2022

SZ4D

IMPLEMENTATION PLAN

NSF

SZ4D

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PREFERRED CITATION

Hilley, G. E. (ed.), Brodsky, E.E., Roman, D., Shillington, D. J., Brudzinski, M., Behn, M., Tobin, H. and the SZ4D RCN (2022). SZ4D Implementation Plan. Stanford Digital Repository. Available at *https://purl.stanford.edu/hy589fc7561*. *https://doi.org/10.25740/hy589fc7561*

ACKNOWLEDGMENTS

We gratefully acknowledge the intellectual contributions of the 3400 participants in SZ4D activities between 2020-2022. The generous and deep commitment of the community has built this plan during some of the most difficult years of our personal and professional lives. SZ4D efforts have been supported under NSF grants *EAR-1828096*, *EAR-1824343* and *EAR-2221947*. This document is the final report of both the SZ4D RCN and the MCS RCN, which were supported under the first two of these awards.

This document was released in November 2022

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SZ4D

IMPLEMENTATION PLAN

2022

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.

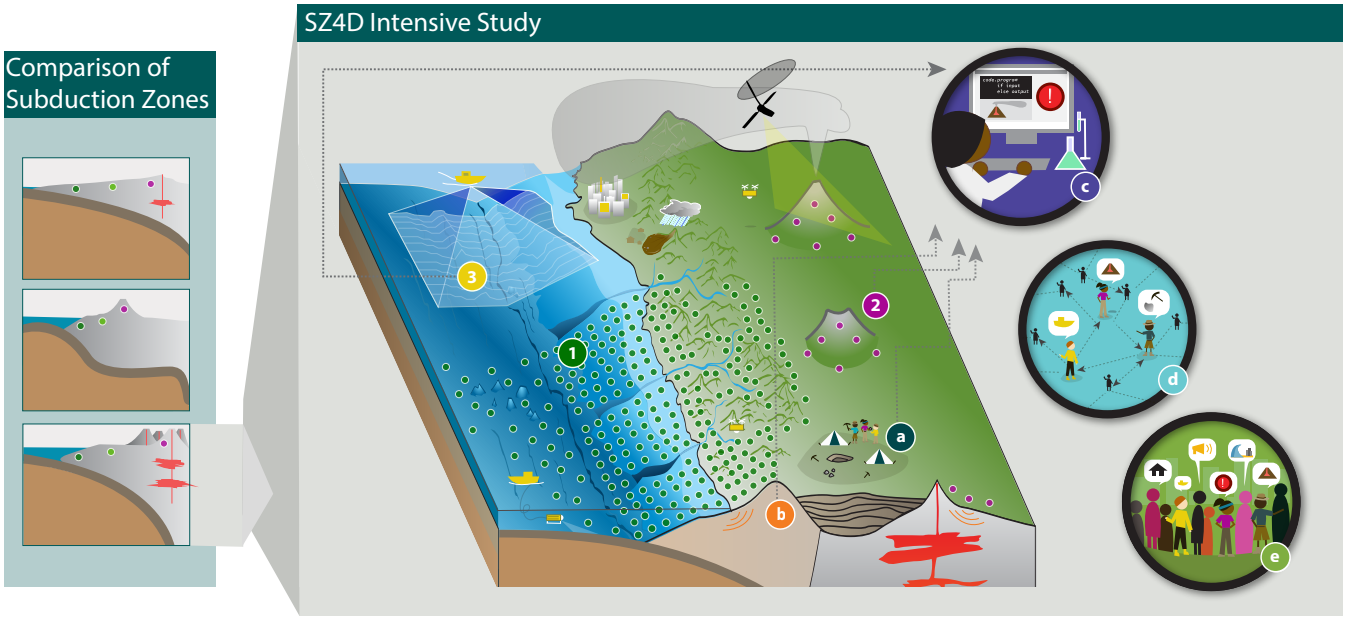
5. A **Laboratory and Sample Consortium.** This Consortium would enable the study of material properties, rheology during deformation, and phase equilibria of molten systems.

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.

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



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

SIDEBAR 1

What is a subduction zone?

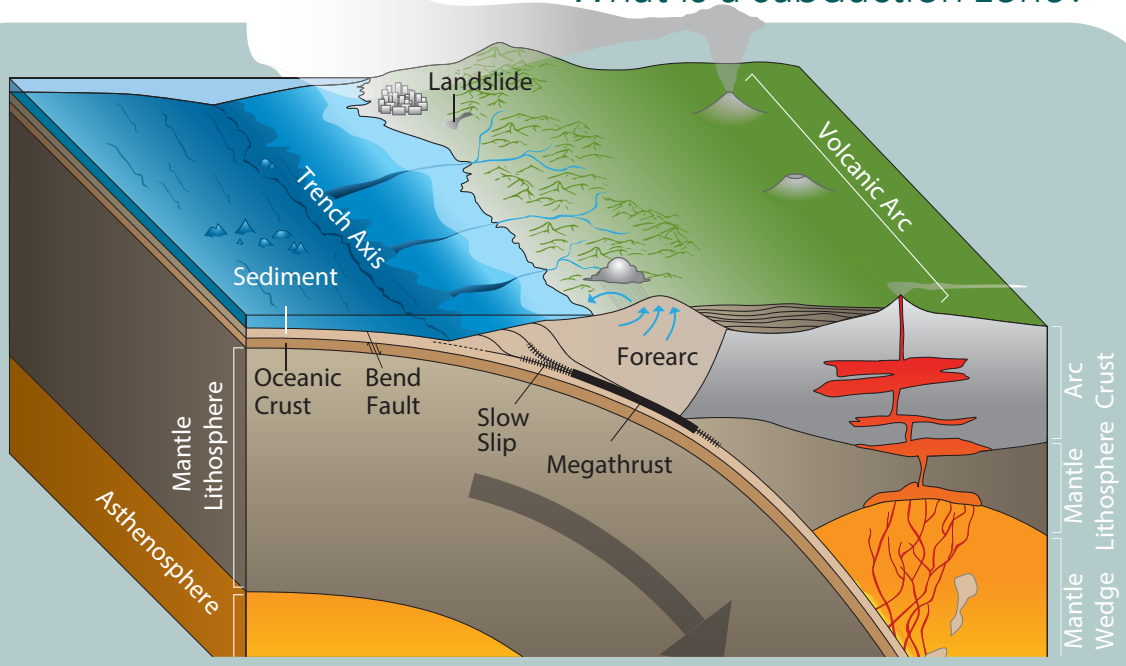


Figure S1-1. *Representation of a subduction system, identifying many of the components discussed in this document. A subduction zone is created where two plates converge, with one sinking into the mantle. Subduction connects features on the incoming plate to dynamics along the plate interface that create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

INTRODUCTION

Rationale for an SZ4D Initiative

The most devastating geohazards on Earth occur along subduction zones. Within these narrow coastal belts, energy is concentrated mainly along continuous faults that can extend more than a thousand kilometers and are capable of hosting great earthquakes. Volcanoes that can spew ash and noxious gases tens of kilometers into the atmosphere rise parallel to the trench, and steep, unstable terrain that extends hundreds of kilometers inland can unleash destructive mass-wasting events. These geohazards pose a significant risk to human population centers ranging from small coastal communities to large cities.

Although we have limited understanding of the physical and chemical processes controlling the occurrence, timing, and magnitude of subduction zone hazards, new data and techniques promise significant progress. In the past two decades, bathymetric, seismic, geodetic, geochemical, and remote-sensing data have revealed a rich array of slip processes during an earthquake cycle, novel volcanic eruption precursors, detailed spatial patterns of earthquake-triggered landslides, and a host of new geomorphic processes on landscapes and seascapes. These advances provide an unparalleled opportunity to organize a comprehensive, multidisciplinary, coordinated effort to collect observations, conduct laboratory experiments, and develop models that would significantly mitigate the risk of geohazards by allowing catastrophic events to be placed in a fully four-dimensional physical context. **Subduction Zones in Four Dimensions, or SZ4D**, is a community-driven initiative to study the places where Earth's tectonic plates converge, with a focus on understanding the physical and chemical processes that control the occurrence and magnitude of significant earthquakes, tsunamis, volcanic eruptions, and mass movements at Earth's surface (**Figure I-1**).

Because of their unique geometry and global distribution, subduction zones provide ideal natural environments to isolate the processes controlling the variability of geohazard behavior. The interrelated physical and chemical processes that occur as one tectonic plate descends beneath another define and ultimately control the surface expressions of earthquakes, volcanoes, tsunamis, and landslides. With increasing depth, variations in temperature and

pressure exert first-order control on geohazard processes. Similarly, identifiable lateral variations along the subduction zone become manifest in the differences in geohazards. These lateral variations range from the expected, such as variations in plate convergence rate, which corresponds to the number, size, and occurrence of earthquakes and eruptions, to the subtle, such as variations in terrestrial erosion rate that may then influence magma generation and volcano locations. Such large-scale and long-term variability provide critical boundary and initial conditions for geohazards that can be assessed in numerical models.

This **SZ4D Implementation Plan** is the result of sustained effort by the members of the SZ4D umbrella Research Coordination Network (RCN) and the Modeling Collaboratory for Subduction RCN. The plan identifies the overarching scientific drivers of the next level of research effort in subduction earthquakes and tsunami generation, the magmatic processes that lead to the eruption of arc volcanoes, and the mass movements and energy distribution that drive surface processes leading to slope failure, debris flows, and other catastrophic events on land and under the sea. This document lays out a set of essential primary observations and experiments that would address each scientific question and be part of a sustained research program at key geographic locations. The plan identifies and outlines the means to develop and nurture a cross-disciplinary SZ4D research community that will promote equity and inclusion among personnel within the United States and our international partners. It also lays out the necessary novel research infrastructure to accomplish these goals, as well as a potential SZ4D program structure that would serve the needs of a diverse and vibrant research community for decades to come.

Research Coordination Network Process

The beginnings of the RCN process stemmed from a meeting in late 2016 in Boise, Idaho, where more than 250 scientists from 22 countries envisioned an SZ4D initiative, culminating in the report, *The SZ4D Initiative: Understanding the Processes that Underlie Subduction Zone Hazards in 4D* (McGuire et al., 2017). In this document, the science community articulated the need for investments in infrastructure and a comprehensive science program focused specifically on geohazards in subduction zones. Subsequently, in 2018, the National Science Foundation (NSF) established two Research Coordination Networks—the SZ4D Umbrella RCN and the Modeling Collaboratory for Subduction RCN—to enable the US research community to work together to develop a consensus plan for an SZ4D program.

The SZ4D RCN (**Figure I-1**; **Appendix I-1**) was charged with translating the broad vision in the McGuire et al. (2017) report into a concrete and viable blueprint for a future SZ4D program. The National Academies' Catalyzing Opportunities for Research in Earth Sciences (CORES) committee recognized the continual development and ultimate funding of SZ4D as a high-priority activity for the NSF Division of Earth Sciences in their report *A Vision for NSF Earth Sciences 2020–2030: Earth in Time* (NASEM, 2020).

The RCN first established a Steering Committee and pursued the development of an SZ4D program by obtaining input from a broad and representative cross section of the subduction geohazards research community. Working groups on the three core scientific themes were identified through consultation with the initial RCN membership. These groups have

worked to develop the detailed plans laid out in **Chapters 2, 3,** and **4** of this implementation plan. Simultaneously, two integrative groups collected community input to assemble the guiding plans described in **Chapters 5** and **6**, representing our collective vision for BECG via the SZ4D research community and a program for creating a next-generation modeling capability and community for subduction zone research (MCS), respectively.

The 74 members of the working and integrative groups met continuously throughout 2020–2022 to build this implementation plan. Along the way, the RCN engaged over 3400 participants through workshops, webinars, town hall meetings, and special interest group sessions tied to specific professional conferences and meetings, all during the challenging pandemic remote work era of 2020-2021. The RCN also hosted 13 webinars that brought insights from experts from 11 countries. Working and integrative group membership included diverse voices from the research community to balance the need to create a focused and specific plan while respecting the consensus priorities of the hundreds of scientists they represent.

The working and integrative groups initially focused on developing research questions and critical observations throughout 2020, when community input was solicited through a series of webinars. Based on this community input, as well as input from the other working groups, each group further refined its research questions and key measurement requirements throughout 2020 and 2021. Once a framework was established, the questions were mapped onto traceability matrices that depicted how the science goals and objectives "trace" (flow down) to instrument and data requirements. The groups then developed notional experiments that captured key activities. In parallel, the RCN developed an inventory of subduction zones globally to be assessed for suitability for the notional experiments. The working and integrative groups then combined their requirements and recommendations for geographic areas and developed a phased plan of experiments and activities.

As part of this process, each working group completed a draft document identifying the key research questions, the measurements required to address them, the types of experiments

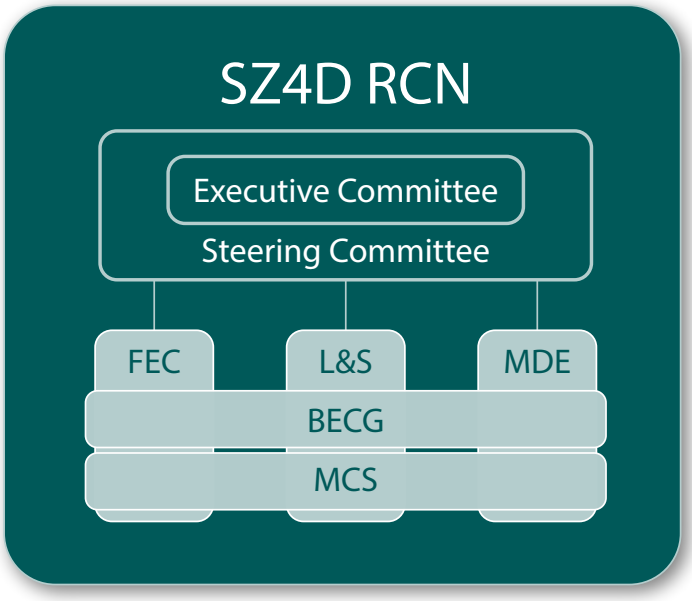


Figure I-1. *Organization chart of the SZ4D Research Coordination Network (RCN). Disciplinary groups: L&S: Landscapes and Seascapes, FEC: Faulting and Earthquake Cycles, and MDE: Magmatic Drivers of Eruption; SZ4D integration groups: BECG: Building Equity and Capacity with Geoscience, and MCS: Modeling Collaboratory for Subduction.*

needed to test specific hypotheses derived from the research questions, and the geographic locations where these experiments might be carried out. Each group opted to frame their work in terms of research questions, science questions, or hypotheses. These variations reflect the organic nature of the working group process, which melded multiple communities with distinct traditions in describing their scientific goals. These draft reports were cross-reviewed by other working groups to identify and highlight the scientific questions and measurement requirements that span the larger subduction zone science community. This full draft report was released for community feedback in October 2021 to ensure that the documents articulate a consensus scientific opinion about the most important scientific questions and the instrument and modeling networks we will need to address them.

During the subsequent year, the ensuing community comments were combined with additional international input, allowing for greater planning specificity. Geographic discussions were focused on Chile as the critical international site, and an in-person workshop was held in Los Andes, Chile, in May 2022 (i.e., as soon as the exigencies of the global pandemic allowed such a meeting). The insights of the more than 60 Chilean scientists allowed more concrete planning to progress with the relative merits of scientific and geographic targets more clearly delineated. International collaborations grew further with a June 2022 in-person meeting in Potsdam, Germany, to incorporate the work of the long-term European efforts in the region. Cascadia and Alaska were identified as domestic sites for targeted new observations and studies leveraging existing data.

Science Plan Overview

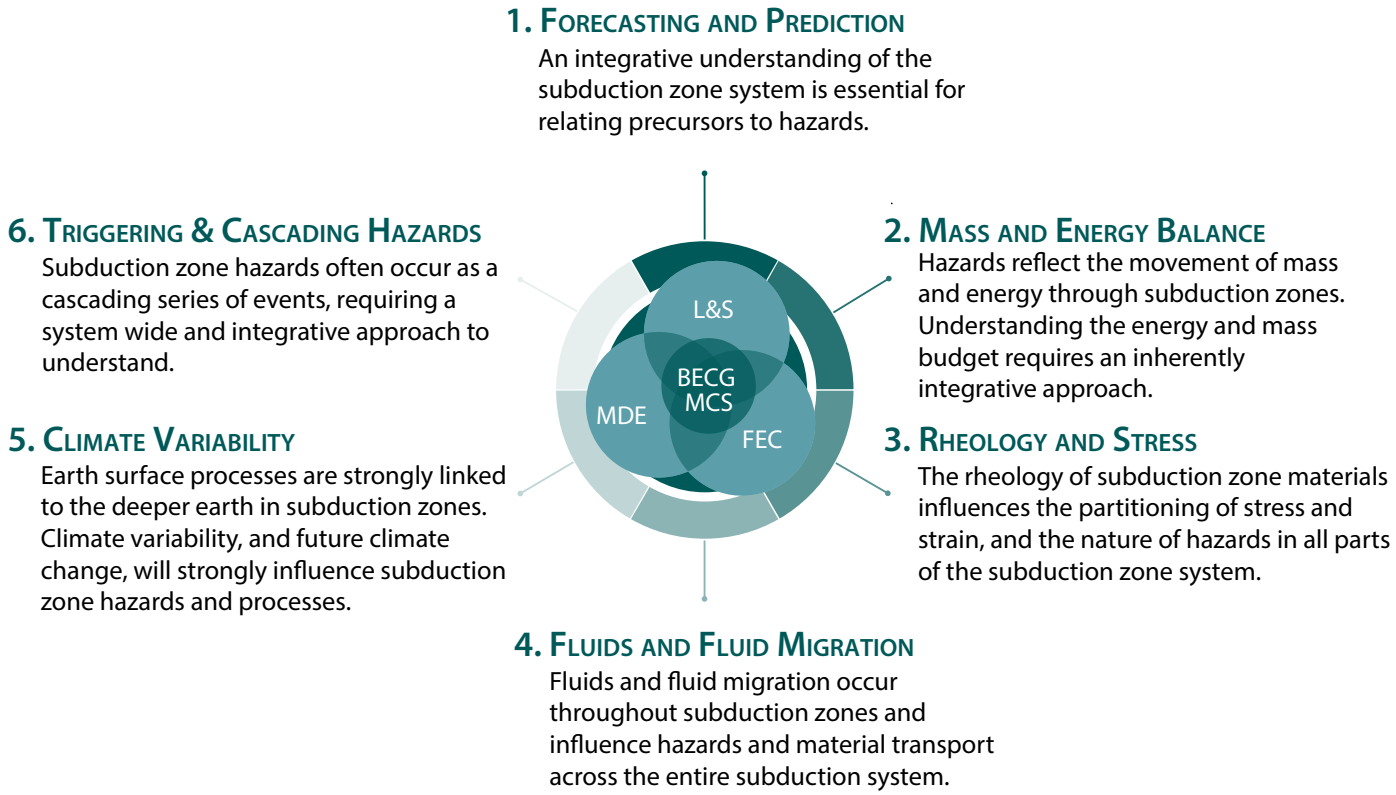
The overarching objective of SZ4D is to gain insight into the fundamental physical and chemical processes that underpin geohazards at subduction zones. **Chapter 2** outlines the critical geohazard-related crosscutting themes that span all of the working groups. One of the key emerging themes is forecasting and predicting geohazards, which is desirable but currently only achievable to varying degrees. Forecasting is a mature field that probabilistically anticipates various hazards or risks. The closely related study of prediction focuses on scientific hypotheses of future behavior. Scientific prediction can be fully deterministic or probabilistic depending on the degree of certainty of the physical state and the underlying dynamics of the system. The focus of SZ4D on process leans more heavily toward assessing the physics-based predictability of subduction-related geohazards. A pivotal element to both forecasting and prediction is the existence or absence of precursory behavior and its identification.

Predictability has remained challenging or elusive for all subduction zone hazards; is this merely due to a lack of adequate measurement of the controlling variables, or is the process intrinsically stochastic or chaotic? Could we forecast all volcanic eruptions by deploying sufficient instrumentation to detect subtle signals, or do fundamental differences in process or mechanical state need to be elucidated before achieving this goal? Theory and laboratory experiments suggest that precursory signals of earthquakes and landslides should exist. Is prediction simply a matter of insufficient observations or of studying key precursory processes that are not yet understood?

In addition to forecasting and prediction, the SZ4D working groups identified five other crosscutting themes (**Figure I-2**). In order to understand the location, magnitude, and potential destructiveness of subduction zone hazards, it is essential to unravel **the stress, mass, and energy balance** within subduction systems. Mass transfer couples the subduction system and hazardous events, and involves transforming energy from one form to another. The connection between stress and strain is the domain of **rheology**, which is essential to all facets of the SZ4D effort. Observations of deformation generally measure strain, yet predictive understanding of processes requires knowledge of stress. **Fluids** provide the fastest mode of transport across the system and exert first-order control on geohazards both in the deep and shallow system. **Climate variability** changes the exposed land and forcings, which in turn affects the subsequent hazard. The geohazards can also directly interact, and the combined effort of SZ4D can capture these **triggering cascades** that can potentially result in catastrophic multi-hazard scenarios.

These crosscutting themes and working group questions demand major observational and data-gathering efforts, which fall into two categories: instrumentation arrays and activities undertaken by a collective of scientists.

Figure I-2. *A visualization of six crosscutting science themes that link the three main SZ4D disciplinary groups, Landscapes and Seascapes (L&S), Faulting and Earthquake Cycles (FEC), and Magmatic Drivers of Eruption (MDE); and two SZ4D integration groups, Building Equity and Capacity with Geoscience (BECG) and the Modeling Collaboratory for Subduction (MCS). Each science theme incorporates fundamental questions and goals that transcend a single discipline and are enhanced through a system-scale approach.*



First, SZ4D requires **amphibious geodetic and seismic instrumentation** deployed in an array (**MegaArray**) that spans an entire ~500 km-long segment and is densified in critical areas, **volcano arrays** (**VolcArray**) of standardized, multiparameter volcanic instrumentation packages, and **surface and environmental change detection arrays** (**SurfArray**) that image changes in Earth's surface, sediment transport, and rainfall. These instrument arrays can only be interpreted and utilized with complementary efforts to:

1. Mine the geological record for rheological, chemical, and historical context through geological and experimental studies;
2. Image the subsurface to directly determine structures;
3. Create a modeling environment that can integrate and guide the observations in concert with data obtained from laboratory experiments;
4. Build the human capacity to perform the research, embracing the full diversity of people available; and
5. Translate the scientific findings into knowledge that provides tangible benefits to communities affected by subduction zone hazards.

Items 1 and 2 are addressed within the working groups' plans (**Chapters 3.1 to 3.3**). Item 3 is addressed by the MCS integrative group (**Chapter 4.2**), resulting in a recommendation for a facility devoted to this issue. **All parts of SZ4D require items 1–3 and thus provide another important linkage across the program and a mechanism for building a comprehensive portrait of subduction zone structure and behavior.**

Items 4 and 5 require special attention and strategizing. Without reaching these human-centered goals, the impact of the entire SZ4D effort is limited. The Building Equity and Capacity with Geosciences integrative group has formulated a plan (**Chapter 4.1**) that includes specific activities that will foster international capacity building, hazard equity, social justice, education and training, distributed outreach, and interdisciplinary collaboration, and that will increase diversity, equity, and inclusion. The key needs would be met through a coordinated effort involving community engagement, social science and education research, and resource centralization. The SZ4D community would participate in a cooperative network seeking to accomplish long-term, sustainable broader impacts by leveraging existing nonprofit and nongovernmental organizations that currently work with communities in the SZ4D footprint.

