EXECUTIVE SUMMARY

SCIENTIFIC AND SOCIETAL RATIONALE

Subduction Zones in Four Dimensions, or SZ4D, is a new community-driven, multi-decadal interdisciplinary scientific initiative that strives to understand how the different components of subduction zone systems interact to produce and magnify geohazards over time. It addresses major gaps in our understanding of geohazards by capitalizing on the availability of new observational, analytical, and computational techniques and by coordinating fundamental research on the physical and chemical characteristics and processes in subduction zones. Subduction zones provide the opportunity to strategically investigate integrated hazards simultaneously and conduct well-controlled natural experiments that can be used to isolate and study key factors that drive geohazards. A cornerstone of SZ4D is bringing together scientists with a diverse range of geoscience backgrounds and skill sets who study earthquakes, volcanic eruptions, and surface processes.

Earth's principal geohazards are concentrated in subduction zones, locations where one tectonic plate slides beneath another. Earthquakes and tsunamis can cause devastation on enormous scales, disrupting entire societies. Large volcanic eruptions have repeatedly destroyed cities and altered weather patterns throughout human history, resulting in crop failures, famines, and population decline and migration. Landslides, debris flows, and floods have erased mountain towns and villages, disrupted agriculture, severed transportation routes, and profoundly affected urban and rural populations alike. Despite the global ambition to forecast these geohazards, we have only limited understanding of the complex physical and chemical processes that interact to trigger earthquakes, tsunamis, and volcanic eruptions. We also have limited understanding of the many ways in which these geohazards are linked to Earth surface processes such as sediment erosion and deposition.

To date, progress in understanding the potential predictability of geohazards has not only been limited by persistent knowledge gaps, it has been hampered by studies that have historically been conducted within disciplinary boundaries. Yet, there are obvious, shared crosscutting themes that link subduction zone studies, suggesting an interdisciplinary approach would significantly advance the science.

This document provides the details of how the scientific community will implement SZ4D over the initiative's decadal lifespan. It describes the observational, experimental, and numerical components required to capture the range of spatial and temporal scales over which subduction zone processes operate and the significant and sustained investment in human and physical infrastructure needed to support this effort. Using a collective impact model, scientists will closely coordinate their research across disciplines and will leverage existing efforts so that new activities build on the scaffolding of past successes. To enable close integration and phasing within and between components of this implementation plan, a center will coordinate deployment of instrumental and human resources, while individual investigators will also be empowered to be creative through a dedicated SZ4D science program. With the involvement of a diverse community of scientists and stakeholders in this SZ4D effort, we are poised to make a major leap forward in our understanding of subduction zone hazards for the benefit of society.

IMPLEMENTATION PLAN DEVELOPMENT

SZ4D comprises 74 member representatives from US research communities that study earthquakes, volcanic eruptions, and surface processes at subduction zones.

SZ4D is organized into:

Three working groups

- Landscapes and Seascapes (L&S)
- Faulting and Earthquake Cycles (FEC)
- Magmatic Drivers of Eruption (MDE)

Two integrative groups

- Building Equity and Capacity with Geoscience (BECG)
- Modeling Collaboratory for Subduction (MCS)

Through a combination of meetings, workshops, webinars, and town halls, SZ4D has engaged more than 3400 participants who have collaboratively identified community priorities and key observations and measurements that will enable the scientific advances necessary to better understand geohazards in order to mitigate their risks to society. The **SZ4D Implementation Plan** is the initial product of these discussions.

The **working groups** and **integrative groups** synthesized community input and identified key questions that the SZ4D initiative must address:

- When and where do large damaging earthquakes happen?
- How do trans-crustal processes initiate eruptions at arc volcanoes?
- How do events within Earth's atmosphere, hydrosphere, and solid Earth generate and transport sediment across subduction zone landscapes and seascapes?
- What fraction of a subduction zone's energy budget goes into building and shaping subduction zone land- and seascapes?
- How can we transform the mindset of our community to embrace education, outreach, accessibility, international partnerships, diversity, equity, inclusion, and social science as critical components for the success of the geosciences?

Several crosscutting themes emerge from these questions. All geohazards studies strive to establish the circumstances under which catastrophic events can be forecast, if these circumstances actually exist or can be measured. The occurrence of large earthquakes, volcanic eruptions, and landslides all reflect the way in which mass and energy are introduced into, balanced, and transferred within subduction zones. Stresses that reflect these mass and energy inputs give rise to motions that depend on the rheology of Earth's materials, whether they are within the solid Earth, near the surface, or part of the atmosphere. Fluids, and how they migrate through the Earth system, are key determinants of where, when, and how large landslides, volcanic eruptions, and earthquakes will occur. Climate change and variability can alter surface loads that influence transport of volcanic fluids, stresses within the crust, and near-surface hydrology that can trigger landslides. Finally, geohazards do not occur in isolation from one another, but can both trigger and result from a cascade of other hazards that can amplify the impact of these phenomena.

