples exist already of strong linkages between decision-makers and scientists in this realm. The USGS, responsible for national earthquake hazard maps, has partnered with the academic community in the development of the Uniform California Earthquake Forecast model (UCERF3). This model was a substantial leap forward both for its methodology and for its end products, and could not have been achieved without significant basic research. Correspondingly,

FIGURE 8.2. EarthScope scientists in Washington, DC. *Photo credit: B. Bartel*

NOAA operates the National and Pacific Tsunami Warning Centers, where earthquake and tsunami source products and physics-based tsunami intensity hazard estimates for entire ocean basins can be traced to fundamental research made in the academic sphere. A new call for improved connections between the academic volcanological community, engaged in basic research into the understanding of eruptions, and the USGS, responsible for eruption warnings and disaster assistance, is a central theme in a new National Academies report by the Committee on Improving Understanding of Volcanic Eruptions. The Alaska Volcano Observatory is one example of a successful organization model that engages the government (USGS), academic (University of Alaska), and the state survey in jointly supporting research, hazard assessment, and public outreach. The ***SZ4D Initiative*** can play an role in connecting fundamental research in subduction zone processes to the government agencies that can put this knowledge to use in risk mitigation.

Coordinating with the Engineering Community. ***SZ4D*** should broaden efforts to engage with the engineering communities involved in earthquake and coastal hazards. One successful example is the close collaboration between the academic, societal, and governmental spheres in the Pacific Earthquake Engineering Research Center (PEER), a multi-institutional research and education center focused on performance-based earthquake engineering in disciplines including structural and geotechnical engineering, geology/seismology, lifelines, transportation, risk management, and public policy. They are responsible for projects such as the ground motion prediction equations used by engineers in the United States to account for earthquake shaking when planning structures. A second example is the coastal engineering community who, through the American Society of Civil Engineers (ASCE), routinely engages with ports and other coastal infrastructure stakeholders, as well as local governments to plan for and mitigate tsunami risk. ***SZ4D*** should develop new avenues to better communicate and collaborate with engineering organizations on the physical processes that drive geohazards.

Coordinated Communication to Funders. An effort as large and potentially distributed as ***SZ4D*** requires organized and coordinated communications to the funders. Nontraditional avenues of communication will be needed to ensure science discoveries and outreach outcomes are conveyed to program officers and made accessible to individuals outside of their agencies.

8.3 In-Reach (Within the Academic Community)

To build the interdisciplinary intellectual infrastructure needed to execute the ***SZ4D Initiative*** requires strong internal communication and education among all scientists studying subduction, from students to senior scientists. Three types of effort are envisioned:

1. **Student Education:** Engaging and training a diverse new generation of Earth scientists to work across borders and disciplines, including undergraduates (**Figure 8.3**).
2. **Early Career Investigators:** Engaging and launching the careers of scientists who completed the PhD within the last six years
3. **Interdisciplinary Science:** Promoting programs to encourage investigators at all levels to engage in science discovery and integration using tools, observations, and theory from multiple disciplines (see **Box 8.1** for some examples of activities to support each of these efforts)

FIGURE 8.3. Undergraduates learning geology in the field. *Photo credit: A. Morris*

Box 8.1. In-Reach Within the Academic Community

Building the intellectual infrastructure to support subduction zone science

Examples of Graduate Student Programs

- Multinational field schools that conduct training in natural hazards (earthquakes, landslides, volcanoes, tsunamis)
- Three to six month training courses to offer a credential or certificate
- "Roving school" that moves from country to country or among universities
- Exchange of graduate students across international programs and disciplines.
- Opportunities for international graduate students to visit and/or carry out research in the United States

Early Career Investigator (ECI) Programs

Early career scientists may be better positioned to leverage opportunities provided by the ***SZ4D***—including interdisciplinary science, international research experiences, education and outreach, and capacity building—because they are still identifying their professional interests. Some examples include:

- Short courses or interdisciplinary, "cross pollination" workshops, including in international settings
- Small seed grants for early career investigators to pursue ***SZ4D*** research, launch collaborations
- Annual networking opportunities for ***SZ4D*** early career investigators

Early career faculty and graduate students participating in a geophysics short course. *Photo credit: B. Pratt-Sitaula*

Programs for Advanced Undergraduates

- Summer internships
- Target and support diverse students to enter the research pipeline

Promoting Interdisciplinary Science

Truly interdisciplinary research requires sustained cross-fertilization and education among the diverse disciplines involved in subduction science. Examples of programs to promote interdisciplinary research for scientists at all stages of their careers—students, early career investigators, senior faculty—include:

- Thematic workshops that bring disciplines together to attack the Big Questions in subduction science
- Summer schools that involve short courses, tutorials, and interdisciplinary research projects. One successful model is the CIDER summer school
- A sabbatical support program to stimulate research collaborations between faculty in different disciplines and/or different countries

The 2016 cohort students participating in the UNAVCO Research Experiences in Solid Earth Sciences (RESESS) program. The goal of RESESS is to increase the number of students from groups that are underrepresented in the geosciences relative to their proportions in the general population. *Photo credit: K. Russo-Nixon*

8.4 International Capacity Building

Capacity building encourages international scientific partnerships, with the intention of transferring skills, data, technology, and expertise (**WP23**, **WP32**). It is a form of human resource development. The ***SZ4D*** capacity building programs will align with scientific targets in both emerging and developing countries in order to sustain physical infrastructure, train scientists, understand hazards, and build resiliency. It is the opposite of "parachute science" in which investigators from developed countries collect data, return home, and publish papers. For example, scientists from Germany and the United States have contributed initial seed funding, equipment, and training over the past 10 years in partnership with the Chilean geophysical community to create a world-class national geophysical network. This long-term partnership has paid off in scientific advances and important long-term collaborations that enable projects that could not otherwise be realized (see **Box 6.3**). In another example, Japan and Germany's investment in sensor networks in Indonesia has benefited local populations, Indonesian scientists, and the scientific community. The USGS's Volcano Disaster Assistance Program provides both support during volcanic events and training for local scientists to develop sustainable monitoring, research, and outreach (**Box 8.2**). The Swedish Network of Atmospheric and Volcanic Change (NOVAC) and the Deep Carbon Observatory's Deep Earth Carbon Degassing (DECADE) programs have expanded both gas monitoring and workforce capacity to dozens of volcanoes around the world.

Some guiding principles and potential components of an ***SZ4D*** International Capacity Building Program are listed in **Box 8.2**. The exact form of the capacity building efforts will undoubtedly evolve over time and will require governance and oversight from a skilled advisory committee. Given the global importance of the subduction zone hazards, their scientific diversity, and the need to study them in multiple locations, this type of effort is both a societal imperative and a scientific necessity that can yield transformative outcomes on both fronts.

Box 8.2. International Capacity Building

Partnerships to transfer skills, data, technology, and expertise

Guiding Principles for International Capacity Building

- Efforts must satisfy mutual interests.
- Hazards are the key driver for science in many countries, and activities should provide operational training.
- Continuity is of prime importance. Even small projects like workshops require follow-up activities, long-term goals, and accountability.
- Programs need broad geographic participation from multiple institutions, including the full range of stakeholders.
- Seek collaborative opportunities with established organizations (e.g., USAID, the World Bank, and USGS Volcano Disaster Assistance Program; see photo, right);
- Lay the groundwork for events long before the events themselves take place.
- Training should encompass the full range of skills necessary for successful science, from data acquisition, through analysis and interpretation, to publication and communication of results.
- Steering committees should include partners from numerous host countries to ensure that programs address real needs and align with key institutions in each country.

International Capacity Building Components

- There must be a direct link with the ***SZ4D*** rapid response facility (see Box 7.3) so that key participants are identified ahead of time, and are involved in the planning, data collection, and analysis.
- Provide internships for operational professionals and students at U.S. universities, NSF facilities (e.g., UNAVCO, IRIS), or government agencies (e.g., USGS, NASA).
- Conduct training programs that result in a credential or certificate of completion.
- Organize workshops, advanced studies institutes, and "boot camps."
- Implement a roving "Subduction Zone School" that moves from country to country.
- Hold multinational field schools.
- Conduct programs that take advantage of the Maker Movement to develop engineering and programming skills while providing useful devices.