Second, enabling SZ4D will require investment in facilities, some of which currently exist and others that need to be developed, combined, or augmented. As discussed in **Chapter 5.4**, facility support is necessary in several key areas.

1. **Offshore Instrumentation**, including the 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 components 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, 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 scale and scope of the proposed comprehensive program require a carefully phased approach, as outlined in **Chapter 5.3**. Phase 0 activity is largely complete through the work of the SZ4D community to develop this implementation plan. Phase 1 is currently underway, with ongoing development of detailed experiment designs and analytical protocols, technology, and facility and data center support to meet later scientific needs. Pilot reconnaissance-level field efforts and modeling activities are also being pursued. Phase 2 will encompass the decadal-scale, full-fledged deployment of field campaigns to observe and analyze subduction systems comprehensively. The arrays will be guided by and, in turn, guide model development and laboratory research. Finally, Phase 3 entails the digestion and synthesis of all the multi-faceted SZ4D activity, consolidating insights into these complex Earth systems.

Subduction zone geohazards are affecting more people as population density increases along the coasts and infrastructure expands. Vulnerability is high, and better knowledge of hazard prediction is clearly desirable. Current approaches to eruption and landslide prediction are empirical; earthquake prediction remains beyond our grasp. A rich suite of processes is responsible for each of these hazards, but capturing the signals that lead up to hazardous events with sufficient fidelity and geologic context for understanding has been elusive. By providing dense, continuous, standardized data that can be readily integrated into an interpretive framework, SZ4D will provide the fundamental understanding needed to better assess the risks of earthquake, volcanic, landslide, and tsunami hazards to communities in subduction zone regions.

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CROSSCUTTING SCIENCE THEMES

An Integrated Vision for Subduction Zone Hazards

Introduction

Subduction zone hazards such as earthquakes, volcanic eruptions, landslides, and tsunamis have large, expensive, and long-lived impacts on human societies. Modern examples include great earthquakes and tsunamis in Alaska (1964), Sumatra (2004), and Japan (2011); the 2014 Oso landslide in Washington State; and the 1980 eruption of Mount St Helens. All these events resulted in significant loss of life and long-lasting disruptions at local, regional, and in some cases, global scales. Although the impact to societies from major subduction zone hazard events is very high, the underlying science needed to understand such damaging phenomena remains far from settled.

The overarching goal of the SZ4D initiative is to develop an integrated understanding of how the different components of subduction zone systems interact to produce and magnify geologic hazards. Key to this understanding is unraveling the roles subduction zone physical and chemical processes play in initiating and then linking different hazards in space and time. Just as people living in subduction zones do not worry about "just" earthquakes, "just" tsunamis, "just" volcanic eruptions, or "just" landslides, SZ4D doesn't focus on "just" individual hazards. The processes at work in subduction zones often produce a cascade in which an initial hazardous event may trigger additional hazardous events that prolong and magnify the impact of the linked geohazards.

The integrative and disciplinary crosscutting nature of the SZ4D approach is deliberate and evident at all levels of the initiative.

Examples include:

- Our fundamental approach of collocating science and human resources to provide efficiency and integration throughout our activities.
- Our geographic approach, which is designed to allow integration and comparison of subduction zone processes across multiple subduction zones.
- Our organizational structure, where each working group consists of individuals who have a range of disciplinary specialties and who collaborate around common science and community goals. In addition, integrative groups, such as MCS and BECG, address identified needs that extend across all science and inclusivity goals.
- Our nurturing of a number of other integrative efforts, including designing and deploying instrument arrays that support multiple working group goals, designing a human deployment facility to address fieldwork needs across working groups, and ongoing organizing of groups around other needs—such as experimental and analytical methods—that also support multiple science goals.

SZ4D Crosscutting Science Themes

The integrative and synergistic nature of the science that motivates SZ4D is evident in the number of research themes that crosscut individual working groups (**Figure CST-1**). This chapter explores several of these themes in greater detail and highlights areas where our investigations and results provide the best opportunities to make fundamental advances across all SZ4D working groups.

Forecasting and Prediction

How do we recognize precursor signals to devastating subduction hazard events, what techniques do we need to use to monitor them, and how do we relate such precursors to the eventual magnitude and style of the hazardous event?

Subduction zones generate some of Earth's most devastating geohazards including earthquakes, landslides, volcanic eruptions, and tsunamis. Providing robust forecasts and warnings to vulnerable populations is important for mitigating the potential impacts of these disasters. The concept of forecasting is simple in principle but exceedingly difficult in execution: robust forecasts are grounded in a thorough understanding of the entire system, its uncertainties, and how it responds to changes. In this framework, the driving forces and precursory signals that lead to hazardous events (e.g., earthquake foreshocks, volcanic unrest, and slope creep) provide some information about relative hazard levels, which allow detailed monitoring to provide an ongoing evaluation of hazard potential.

While relative hazard levels can be coarsely gauged, these often inconsistent and unreliable indicators of activity cannot easily be translated into confident predictions as to when and where subduction hazards occur. This reflects gaps in our understanding of the subduction system, the nature of precursory signals, and the way the system responds to forcings. As a result, the warning signs of an impending subduction zone hazard are often difficult to determine,

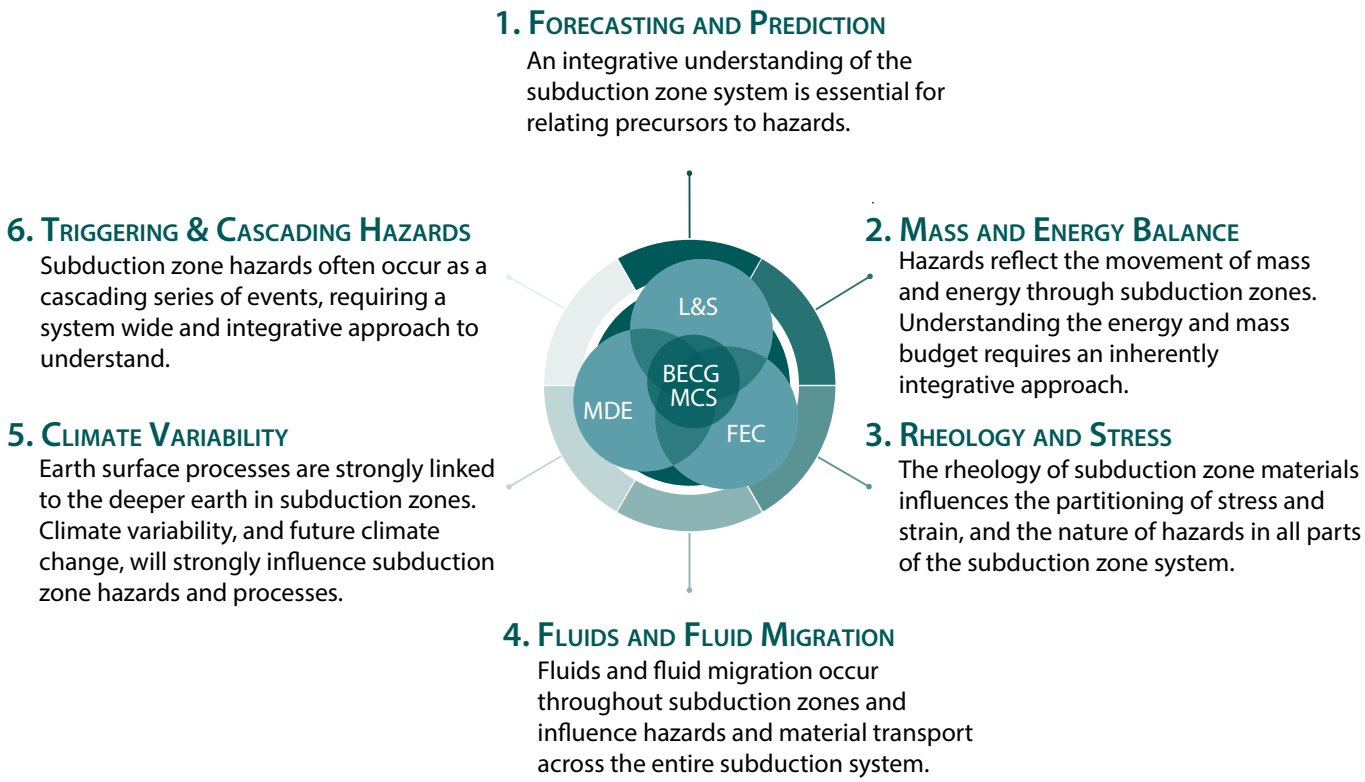
and catastrophes can occur with little or no warning. Thus, a focus of the SZ4D initiative is to study possible precursory signals and connect them to potential hazards through a robust understanding of the physical and chemical processes active in subduction zones and the liquid, solid, and gaseous materials that flow in and out of them.

Although the SZ4D disciplinary working groups agree that the ability to identify precursory signals is central to forecasting subduction zone hazards, most also agree that data collected on precursory events do not currently provide the information needed to predict the magnitude, duration, and area of impact of an eventual hazard. Important examples include the relationships between:

1. Foreshocks and earthquakes,
2. Deformation and seismic precursors,
3. Mechanisms and styles of volcanic eruptions,
4. Rapid sediment transport and flood prediction.

Large landslides also have precursory signals similar to some volcanic eruptions and earthquakes. However, the fundamental controls on the initiation and runout of landslides, turbidity currents, and other mass flow events remain less clear.

Figure CST-1. *A visualization of six crosscutting science themes that link together the three main SZ4D disciplinary groups, Landscapes and Seascapes (L&S), Faulting and Earthquake Cycles (FEC), and Magmatic Drivers of Eruption (MDE); and two SZ4D integrative groups, Building Equity and Capacity with Geoscience (BECG) and the Modeling Collaboratory for Subduction (MCS). Each science theme incorporates fundamental questions and goals that transcend a single discipline and are enhanced through a system-scale approach.*



To obtain an integrated understanding of the processes and materials needed to relate precursory signals to hazards also requires us to approach subduction zone studies in novel ways and go beyond traditional disciplinary boundaries in our research. An important emphasis will be on model-data fusion. This technique is extremely useful for investigations of hazard prediction and forecasting and is also important to many other SZ4D studies. Model-data fusion requires integrating information from multiple data sources across modeling and observational domains to produce results that are more consistent, accurate, and useful than those provided by any individual data source.

The MCS integrative group is poised to fill this computational gap in the geosciences and provide physics-based and data-driven frameworks for combining the multi-scale, multi-parameter, multidisciplinary observational and laboratory datasets collected by SZ4D. The MCS will allow SZ4D scientists to apply data inversion techniques to multiple data streams to reveal the relationships between potential precursors and hazards over many different timescales. Progress in model-data fusion is specifically needed for forecasting, which uses very large volumes of diverse data from centralized and distributed sources (e.g., earthquake recordings, satellite observations, GNSS measurements). Over the past decades, significant progress has been made in statistical data assimilation in the fields of climate modeling, hydrology, and physical oceanography, and these provide important scaffolding for future MCS efforts in subduction zone hazards, where significant work to advance this field remains. Another goal of the MCS is to make it easier for SZ4D scientists to use model-data fusion methodologies in their research. The MCS will enhance and support the interoperability of data and software and enable integration and collaboration across different subduction scientific domains.

Mass and Energy Balance

How do we track the passage of mass and energy through subduction zones, and how do we relate critical transitions in mass and energy transfer to hazardous events?

Our understanding of the location, magnitude, and potential destructiveness of subduction zone hazards hinges upon our knowledge of mass and energy distribution and balance within subduction systems. Major changes in the distribution of mass and energy occur within and across Earth's surface at subduction zones in response to plate tectonic motions and atmospheric processes. Hazardous events such as earthquakes, tsunamis, landslides, and volcanic eruptions are both responses to, and manifestations of, this redistribution. As a result, recording changes in the distribution of mass and energy before, during, and after hazardous events in multiple subduction zones will provide the information necessary to significantly advance understanding of the factors that control hazards.

One example of how knowledge of mass and energy distribution cuts across traditional disciplines is the study of the relationship between sediment transport and subduction behavior. Sediment transport at the trench can affect slip processes and rates along the megathrust, and uplift associated with seismic activity strongly influences sediment transport. Subducting sediments also contribute to volatile species that influence the behavior of the megathrust at shallow levels in the subduction zone and impact deeper magma production rates, which ultimately contribute to volcanic activity and hazards. Mass and energy exchanges within a

subduction zone also influence crustal tectonics, the rates of uplift, and the evolution of topography, where gravitational potential energy is converted into kinetic energy through sediment transport—including destructive events such as landslides and debris flows.

Accumulation of energy within the subduction system drives hazardous events and controls the scale of the event. Thus, although knowledge of the stress state might tell us how close a system is to failure, additional information on the mass and energy balance is needed to forecast the size of that failure.

Calculating the energy and mass budget of a subduction zone with sufficient detail and accuracy requires knowledge of the heat flux, strain, and stress associated with volcanism, earthquakes, and deformation, and their changes at Earth's surface (**Figure CST-2**). These measurements will be integrated into numerical models of the subduction system at a range of pressures, temperatures, and strain rates to provide a more accurate 4D picture of potential subduction zone hazards.

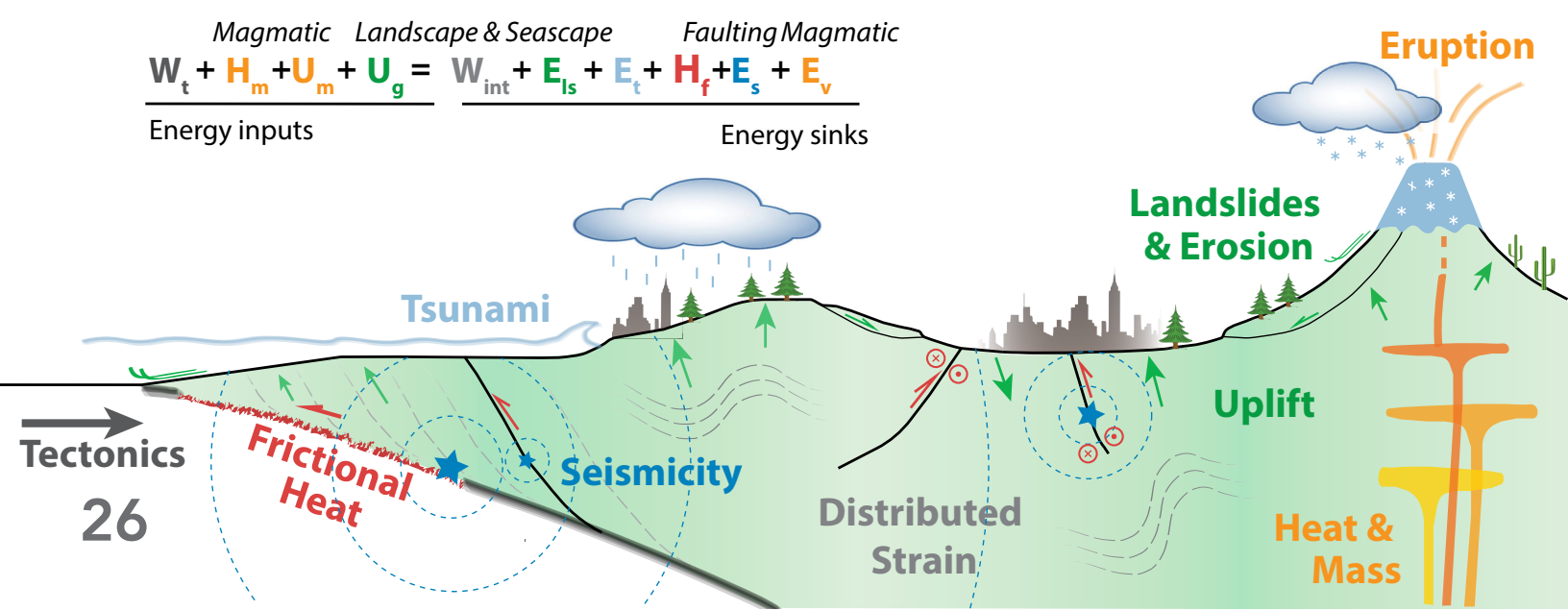
Rheology and Stress

How does the rheology of subduction zone materials influence the partitioning of stress and strain, and how does this control the nature of hazards across the subduction zone system?

When subduction zone hazards initiate, potential energy is converted into strain in the solid and fluid Earth according to the rheology of Earth materials involved in the energy release. Additionally, rheology controls the way in which continued geodynamic loads are released in time and space. Thus, understanding the rheology of subduction zone materials will enhance forecasting future earthquakes and volcanic eruptions, and the initiation and runout of mass movements such as landslides and debris flows.

Knowledge of the rheology of the Earth

Figure CST-2. *Schematic first-order energy budget of the entire subduction zone. The inset equation outlines in the energetic inputs (Wt - tectonic work; Hm - heat; Um - gravitational potential energy from mass in/out of the system), conservative energy terms (Ug - work of uplift against gravity; Wint - internal deformation work) and energetic sinks that are lost to the system (Els - kinetic energy of sediment transport; Et - tsunami energy; Hf - frictional heat of earthquakes; Es - seismic shaking and Ev - heat and kinetic energy of volcanic eruptions). Understanding the relationships between subduction zone processes provides information about the energy available within the system to drive damaging hazards.*



materials involved in each of the major subduction zone hazards is limited, thus activities focused on rheology have broad application. For example, granular flows are mixtures of solid and fluid components and can exhibit highly complex and variable rheology and hydrodynamics where the constitutive laws are still under debate. Predicting the behavior of water-borne sediments, fault interfaces, lava and pyroclastic flows, and mass flow deposits produced by landslides all require understanding granular flow and thus concerted experimental, observational, and modeling efforts are needed here. Similarly, changes in rheology that occur during ongoing strain and deformation can produce dynamic weakening of lower crustal and mantle rocks that affect our understanding of volcanic systems, fault loading, and the support of topography.

Activities within SZ4D will sharpen our knowledge of the rheology of critical Earth materials. Leading-edge laboratory experiments will provide direct measurements of the rheology of fault-zone materials, crustal rocks, and granular flows mixtures that map how stresses are converted to strains in these materials at the relevant strains, strain rates, pressures, and temperatures. Geological data can reveal evidence of small-scale processes such as pressure solution, microcracking, crystal plasticity, and metamorphism. Geophysical measurements from the observational arrays will measure the motions of subduction zone materials at the scale of the subduction zone system in response to modeled and observed stresses, and thus provide information about in situ rheology. These rheological descriptions will be combined with geodynamic models to understand how loading interacts with the rheology of subduction zone materials to produce the motions that we observe. Rheology, studied in the laboratory and inferred at the scale of the subduction zone system, is central to understanding the dynamics that produce subduction zone hazards.

Fluids and Fluid Migration

How does fluid migration influence hazards and material transport across the entire subduction system?

A greater understanding of the distribution of fluids, the nature and consequences of fluid migration, and the physical and chemical impacts of solid-fluid interaction is integral to all parts of the SZ4D initiative. Existing work, including studies conducted by previous NSF initiatives such as MARGINS and GeoPRISMS, have provided significant insight into fluid distribution in subduction zones. The gap that remains is in our knowledge of how fluids and fluid migration mediate energy and mass exchanges at subduction zones, and how interplay of these processes produce natural hazards.

Subduction involves entry of a strongly hydrated oceanic plate into Earth's mantle. The cycling fluids into the mantle and then back into the crust drives myriad subduction zone processes. The transport of fluids deep into Earth promotes melting and magma formation and controls seismicity on the megathrust and other related faults—including those that produce the most destructive earthquakes. In addition, fluid flow throughout the subducted oceanic crust and along the subduction channel strongly controls many of the physical and chemical properties of the subducting lithosphere, and as a result modulates much of the complex mineralogical and chemical exchanges in this region.

Fluids and fluid migration also modulate processes within the shallow crust and at Earth's surface. Local fluid pressure strongly influences

shallow fault systems, and changes related to fluid migration can significantly impact earthquake activity. Interaction between shallow crustal fluids and magmas can also produce phreatic and phreatomagmatic eruptions, such as the deadly recent eruptions at Mount Ontake, Japan, in 2014; and Whakaari/White Island, New Zealand, in 2019 (**Figure CST-3**). Alteration of volcanic edifices via shallow hydrothermal circulation can lead to edifice failure and mass wasting events. Hydrothermal fluid circulation leads to the formation of important mineral deposits, including many metals needed for "smart" technologies and for low-carbon geothermal energy components.

Climate Variability

How will climate variability, and future climate change, influence future subduction zone hazards and processes?

Subduction zones are the primary plate tectonic environments where the deep Earth directly connects to and influences materials and processes at Earth's surface, and vice versa. Interactions between the atmosphere, hydrosphere, and lithosphere alter the properties of subduction zone materials and influence surface loading and mass transport. Regional climate and climate variability strongly influence these surface processes. Thus, future climate change may have important ramifications for the types, frequency, and magnitude of subduction zone large storms, atmospheric rivers, and the mass wasting and flooding that they trigger.

Climate variability and change modulate subduction zone hazards on long ($\geq 10^6$ yrs), intermediate (10^6–10^4 yrs), and short ($\leq 10^4$ yrs) timescales. Long-term regional climate impacts water availability, the phase (e.g., rain vs. snow) and amount of precipitation, topography, and weathering intensity and rates. On intermediate timescales, climate oscillations impact terrestrial hydrology, sea level, and vegetation, which may alter the generation, flux, and routing of sediment in subduction zones (**Figure CST-4**). On shorter timescales, climate variability impacts hydrological cycling, extreme weather events, stochastic sediment transport, and vegetation coverage.

On long and intermediate timescales, climate variability affects erosion and sediment transport systems. Variations in surface loading from glacial advance and retreat, sea level change, and surface erosion also impact the state of stress at depth. Changing ice volumes increase and decrease loads on subaerial volcanoes, and rising and falling sea levels do the same to submarine and island volcanic systems, which can impact the frequency and style of volcanic unrest. Similarly, earthquake activity can be modulated by climate-driven variations in ice and water volumes. Climate oscillations also modulate sediment supply and water discharge, tightly coupling the rates of erosion and sediment transport to climate, and influencing the onshore-to-offshore sediment transport system. Climate-modulated variations in surface erosion might impact the state of stress on upper plate faults and volcanic systems in ways not yet fully understood.

Climate warming since the end of the last glacial maximum ($\leq 10^4$ yrs) has intensified some subduction zone geohazards. The retreat of alpine glaciers has resulted in elevated rates of mass wasting, more frequent glacial lake outburst floods, and glacial melting on volcanic edifices that can increase eruption frequency and impact associated volcanic hazards such as debris flows or jökulhlaups (glacial outburst floods). As seen in 2022 in Pakistan, climate-induced

Figure CST-3. *Examples of important fluid processes and fluid migration events. A: The deadly 2019 phreatic eruption of Whakaari, New Zealand (Lillani Hopkins/AP); B: Lahar deposits in the Toutle River, Mount St Helens, 1980 (USGS); C: Cold springs feeding the Metolius River, OR (Travel Oregon); D: Sand boils associated with the 2011 Christchurch, New Zealand, earthquake (Wikimedia Commons); E: Scaly clay melange from the Franciscan Terrain (Wikimedia Commons); F: A schoolhouse destroyed by the Sidoarjo ("Lusi") mud volcano, Indonesia (Wikimedia Commons).*

glacial melting and rainfall events can catastrophically influence flooding and mass wasting frequency. Rising sea levels also have important implications for tsunami hazards. Changes in weather patterns also impact the frequency and magnitude of large storms and wildfires, which also increase mass-wasting and flooding hazards.

The differences in climate regimes between contrasting geographies provide SZ4D with an unparalleled opportunity to conduct natural experiments to assess the effects of long- and medium-term climate variability and change on subduction zone processes and hazards. By characterizing and quantifying differences in erosion, weathering, sediment transport, and seismic and volcanic activity among different areas, SZ4D will be able to tease out how the subduction systems respond to perturbations brought about by climate change, and the impacts these changes have on subduction zone hazards, especially in the short term, which is of most concern to human populations.