INFRASTRUCTURE REQUIREMENTS

To answer the key science questions posed by SZ4D requires collecting a diverse set of observations at a range of temporal and spatial scales both on land and under the sea (**Figure ES-1**). Three key components of in situ SZ4D infrastructure make this data collection possible:

1. **MegaArray** | A large-scale, long-term backbone array of *amphibious* (i.e., seamlessly integrating onshore and offshore observations) geodetic and seismic instruments, densified in key areas
2. **VolcArray** | A multi-component, standardized volcanic array
3. **SurfArray** | A set of surface and environmental change detection arrays that images changes in Earth's shallow subsurface, surface, and atmospheric conditions

While the primary arrays will provide new constraints on different facets of subduction zone behavior, **additional observational, experimental, and modeling efforts, as well as human development programs**, are required to contextualize and explain that behavior; each of these components has associated infrastructure needs. Essential to this effort is the computational infrastructure provided by the MCS integrative group, which will enable the community to integrate results from the arrays and other activities, resulting in a portrait of subduction zones in space and time.

To foster a culture change in research endeavors and ensure results are communicated to communities affected by geohazards, the BECG integrative group developed a comprehensive set of activities to be implemented by the SZ4D community. These efforts can be enabled under a collective impact model that emphasizes high priority activities, which include establishing sustained partnerships and coordination that will enable social change through communities of practice and target PI BECG work towards areas with maximum impact.

PHASED IMPLEMENTATION AND ENVISIONED TIMELINE

All SZ4D components highlight the importance of phasing, in which later phases are based on information generated by earlier phases. The proposed phasing of each working and integrative group's activities has a different timeline. The MegaArray and associated geophysical imaging and geological characterization will begin at a large scale and then proceed after five years to identify key target areas that warrant focused study and densified arrays. The VolcArray will first develop and test instrumental networks on a few volcanoes and then expand to a portfolio of approximately 30 restless systems for long-term observations and six key systems for dense study. The landscapes and seascapes researchers will take a similar approach with SurfArray, but build toward a carefully designed comparison of paired locations to discriminate key processes. In parallel to observational efforts, modeling and experimental efforts will also follow a phased approach to data assimilation, workflow development, and collection of backbone data. Coordination of phasing between observational, experimental, and numerical efforts is necessary to integrate results, to inform planning of future phases, and to answer SZ4D research questions. In summary, the timing of all SZ4D components must be phased in a way that allows the different, interdependent components to be executed smoothly over the lifetime of SZ4D.

GEOGRAPHIC SITES

The SZ4D working and integrative groups systematically evaluated the characteristics of the world's subduction zones to determine whether an effort focused on one or more regions would enable researchers to answer SZ4D science questions. The groups also recognized the imperative for a US-funded initiative to contribute substantially to filling in the fundamental knowledge gaps that affect domestic risk and hazard mitigation. After considering the needs of all of the communities represented by the working and integrative groups as a whole, SZ4D recognized that focused comparisons between international and national subduction zones offered the best opportunities to address the key science questions. Chile, Cascadia and Alaska were recognized as ideal locales for SZ4D efforts. The Chilean subduction zone is sufficiently geologically active to provide useful information during a scientific deployment, is highly accessible with significant scientific and intellectual infrastructure in place in a single partner country, and has regions that form important comparative studies to our domestic sites. The groups recommend deploying ~70% of instrumentation efforts in Chile, ~20% in Cascadia, and ~10% in Alaska. The groups also recognize that associated scientific activities such as geological studies, modeling, laboratory experiments, and building equity and capacity are appropriately balanced differently. The groups recommend a portfolio of ~50% activities in Chile, ~40% in Cascadia, and ~10% in Alaska. Global comparisons with other subduction zones are needed to generalize results from these locations, and this can be most effectively and meaningfully accomplished by developing an international scientific network that leverages parallel efforts by other countries. Developing robust international partnerships globally with complementary smaller-scale projects would provide the diversity of involvement and range of subduction zone processes required to build a generalized view of subduction zone geohazards.