Installation of monitoring equipment in Northern Sulawesi, Indonesia. On-site training is an important part of USGS Volcano Disaster Assistance Program capacity building around the world. *Photo: https://volcanoes.usgs.gov/vdap/activities/capacity/nsulawesi.php*

Partially installed GPS monument for site NC47. UNAVCO field engineers worked with faculty and students from the University of the West Indies Seismic Center on the installation. *Photo credit: J. Sklar*

9. Building the SZ4D Initiative

The ***SZ4D Initiative*** is motivated first and foremost by the potential for answering fundamental scientific questions through significant new investment in infrastructure, research, and partnerships. A critical level of infrastructure investment will allow an array of essential observations to be collected. Sufficient research funding will enable these multidisciplinary observations to be synthesized into a new understanding of the science that underlies earthquake, tsunami, ground failure, and volcanic hazards, and permit broader connections to be made between hazards and fluid cycling, continent formation, and the climate system. Such ambitious goals require at least a decade-long commitment to making many types of observations that cross the shoreline. The program should have a geographic focus in several regions, which could include U.S. and international subduction zones. Such a program does not have to start from scratch. Extensive existing programs run by multiple U.S. agencies, including NSF, USGS, NASA, and NOAA, and international organizations, may be used as a basis for building and coordinating efforts. The ***SZ4D Initiative*** provides an opportunity to coordinate efforts across agencies and with international partners. The program will require phasing, but many activities could start right away. Theoretical institutes and community models can begin to synthesize existing observations and motivate new ones, that then lead to community research infrastructure and specific facilities to address ***SZ4D*** scientific questions.

9.1 Building Partnerships with Existing Organizations

One essential goal of the ***SZ4D Initiative*** is to enhance collaboration and coordination among the diverse efforts that are being made both within the United States and globally. Significant resources are already being used to study various phenomena at different subduction zones. To maximize the utility of available resources, a critical step will be to coordinate these efforts and exchange expertise between them. Multinational coordination, such as the recent experience in Chile (see **Box 6.3**) can expedite progress. We are at a defining moment to bring together and strengthen global efforts.

Partnerships will be based on mutual interests and investment (not limited to financial capabilities) between ***SZ4D*** and other entities regarding the type of observations/studies, particularly those that are not possible otherwise. The needs for such partnerships exist in various parts of the world, particularly in developing countries where the support for capacity building in geoscience observations and education is lacking (**Box 8.2**). Further, natural hazards and natural resources that result from plate subduction often cross geographic boundaries, and coordinating efforts internationally is becoming more critical, not only for science diplomacy, but also for access, foreign policy, and aid.

Building partnerships with existing organizations and programs nationally and internationally clearly has significant advantages. ***SZ4D*** will better prioritize resources and more efficiently collect and interpret data by coordinating our efforts with those that provide infrastructure for geophysical and geochemical observations (e.g., IODP, and a number of seismic and geodetic networks operating in different parts of the world through various programs), those that monitor and study natural hazards (e.g., USGS, UNAVCO, NOAA, GSN, NASA), and analytical and experimental facilities and modeling communities that investigate subduction-related phenomena over various temporal and spatial scales. Such partnerships allow mutual leveraging of resources that benefit both parties, and increase observational and analytical capabilities.

Building international partnerships requires a well-managed organization that allows coordination and communication with scientists around the world. To assure the success of ***SZ4D***, one of the approaches is to learn from the existing organizations that operate under strong partnerships with successfully sustained capacity building, such as the International Centre for Theoretical Physics (ICTP), and to build on their organizational models.

9.2 What We Can Do Right Away

Full implementation of an ***SZ4D*** program necessarily involves planning, infrastructure development, and working with multiple agencies and international partners to ensure adequate support, which will take a number of years (see **Table 9.1**). Nonetheless, there are important tasks that can be accomplished in the short term.

Research Network Building. A successful ***SZ4D Initiative*** requires interdisciplinary and international collaboration, and this can start right away. NSF's Research Coordination Networks program funds the development of research networks, including international ones, with grants up to $500,000 over a period up to five years. Another NSF program,

TABLE 9.1. Proposed timeline for building the ***SZ4D Initiative***

	2016	2017	2018	2019	2020
Integration		SZ4D Working Group/ Steering Committee	→	→	→
Interdisciplinary Science Program	SZO Boise Workshop	SZ4D Initiative Vision Document RCN/PREEVENTS Proposals Rapid Response Planning Group	Thematic Workshops on Science Questions (e.g., Where Large EQ? Melt Production, Run-up to Hazardous Events, Erosion and Landslides) Community Experiments (e.g., Seafloor geodesy, Laboratory volcano, Fore-arc faults to surface)	→ Start of SZ4D Interdisciplinary Science Program → →	→
Community Modeling Collaboratory			Modeling Collaboratory Proposal Planning RCN/PREEVENTS Proposals	Modeling Collaboratory Proposal	Modeling Collaboratory Begins →
Large-Scale Infrastructure			Planning Workshops for Mid-Scale Infrastructure/MRI Proposals	Design Workshops for Mid-Scale Infrastructure/MRI Proposals	SZ4D Infrastructure Proposal →

PREEVENTS (Prediction of and Resilience against Extreme Events), is aligned with ***SZ4D*** in supporting the understanding the fundamental processes underlying natural hazards. The PREEVENTS program, however, does not support collection of new data, which is central to ***SZ4D*** and essential to making progress on the most fundamental science questions (see **Section 2**). Other activities strategic to ***SZ4D*** ramp-up, such as synthesizing existing data, model testing, thematic workshops, and/or coordinating rapid response to events, could proceed under these or other funding mechanisms.