Triggering and Cascading Hazards

How do cascading sequences of events impact subduction zone hazards?

One example of the importance of taking an integrated approach to understanding subduction zone processes is the role triggering and cascading processes play in subduction zone hazards. Cascading hazards refers to how individual events, such as individual earthquakes or volcanic eruptions, can trigger other events that can be as, or more, hazardous than the original sequence. Examples of this process abound. Earthquakes, volcanic flank collapses, and submerged mass slumping trigger tsunamis. Landslide activity may increase due to thick tephra-coverage of hillslopes after volcanic eruptions. Earthquakes can trigger volcanic eruptions as well as fault slip in other parts of a system. Eruptions and earthquakes can initiate mass transport events both onshore and offshore.

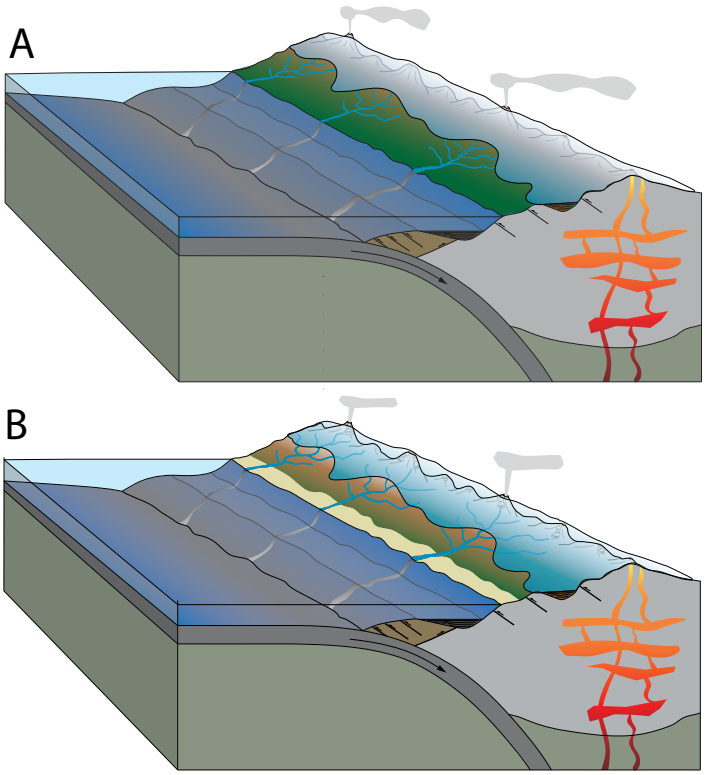


Figure CST-4. *Schematic of a subduction zone segment during a glacial (A) and an interglacial (B) period. Ice extent is greater and sea level is lower during the glacial period. Changes in ice volume and sea level will affect the stress state in the upper and middle crust, which can modulate the frequency of volcanic eruptions and upper plate fault activity. Exposure of the coastal shelf during glacial periods at sea level lowstands will change the dynamics and connectivity of the onshore-to-offshore sediment transport system. Furthermore, these climate variations will impact vegetation, water availability, and weathering, and thus modulate sediment supply and water discharge, resulting in unsteady sediment transport through time.*

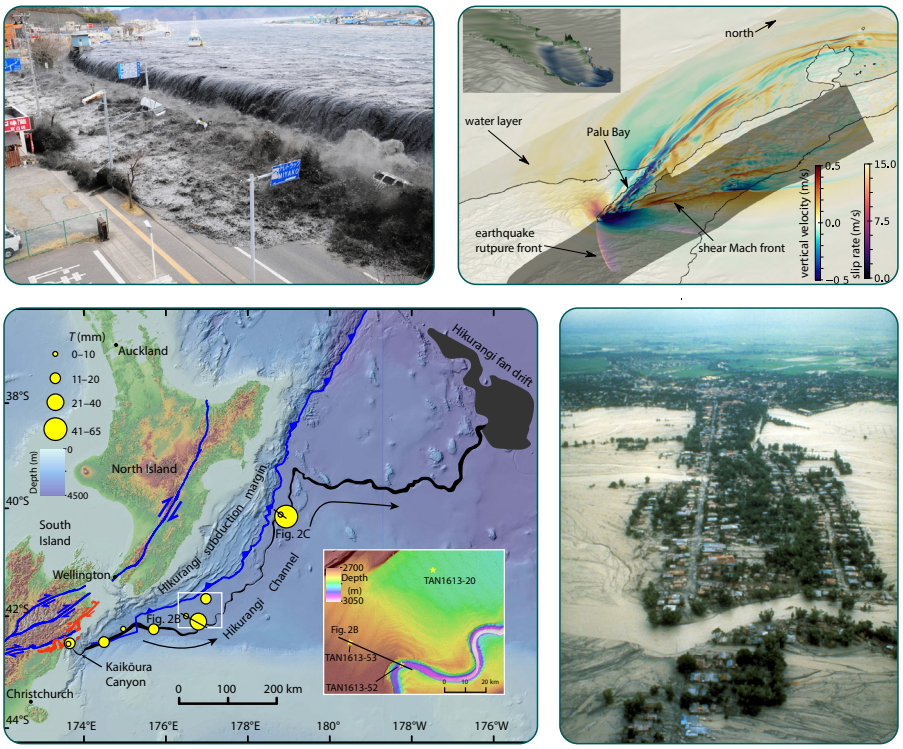


Figure CST-5. *Examples of triggering and cascading subduction zone hazards. From left to right: The 2011 Tōhoku-Oki tsunami (Reuters) caused more fatalities than the shaking of the Mw9.0–Mw9.1 earthquake. High-performance computing (HPC) model of the multi-physics of earthquake rupture and seismic, acoustic, and tsunami wave interaction during the 2018 Palu, Sulawesi, Indonesia, earthquake and tsunami (Krenz et al., 2021). Turbidity current over 680 km triggered by the 2016 multi-fault Kaikoura, New Zealand, earthquake (Mountjoy et al., 2018). Mt. Pinatubo Lahar in 1991 (Reuters).*

The risks to human populations from triggered events such as tsunamis, landslides, and lahars can often be greater than that from primary causes such as seismic shaking and eruptions that initiated them (**Figure CST-5**). Thus, mitigating the risk of hazards requires accounting for the complex dynamics of the subduction system across multiple spatial and temporal scales. Such an accounting can only be achieved with an integrative, system-wide approach to studying subduction zone hazards, such as that proposed by SZ4D.

While the cascading nature of subduction zone hazards is generally accepted, the underlying mechanisms are often poorly constrained. Triggering mechanisms can range from direct effects, such as earthquake shaking, to more indirect impacts, such as the rapid drawdown that occurs when an earthquake-generated tsunami first approaches a shoreline. Such cascading and interacting events are a topic only now emerging in operational hazard assessments, and they present a challenge to existing empirical, disciplinary, data-driven approaches. However, they are also an opportunity to fuse subduction science disciplines and observations toward interoperability, and to identify opportunities to raise hazard alert levels early.

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FAULTING AND EARTHQUAKE CYCLES

When and where do large earthquakes happen?

SCIENTIFIC MOTIVATION

When and where do large, damaging earthquakes happen? There has been remarkable progress on this central question in earthquake science in the twenty-first century. We now directly observe that faults fail sporadically at a range of rates and timescales, with slow and rapid slip interacting to produce complex temporal and spatial patterns of movement. The exceptional number of great subduction zone earthquakes in the last 15 years has enabled evaluation of their relationship to tectonic setting and prior activity. In subduction zones, networks of faults accommodate deformation, including the megathrust and faults in the overriding and subducting plates, and all of these fault systems contribute to earthquake and tsunami hazards. Evidence is accumulating that there are systematic relationships among subduction zone architecture and deformation history, fault properties, and the tendency for large earthquakes. Furthermore, tantalizing new observations of possible relationships among different types of fault slip behavior open up new avenues of exploration that will allow us to make significant strides in understanding controls on modes of deformation and earthquake hazards. Many of these observations are coming from subduction zones, where the world's largest earthquakes happen. The SZ4D Faulting and Earthquake Cycles (FEC) effort focuses around four central questions, detailed below, that define the limits of what we know about when, where, and why large earthquakes occur.

Significant overlaps exist between FEC and other components of the SZ4D initiative. Subduction zone hazards, including earthquakes, are linked through their shared dependencies on architecture, material properties, fluid migration, and the state of stress. These properties are shaped by systems-scale tectonic, magmatic, and sedimentary processes operating over millions of years. Faulting and earthquakes shape geomorphology, modulate the state of stress, and trigger mass wasting events, volcanic eruptions, tsunamis, and earthquakes in other parts of the system. As a result, a fundamental understanding of the science that drives subduction hazards requires ambitious and integrated observational, modeling, and experimental efforts to illuminate the interactions between tectonic evolution, faulting and earthquakes, landscape and seascape evolution, and magmatic processes.

This chapter describes FEC science questions, required information and activities to address those questions, a phased scientific plan, and an assessment of subduction zones most well-suited to address FEC science questions.

Science Questions

The overarching question of the Faulting and Earthquake Cycles component of SZ4D is: **When and where do large, damaging earthquakes happen?** A major goal of earthquake studies is to be able to predict relationships between geographic location and earthquake and tsunami hazards. Prediction of specific earthquakes may be impossible, but physical models of fault failure are capable of predicting important features of the earthquake cycle when developed in collaboration with observational and experimental studies. We break up this major question into four sub-questions that focus on different aspects of the subduction zone earthquake problem, each of which has societal importance. Addressing these four questions by integrating observational, laboratory, and modeling efforts will allow us to make progress on the grand challenge of earthquake predictability.

1. How do subduction zone fault systems interact in space and time? How do these fault systems and associated deformation regulate subduction zone evolution and structure?
2. What controls the speed and mode of slip in space and time?
3. Do distinctive precursory slip or distinctive foreshocks occur before earthquakes? What causes either foreshocks or precursory behavior?
4. Under what physical conditions and by what processes will slip during an earthquake displace the seafloor and increase the likelihood of generating a significant tsunami?

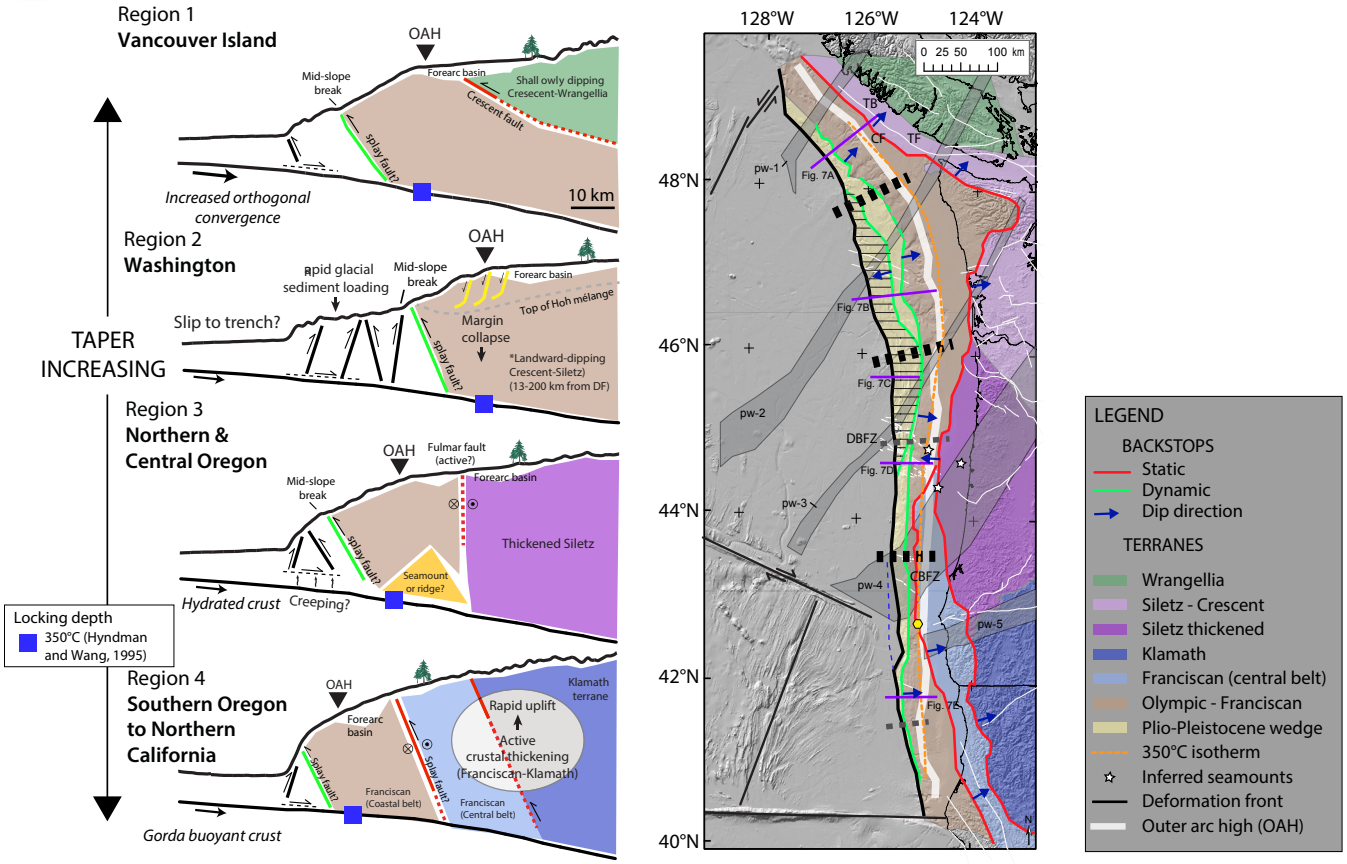


Figure FEC-1. *Synthesis of tectonic geomorphology, outer wedge taper, and structural vergence in the Cascadia subduction zone forearc. Forearc morphology is connected to megathrust behavior. From Watt & Brothers (2021).*

FEC Science Question 1

How do subduction zone fault systems interact in space and time? How do these fault systems and associated deformation regulate subduction zone evolution and structure?

Subduction zone deformation occurs through localized faulting and distributed strain within the plate interface, overriding plate, and downgoing plate at temporal scales ranging from earthquakes (seconds) to millennia. Feedbacks between faulting and distributed deformation across this system are critical to dictating where, when, and how subduction zone deformation leads to hazardous events (e.g., **Figure FEC-1**). For example, slip on the megathrust can propagate onto upper plate splay faults (Fan et al., 2017; Obana et al., 2018; Coffey et al., 2021), lead to triggered slip, or be triggered by slip on faults in the overriding and downgoing plates (e.g., Dmowska et al., 1988; Bouchon et al., 2016; Lay et al., 2011; Gomberg & Sherrod, 2014; Hollingsworth et al., 2017); load crustal faults to failure (e.g., Loveless & Meade, 2010); and trigger mass wasting and magma migration events (Linde & Sacks, 1998; Leithold et al., 2017; Roland et al., 2020). Spatial and temporal coseismic slip distribution and potential triggering of mass wasting determine tsunami generation. The

location and mode of strain accumulation and release on faults (**Figure FEC-2**) is modulated by spatial variations in the physical and rheological properties of the crust and mantle in the overriding and downgoing plates (e.g., Wells et al., 2017; Sun et al., 2020, Watt & Brothers, 2021, **Figure FEC-1**), the hydraulic connectivity of fault systems (Warren-Smith et al., 2019; Bonini, 2019; Gosselin et al., 2020), and the composition, mechanics, fluid properties of subducted sediments, whose distribution and delivery are climatically, geomorphically, and tectonically controlled (e.g., Lamb & Davis, 2003; Sweet & Blum, 2016; Meridth et al., 2017).

There are several gaps in our understanding of how subduction fault systems deform and interact to generate tsunamis, ground shaking, and mass wasting events that impact coastal population centers. For example, even though faults in the overriding and downgoing plates can produce large earthquakes and tsunamis, the geometry, extent, and rupture history of these faults, and their connectivity, are less well-constrained than those of the megathrust. In situ pore fluid and stress conditions, and their spatiotemporal variations, are key properties proposed to control coupling and interactions between slip along megathrust and other faults, but measuring these parameters requires dense instrumentation and monitoring systems. Finally, integration of geological, geochemical, geophysical, and rock deformation data is essential to quantify fault interactions, but few locations have coordinated data collection and synthesis that permits system-scale analyses.

SZ4D is uniquely poised to determine the conditions that trigger events and the role of upper and lower plate faults in modulating the accumulation and release of strain associated with plate convergence. To understand fault interaction on short and long timescales requires detailed information on the geometries, stress state, distribution of fluids, and material properties of subduction zone fault systems and surrounding rock. Key requirements include deformation and fluid flow from high-precision seismicity and geological studies, fault geometries and distribution of fluids from seismic reflection and controlled-source electromagnetic (CSEM) imaging, fault properties

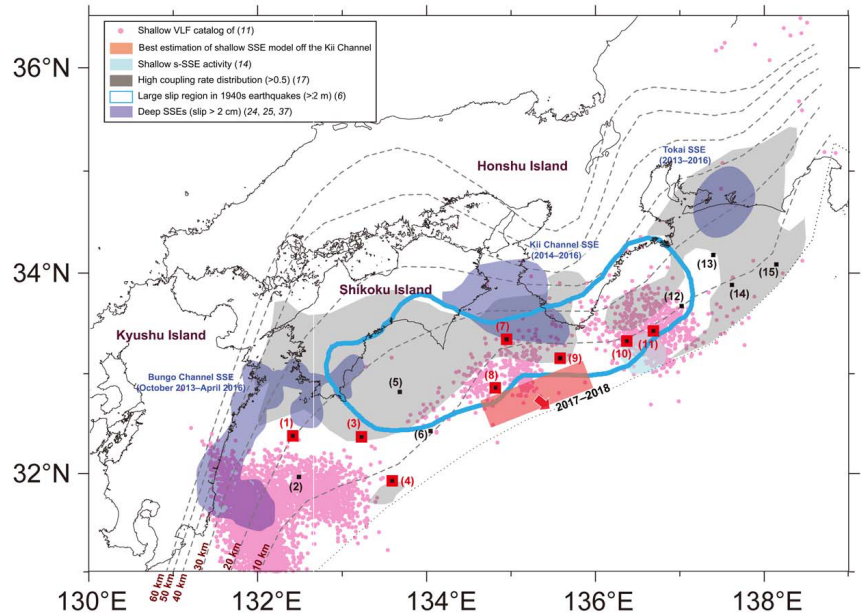


Figure FEC-2. *Spatial relationships between different modes of slip detected by seafloor instrumentation in the Nankai Subduction Zone. Gray shaded area - regions with a coupling coefficient greater than 0.5. Blue contour - regions of high slip during two M8 events in the 1940s. Red rectangle - location of the 2017–2018 shallow slow slip event. Blue regions - locations of deep, slow slip events. Pink circles - locations of very low frequency earthquakes. From Yokota & Ishikawa (2020).*

from exhumed fault systems, slip history from paleoseismic records, and material properties from experiments. Geodetic data are needed to constrain the distribution of deformation across fault systems. Numerical modeling is required to determine the roles of material properties and stress state on fault interactions, extrapolate through space and time, and guide ongoing data collection. Code development for geodynamic timescales is needed to understand feedbacks between localization and formation of faults, thermal structure, loading from mantle convection and plate tectonic forces, and the evolving landscapes and seascapes.

FEC Science Question 2

What controls the speed and mode of slip in space and time?

Slip along the subduction megathrust ranges from continuous creep to the punctuated rupture characteristic of major subduction earthquakes. In between these two extremes, there is a spectrum of slip behavior, including quasi-episodic slow slip events (SSEs) and low and very low frequency earthquakes (LFEs and VLFEs). These different styles of slip determine whether strain accumulation and release are expressed violently through damaging earthquakes or harmlessly through slow fault slip. One of the major goals of SZ4D is to understand the physical processes and conditions that control the speed and mode of fault slip and how these processes and conditions evolve in space and time.

It has long been understood that slip behavior varies spatially along the megathrust. The ability to measure deformation in some subduction zones using geodetic methods now allows us to distinguish segments that are locked and accumulating strain toward the next earthquake rupture from others inferred to be less seismically coupled or even continuously sliding, and to identify areas experiencing quasi-episodic SSEs. Furthermore, the discovery of "slow" earthquakes (e.g., tremor, VLFs) and aseismic, geodetically detected slow slip, demonstrates that slip behavior is diverse and that fault coupling also varies in time (e.g., Dragert et al., 2001; Obara, 2002; Frank, 2016). The resulting picture is complex, with substantial variations in spatiotemporal patterns of locking and strain energy release, manifested in varying styles of slip (e.g., Ito et al., 2013; Ruiz et al., 2014; Yokota & Ishikawa, 2020; **Figure FEC-2**).

Many hypotheses have been proposed to explain the distribution of slip in space and time. Some focus on physical properties of fault zone materials, including fault composition, structure, and rheology across length scales of nanometers to kilometers (e.g., den Hartog & Spiers, 2013; Hawthorne & Rubin, 2013; Ujiie et al., 2013; Saffer & Wallace, 2015; Trütner et al., 2015) and heterogeneity that leads to a mixed brittle-ductile behavior (e.g., Fagereng & Sibson, 2010; Skarbek et al., 2012; Barnes et al., 2020). Other studies suggest the distribution and composition of pore fluids and pore-fluid pressures are highly important (e.g., Liu & Rice, 2007; Kitajima & Saffer, 2012; Song et al., 2009; Warren-Smith et al., 2019; Hooker & Fischer, 2021) or focus on the roughness and topography of the downgoing plate (Wang & Bilek, 2011, 2014). A comprehensive evaluation of these and other proposed processes through a combination of observations from well-studied regions, geologic studies of analog systems, experimental studies, and numerical modeling are needed to determine fundamental controls on the speed and mode of slip. The factors above lead to our overarching hypothesis that the location and extent of hazardous earthquakes

are, to some extent, predictable from measurements of coupling, strain accumulation, and past slip behavior.