SZ4D ORGANIZATION AND GOVERNANCE

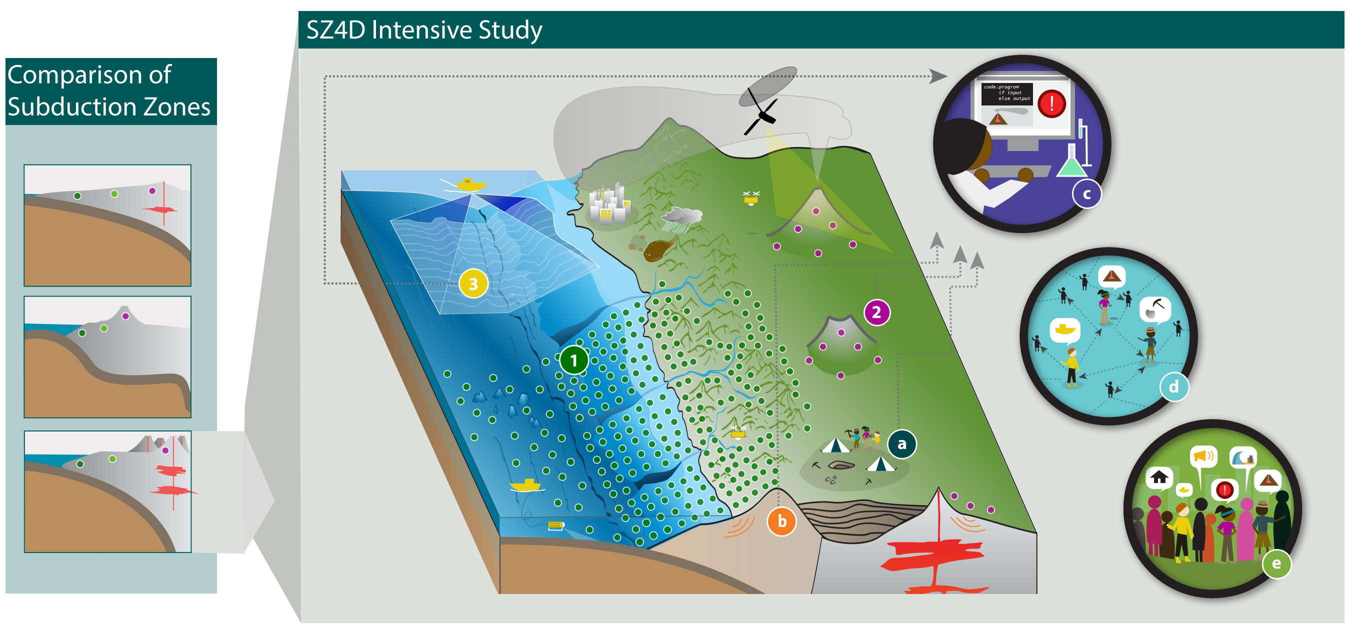
SZ4D implementation requires investment in several key areas, some of which currently exist, and others that need to be developed, combined, or augmented. The first, a central management structure, called the **SZ4D Center**, will coordinate the different existing and new facilities responsible for the vast majority of data collection, facilitate SZ4D science integration, and coordinate these elements with partners and stakeholders to maximize the collective impact of SZ4D efforts. The Center would be overseen by a Center Steering Committee, whose members will be chosen by an open process overseen by the BECG group so that diversity, equity, and inclusion are at the heart of the process. The second key area of investment encompasses five new and existing facilities.

1. **Offshore Instrumentation**, including MegaArray and SurfArray. This new facility will provide dedicated support for seismic and geodetic instrument pools, collection of high-resolution bathymetry and other geophysical imaging data, operational engineering teams, and marine vessels (crewed and autonomous) for deployment, service, and rapid response near the site(s) of dense deployment.
2. **On-land Instrument Arrays**, including component of VolcArray, SurfArray, and MegaArray. Current facilities may, in part, be leveraged to service the needs of the onland instrumentation pool.
3. Logistics for sample collection, instrumentation, and field programs that involve **Human Deployments** as the primary observational instruments to collect systematic, standardized data including paleoseismology, framework mapping, samples for geochronology, geochemistry, and petrology. We envision a facility including a field station that could support field logistics, imaging acquisitions, and sample permitting, archival and transport.
4. A **Modeling Collaboratory.** This facility would develop new subduction zone physical models and computational tools that leverage advances in machine learning for data-driven science, as well as provide resources for their use by the whole SZ4D research community including students, postdocs, and researchers.
5. A **Laboratory and Sample Consortium.** This Consortium would enable the study of material properties, rheology during deformation, and phase equilibria of molten systems.

The final component of the SZ4D Initiative is a **Science Program** at the National Science Foundation that identifies and enables the most important emerging SZ4D-related scientific research using a merit-based panel review mechanism. Regular communication between the science program and SZ4D Center Steering Committee would help coordinate data collection and identify science priorities throughout the duration of the program. The three-pronged approach advocated here—a Center, Facilities, and Science Program—will maximize the scientific and societal impact of the SZ4D initiative and help train the next generation of multi-hazard geoscientific researchers.