Technology Development Programs. Some critical capabilities are currently being developed, such as seafloor geodesy (**Box 4.4**), and efforts should be accelerated to obtain strategic data and foster development that will enable deployment at greater scale and in more locations. It is important that these developments takes place while the rest of the initiative takes shape, so that deployment and implementation can take place as the initiative matures. Thus, important development projects could be funded out of the normal programs during this time, with the imperative from strong community support behind the developments.

Planning for a Subduction Zone Science Program. Although implementation of extensive subduction zone research infrastructure may require development over years, planning for a broad research program should begin immediately. Initiating an ***SZ4D*** science research program in the near to mid-term (i.e., next few years, **Table 9.1**), prior to the deployment of costly infrastructure, has the advantage of building the science base and helping to focus infrastructure on what is truly needed. The planning will require coordination between different disciplines and agencies, as well as different parts of NSF. This development should begin with the formation of one or more planning committees across the disciplines and across the subduction system, from the shallow thrust zone to the volcanic arc. A formal planning process could also be a vehicle for starting discussions with International partners about how to most effectively collaborate and possibly start exploring coordinated activities such as data sharing, model development, and technology exchanges. The committee should be tasked with and include experts on developing capacity building, and education and outreach activities in coordination with the facility developments. The committee or working group could evolve over time into a group that facilitates coordination and science integration activities, and ensures that the longer-term goals of a well-motivated infrastructure are progressing.

9.3 The 10-Year Vision

The SZO workshop participants recognized that a variety of programmatic approaches are required to advance subduction zone science, that many styles have been successful in the past, and that different aspects could be phased in over time. Three key components were identified that, in combination, over a 10-year effort, could help realize the vision for a deeper understanding of 4D evolution of subduction zone systems, with the goal of improving forecasting of geological hazards. While the three components—a community modeling collaboratory, an interdisciplinary science program, and a large infrastructure program—could be managed independently, their impact will be maximized if there is a clear mechanism for encouraging an interactive and iterative relationship among them.

A Community Modeling Collaboratory. Community modeling will serve as a primary vehicle for enabling intellectual collaborations in subduction science. Community models to be developed could include a physics-based volcano model (**WP43**), a fault model that captures rupture and the seismic cycle, and a slab thermomechanical model, eventually including fluid transport and evolving plate boundary configurations (**Box 7.7**). The collaboratory could build strong ties to interdisciplinary data centers being developed through EarthCube-type efforts that would allow the model outputs to be compared to the full suite of observables collected by ***SZ4D*** and other efforts. The IT infrastructure developed in support of the initial models could be deployable for any number of specific subduction systems and serve as a way to catalyze and facilitate international collaboration. The collaboratory could grow into a joint effort between the NSF, USGS, NASA, and other agencies. The long-term effort that follows the initial building blocks could focus on integrating smaller-scale models of the various components into an integrated model of the overall system.

An Interdisciplinary Science Program. The SZO workshop participants recognized a need for PI-scale projects along a number of possible themes, including data analysis, model development, education and outreach, and targeted marine and terrestrial data collection. Particularly key is the ability to work on fully interdisciplinary projects relevant to ***SZ4D*** science goals that can be difficult to fund in the more disciplinary core programs. The successes of long-term programs that have encouraged multidisciplinary research (e.g., GeoPRISMS, EarthScope, SCEC) and crossed traditional geographic boundaries such as the shoreline provide successful models. Moreover, there is a strategic need for PI-level projects that push the leading edge forward and help provide motivation for the evolution of the larger-scale infrastructure program.