Answering Question 2 and addressing the associated hypothesis that earthquake locations and sizes are foreseeable based on geodetic and historic observations requires gathering those measurements of slip events over a wide range of timescales in both onshore and offshore environments. A combination of seafloor geodetic instruments and densely distributed ocean-bottom seismometers are needed to acquire the necessary very high-resolution data offshore. The onland component of the observations can be achieved using a combination of terrestrial seismometers, the Global Navigation Satellite System (GNSS), and the new capability of the planned NASA-ISRO Synthetic Aperture Radar (NISAR) mission. Once these fundamental observations of subduction zone behavior are obtained, an integrated numerical modeling, experimental, and observational effort will be needed to understand the processes responsible for this behavior. This will include mapping structure from geophysical imaging and field mapping, collecting physical properties measurements downhole and from recovered cores, studying exhumed fault zones

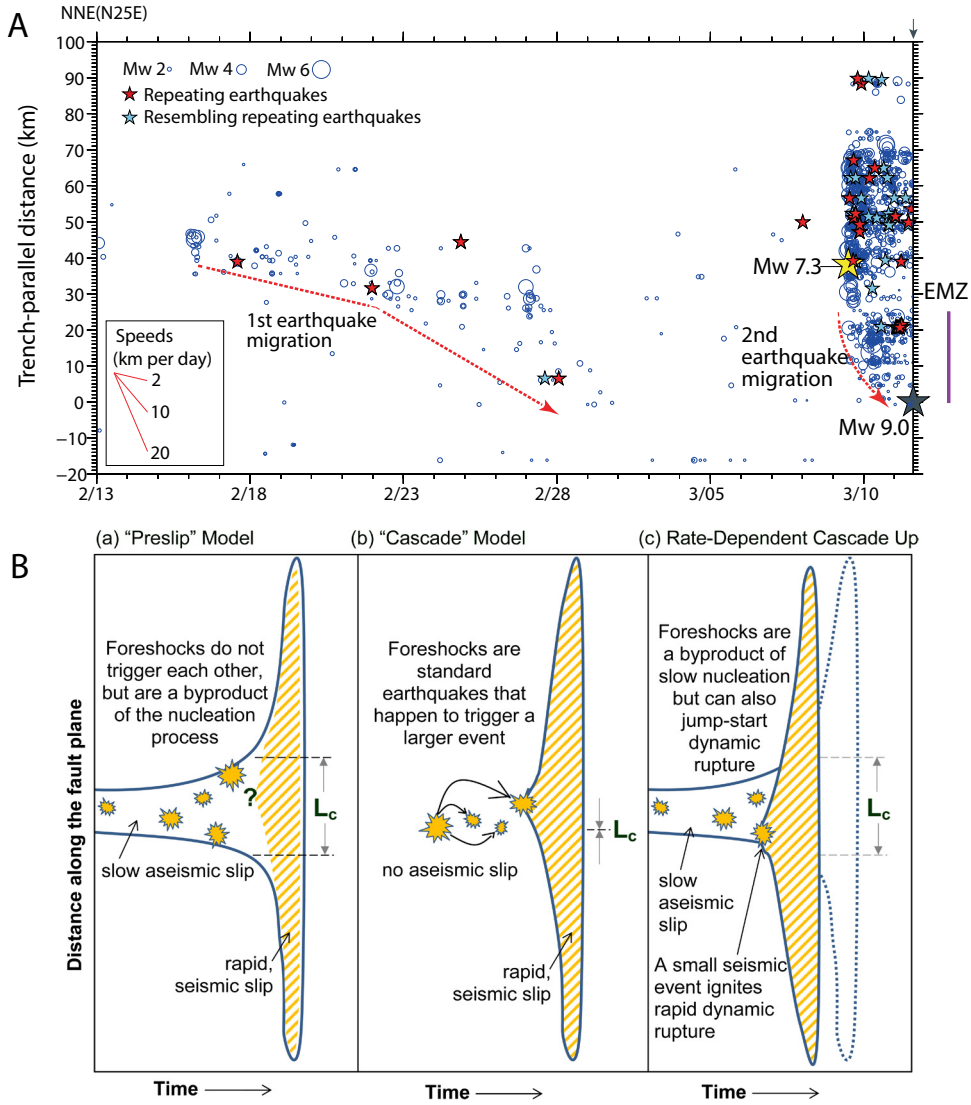


Figure FEC-3. *(A) Spatiotemporal evolution of foreshocks (blue circles) preceding the March 11, 2011, M9 Tōhoku-oki earthquake. Red dashed lines show apparent earthquake migration fronts propagating at 2 to 10 km per day. Note the clear spatio-temporal progression both during late February of 2011 and between the M7.3 foreshock and the mainshock (from Kato & Ben-Zion, 2020, modified from Kato et al., 2012). (B) Illustration of possible earthquake initiation models and associated foreshock scenarios involving substantial slow slip (preslip model), standard triggering relations (cascade model), or a combination of the two (rate-dependent cascade up model). Laboratory experiments support an accelerating earthquake nucleation process that expands to a critical nucleation length scale (Lc) preceding the dynamic mainshock rupture (from McLaskey, 2019).*

at analog sites, measuring material properties in the laboratory, and determining the history of slip events and tsunamis from paleoseismology.

Integrative modeling requires the development of 3D community codes to simulate dynamic ruptures and the earthquake cycle, in particular accounting for realistically complex geometry and material properties, viscoelasticity, inelastic yielding, and fluid transport. Augmenting these codes, and/or associated reduced order models, with data assimilation methods will enable direct integration of geophysical data.

FEC Science Question 3

Do distinctive precursory slip or distinctive foreshocks occur before earthquakes? What causes either foreshocks or precursory behavior?

Most, but not all, large earthquakes are preceded by foreshocks close in space and time, which suggests that a preparatory process may lead to the eventual mainshock (e.g., Bouchon et al., 2013; Trugman & Ross, 2019). However, such foreshock sequences are currently only recognized in retrospect. There is a long history of investigations of such seismicity changes leading up to large earthquakes, given the clear implications for short-term earthquake forecasting (e.g., Mogi, 1969; Hardebeck et al., 2008; Brodsky and Lay, 2014; Kato & Ben-Zion, 2020; **Figure FEC-3**). In some cases, there is evidence from geodetic observations or the occurrence of repeating microearthquakes that such precursory foreshock activity is associated with slow slip (e.g., Roeloffs, 2006; Kato et al., 2012; Ruiz et al., 2014; Meng et al., 2015; Radiguet et al., 2016; Obara & Kato, 2016; Socquet et al., 2017). Earthquake cycle computer simulations and laboratory experiments also suggest that slow slip events in or near the area of final rupture may be common (e.g., Matsuzawa et al., 2013; Nakata et al., 2016; McLaskey, 2019; Barbot, 2020).

A better understanding of precursory slip behavior would potentially provide an opportunity to raise hazard alert levels when precursory slow slip and/or foreshocks occur (e.g., Mignan, 2014). Although slow slip transients spatially and temporally related to earthquake activities have been observed in many convergent plate boundaries (e.g., Liu et al., 2007; Bartlow et al., 2014; Wallace et al., 2017; Colella et al., 2017), the underlying physics remain poorly understood. For instance, migrating foreshocks prior to the M9 Tōhoku earthquake (**Figure FEC-3A**) are intriguingly similar to seismological and geodetic observations prior to the M8 2014 Iquique earthquake (Ruiz et al., 2014). However, there does not appear to be a universal pattern to the existence or spatial and temporal scales of such precursory activity (e.g., Bürgmann, 2018, and references cited therein). As a result, recognizing and understanding foreshock sequences remains a challenge (Pritchard et al., 2020).

We hypothesize that precursory signals are distinctive and correlate with certain characteristics of large earthquakes, such as magnitude and tectonic setting. If precursory signals are to be useful in hazard risk mitigation, they must not only be recognizable but also detectable. One example of a possible precursory signal is a distinctive change in SSE recurrence interval and peak slip rate of SSEs before large megathrust earthquakes.

Testing this hypothesis requires acquiring the geodetic and seismic signals that precede earthquakes in order to constrain deformation over the entire seismic cycle. Because the purported precursors can be small and thus require near-fault instruments, and the part of

the megathrust where major earthquakes initiate is predominantly under water, seafloor geodetic and seismic observations will be essential and complemented by interferometric synthetic aperture radar (InSAR), GNSS, and seismometers on land. It is equally important to be strategic about site selection for this question because we cannot currently predict earthquakes based on the occurrence of foreshocks, transient creep, or other phenomena. Subduction segments that are known to be capable of seismogenic-zone-spanning earthquakes and are late in the earthquake cycle provide the best chances of capturing needed data. To maximize the overall probability of definitively delineating the extent or absence of precursory activity before large earthquakes, it is necessary to build a portfolio of instrumented subduction zones by leveraging international observational efforts through SZ4D efforts and international collaborations. In addition, we need to better understand precursory signals across space-time and disciplinary scales. Precursors have been successfully identified at the laboratory scale (Yamashita & Ohnaka, 1992; Bolton et al., 2019), in various tectonic settings, and exhibiting different faulting mechanisms (Savage et al., 2017; Cabrera et al., 2022; Simon et al., 2021; Duboeuf et al., 2017), and have been proposed from examination of paleoseismic/morphotectonics records (Hawkes et al., 2005; Cicerone et al., 2009). Informative observations may also include a lack of precursory signals before large earthquakes (e.g., Wu et al., 2014). Diverse precursory observations allow modelers to test hypotheses for the nature of asperities and the role of frictional, rheological, and geometrical controls on slip behavior across the seismogenic zone and below it while challenging the validity of proposed mechanical models and their ability to capture the range of precursory and long-term transient pre- (and post-) deformation signatures.

FEC Science Question 4

Under what physical conditions and by what processes will slip during an earthquake displace the seafloor and increase the likelihood of generating a significant tsunami?

Tsunamis can be disastrous accompaniments to major subduction zone earthquakes. However, it is unknown what circumstances trigger large fault offsets at the seafloor that in turn can generate major tsunamis. Factors may include unusual near-trench locking of the overriding and downgoing slabs, presence of splay faults within the downgoing slab, anomalously thick or low-friction sediments in the trench, inelastic accretionary wedge deformation, and low rigidity of the shallow forearc slab (Cummins & Kaneda, 2000; Seno, 2000; Fujiwara et al., 2011; Lay et al., 2012; Sallares & Ranero, 2019; Kodaira et al., 2020; Du et al., 2021; Wilson & Ma, 2021). Also key is understanding how plate convergence is accommodated in the subduction toe. How much deformation is inelastic and distributed vs localized as slip on the decollement and splay faults? Also of interest are "tsunami earthquakes," which generate larger tsunamis than can be readily explained by earthquake magnitudes estimated from standard seismic wave analysis (Kanamori, 1972). Because tsunami earthquakes are relatively deficient in high-frequency energy, they are particularly dangerous to local populations, who are unlikely to self-evacuate as they would for an earthquake with ground motion that is more strongly felt. Subduction zone earthquakes can trigger both submarine and subaerial landslides, which can further contribute to tsunamigenesis. Such cascading hazards constitute an important link between the FEC and L&S components of

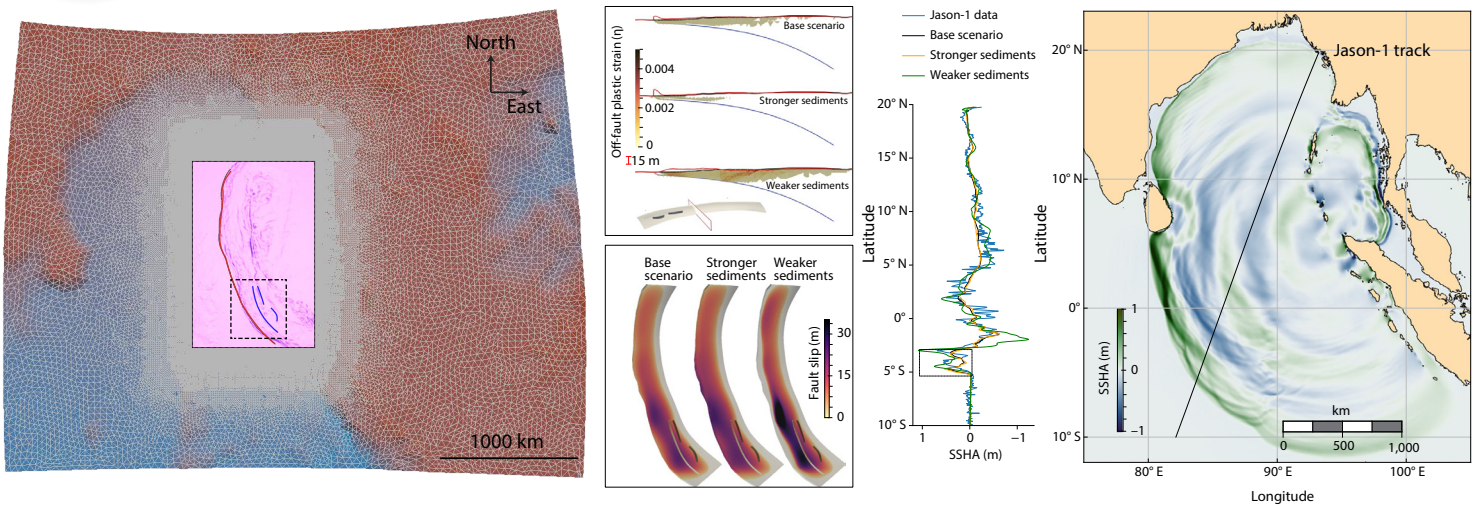


Figure FEC-4. *Observationally constrained three-dimensional dynamic rupture model and tsunami models of the 2004 Sumatra events demonstrating the importance of stress, rigidity, and sediments for earthquake tsunami dynamics. from Ulrich et al. (2022).*

SZ4D and are a feature of subduction zones in general, as described in **Chapter 2**.

The primary knowledge gap in models of tsunami inundation is often the details of near-trench rupture processes that control seafloor uplift and hence tsunami generation (Tanioka & Satake, 1996; Satake, 2015; Saito, 2019; Dunham et al., 2020). Recent work has vividly demonstrated that anticipating tsunami generation, which depends on fault rheology and system stiffness, requires accurate seismic and stress data and rock characterization (**Figure FEC-4**).

Improving our understanding of the conditions that generate tsunamis will require using historical records and/or paleotsunami studies to target regions with a known history of tsunamis and densely instrumenting the near-trench region. Linking earthquake source models to tsunami models (e.g., Lotto et al., 2019; Madden et al., 2021; Ulrich et al., 2022; **Figure FEC-4**) has the potential to revolutionize our understanding of when and where tsunamis occur. This can be accomplished by including constraints on the shallow configuration of the plate boundary acquired from high-resolution seismic imaging and constraints on frictional properties of the plate boundary fault near the trench from geological and experimental data. In particular, we aim to test the null hypothesis that tsunami generation arises from coseismic elastic deformation from fault slip, with possible rupture propagation onto splay faults predictable from the long wavelength state of stress and fluid pressure distribution, material structure, and frictional properties.

ACTIVITIES REQUIRED TO ADDRESS THE SCIENCE QUESTIONS

Recent advances in technology and increased understanding of faulting processes position the scientific community to make significant progress in answering these four questions. To assist in developing a strategy to address each question, we assembled *traceability matrices* that rigorously evaluate the required activities (**Appendix FEC-1**).

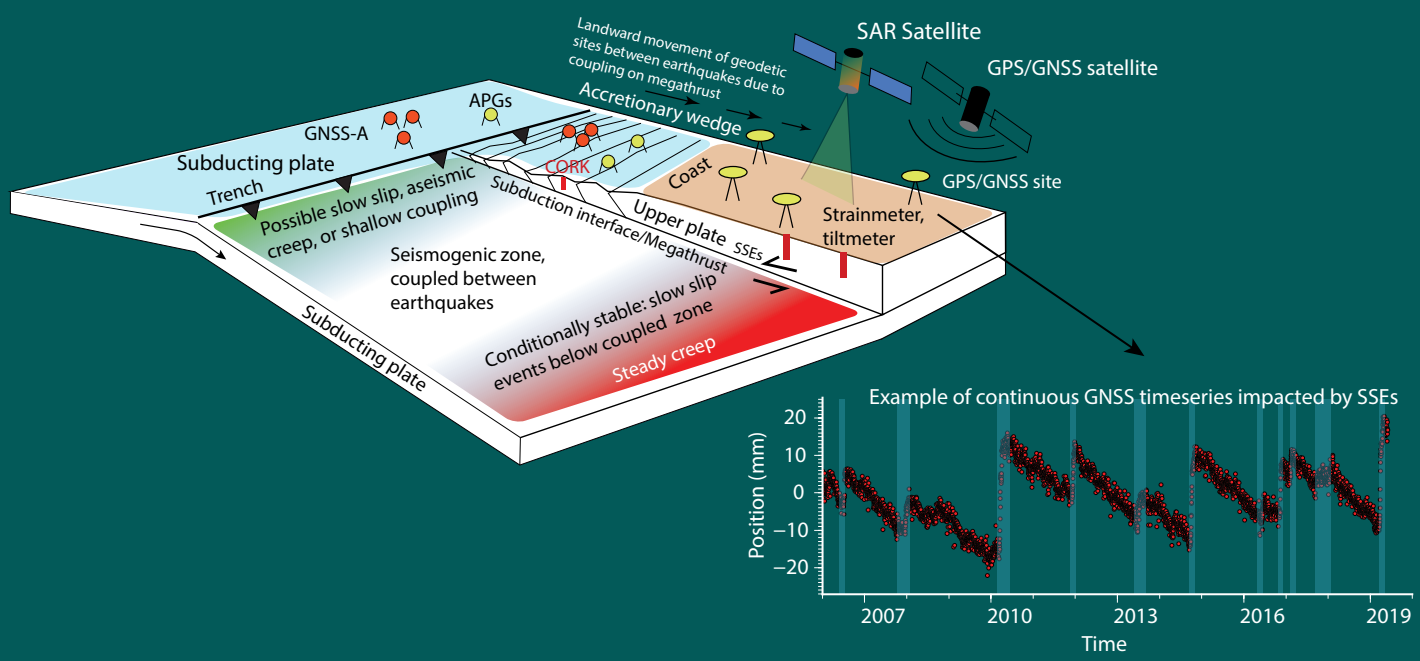
A first-order conclusion from the traceability matrices is that there are many commonalities in the information and activities required to answer the four FEC science questions, which fall under two overarching categories:

1. **New amphibious observations of subduction zone behavior, and**
2. **Innovative observational, geological, experimental, and modeling activities to understand what controls subduction zone behavior.**

An ambitious geophysical instrumentation effort is needed to acquire data that can provide a comprehensive characterization of subduction zone slip behavior over a range of temporal and spatial scales, including relationships between geodetic coupling, seismicity, tremor, and other types of slip behavior (e.g., **Figure FEC-5**). Historical, paleoseismologic, and geomorphologic data are necessary to build complete geological records of subduction zone earthquakes and deformation, estimate rates of geological processes, and provide context for present-day fault behavior.

An understanding of the processes and properties that control fault system behavior over the range of relevant scales will require tight integration of in situ and analog geological studies to integrate structure, conditions, and processes across temporal and spatial scales (e.g., **Figure FEC-6**); high-resolution geophysical imaging data to characterize subduction zone architecture and fault zone properties (e.g., **Figure FEC-7**); novel experiments that measure material properties and simulate processes at conditions currently inaccessible in the laboratory (**Figure FEC-8**); and the development of numerical models to test hypotheses across spatial and temporal scales and evaluate the interconnectedness of subduction system processes.

Figure FEC-5. *A schematic illustration of the types of slip on a subduction plate interface and the geodetic measurements that can be used to constrain these behaviors. Actual subduction zone behavior may vary significantly from this simple diagram. APG = Absolute Pressure Gauge. CORK = Subseafloor observatory. GNSS = Global Navigation Satellite System. SAR = Synthetic aperture radar. From Wallace et al. (2021).*



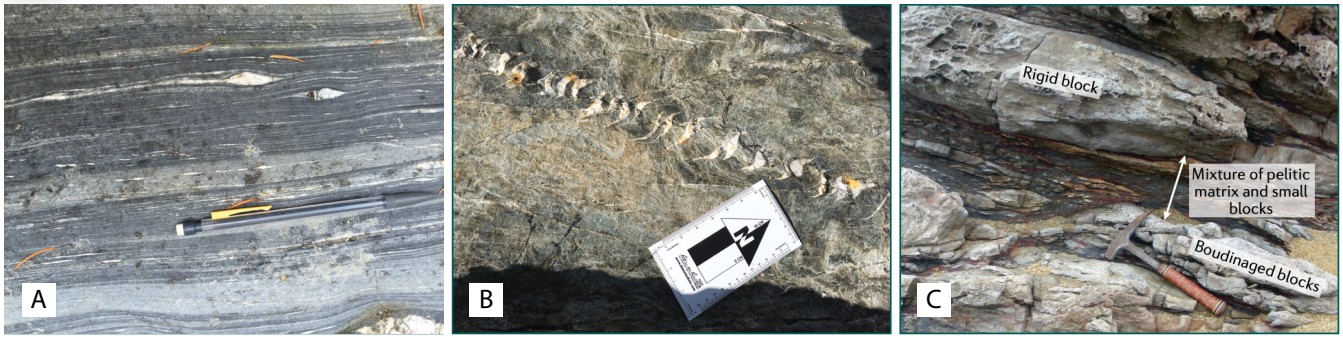


Figure FEC-6. *Field photos of exhumed subduction zone rocks: (A) mylonite from the Leech River paleo subduction thrust, Vancouver Island, BC, Canada; (B) en échelon veins from the Arosa Zone, Swiss Alps; (C) distributed deformation in an accretionary melange, Chrystalls Beach, New Zealand (from Kirkpatrick et al., 2021).*

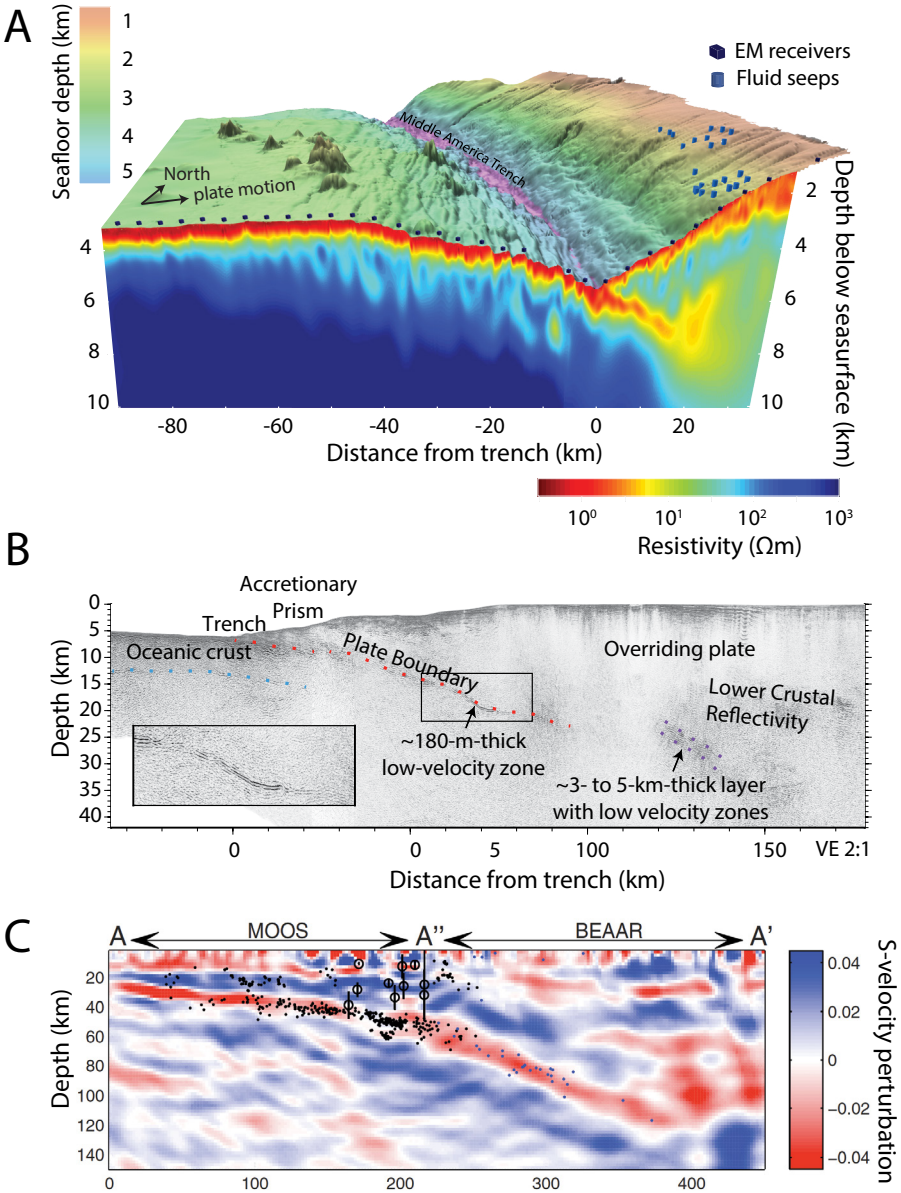


Figure FEC-7. *Complementary geophysical imaging of plate boundary geometry and properties by (A) CSEM imaging (from Naif et al., 2016), (B) seismic reflection imaging (from Li et al., 2015), and (C) Receiver function imaging (from Kim et al., 2014).*