OUTLOOK

SZ4D is poised to make major advances in understanding the science behind subduction zone hazards by strategically deploying new instrumentation in pairs of subduction zones, developing more sophisticated and accurate models using advances in computation, coordinating the breadth of geohazards research using a collective impact approach, and integrating a diverse community of scientists and stakeholders who will bring a wide range of skills, knowledge, and ideas to this effort. To be successful, this long-term collaborative effort requires close coordination among all components and deep integration throughout the program, starting in its earliest phases. Achieving SZ4D goals will not only provide new understandings of the physical and chemical processes at work in subduction zones, it may provide tangible benefits to communities who live in regions affected by subduction zone hazards.



1 **MegaArray** (densified in areas of key interest)

2 **VolcArray** (augmented by rapid-response deployments)

3 **SurfArray**

a Mine geological record for rheological, chemical, and historical context

b Image subsurface to directly determine structures

c Build computational models that integrate field observations and laboratory data

d Build human capacity to perform this multidisciplinary research using the full diversity of people available

e Transform this information into meaningful results that can be immediately utilized by affected communities

Figure ES-1. *Schematic of major instrumental arrays and activities of SZ4D. (Katy Cain/Carnegie Institution for Science)*

SIDEBAR 1

What is a subduction zone?

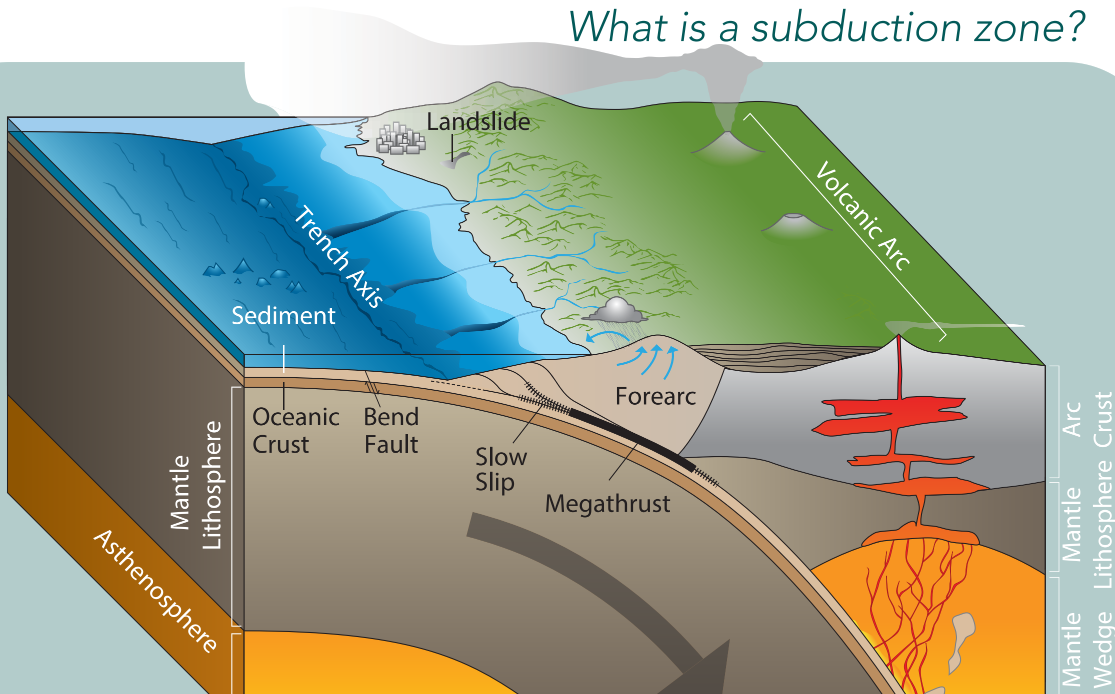


Figure S1-1. *Representation of a subduction system, identifying many of the components discussed in this document. A subduction zone is created where two plates converge, with one sinking into the mantle. Subduction connects features on the incoming plate to dynamics along the plate interface that create 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. Figure retrieved from the* ***SZ4D Vision Document***

At subduction zones, two tectonic plates converge, and one is thrust beneath the other. These settings host profound geohazards. The largest earthquakes on Earth are generated on the contact between these two tectonic plates, and the resulting motion at the seafloor triggers large tsunamis. Chains of active volcanoes form along subduction zones, many of which are capable of explosive eruptions. These seismically and volcanically active settings create dynamic landscapes that can produce catastrophic landslides. Large population centers around the world are located along subduction zones and thus immediately exposed to the hazards they pose, including within the United States. The Pacific Northwest experienced an earthquake on the scale of the 2011 Tōhoku earthquake 323 years ago and is capable of hosting future earthquakes of this size. 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. Even more people are vulnerable to the far field effects of subduction zone hazards, as painfully illustrated by the tsunami produced by the 2004 M9.1 Sumatra earthquake. Despite the enormous social significance of these hazards to many, the basic physical and chemical processes controlling the occurrence and magnitude of these natural events remain poorly understood. The purpose of SZ4D it to provide transformative new insight into controls on the fundamental processes underlying these hazards.