This ***SZ4D*** component will be key for extracting 4D data sets ranging from volcano lifetimes (millions of years) to paleoseismic time scales (thousands of years). It could also be the mechanism for implementing many of the in-reach and outreach efforts described above such as targeted institutes, workshops, and field schools (**WP36**). Additionally, this program could initiate community-scale experiments that require a larger-scale effort than normal PI proposals and have been endorsed by workshops or a steering committee. These would be short-duration data collection efforts that could kick start the program (**Table 9.1**). For instance, collecting a LiDAR data set over an entire forearc, conducting full-wavefield imaging passive seismic experiments, conducting 3D active source seismic experiments, systematically sampling erosion rates, conducting large-scale MT experiments, and developing an arc-sector-wide geochronology all received considerable support at the workshop. These may be distinct from the longer time-series efforts of the large infrastructure program, and discussing the partitioning of community-level data collection efforts between these two should be part of the planning processes that begins soon.

Large-Scale Infrastructure Projects. The workshop prioritized the need to produce 4D data sets on the time scales that are inherent to different parts of the system. Many major questions focus on cyclicity and temporal variability that require decade or longer time series to address, and piecing together a picture of a complete cycle from multiple locations. New technologies and critical data gaps present opportunities for progress if we invest in new, long-term observatories at a significant scale. Significant support was voiced at the workshop for seafloor geodetic networks (**Box 4.4**), arc-scale volcano observatories (**Box 7.1**), seafloor instrumentation to catch M8 earthquakes on a Pacific-wide scale (**Box 7.2**), dense observatories focused strategically on seismic gaps (**Box 7.3**), multiscale imaging of forearcs to get at deformation and erosion (**Box 7.5**, **WP37**), and open experimental laboratories (**Box 7.6**). These potential community-scale projects require significant planning before construction can begin (**Table 9.1**). This suite of activities could be grouped into a single, large, coordinated program or be a more loose federation of smaller, right-sized, mid-scale projects that implement specific types of multidisciplinary observatories in the most appropriate locations.

The workshop emphasized that from a strategic point of view, maintaining flexibility is key. Opportunities may arise that require new geographic locations or shifts in technology. Thus, these Infrastructure facilities will require strong oversight from the ***SZ4D*** science programs above so that they provide the most valuable data sets. These projects could start in a sequence over the next few years as plans develop and funding is secured. Some technologies have already demonstrated radically enhanced capability (e.g., to measure volcanic gas and seafloor deformation), and others require long-term efforts and larger amounts of support (e.g., borehole or cabled observatories).

The overall suite of efforts contained these three components needs to be structured in such a way that the balance between science funding and infrastructure is regularly evaluated to ensure that ***SZ4D*** goals are achieved. A successful ***SZ4D*** program will lead to scientific discoveries and applications otherwise not possible. The infrastructure will enable observations in 4D that would otherwise not get made. To realize the ***SZ4D*** vision of a new understanding of subduction zone processes and hazards requires a sufficient level of science funding to analyze, integrate, and synthesize these new observations. A key to succeeding in this balance over a 10 year or more timeframe is to build in mechanisms that preserve scientific agility. The long-term goals of the ***SZ4D Initiative*** will require international partners and a framework that will outlast its construction, benefiting the science community after 10 years. The entire suite of efforts could be overseen by an advisory structure that evaluates the balance between the components to maximize discovery.

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Appendix 1. SZO Workshop White Papers

Click on the White Paper titles below to read the full text posted on the SZO workshop website (https://www.iris.edu/hq/workshops/2016/09/szo_16).

1 Aaron Wech » A boatload of science

2 Adam Kent » Have we adequately characterized the volcanic flux in Cascadia and other subduction zones?

3 Andreas Rietbrock » Subduction Zone Observatory and beyond: Towards modelling guided global-scale observations

4 Andrew Newman » An opportunity to image the complete seismic cycle exists at the Nicoya Seismic Cycle Observatory (NSCO)

5 Andrew Smye » An inter-disciplinary effort toward constraining the initial hydration state of the slab mantle

6 Andy Frassetto » A Subduction Zone Observatory based on lessons from USArray and employing a potential framework in Latin America

7 Anne Meltzer » Earthquake rapid response in subduction zone observatories

8 Anne Trehu » PICTURES and CEVICHE: Controlled source seismic experiments to probe the relationship between subduction zone slip and geologic structure in Chile

9 Ben Edwards » The role of volcano-ice interactions in understanding subduction zone magmatism

10 Christy Till » The role of social sciences and humanities in facilitating interdisciplinary subduction zone science

11 Dave Chadwell » Campaign-style GPS-acoustic with Wave Gliders and permanent seafloor benchmarks

12 David Fee » Integrating infrasound into a future SZO

13 David W. Scholl » Global observations identify two reinforcing reasons why the Aleutian-Alaska subduction zone is prone to rupture in high magnitude earthquakes