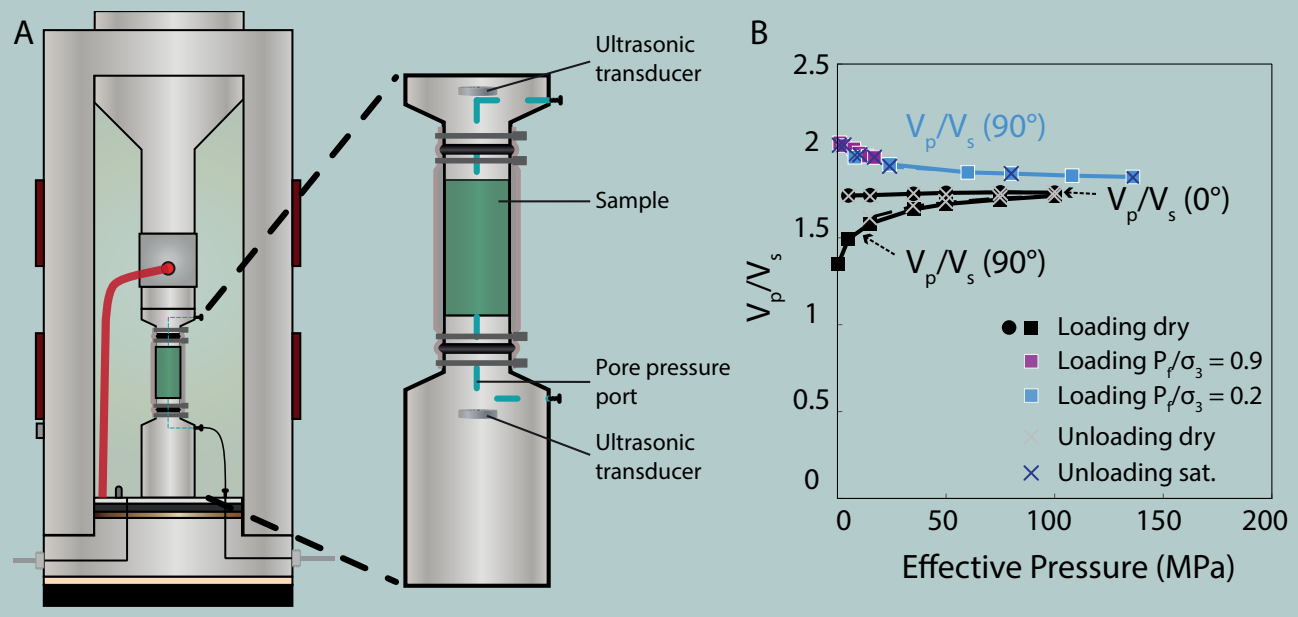


Figure FEC-8. *(A) A triaxial deformation apparatus used to measure rock properties in the laboratory, in this case elastic wave speeds in metasediments; (B) Vp/Vs determined from laboratory measurements for comparison with seismic tomography. From Fliedner & French (2021).*

The coordinated, amphibious and interdisciplinary efforts described above require significant human and physical infrastructure. **Our highest priorities for near-future physical infrastructure are seismic and geodetic instrumentation to measure megathrust behavior; experimental deformation apparatuses capable of simulating the fluid conditions, pressures, temperatures, and strain rates that are required to study the processes that control faulting and earthquake hazards in subduction zones but are currently inaccessible with existing experimental equipment; and field infrastructure to support a coordinated and sustained effort to characterize modern and analog fault systems**. We also emphasize the urgent need for other infrastructure and activities for building comprehensive portraits of subduction zone fault geometries, properties, and histories, all of which are essential to provide context for results that will arise from SZ4D geophysical and experimental infrastructure.

Based on the *traceability matrices*, we have constructed an integrated science plan, including observational, experimental, and numerical activities, which is described in the following section.

SCIENCE PLAN OVERVIEW

The science questions and *traceability matrices* provide a framework for defining the strategy and scale of the Faulting and Earthquake Cycles component of SZ4D. Addressing the FEC science questions requires:

1. An ambitious geophysical observational effort to characterize fault behavior over the entire seismogenic zone, and
2. Modeling, geological studies, experimental work, and geophysical imaging to contextualize and understand the physical processes underlying fault behavior.

Close integration of these components requires a coordinated planning process throughout SZ4D and a phasing of activities. While specific

details will depend on the regions selected for instrument deployment and field study, the general design and phasing of activities to achieve the project goals can be anticipated.

The primary component of the FEC geophysical observational effort is an amphibious geodetic and seismic network (hereafter called MegaArray). Our focus on great earthquakes requires constraining the kinematics of slip over the length and width of a seismogenic segment, including regions updip and downdip of the seismogenic zone, regions of transitional behavior, and other faults in the overriding and incoming plates (~500 x 500 km). Spatial variations in deformation over this scale are expected to control where sufficient elastic energy can accumulate to rupture in an earthquake of magnitude approximately 8 or larger. Likewise, large slow slip events, including those purported to be precursors to large subduction zone earthquakes span ~100 km (e.g., Ito et al., 2013) and thus also require a large study area. On the other hand, knowledge of the earthquake source location at high precision and detailed measurements of slow slip are also required to examine fault interaction (Question 1) and relationships between different modes of slip (Question 2). To meet both of these needs, we outline a phased effort for MegaArray involving backbone characterization over the entire study area (Phase 2a) followed by densified observations in areas of interest (Phase 2b; **Figure FEC-10**). To ensure the full three-dimensional regional context of faulting is known, additional complementary data are also required over the footprint of MegaArray, including bathymetric mapping and geophysical imaging.

Geological, modeling, and experimental efforts need be coordinated with phasing of the MegaArray, both to inform design of different phases of the array and to interpret the results that emerge from it. Geological work will follow a parallel phasing involving backbone site characterization, sampling, and testing followed by densified characterization of deformation processes, rock properties, and slip history (**Figure FEC-10**). Experimental work will follow a similar phasing and will evolve as new observations and samples are available and as equipment is developed.

The Modeling Collaboratory for Subduction has identified several critical needs to facilitate FEC-related modeling (Dunham et al., 2020). These include community earthquake cycle modeling codes that couple subduction zone fault slip with additional relevant processes (viscoelasticity, inelastic yielding, fluid transport, pore pressure, temperature evolution, and tsunami generation), which are required for physics-based seismic hazard assessment and early warning capabilities. They will also be necessary to understand linkages between subduction zone behaviors and structures, and to understand processes and quantitatively test hypotheses. Results will depend on the stress state and material structure, motivating development of codes for longer timescale geodynamics that account for feedbacks with the evolving land- and seascape, localization of deformation and formation of faults, thermal structure, and loading from mantle convection and plate tectonic forces. Regional-scale modeling must be paired with global geodynamics modeling to account for processes such as trench rollback. The development and utilization of these codes can begin immediately and are anticipated to extend across all phases of the SZ4D instrumentation effort, with focused modeling efforts at specific times to help guide array design and data interpretation as described subsequently in the phasing plan.

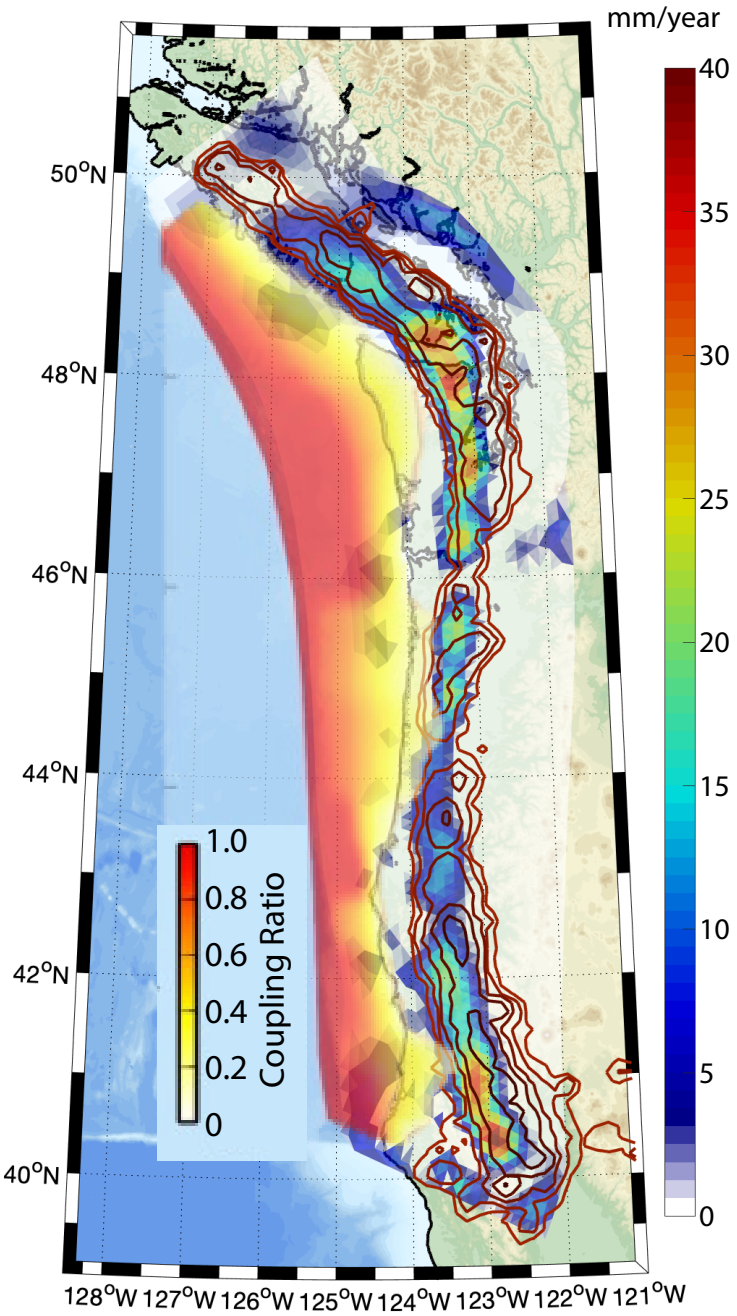


Figure FEC-9. *Comparison of geodetically detected plate coupling (red to yellow colors), geodetically detected slow slip (rainbow colors, reported as a long-term average slip rate), and seismically detected tectonic tremor (brown contours) in the Cascadia subduction zone from existing onshore seismic and geodetic data (Bartlow, 2020). Coupling model is from Schmalzle et al. (2014), and tectonic tremor is from the Pacific Northwest Seismic Network catalog (Wech, 2010).*

Overall, three primary phases of activities have been defined for project implementation, which parallel the other parts of SZ4D and are summarized below. During all three phases of the program, instrumental and field observations, laboratory experiments, and numerical modeling will inform each other (e.g., planning of new data acquisition and planning for new experiments and models). Details on activities envisaged for each phase are given in **Appendix FEC-2**. Although all components need to be closely coordinated, phasing may take place on different timescales dictated by specific needs and funding opportunities. Furthermore, analysis and integration of all components need to be ongoing throughout the SZ4D program.

PHASE 0 is a preparatory phase to develop and refine the SZ4D implementation plans. This phase includes assessing existing infrastructure in possible study areas and identifying how SZ4D can strategically build on them, and focused modeling efforts to inform the design of future observational programs. This phase will also involve building partnerships with possible domestic and international partners.

PHASE 1 includes:

1. Synthesis and analysis of existing data, modeling, and experimental work with existing capabilities aimed at addressing FEC scientific questions;
2. Technology development to ensure the availability of appropriate instrumentation, and laboratory and modeling capabilities; and,
3. Continued organizational and planning tasks to develop and strengthen partnerships. Because this phase leverages existing data, it can and should have a large geographical scope.

A wealth of existing data from many subduction zones affords us the opportunity to make progress toward SZ4D goals during Phase 1 prior to the availability of new, dedicated observations or experimental capabilities. Although the volume and quality of existing data vary greatly between subduction zones, comparative studies are necessary to generalize results from any specific subduction zone to general subduction processes. For example, studies should include:

1. Mapping plate boundary fault system architecture and determining fault zone properties,
2. Constraining the thermal state of the subduction zone from available thermal data, and
3. Evaluating subduction zone inputs, including sediment thickness and composition, porosity, heterogeneity, and roughness of the incoming plate. Compilation, selective reprocessing, and integration of existing data will help evaluate the importance of these observables and highlight critical data gaps.

Likewise, reevaluation and interpretation of existing geophysical data on subduction zone slip behavior can be used to address FEC science questions and guide planning for future data acquisition. For example, employment of new methods (e.g., machine learning techniques) can improve identification of slow slip events and slow earthquakes (e.g., **Figure FEC-9**) and can advance characterization of uncertainty in estimates of fault coupling and earthquake source parameters.

Multi-cycle numerical simulations will play a significant role in predicting which results can be generalized, as the global portfolio of subduction zones covers the entirety of the seismic cycle (inter-, pre-, co-, and post-seismic); these efforts should begin in Phase 1 and continue throughout SZ4D. Initial numerical modeling using current capabilities will be performed for the target site(s) to establish integrative, large-scale system attributes.

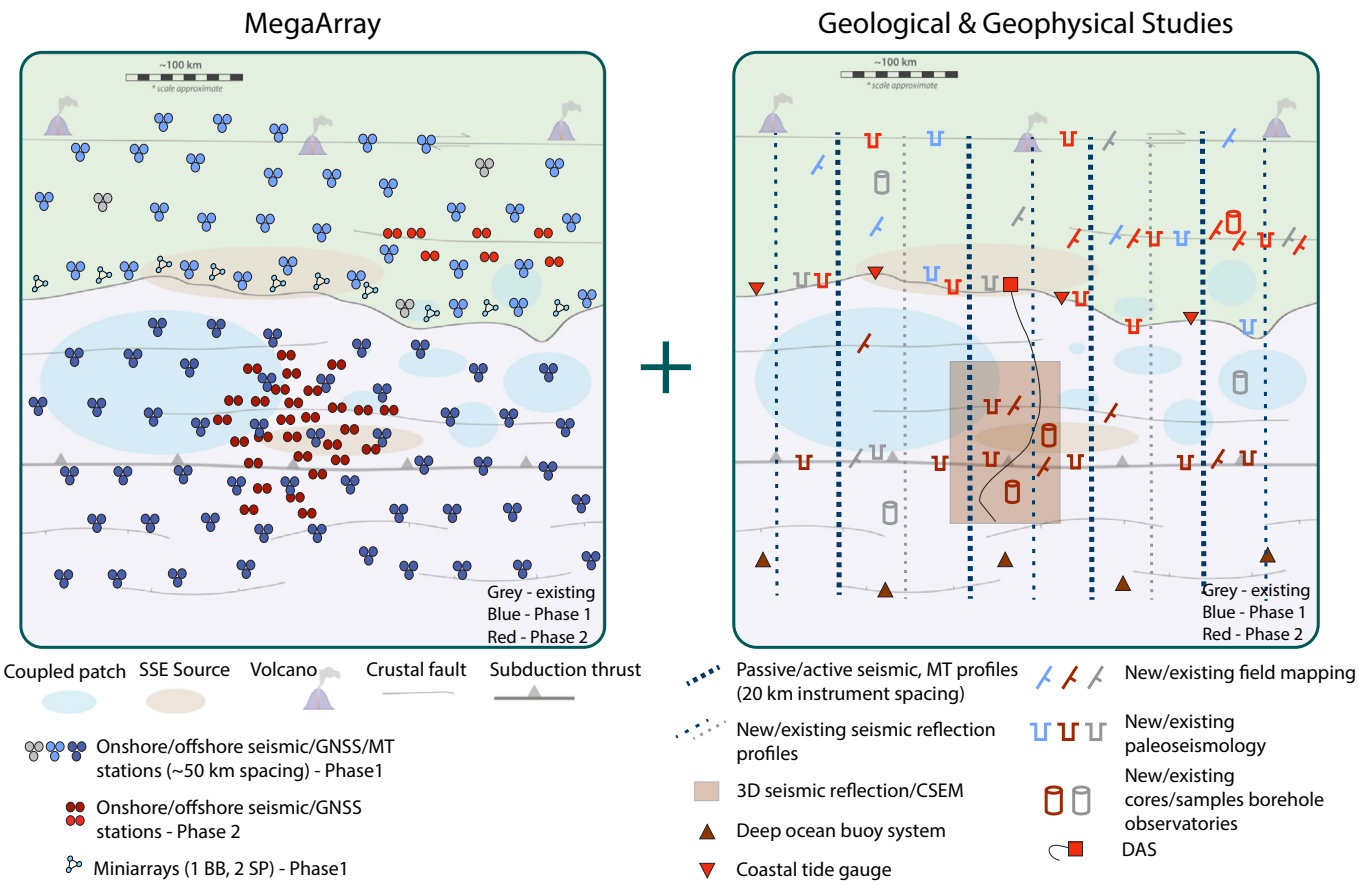
Geological and experimental efforts should also begin in Phase 1. To provide long-term temporal patterns of earthquakes, paleotsunami recurrence and inundation extent, spatial patterns of shaking intensity, along-strike rupture dimensions, and the vertical component of the earthquake deformation cycle, paleoseismology studies can be undertaken immediately and integrated with complementary geological and geophysical datasets (e.g., Clark et al., 2019; Walton et al., 2021). A compilation of existing studies of exhumed subduction rocks and the processes that they record is also needed to inform decisions on prioritization of new measurements and data collection (e.g., Phillips et al., 2020). This compilation would summarize deformation conditions, structure, composition, and fluid properties and the corresponding evidence of deformation processes over the full range of conditions from the seafloor to downdip of the seismogenic zone (Rowe et al., 2013; Agard et al., 2018; Behr & Burgmann, 2021; Kirkpatrick et al., 2021). Targeted reconnaissance work to constrain undocumented properties and processes of potential analog sites will be required. The experimental communities can conduct research on available samples and at the conditions of existing laboratory equipment and synthesize existing experimental data.

Phase 1 will also involve infrastructure development needed for Phase 2 observations. Examples include development of ocean

bottom seismometers capable of recording for 5 to 10 years, and experimental apparatuses capable of measuring physical properties over the full range of seismogenic zone pressures and temperatures, as well as conditions relevant to slow slip and tremor. Despite rapid advances in (super-)computing and data-driven modeling, currently there exist no full-physics models that capture all planned observational and laboratory data streams. The modeling community will identify numerical methods and specific model development needed to handle the anticipated increase in data volume and diversity, unprecedented data resolution, and associated uncertainties expected from the proposed experiments. Infrastructure needs for an ambitious, coordinated onshore geological effort also need to be defined.

Organizational activities will involve strengthening partnerships. International collaborations are essential for the global scope of the SZ4D project. SZ4D efforts to understand the processes underlying geohazards complement work by US science agencies on hazard characterization and mitigation. Finally, discussions with offshore

Figure FEC-10. *Illustration of ideal notional acquisition of geophysical and active-site geological data during Phase 2a (blue symbols) and Phase 2b deployments (red symbols). The left panel shows MegaArray and the right panel shows geological and geophysical studies required to provide context for MegaArray. Note that the backbone amphibious seismic/geodetic network deployed during Phase 2a would remain in place during Phase 2b. Phase 2a would leverage existing data (gray symbols). Paleoseismology includes trenching, coastal inundation, shaking/mass slumps and terraces/crustal uplift. Additionally, bathymetry data offshore and InSAR data onshore are also needed across the study area. SSE: Slow-slip event, MT: Magnetotelluric, CSEM: Controlled-source electromagnetic, DAS: Distributed acoustic sensing, GNSS: Global Navigation Satellite System.*



cable operators and owners could potentially open up detection capabilities that would be impossible under any other circumstance.

PHASE 2 will involve new observational programs coupled with experimental and numerical studies. The observational and experimental components are divided into two parts. The first part (Phase 2a) will involve lower resolution, backbone characterization of subduction zone behavior and structure across the entire study area, while the second part (Phase 2b) will involve detailed, higher resolution characterization in areas of interest (**Figure FEC-10**).

The heart of the Phase 2 geophysical effort is the amphibious MegaArray, whose aim is to characterize geodetic locking and slip behavior (e.g., earthquakes, slow slip events). MegaArray is the centerpiece of observational effort and the highest priority component of the envisaged geophysical infrastructure. To address the FEC science questions, this array needs to span a minimum area of approximately 500 x 500 km, extending from ~100 km seaward of the trench to the backarc. Given this significant scale, the aim of MegaArray during Phase 2a is to capture the behavior at intermediate resolution (~40–50 km); MegaArray will comprise a backbone network of on-land and offshore geodetic and seismic instruments for a minimum of 5–10 years. Informed by the Phase 2a results, additional instrumentation will be deployed to densify MegaArray during Phase 2b to obtain higher-resolution constraints on slip behavior in smaller areas of interest, such as slow slip patches or places where there might be changes in fault coupling (**Figure FEC-10**). The part of MegaArray deployed in Phase 2a will remain in place during Phase 2b, and the combined MegaArray network will operate for at least another five years.

The processes underlying observed active deformation can best be understood with supporting geologic measurements; electromagnetic, active-source seismic, and heat flow profiles; swath bathymetric maps; and SAR data (**Appendix FEC-2**), and these will following a similar phasing to MegaArray, with backbone characterization during Phase 2a and more detailed efforts in Phase 2b. Some of the datasets needed for Phase 2a may already exist or can be acquired by domestic or international partners and can be leveraged by SZ4D.

Phase 2a will include active/passive geophysical imaging of subduction zone architecture across the same footprint as the MegaArray to determine the geometries and properties of the megathrust and other faults and characterize the subducting and overriding plates (e.g., **Figure FEC-7**). During Phase 2b, higher-resolution geophysical imaging will be done in areas of interest, particularly areas of densified instrumentation for MegaArray (**Figure FEC-10**). One potential opportunity is the use of seafloor seismic nodal deployments, which are currently not common in academic studies.

During Phase 2a, relevant onshore exhumed analog sites will be identified and sampled, and laboratory experiments on reference, offshore, and onshore materials can be conducted as sampling proceeds (**Figures FEC-10** and **FEC-11**). Samples collected from the regional and analog sites will be analyzed as well as additional reference materials. Paleoseismology studies will also be carried out to best constrain past megathrust and upper plate fault ruptures. During Phase 2b, studies of onshore exhumed analogs and laboratory experiments will continue but will become more targeted to address emerging observations from instrumentation and modeling efforts. Targeted and intensive

geological observations will also be collected, including denser fault characterization and paleoseismology studies. Another important component of Phase 2B will be targeted drilling to obtain samples and to install offshore borehole observatories.

Throughout Phase 2, numerical, analytical, and statistical modeling that incorporates newly acquired data and results will continue and complement observations, and will further guide densification and expansion of observations for Phase 2b. Modeling of deformation processes will proceed and be updated as high-resolution data are acquired.

PHASE 3 will involve continued integration and interpretation of the observations, experiments, and numerical models from the FEC Phase 2a and 2b efforts and those of other parts of SZ4D. A significant and dedicated synthesis effort is required following the completion of most aspects of the observational program to integrate results from interdisciplinary components of SZ4D and address the science questions. This phase will also involve integration of SZ4D results into regional hazards assessments in partnership with local stakeholders.

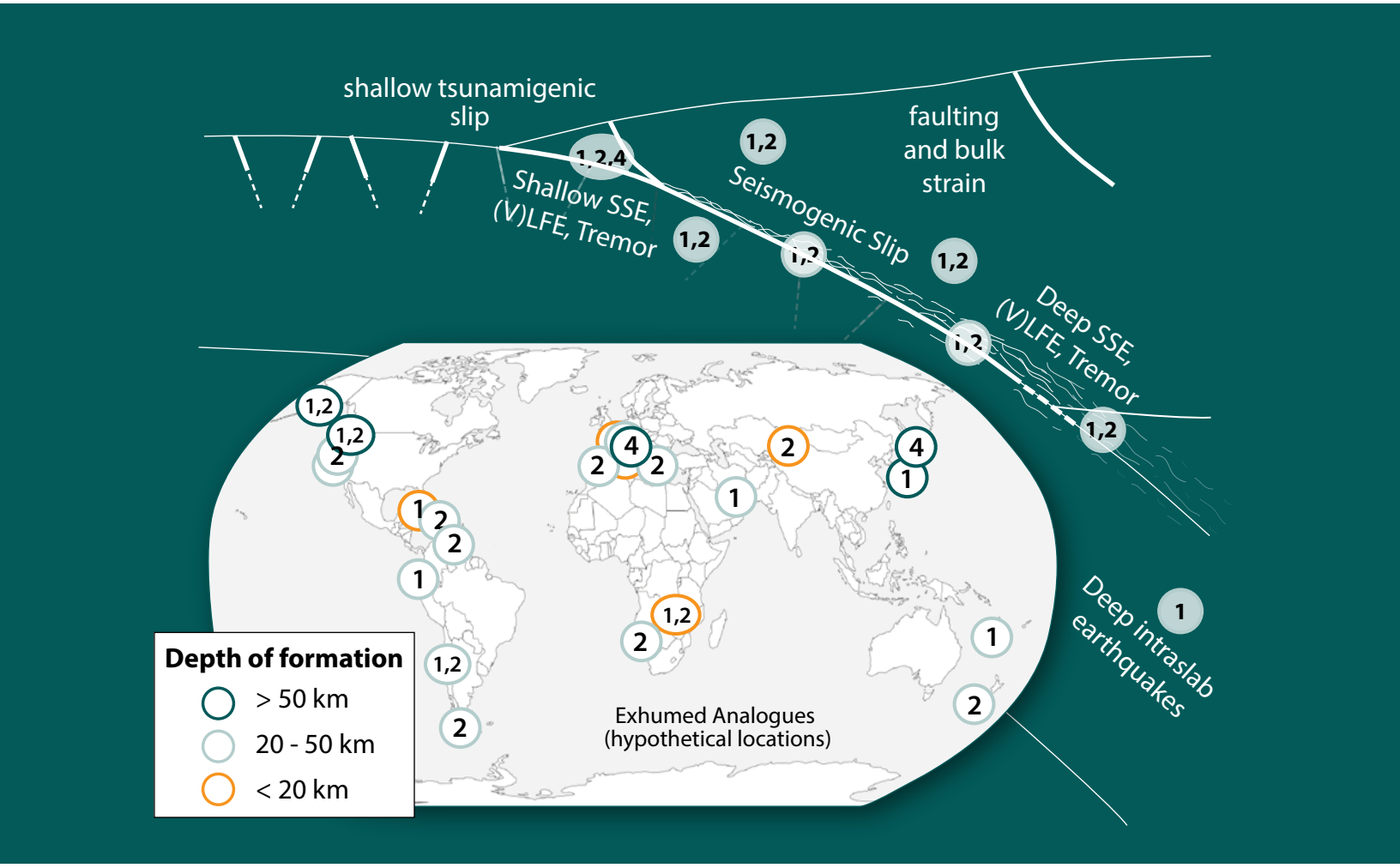


Figure FEC-11. *Illustration of strategy for sampling and analysis of exhumed samples. Circled numbers indicate FEC science questions for which exhumed samples from a given part of the subduction system would be most relevant.*

PORTFOLIO STRATEGY AND SITE SELECTION

To address all of the FEC science questions, new observations of active subduction zone systems are critical, and a strategy is necessary to define the suite of sites. Our strategy is to build a portfolio of sites capable of producing large subduction zone earthquakes and tsunamis and that have locked fault zones. The sites should also exhibit variability in the mode and speed of slip within and between them. The data gathered from this portfolio of sites will be used to understand controls on slip behavior on the megathrust and on other subduction zone faults. Knowledge of seismic coupling is important for addressing all four science questions; the degree to which the plates are locked affects all aspects of the seismic cycle as well as the related landscape and volcanic processes. Question 3 on earthquake precursors demands studying a suite of sites in order to maximize success. For this particular question, the stage in the seismic cycle is an important factor in site selection for focused SZ4D observational programs. We expect to rely heavily on leveraging international partners to ensure that the collective global portfolio of instrumented subduction zones will capture key information.

Guided by the science questions and the Traceability Matrix (**Appendix FEC-1**), which specify the detailed measurements needed to address the science questions, a list of required scientific attributes was developed (**Figure FEC-12**). Note that all the high-priority attributes can be traced to the scientific questions (**Figure FEC-12**). A subset of these criteria is relevant to the hazard associated with a particular subduction zone, which is relevant to the overarching mission of SZ4D and to potential domestic and international partners. An Inventory of Subduction Zones was assembled that tabulates these high-priority attributes for Earth's major subduction zones (**Appendix FEC-3**) and thus can be used to inform decision-making about site selection. Based on our compilation, we score each subduction zone on how well it satisfies a given scientific criteria, weighting each criterion based on the number of science questions for which it is relevant (**Figure FEC-12**) and on the relevance of that criteria to the hazard of the subduction zone. See **Appendix FEC-3** for details. The thresholds in this scoring are arbitrary, and the total scores given to a particular subduction zone would vary if different thresholds were chosen; consequently, the specific score given to any particular subduction zone is not meaningful. Other important factors for identifying possible study sites include consideration of overlaps with other components of SZ4D, the priorities of potential domestic and international partners and local stakeholders, the availability of existing data and infrastructure, and logistical considerations.

The screening of sites in **Appendix FEC-3** highlights some regions that would be particularly favorable for addressing the FEC science questions. Several subduction zone segments along South, Central, and North America possess many of the high-priority scientific attributes, including parts of the Chilean subduction zone, Ecuador, Mexico, Cascadia, and parts of the Alaska/Aleutian subduction zone. Other sites that score highly in this screening are parts of the Japan and Sumatran subduction zones. Considering this screening, logistical considerations, and the needs of other parts of SZ4D, we propose that the ideal portfolio includes **Chile, Cascadia, and Alaska**. All sites are capable of producing large earthquakes and exhibit regions of strong coupling. These sites

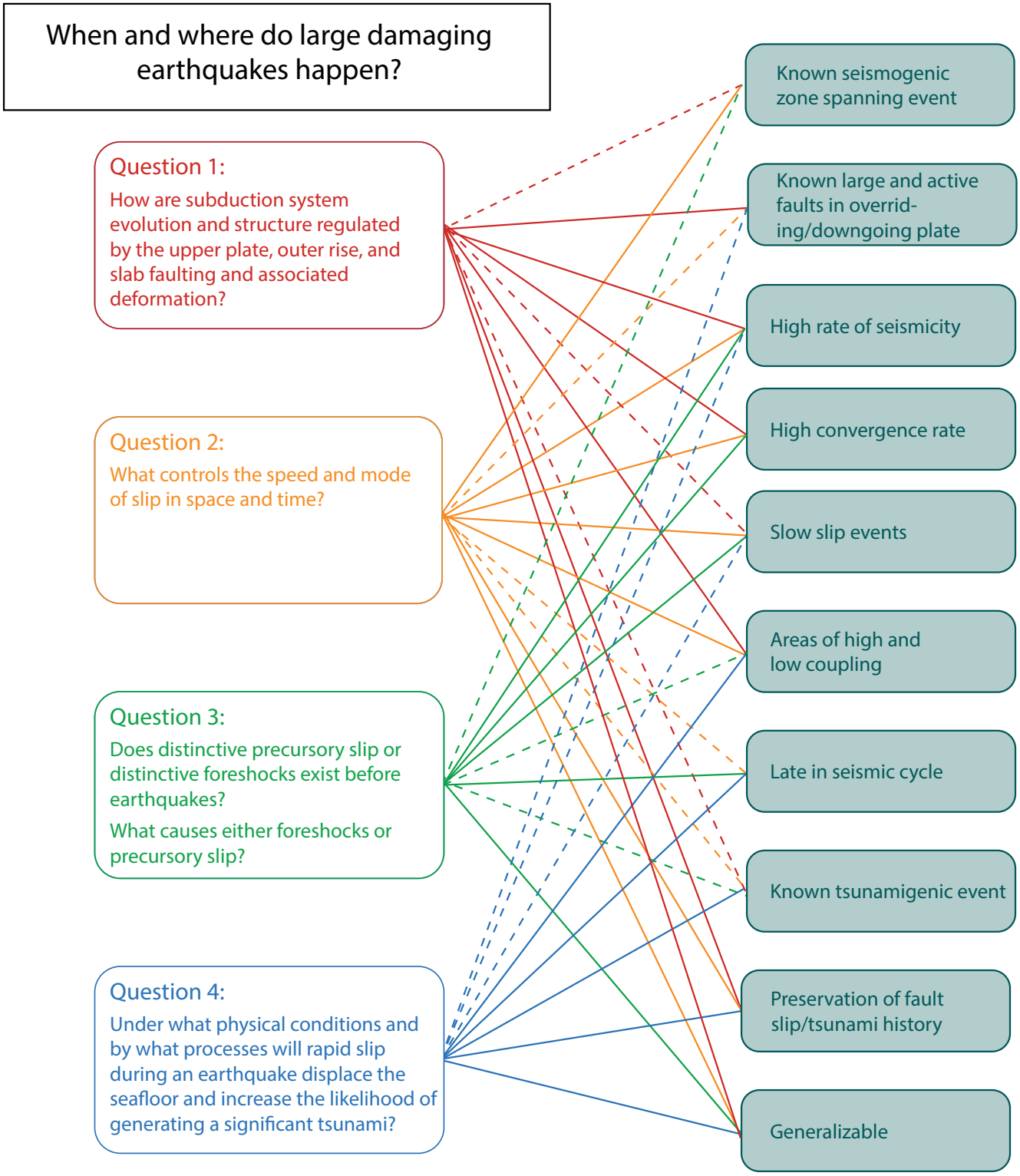


Figure FEC-12. *Wiring diagram showing relevance of subduction zone criteria to each scientific question. Thick, solid lines indicate that the criterion is required to address the question. Thin dashed lines indicate that the criterion is desirable but not required to address the question.*

display differences and similarities in behavior and hypothesized controlling parameters (e.g., thermal structure, subduction inputs) and stage in the seismic cycle, enabling comparisons that are important to address the science questions and that will advance our understanding of hazards in all sites. Foundational observations and knowledge exist in all sites that can be leveraged by SZ4D. Finally, this combination of sites enables excellent national and international partnerships.

The largest risk in the United States from subduction earthquakes is Cascadia; however, that subduction zone poses fundamental challenges to geophysical observation. The slow convergence and low earthquake rate limit the opportunities to learn from events prior to a catastrophic occurrence. A focused effort on Cascadia would be likely to either fail to capture any major earthquake or, perhaps worse, capture the anticipated devastating earthquake without having a chance to utilize any new information from SZ4D beforehand. A faster, but otherwise analogous subduction zone, provides a much higher probability of learning and developing our knowledge base so that we can usefully address the Cascadia problem.

Both Chile and Alaska are useful analogs for Cascadia, however, the logistical challenges of the limited land, rough seas, and extreme weather of Alaska also impact the infrastructure that would be required for MegaArray. Thus, we recommend focusing MegaArray in Chile. Targeted geophysical observations should be collected along the Cascadia and Alaska subduction zones to fill knowledge gaps and enable comparisons; one possible example is seafloor geodesy in Cascadia and Alaska. Analyses of existing data, field studies of active deformation, and numerical modeling are expected to be spread more evenly across these three sites. Analog studies will require a larger geographic spread.

To understand the processes that control subduction zone fault slip behavior, we also require geologic and experimental studies. Thus, the geological component of FEC also requires portfolios of multiple active and analog geology sites. Geologic studies of active subduction zones are necessary to constrain deformation over geologic timescales and modern deformation on upper plate faults and will be coordinated with the sites of instrument deployment for FEC and L&S. Study of onshore exhumed analog sites will be required to define the structures, rock compositions, and physical conditions at depth that control variations in coupling and slip behavior in space and time (e.g., **Figure FEC-11**). A preliminary **inventory of potential analog field sites and their characteristics** provides a useful starting place for assessing the geological possibilities. Phase 1 will build on this work to develop a short list of potential analog sites.

The final selection of study areas and balance of activities and infrastructure between them will take into account overlapping needs of the other SZ4D working groups, logistical considerations, and the priorities of domestic and international partners and local stakeholders as discussed in the Geography section of this plan (**Chapter 5.1**).

SUMMARY AND OUTLOOK

A long-standing grand challenge in Earth science is understanding when and where large earthquakes occur. We have identified four sub questions where the scientific community is poised to make major new advances due to

recent progress in understanding, the availability of new instrumentation and advancements in computational capabilities. Addressing these questions and the broader grand challenge of controls on large earthquakes necessitates collection of high-resolution data. These data will provide new constraints on subduction zone fault behavior. Detailed geological, experimental, and geophysical studies will enable characterization of fault zone properties and architecture. The measurement and modeling of fault zone properties and processes will lead to a better understanding of fault zone behavior and contextualize it, as detailed in FEC traceability matrices. A concerted and focused community effort involving ambitious and coordinated observational, experimental, and modeling components is needed, both within the FEC part of SZ4D and with other parts of SZ4D. To be successful, this deep and long-term collaborative effort necessitates that activities are interleaved and phased, as described in the FEC notional science plan. The FEC component of SZ4D also has significant facility needs; the technically complex physical infrastructure of the geophysical and laboratory components requires professional support. The need for both tight integration and significant observational infrastructure supports a geographical focus on a small number of active subduction zones. We are optimistic that the strategy described here will yield fundamental new insights into subduction zone deformational processes and on the resulting hazards.

Achieving the goals set forth by the FEC component of SZ4D will not only provide new understandings of the fundamental processes that control when and where large, damaging earthquakes happen, but will also result in tangible improvements in our ability to mitigate risks posed by earthquake and tsunami hazards. Answering the four driving science questions will provide improved physics-based models for earthquake and tsunami hazards in all parts of the subduction fault system that will both allow for regional assessment of and planning for hazards, as well as result in an improved ability to monitor, interpret, and respond to the precursors to large earthquakes in real-time. While the scope of SZ4D necessitates geographic focus, through integrative and comprehensive study, FEC will provide a fundamental understanding and the development of new conceptual and physical models of earthquake hazards that can be employed in other regions to improve hazard mitigation.

SIDEBAR 2

A modern view of subduction-zone earthquakes

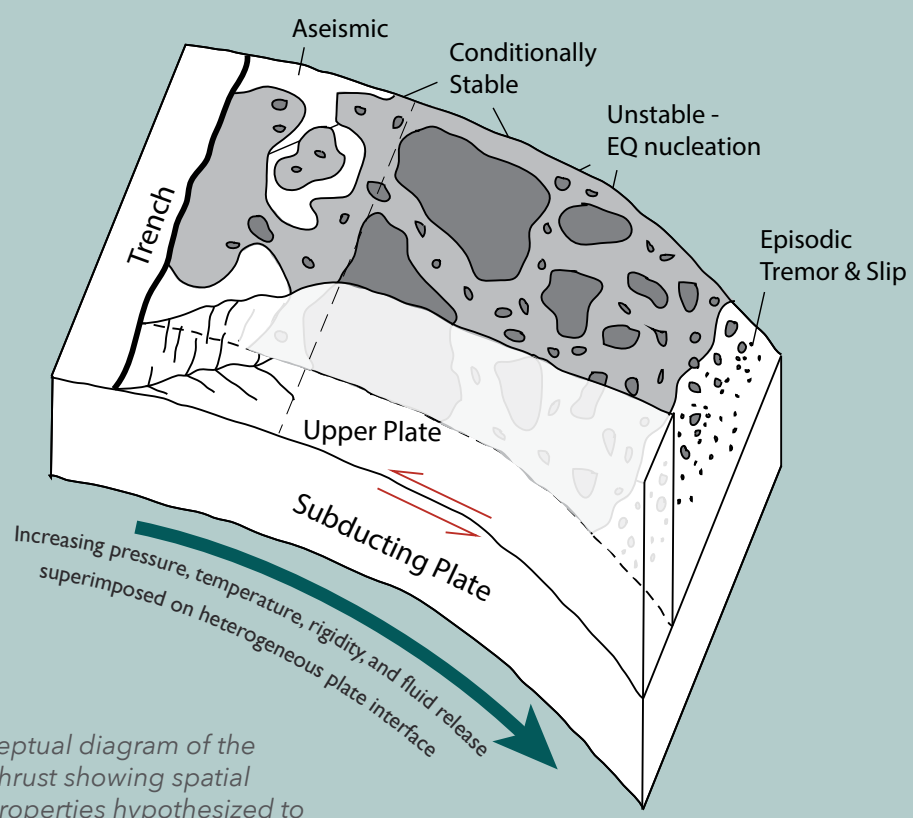


Figure S2-1. *Conceptual diagram of the subduction megathrust showing spatial heterogeneity in properties hypothesized to underpin the diverse spectrum of observed slip modes. After Li et al. (2015) and Lay et al., (2012).*

Over the past 2.5 decades, the advent and deployment of modern instrument networks has sparked a revolution in our view of subduction zone earthquakes. This view has evolved away from simplified models in which a "seismogenic zone" that locks interseismically and hosts great earthquakes is restricted to a specific depth band, and is bounded by regions where the megathrust slips via continuous creep. Instead, we see a much more complicated and heterogeneous picture (**Figure S2-1**). A rapidly growing body of observations has revealed a spectrum of slip behavior on subduction megathrusts globally, spanning timescales from seconds to years. These modes of slip include regular (fast) earthquakes; tsunami earthquakes and low frequency and very low- frequency earthquakes characterized by a higher abundance of low-frequency energy in radiated seismic waves than for typical earthquakes; slow slip events, in which transient fault motion occurs over weeks to months; and continuous aseismic creep. These diverse slip behaviors are in some cases patchy, overlapping in their spatial extent, and are not restricted to specific depth, temperature, or pressure conditions.

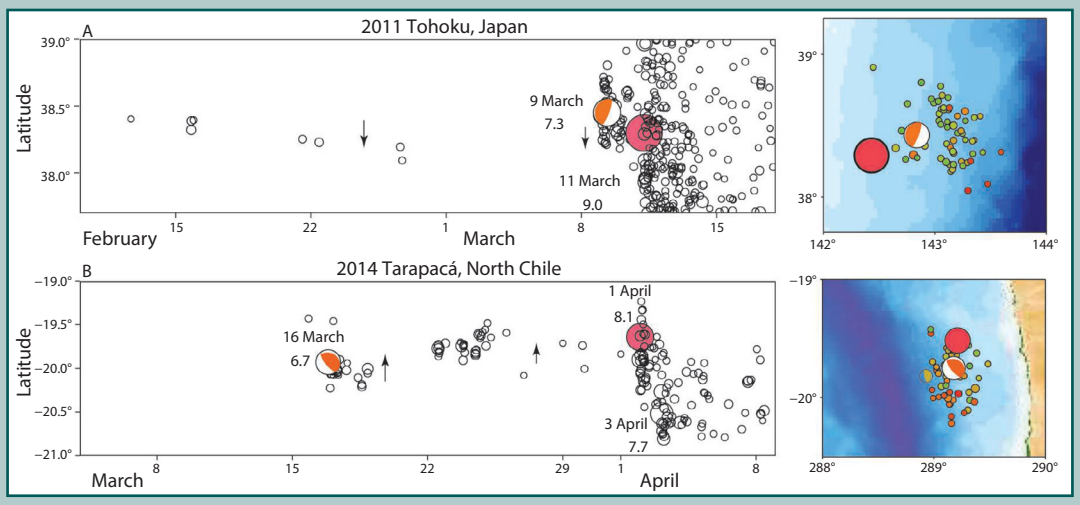


Figure S2-2. *Spatiotemporal evolution of seismicity leading up to the 2011 M 9.0 Tohoku (top) and 2014 M 8.1 Tarapaća (bottom) earthquakes (reproduced from Brodsky & Lay, 2014), showing the migration and coalescence of foreshocks leading up to the mainshocks of these great earthquakes.*

The recognition of these diverse slip behaviors has sparked a revolution in seismology, geodesy, and laboratory rock/fault mechanics – opening new windows to understand the properties [rheology?] of the subduction interface; the interplay of fluids, geology, and metamorphism; and the physics and scaling of earthquakes. Additionally, modern observations of foreshock migration and coalescence show that for at least some large events, a preparatory phase may occur and be detectable with a sufficiently dense network (**Figure S2-2**). These emerging observations also highlight potentially important interactions of fault patches, including triggering and precursory phenomena.

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LANDSCAPES AND SEASCAPES

How do subduction zones control surface hazard and landscape evolution

Scientific Motivation

Earth surface and solid Earth processes play a central role in shaping subduction zone landscapes and seascapes and drive hazards that impact civilization. Storms and earthquake shaking mobilize rocks, sediment, and soil, which are continuously transported seaward by the ebb and flow of flooding rivers and offshore currents. Catastrophic and punctuated erosional pulses across landscapes and seascapes can initiate complicated responses and adjustments that persist for years or even decades following the events that precipitated the geomorphic cascade (e.g., Gran, 2012; Bruni et al., 2021). Slope failures resulting from volcanic sector collapse, earthquake land-level changes, and storms can all dam river channels, leading to continuous adjustments in response to changes in sediment supply or outburst floods that rapidly alter river channel morphology (e.g., Capra & Macias, 2002) - both of which can impact downstream communities. The deposition of large volumes of detritus resulting from subduction zone disturbances can modify river networks for decades to years, changing both their forms and processes in ways that may produce more frequent flooding and promote channel widening (e.g., Major et al., 2016; Korup et al., 2019). These geohazards reflect long-term solid Earth processes acting within the subduction zone (e.g., Ott et al., 2021). For example, faulting and folding of the crust between the trench and the volcanic arc modify sediment transport systems (e.g., Wells et al., 1988), build climate-altering topography, and produce ground failures (e.g., Bhattacharya et al., 2018). Volcanic and magmatic processes likewise build topography (e.g., Karlstrom et al., 2018) and influence the thermal and mechanical state of the crust (e.g., Karakas et al., 2017), which impacts short-term volcanic hazards.

Despite the substantial risks to ecosystems, communities, and infrastructure within subduction zone landscapes and seascapes posed by Earth surface disturbances and their cascading impacts, we are still unable to determine when catastrophic surface disturbances will be initiated, where the detritus produced by these events will go, and how long and how far the cascading impacts that are produced by these disturbances will extend. Likewise, it remains unclear what controls the amount of subduction zone convergence that accumulates between the trench and arc, which determines the potential for earthquakes, tsunamis, and seismically triggered mass wasting in areas often proximal to populated areas and sculpts the topography that defines subduction zone environments.