14 Diana Roman » A vision for community-scale volcano science activities under the auspices of a Subduction Zone Observatory

15 Donna Shillington » Marine active-source seismic data: An essential ingredient of the SZO

16 Emily E. Brodsky » Observatories for capturing 4-D strain, fluid-flow, seismicity, and tsunamigenesis

17 Enrique Cabral-Cano » TLALOCNet: A continuous GPS-met backbone in Mexico for seismotectonic, subsidence and atmospheric research

18 Estelle Chaussard » Seamless integration of multidisciplinary datasets for Subduction Zone Science

19 Frederik Tilmann » Towards the vision of a global long-term SZO: Harnessing submarine telecommunications cables for Earth monitoring

20 Gavin Hayes » Advancing knowledge of subduction zone earthquakes

21 Gene Yogodzinski » Lessons learned from along-strike changes In Aleutian volcanic rock compositions

22 Geoff Abers » An Alaska-Aleutian subduction observatory

23 Hector Mora-Paez » What do we expect from the SZO in capacity building?

24 Hitoshi Kawakatsu » Izu-Ogasawara (Bonin) Arc as integrated Subduction Zone Observatory – Is there aseismic subduction zone after all?

25 John Lyons » The sweet sound of hydroacoustics in the Subduction Zone Observatory

26 John N. Louie » Pacific plate dynamics from HUMOUR: Tracing the base of the plate from the Hikurangi subduction margin to outer rise

27 John Orcutt » Extending seismogeodetic observations to the oceans

28 Kelin Wang » Study megathrust creep to understand megathrust earthquakes

29 Ken Creager » Harnessing the full arsenal of observations to study slow slip, including seismic arrays and borehole instruments

30 Kerry Sieh » The Sunda subduction zone as a target for a Subduction Zone Observatory

31 Lara S. Wagner » Seismic contributions to a multi-disciplinary Subduction Zone Observatory

32 Lidia Torres Bernhard » Subduction Zones Observatory – A set challenge, a scientific need!

33 Marcos Moreno » Improving spatiotemporal resolution of megathrust kinematics with an exceptionally dense continuous GPS deployment

34 Marino Protti » Osa Peninsula, Costa Rica: A unique opportunity for inland drilling and instrumenting of the seismogenic zone of large megathrust earthquakes

35 Masa Kinoshita » Onland-seafloor-drilling integrated observatory for dynamic imaging of earthquake and volcanic eruption – Challenge of the spatio-temporal informatics in subduction zones-

36 Maureen Feineman » ExTerra: Exploring Subduction through the Study of Exhumed Terranes

37 Maximiliano J. Bezada » On the need for a comprehensive synthetic data set for the benchmarking and testing of subsurface imaging algorithms

38 Meng (Matt) Wei » Seafloor geodesy for a future Subduction Zone Observatory

39 Michael Schmitz » SAMARRAY – A seismological backbone linked to a South American Subduction Zone Observatory

40 Myo Thant » New probabilistic seismic hazard models of Myanmar

41 Nicholas W. Hayman » Deep submergence vehicle applications for subduction zone research

42 Paul Bodin » Extending the scientific and societal reach of an SZO with a Coastal Change Collaboratory (C3)

43 Paul Segall » Subduction Zone Observatory multidisciplinary system scale models of volcanic systems

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47 Peter Kelemen » The leading edge of the mantle wedge: Structural and metamorphic studies of peridotite thrust over metasediments & basalts

48 Philipp Ruprecht » Bringing the scientific and economic geology communities together as part of the Subduction Zone Observatory

49 Roland von Huene » A possible tectonic source mechanism of the 1946 Unimak Island tsunami In reprocessed seismic data

50 Roy D. Hyndman » Global studies of subduction initiation: Example of the Queen Charlotte margin of Haida Gwaii

51 Roy D. Hyndman » CCArray: Current and past plate interactions within the Canadian cordillera and across the North American plate boundary

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54 Susan Beck » Latin America Subduction Zone Observatory (LASZO) concept

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58 William Wilcock » Sustained offshore geophysical monitoring in Cascadia

59 Xyoli Pérez-Campos » Maximum expected magnitude, interface coupling and seismic cycle in the Mexican subduction zone

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61 Yoshihiko Tamura » Crust-mantle connections in the Kermadec Arc

62 Yue (Merry) Cai » Studies of exhumed plutonic and volcanic rocks in arcs

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