Recently developed and emerging technologies now allow us to study these Earth surface and solid Earth processes in ways never before possible. Advances have been made in the ability to observe the initiation, transport, and long-term impact of mass wasting events and to simulate the physics of the associated processes at the scale of subduction zone systems. High-resolution space-borne imaging methods now allow us to locate where and when mass wasting events are initiated, and in some cases, characterize rates of motion. Suborbital plane and drone-based platforms, coupled with computer vision developments, allow detailed characterization of downstream impacts produced by disturbances. Submarine drone and continuous monitoring technologies have very recently allowed us to capture seascape changes produced by submarine fault scarp degradation (Hughes et al., 2021) and sediment density currents that may be initiated by earthquake-generated submarine landslides. Likewise, these technologies enable us for the first time to gain both a detailed and synoptic view of the way in which areas between the trench and the volcanic arc deform in four dimensions, which allows us to begin to constrain the total subduction zone energy budget. High-precision satellite geodesy, repeat laser altimetry, drone-based and new submarine monitoring and imaging technologies, and high-resolution optical and multispectral imagery can now quantify Earth's continuous deformation and erosion in near-real time. Simultaneously, developments in computer hardware now provide petaflop-scale computation to researchers, while developments in numerical methods allow accurate simulation of multiphase physics of the flows produced by disturbances and cascading impacts. These advances allow us to use state-of-the-art numerical models that couple surface process actions and subduction-zone geodynamics to link observations to the energetics and dynamics of the processes that shape subduction zone landscapes and seascapes. This work is foundational for understanding the risks that hazardous tectonic events pose to communities occupying subduction zones. Through a decade-long effort, many of these advances will allow the community to address fundamental questions that underlie our ability to understand these hazardous events.

Research Questions

The L&S component of the SZ4D has identified two research questions and related hypotheses that leverage this suite of new observational technologies, computational capabilities, and model developments. Addressing these questions will enhance progress toward reaching the goals of the SZ4D FEC and MDE working groups, and provide a framework for interdisciplinary research that will lead to transformative advances in subduction zone science.

How do events within Earth's atmosphere, hydrosphere, and solid Earth generate and transport sediment across subduction zone landscapes and seascapes?

For example, what are the fundamental controls on the initiation and runout of landslides, turbidity currents, liquefaction, and other surface processes, including those influenced by earthquakes and volcanic events? How do surface processes produce cascading and persistent impacts as material is transported across the landscape and seascape? What are the feedbacks between subduction zone earthquakes and volcanic eruptions, and sediment generation and transport across landscapes and seascapes?

What fraction of a subduction zone's energy budget goes into building and shaping subduction zone landscapes and seascapes?

For example, how much permanent deformation is absorbed in the upper plate of the subduction zone and what factors control this? How do the subduction interface, upper plate structures, and magmatic systems collectively modify sediment transport systems and respond to landscape and seascape change? How does the interplay of processes across the subduction zone contribute to the deformation energy budget that constrains the potential energy that drives landslides and the conditions that trigger earthquakes and eruptions? How do periodic changes in climate affect the crust's stress state?

From these two research questions, we have developed **testable hypotheses** in subduction zone systems. We organize these hypotheses in terms of each research question:

- Testable hypotheses for Research Question 1 | **Figure LS-1**

A broad working hypothesis addressing this question is that the frequency of events that initiate mass movements and mobilize sediment control sediment generation and transport. When sediment is generated by hillslope mass failures during storms, atmospheric rivers, and high precipitation events more frequently than solid Earth events (e.g., earthquake shaking and volcanic unrest), the former will dominate sediment generation and transport (e.g., as in LaHusen et al., 2020; Major et al., 2021). Conversely, solid Earth events may play a large role in shaping landscapes when these types of large storms, atmospheric rivers, and high precipitation events are infrequent (e.g., Bruni et al., 2021). Thus, the ratio of the recurrence time of "landscape-impacting" atmospheric events, to "landscape-impacting" solid-Earth disturbances determines the imprint that atmospheric versus solid Earth processes play in shaping various parts of a subduction zone landscape. In the case of hillslopes, when large, landslide-generating atmospheric events occur frequently, their impacts dominate landslide-related hillslope transport. When these events occur less frequently, earthquake shaking or intense volcanic rock weathering may play a significant role in the initiation of landslides. The initiation of density currents by onshore storms versus offshore seismically generated mass failures varies throughout the submarine tributary system, as the relative recurrence times of these generative events vary. In the main canyon system during sea level low stands, the main channel may be frequently occupied by onshore-generated hyperpycnal flows that ignite density currents often enough to reduce the role that large shaking events play in generating these events. In contrast, canyon tributaries within the continental slope receive few density flows initiated onshore

such that seismically produced mass failures dominate density current generation. For the case of rivers, the role of atmospheric versus solid Earth events in transporting sediment depends on their relative rate of recurrence. Large magnitude injections of sediment into rivers by, for instance, volcanic eruptions, lahars, and widespread earthquake-generated landslides can locally overwhelm the transport capacity of rivers, producing large changes in aggradation and deposition within the channel. When sediment generation from hillslopes is continuous, steady transport of sediment in rivers causes few appreciable changes in river morphology.

- Testable hypotheses for Research Question 2 | **Figure LS-2**

A central working hypothesis is that the style of upper plate deformation is regulated by plate motions and coupling along the subduction megathrust, elastic and inelastic deformation processes in the upper plate, body forces generated by topography, and the rheological configuration of the upper plate (e.g., Béjar-Pizarro et al., 2013; Penserini et al., 2017; Malatesta et al., 2021). Tectonic boundary conditions, such as the plate motion vector and distribution of coupling along the subduction megathrust, which might be related to rheological changes or spatial/temporal variations in basal fluid pressures within the forearc and subduction megathrust (e.g., Barnes et al., 2019), limits the lateral stresses present in subduction zones. These tectonic stresses can conspire with tractions acting along the base of the crust, body forces generated by time-evolving topography and crustal magmatic addition, and surface loads produced by ice, extrusive volcanism, and deposition to result in the state of stress within the crust (e.g., Willett, 1999; Fuller et al., 2006; Dielforder et al., 2020; Wang, 2020).

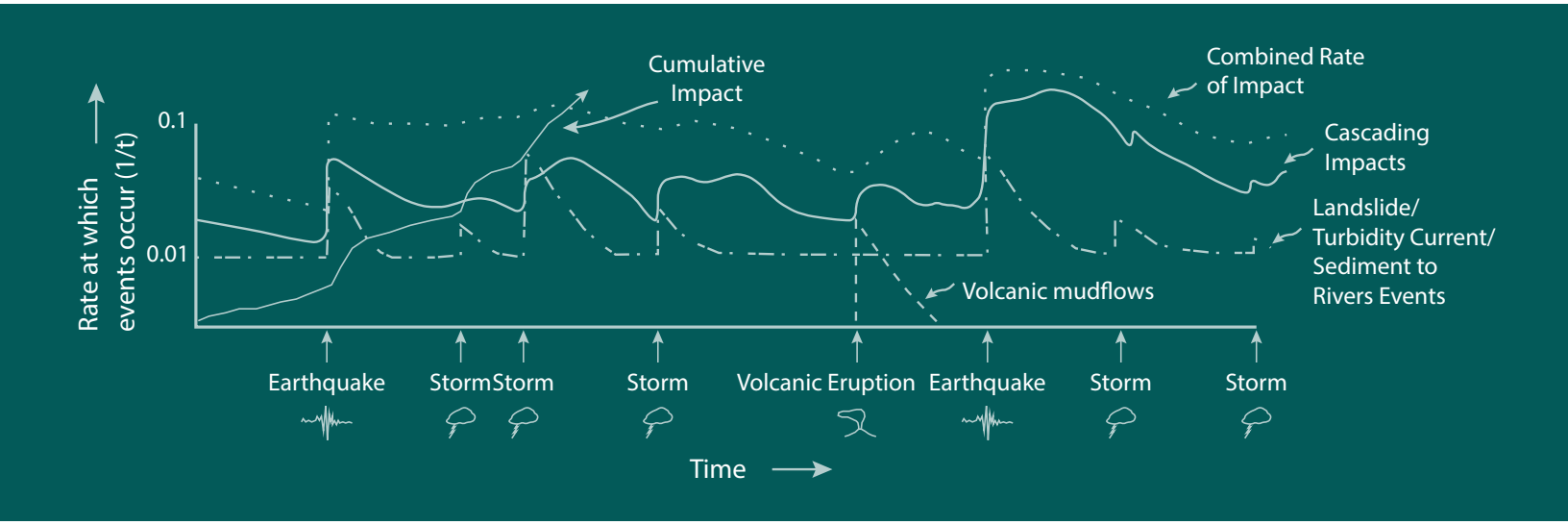


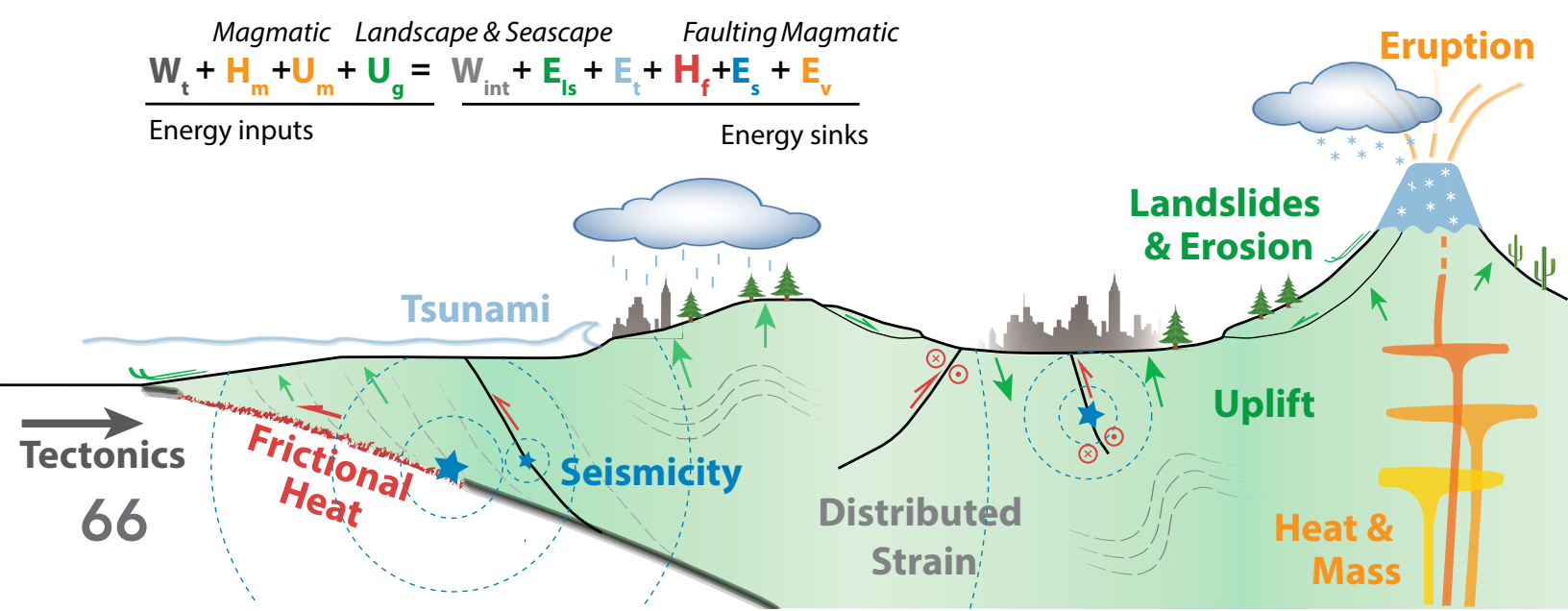
Figure LS-1. *Schematic representation of the drivers of cascading Earth surface hazards. Punctuated events, such as earthquake shaking and large storms can increase the incidence of mass failure (dash-dot line) during the event and in its wake. Likewise, volcanic eruptions can instigate mudflows (dashed line), whose impacts persist long after the eruption has occurred. These punctuated transport processes introduce large mass inputs to rivers, whose geometries may be persistently impacted in a way that generates hazards such as flooding for decades following the instigating events (solid line). This array of instantaneous and cascading impacts can produce substantial and persistent long-term repercussions that propagate throughout entire large watersheds, affecting downstream communities and infrastructure (dotted line).*

The interaction of this background stress state with the physical properties of the upper plate (such as crustal weaknesses due to preexisting terrane boundaries and thermally weakened zones) can determine the nature, degree, and distribution of elastic and inelastic strain in the forearc, and the dynamics of magmatic intrusion and eruption within subduction zone systems (e.g., Watt et al., 2013; Karlstrom et al., 2017). The state of stress informed by energy investigations provides critical constraints on the conditions that initiate earthquakes (e.g., Harris et al., 2009), landslides (e.g., Martel, 2004), and volcanic eruptions (e.g., Gudmundsson, 2012), while the energy budget itself provides constraints on the power available to drive these hazard events (e.g., Del Castello & Cooke, 2007). Such an energy budget framework provides a mechanism to connect long-term subduction zone processes to the drivers of short-term geohazards.

TRACEABILITY OF THE SCIENTIFIC QUESTIONS THROUGH PRACTICAL ACTIVITIES

The L&S working group defined measurement priorities using a Science and Applications Traceability Matrix (SATM), presented in *Table A-LS1*, which relates our research questions to the geophysical observables, measurement requirements, and in some cases, technologies that may be employed to collect these measurements. The SATM has several important shortcomings, which we attempt to address in this chapter. First, the SATM framework is best suited to defining measurement requirements, but cyberinfrastructure and data management associated with data collection and analysis are also essential to the success of the L&S component of SZ4D. Furthermore, the SATM does not easily address needs such as numerical model

Figure LS-2. *Schematic first-order energy budget of the entire subduction zone. The inset equation outlines the energetic inputs (Wt - tectonic work; Hm - heat; Um - gravitational potential energy from mass in/out of the system), conservative energy terms (Ug - work of uplift against gravity; Wint - internal deformation work) and energetic sinks that are lost to the system (Els - kinetic energy of sediment transport; Et - tsunami energy; Hf - frictional heat of earthquakes; Es - seismic shaking and Ev - heat and kinetic energy of volcanic eruptions). Understanding the relationships between subduction zone processes can inform the energy available within the system that can drive damaging hazards.*



development and computational resources. For this reason, we supplement the results of our SATM process with a prioritized list of these other essential needs to ensure that the data backbone provided by the SZ4D infrastructure is complemented by the appropriate cyberinfrastructure, model development resources, and computing facilities.

Once the list of required measurements was compiled, they were assigned to one of three tiers, defined and described below, according to their importance in addressing our research questions. The highest priority measurements crosscut the largest number of key science questions and have the greatest potential to benefit the largest swath of surface and solid Earth science contained within the L&S component of the SZ4D. Measurements that might address the needs of the other SZ4D working groups and also strategically engage agencies in data-sharing partnerships were, in some cases, promoted in their relative tier to facilitate broad, multi-agency involvement in the SZ4D effort. In the following nomenclature, Tier 1 measurements reflect those of highest priority, while Tier 3 measurements are important (and in many cases necessary) measurements that did not crosscut a large number of our key science questions. Several components of the Tier 1, 2, and 3 measurements comprise detailed observation of Earth's terrestrial and submarine surface through acquisition of, for example, high-resolution bathymetric data, repeated lidar and satellite-based optical and synthetic aperture radar (SAR) imaging, GNSS monitoring, and environmental monitoring via geophysical and sensor networks. This set of surveying infrastructure, which we call SurfArray, will monitor changes in Earth's surface at unprecedented spatial and temporal detail.

Tier 1 Observational Priorities

Tier 1 priority measurements crosscut virtually all aspects of the L&S research questions and include the active imaging of the solid Earth surface, as well as changes in the surface over time. SurfArray is a critical aspect of this data collection. In particular, gathering comprehensive baseline high-spatial-resolution (<1 m postings) topography and bathymetry data will be essential for mapping past events such as landslides, mass transport via volcanic eruptions and submarine and lacustrine turbidity currents, volcanic summit inflation and collapse events, near-surface fault slip deformation rupturing (earthquake deformations, steady creep, and transient aseismic slow slip), coastal erosion and deposition, glacial loading and rebound, and anthropogenically driven geomorphic changes. We also require repeat, high-resolution imaging of the solid Earth surface in areas where events have occurred to determine the amount of mass mobilized and the surface response to these events. Importantly, these acquisition capabilities must be available for deployment immediately following atmospheric or solid Earth events to provide constraints on the surface response. Additionally, drone-based lidar and optical platforms are important complements to high-resolution subareal imagery. These generally low-cost platforms can collect the ultra-high-resolution topography that is required for change detection, albeit over small-footprint study areas, and are more rapidly deployed than larger airborne assets. Second, measurement of solid Earth surface deformation is a high priority for the L&S component of SZ4D. Satellite-based SAR acquisitions from platforms such as the NASA-ISRO SAR (NISAR) mission can be used to produce interferometric estimates of topography and surface motion, which is crucial for constraining surface deformation due to

slow-moving landslides, soil creep, elastic strain accumulations around faults, and anthropogenic subsidence due to underground resource extraction. This backbone of satellite-based measurements needs to be supplemented with high temporal resolution surface motions provided by continuous and campaign GNSS monitoring. Installation of marine geodetic monuments is a key component of the L&S mission to constrain rates of deformation in the upper plate. The rates of deformation derived from these sources provide crucial constraints on the energy budget across the subduction zone and help to quantify sediment inputs that arise from motions of hillslopes whose rates are modulated over seasons and individual storms.

Tier 2 Observational Priorities

The SATM process identified four Tier 2 measurements, all of which are important for answering components of our key research questions. Several elements of Tier 2 are also central to the SurfArray, while others leverage and build on these long-term monitoring efforts. Repeated, satellite-based, high-resolution (<1 m pixels) optical imaging is a measurement that crosscuts many of our questions, but whose utility is confined to the surface. Numerous (and increasing) constellations of orbiting optical-imaging satellites provide an emerging dataset that allows observations of surface events at high spatial (meter scale) and temporal (daily) resolution. Comparison of daily images can be used to track events that generate sediment along hillslopes (e.g., landslide events) and how channel morphology adjusts as floods transport sediment downstream. Rapid satellite tasking can help target post-event landscape response.

Tracking sediment through the transport system will require networks of sensors that collect a time series of river discharge and sediment concentrations. Additionally, these ground-based sensor networks need to be able to capture the meteorological events that initiate the transport cascade, so that these spatially dense measurements can be used to downscale observations from satellites that capture broad areas at much lower spatial resolution. These sensor networks, when used in conjunction with existing satellite-based climate monitoring systems, provide the information needed to understand the triggers of storms and seasonal climate oscillations that trigger mass wasting on hillslopes.

In addition to this sensor network, a range of geochronologic capabilities will be required to contextualize real-time observations of individual sediment-generation events and constrain the subduction-zone energy budget. An enhanced ability to precisely measure samples using cosmogenic nuclides is rapidly enabling us to quantify rates of denudation at catchment to outcrop scales that span millennia to <~1 Myr. Radiocarbon remains one of the gold standards for Holocene dating. Optically stimulated luminescence and infrared stimulated luminescence methods can constrain deposit ages over tens to hundreds of thousands of years. Longer-term rates of denudation of Earth's crust (>Myr) can be established using a wide number of thermochronologic techniques. Together, these geochronologic measurements can provide insight into changes in the surface of the subduction zone, the ways in which faults accommodate long-term deformation in the upper plate, and the role that intrusions and eruptions might play in the erosion of the mountainous areas of subduction zone systems. Finally, it will be critical to track sediment transport across the subaerial and submarine transport conduits. Environmental geophysical instruments can help to quantify this transport

because they can measure impulses delivered by mobilized mass during large landslide events, flood-related sediment transport, or energetic offshore density currents.

Tier 3 Observational Priorities

Finally, the L&S component of SZ4D identified a number of measurements that are essential for answering specific aspects of our research questions but do not crosscut a majority of these questions, and most of these data needs are not included in the SurfArray. Examples of these priorities include stable isotopes and clumped isotope geothermometry that can reveal past climatic conditions and paleoelevation, coring of specific areas that can reveal local earthquake histories, and trenching used to constrain earthquake history along particular faults. Their rating as Tier 3 priorities is not to be confused with their importance to the efforts of the L&S component of SZ4D. Rather, these types of measurements need to be tailored to the details of specific sites and so are not well suited to provide a "backbone" of data for many scientists studying particular subduction zone segments. Instead, these necessary measurements might be facilitated by individual PI-driven research that is supported by the larger SZ4D effort.

The SurfArray Environmental Sensor Network (ESN)

The importance of collecting ground measurements of climatic, hydrologic, and geomorphologic information led the L&S group to develop and design a network of instrumentation., Ttermed the SurfArray Environmental Sensor Network (ESN), itswhose purpose is to monitor and study the transport of water and sediment throughout a set of targeted watersheds. Key measurements include precipitation, soil moisture, stream water and sediment discharge, and micro-seismicity (ideally measuring three components). Fortunately, many of these variables and conditions can be easily measured with multi-component sensors. When strategically placed, these sensors become a network capable of providing the data needed to understand the environmental conditions that shape the landscape. The envisioned spatial and sensor quality of the ESN will optimize the trade-off between instrumentation costs and essential data needed to address the research questions. We envision that the ESN will operate continuously throughout the lifetime of SZ4D to capture the necessary data needed to define frequency-magnitude relationships. needed to This information will improve understanding of theunderstand dynamics of the meteorological, hydrological, and sediment transport dynamics of the system relevant to upscaling findings beyond the observational window. In addition to this long-lived and stationary network, L&S requires a more nimble, rapid response component to array design and deployment, where instrumentation and expertise can be developed rapidly. This flexible, rapid-response, small-scale array could acquire data from a given region of interest in the immediate aftermath of a landscape-altering event (e.g., large rainstorm or earthquake).

The SurfArray ESN is designed to collect data at a range of spatial scales. At the largest scale, sensors will be deployed to measure precipitation, soil moisture, and micro-seismicity at roughly uniform ~100 km grid-based spacing at the scale of a subduction zone segment (**Figure LS-3A**). The primary intent of this large, evenly spaced sensor deployment is to enable calibration of remotely sensed data products related to precipitation and soil moisture, such as NASA's Global Precipitation Measurement

Mission (GPM) data product. This coarsely spaced sensor array will allow regional calibration of satellite-derived measurements, thereby enabling even broader spatial coverage overto other subduction zone segments that may not contain dense, in situ environmental data.

Within this coarsely spaced sensor suite of sensors, we will also establish a series of sensor arrays that span the coastline to the volcanic arc (**Figure LS-3B**). Using a nested approach, in which relatively coarse estimates of information gathered over large areas will be used to inform more detailed information to sub-domains that are instrumented more densely. Specifically, we will comprehensively characterize several large drainage basins whose mainstems drain roughly parallel to the convergence velocity vector. If two large drainage basins are instrumented, each basin can take advantage of other SZ4D -PI- led comparative experiments, such as the impact of arc volcanism on geomorphic processes and geohazards (**Figure LS-3B**). At the scale of the largest drainage basin, we will deploy an array of the sensor arrays that will capture smaller-scale variability in precipitation, soil moisture, and micro-seismicity across the study area. We anticipate instrument spacing at ~5–50 km, depending on access, permissions, power, and roads. We also plan to install stream water discharge and suspended sediment gauges in the mainstem of the drainage basin. The instrument spacing will be in log-distance or log-drainage area increments to capture more rapidly changing conditions in the headwaters. Within the large watershed-scale array, instruments will be more densely spaced in third to first order drainages that are roughly perpendicular to the flow direction of the mainstem. This spacing will ideally capture much of the tectonic, lithologic, and weather variability from the coast to the arc that results in the observed signals in the mainstem river system. We anticipate instrumenting three to seven smaller-scale basins depending on basin heterogeneity and logistical considerations. Within these small basins, we will have one stream water discharge and suspended sediment sensor at the outlet and four to ten precipitation, soil moisture, and micro-seismicity sensors distributed throughout each basin (**Figure LS-3B**).

We envision using a range of sensors of varying types, quality, and costs. L&S needs high-quality sensors that require a connection to the power grid to operate. At these sites, the highest quality sensors will contain multiple (possibly up to twelve) components. As a baseline for hillslope sites, low-cost precipitation gauges, soil moisture sensors, soil temperature sensors, and micro-seismic instruments will suffice (e.g., Raspberry Shake), but three-component seismometers are preferred. These sites will likely be co-located with MDE and FEC instrumentation to minimize cost and ease logistics associated with instrument maintenance. For river sites, we will need to acquire instruments that measure stream discharge, suspended sediment, precipitation, and microseismsmicro-seisms. These sites might also be outfitted to measure freshwater chemistry and bedload transport via impact plates or higher-quality seismometers. We anticipate that these high-end sites are equipped to transmit data in real time or first process data on-site and then transmit the processed data intermittently. This capability is critical for monitoring station health and data quality and capturing extreme events.

Mid-tier sites do not need to be connected to the power grid and could be powered through high-efficiency batteries charged using solar panels. Mid-tier stations will have fewer sensors than the high-end sites, but we will require

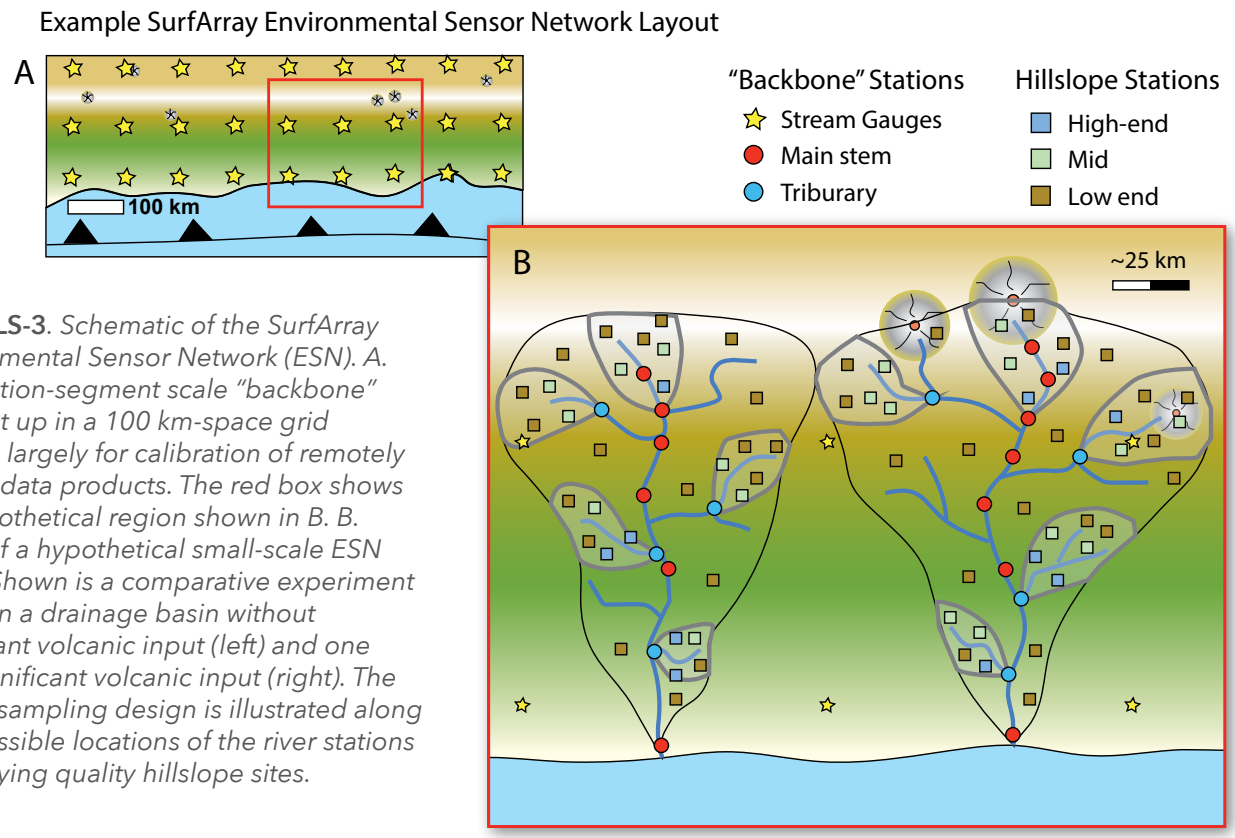


Figure LS-3. *Schematic of the SurfArray Environmental Sensor Network (ESN). A. Subduction-segment scale "backbone" array set up in a 100 km-space grid pattern, largely for calibration of remotely sensed data products. The red box shows the hypothetical region shown in B. B. Zoom of a hypothetical small-scale ESN setup. Shown is a comparative experiment between a drainage basin without significant volcanic input (left) and one with significant volcanic input (right). The nested sampling design is illustrated along with possible locations of the river stations and varying quality hillslope sites.*

precipitation, soil moisture, and micro-seismic measurements at hillslope sites. At river sites, we will need sensors for collecting precipitation, stream discharge, turbidity, and micro-seismic measurements. Similar to the above, mid-tier sites would ideally be capable of transferring data in real time in some form; however, recognizing potential challenges, data loggers will work if no other options are available.

Low-end sites will be on hillslopes only and consist of rain gauges, soil moisture sensors, and low-cost micro-seismometers. These sites can either be run entirely on high-efficiency batteries with software designed to maintain battery life for 6 to 12 months on a single charge. Alternatively, these sites can be connected to solar panels to maintain longer battery life. If positioned in areas with cellular service, these devices can stream data via the internet of things (IoT) at a relatively low cost. In more remote areas without cellular reception, it is likely that these low-end sites will capture and store data on data loggers. Furthermore, the low-cost sites could be distributed throughout the larger drainage basins to provide additional spatial coverage.

Other Infrastructural Needs

While our SATM process was valuable for identifying the key L&S measurement priorities, there are several infrastructural needs that do not cleanly fall within its rubric. The three general categories discussed by our working group included the need for a robust cyber-infrastructure for organizing, distributing, and archiving data from the SurfArray; integrated field-based experiments and observatories to systematically manipulate/observe transport events and coordinate measurements; and the development of high-throughput

geochronologic facilities capable of meeting the demands of the SZ4D project in a way that maintains uniform quality standards. Organizations such as OpenTopography, NASA's Earthdata, and UNAVCO/IRIS may serve as a backbone for cyberinfrastructure, but the heterogeneous data sources will require support to implement. (These needs share affinity with the MDE group.) Field experiments, both onshore and offshore, could be imagined to observe, and perhaps even initiate, mass transport events - coordinated measurements within field observatories would most effectively utilize resources for this type of effort. Additionally, methodologies such as detrital Ar-Ar would be revolutionary for tracking provenance, but new high-throughput geochronology facilities might need to be developed to enable this capability.

Finally, numerical modeling must be a central tool for addressing the hypotheses arising from our key research questions. Five different core modeling needs were identified by the L&S group to investigate the research questions enumerated above. First, investigation of the drivers of geohazards such as landslides requires models of landslide initiation that can approximate self-organization and spontaneous-order for failure plane coalescence and slope instability that are physics-based and can reproduce area-magnitude, area-depth, area-volume, and scaling relationships. These models must be three-dimensional and capable of handling complex surface geometry (i.e., realistic topography) and internal heterogeneity (e.g., fractures and variable material properties such as soils, regolith, and bedrock). Second, simulation of water and mixtures over Earth's surface requires a performant, shallow-water equation solver that simulates flows over arbitrarily complex topography that span clear water to slurries and two-component Coulomb mixtures that allows kinetic sieving of solid phase, water, and sediment exchanges from a potentially erodible bed. Third, simulation of the downstream impacts of mass failures resulting from solid Earth or atmospheric events requires an open-source, performant alluvial transport and bed evolution solver that couples the dynamics of water flow in rivers to sediment transport. These codes must be capable of handling transitions between wetted surface and dry perimeter and must explicitly couple sediment transport mechanics to the evolution of the flows' containers. Fourth, these two sets of codes must be coupled to one another to simulate the cascading hazards studied by the SZ4D. And finally, to analyze the work-energy budget of subduction-zone systems requires coupled surface process and tectonic, geodynamic, magmatic models. Existing efforts (e.g., Computational Infrastructure for Geodynamics [CIG] and Community Surface Dynamics and Modeling System [CSDMS]) and models (e.g., Landlab) provide logical paths forward. But, these models must be run at the resolution required to capture the hillslope-channel transition and must span transport across the entire subduction zone - a requirement that could be met by increased model efficiency and ease of model integration.

Given the diverse L&S modeling requirements, we need a funding structure that enables sustained development of methodologies that simulate landscape-forming processes over the vast range of timescales of their operation and that link these surface processes to solid Earth geodynamics. For example, numerical models of forearc deformation must include elastic and inelastic deformation at short and long timescales, surface processes, localized slip along discontinuities, thermal structure of magmatic systems, and fluid flow architecture

of the forearc. Currently, no single modeling framework handles all of these processes well. In addition to the human resources that are required to develop these coupled models, large-scale computational infrastructure is necessary to run models at the scale of a subduction zone. These essential needs may be met by collaboration with, and commitment from, those with the numerical expertise and access to large-scale computational resources, specifically the SZ4D-MCS, CSDMS, and CIG.

NOTIONAL EXPERIMENTS

The L&S working group developed a set of notional experiments to test the hypotheses derived from our research questions. The design of our notional experiments follows the philosophy that strict tests of conceptual models require some sort of experimental manipulation in which relevant conditions are held constant while a single factor is systematically varied. In natural systems of the scale and complexity of entire subduction zones, this type of experimental manipulation is not possible, and so our approach relies on comparing subduction zone segments where many of the relevant factors are known and the cross-comparison yields insights on the effects of variations in a single factor. The paired experimental design may be used to falsify quantitative models of geomorphic transport and forearc deformation within subduction zones, in a similar way as a strictly controlled experiment might. Finally, such a paired subduction zone segment design is useful for identifying the ideal geographies of our natural experiments, where controlled variations in the particular factors of interest may be present.

Notional Experiment 1

This experiment explores the role of recurrence time of landscape-impacting solid Earth, magmatic, and atmospheric events on the events that generate sediment and transport it to offshore sinks (Research Question 1; **Figure LS-1**). For these experiments, we would ideally use a paired set of subduction zone segments that have either similar solid Earth or atmospheric conditions, while the other set of factors varied between the subduction zone segments. For example, to explore the impact of atmospheric events on sediment generation, we would ideally seek areas with consistent convergence rate, subduction angle, and frequency-magnitude relationships for large earthquakes and magmatic events, while climatic parameters (e.g., precipitation, storminess, and temperature) would vary. The differences in climate would presumably alter the distribution of the frequency, magnitude, and spatial extent of storms impacting the subduction zone landscapes and seascapes. In this case, a successful experiment would require field measurements and data to capture the impact of a single event and the integrated effect of multiple events, as well as longer timescale data that would elucidate how these events cumulated to produce the long-term transport of mass across the subduction zone system. For example, satellite and ground-based measurements of precipitation would allow determination of the associations between storms and mass wasting events. The location and rates of mass wasting could be constrained using seismologic, ground, or remote sensing observations. The magnitude of sediment generation could then be determined by reoccupying portions of the baseline high-resolution dataset, and sediment load measurements and drone resurveys could be used to track how this sediment is filtered

downstream and changes valley morphology.

It is also important to acknowledge that many of the factors that we would like to hold constant in such a paired study may covary with one another because of the processes in operation. For instance, climate-driven sediment delivery to the trench has been hypothesized to impact coupling along the plate interface of subduction zones, and so at least over long timescales, it may be difficult to isolate these factors. Because natural experiments may not allow perfect isolation of controlling factors, parametric studies using numerical models might augment the study of the natural systems by serving as thought experiments to better interpret covariations seen in natural systems. Necessarily, such models should couple solid Earth deformation (earthquakes and magmatic) with surface processes. This will allow comparison with field data that characterize processes occurring at a similarly wide range of timescales.

Notional Experiment 2

This notional experiment seeks to understand the interplay between evolving topography, deformation, and magmatic processes within the upper plate of the subduction zone. (Research Question 2; **Figure LS-2**). While many variations are possible for the notional experiment, two variants outlined here offer key insights into the feedbacks between subduction zone and Earth surface processes. In one variant, we would compare subduction zone segments with similar degrees of accretion rate, coupling, magmatic flux, and forearc lithotectonic complexity, but different mean forearc slopes, to isolate the interplay between topographic loading and upper plate deformation and magmatism. In another variant, we would compare subduction zones with similar viscous coupling depth, mean slope, contraction rate, mantle melt influx rates, and heat flow, but different lithotectonic complexity and duration of subduction, to illuminate the role that crustal structure and subduction history produced by the geologic assembly of the forearc and arc plays in partitioning deformation and magmatism in the upper plate. In both of these cases, high-resolution topography allows identification of active structures in the forearc, provides a base map for field observations, and details the configuration of watersheds throughout the volcanic arc and forearc. Geologic, geochronologic, and thermochronologic observations constrain the long-term rates of exhumation due to the action of forearc structures and magmatic processes. Finally, numerical models that are framed as either parametric studies or simulations can be used to construct predictions that can be ruled in or out using the field observations.

These notional experiments represent abstract aspirational studies that could ideally be performed if subduction zone segments with all of the targeted variations existed. However, natural circumstances do not present all combinations of factors of interest in the notional experiments. Thus, the possible sets of experiments, and the specific forms they will take, depend on the characteristics associated with paired sets of particular subduction zone segments. In this way, it is not possible to divorce the discussion of our notional experiments from the natural conditions available in specific subduction zone systems. The section on **Site Evaluation** lends some specific form to the notional experiments through a review of the properties of different subduction zone segments and a comparison of segment pairs. That chapter seeks to identify obvious sets of subduction zone segments whose comparison might lead to reasonably well-constrained natural experiments. However, the general form of our notional experiments is

intended to allow space for individual PI-driven research that might compare particular aspects of subduction zone segments that are not specifically called out in the **Site Evaluation** section as being most amenable to addressing our research questions through a decade-long, community-wide initiative.

IMMEDIATE SCIENCE ACTIVITIES

While the majority of our proposed hypotheses require new and cutting-edge datasets, significant progress can be made through the analysis of existing data and ideas. Below we describe examples of how existing datasets and numerical models may advance our understanding of how mass is mobilized and transported across landscapes and seascapes, and constrain the energy budget of subduction zone systems. Additionally, we describe the ways in which these analyses could be coordinated with the primary SZ4D experiments.

Recent advances in airborne and terrestrial lidar techniques, as well as autonomous underwater vehicle bathymetric surveys, have provided high-resolution digital elevation models that allow us to explore short- and long-term surface deformation and disturbances across landscapes and seascapes (e.g., Booth et al., 2018; LaHusen et al., 2020; Hilley et al., 2020). For example, in Cascadia, where a significant portion of the landscape has been imaged at high resolution (e.g., Oregon Department of Geology and Mineral Industries, Puget Sound Lidar Consortium), recent work to correlate landslide surface roughness with event age (e.g., LaHusen et al., 2016) enabled researchers to develop landslide inventories based on geomorphic criteria and to test the extent to which climatic changes (e.g., Booth et al., 2018) or ground shaking (e.g., LaHusen et al., 2020) have contributed to changes in landslide abundance. These long-term archives of landslide age and distribution are essential to understanding how solid Earth and atmospheric events mobilize mass across Earth's surface. Yet, only small segments of subduction zone landscapes, where variations in forcing factors may be subtle, have been characterized to date. Newly collected bathymetry and sediment cores may make analogous techniques applicable offshore (e.g., Hill et al., 2020), helping to elucidate the extent of slip on recent megathrust ruptures and to discriminate marine turbidites created during shaking from other triggering mechanisms. Similarly, new analyses of drainage basin morphology shed light on linkages between the subduction zone earthquake cycle and the development of forearc topography (Penserini et al., 2017; Gallen & Wegmann, 2017; Gallen & Fernández-Blanco, 2021), which is directly applicable to testing the subduction zone energy budget. Likewise, new approaches that link surface deformations, coastal and offshore geometry, and interseismic coupling (e.g., Saillard et al., 2017) would leverage existing data to provide an expanded and holistic view of the subduction zone energy budget.

Additionally, modern geodetic techniques such as InSAR can reveal centimeter-scale surface deformation that can provide further insight into crustal deformation during different phases of earthquake cycles, volcanic unrest, landslides, and anthropogenic disturbance (e.g., Bürgmann et al., 2000; Avouac, 2015; Shirzaei et al., 2016; Murray & Lohman, 2017; Handwerger et al., 2019). A holistic view of high-resolution surface change across a subduction zone landscape remains elusive, but the data exist to create a community dataset for monitoring regional surface change (e.g.,

InSAR Norway). Geochronology can provide insight into longer-term rates and patterns of deformation and erosion within subduction systems. For example, cooling-driven exhumation recorded by thermochronology has been used to identify the timing of subduction initiation (e.g., Thomson et al., 1998; Sutherland et al., 2009; Schoettle-Greene et al., 2020) and geodynamically significant events such as subduction of seamounts, spreading ridges, or extrusion and oceanward migration of a slab (e.g., Villagómez and Spikings, 2013; Stevens Goddard & Fosdick, 2019). Luminescence and 10Be surface exposure dating of differentially uplifted marine terraces and shorelines places limits on the timing and rates of subduction zone uplift and active tectonics within the upper plate (e.g., Saillard et al., 2011; Gallen et al., 2014; Binnie et al., 2016; Ott et al., 2019a), while catchment-wide erosion rates from detrital cosmogenic radionuclides allow an estimation of landscape evolution and erosional response to such subduction-driven uplift (e.g., Olivetti et al., 2012; Ott et al., 2019b). Geochronology data such as these are essential for understanding aspects of all proposed hypotheses for SZ4D landscapes and seascapes, from direct observations of surface disturbance and sediment flux to time-evolving boundary conditions for magmatic and tectonic deformation models. Yet, at present, these data are generally limited to individual studies and specialized researchers.

In the context of achieving SZ4D's immediate science goals, modeling studies serve two important purposes. First, models can link various subduction zone processes to one another, elucidating key feedbacks that crosscut the three working groups. For example, in the case of studies situated in extensional systems, models have been used to directly quantify the changes in energy that accompany the creation and destruction of topography. Redistribution of sediment through erosional and depositional processes diminishes body forces in some regions (surface uplift) while increasing loads in others (surface lowering) (e.g., Fuller et al., 2006). Moreover, arc magmatic processes build topography and impact climate while creating impulsive loads on existing topography (e.g., Lee et al., 2015). Simultaneously, magmatism modifies the chemical reactivity of surface rocks, sediment distribution pathways, and underlying crustal rheology. These numerical models have been used to link seemingly disparate observables to one another, such as erosional efficiency to the localization of deformation. For example, models have shown that more erosive conditions localize deformation onto fewer, longer-lived normal faults, while inefficient erosion tends to distribute the strain across many faults with little offset (e.g., Olive et al., 2014). Further, models have associated the location of eruptions in rifts with the creation of rift valley topography (e.g., Maccaferri et al., 2014). Similar models can be readily developed for subduction systems to gain insight into links between solid Earth processes, climate, rock lithology, lithospheric rheology, and magmatism - all of which are central components of the subduction zone energy budget.

SITE EVALUATION

The L&S working group conducted an evaluation of site characteristics to identify those subduction zones that offer conditions to carry out the notional experiments. We evaluated subduction zone segments in steps. First, we performed a comprehensive review of different subduction zone segments, which were defined to achieve roughly equivalent along-strike dimensions (~200–400 km) where tectonic, geologic, and climatic parameters might be viewed

as approximately constant (**Table A-LS2**). We then used an "advocacy" approach, in which working- and interest-group members familiar with these areas summarized the properties of these different subduction zone segments. Importantly, we reviewed both scientific and logistical aspects when considering site appropriateness. In a second step, the working group identified segments that would be problematic for study by the L&S community, either because of a lack of essential attributes or logistical factors that would prevent safe access to those areas. In a third step, we mapped our notional experiments onto sets of these subduction zone segments to determine those groupings that might be used to perform "quasi-controlled" experiments in which many properties were regarded as approximately equivalent, while a limited number of others varied. This process helped to identify a number of combinations of subduction zone segments that appeared to meet the design of the notional experiments.

The group determined **four essential site characteristics** required to carry out our notional experiments and hypothesis testing.

- **First**, at least some proportion of the site must include subaerial forearc exposure (free of ice).
- **Second**, observational constraints must exist or be acquirable at suitable sites. (These observations are described and ranked in the section on **Traceability of the Scientific Questions Through Practical Activities**).
- **Third**, we require at least some portion of the site to include rocks with minerals amenable to geochronology and thermochronology such as quartz, apatite, and zircon.
- **Fourth**, we require that safe access to the study area is at least possible, and that particularities of data release within individual countries do not preclude open export and publishing of data and research results.

In our final step, we discussed the remaining subduction zone segments to identify pairs that might make favorable comparisons and that would allow us to conduct some form of the notional experiments. Although not included among the currently discussed SZ4D focus regions of Chile, Cascadia, and Alaska, we note some of these below either as pairings to segments of these focus regions or independently, as they may be viable for smaller-scale PI-driven notional experiments (e.g., the Hikurangi subduction zone; **Table A-LS2**).

We identified several interesting pairings of the Cascadia subduction zone with other subduction zone segments, particularly Chile. Cascadia is an accretionary margin that experiences large, megathrust ruptures and is situated in a temperate climate. The topography of the subduction zone system lends itself to producing significant orography - an attribute that was of interest to many in the working group. **An ideal first comparison to Cascadia might be the Central Hellenic subduction zone**, which exhibits similar rates of convergence, but whose megathrust largely creeps aseismically and whose forearc is actively extending. The hot summer Mediterranean climate and widespread exposure of carbonates contrast with the climate of, and rock types exposed within, Cascadia. Thus, while their convergence rates are similar, rupture behavior, forearc stresses, climate, and exposed lithology are not. While it was acknowledged that the lack of control on many factors may confound simple application

of the notional experimental framework, there was a sentiment that such a comparison might provide insight into our key research questions. **An ideal second comparison with Cascadia might be made with the Maule-Valdivia segment of the Andean subduction zone**. Here, the two segments share many similar characteristics, including climate, physiography of the arc, the generation of large subduction zone earthquakes, the degree of coupling of the subduction megathrust, and in some areas, the presence of a young downgoing oceanic slab. Yet, the rate of convergence along the Maule-Valdivia segment is far higher than the Cascadia subduction zone, which allows us to systematically vary the time of impacting solid Earth versus atmospheric processes (Research Question 1) by comparing these two segments. Additionally, the rate of energy added to the upper plate due to frictional coupling along the megathrust is likely higher in the Maule-Valdivia segment, which provides a systematic manipulation of the energy inputs into the subduction zone system between these two cases (Research Question 2). **The Central Hellenic subduction zone** exhibits similar rates of convergence to Cascadia but differs in its rupture behavior (its megathrust largely creeps aseismically), forearc stresses (it's actively extending), climate (hot Mediterranean), and exposed lithology (carbonate). While these differences may confound simple application of the notional experimental framework, there was a sentiment that such a comparison might provide insight into aspects of our key research questions.

Another pair of subduction-zone segments that might be compared include the Alaskan (mainland) subduction zone and the Austral Andes. Both of these segments are located in high-latitude areas, where glacial erosion is a central landscape feature. Both have a component of trench-parallel motion, which partitions upper plate strain. However, convergence rates along the Alaska subduction zone segment are far greater than the Austral Andes, allowing a systematic variation of convergence rate, which impacts landscape processes (Research Question 1) and the energy budget of the subduction zone system (Research Question 2). There may be additional utility in the Alaska subduction zone system in this comparison, as systematic, along-strike differences in the nature of the subducted material vary along strike, which could alter the normal tractions acting along the base of the upper plate due to differences in the buoyancy of the subducting material. Logistical challenges in both these segments include poor infrastructure and limited field seasons, which would increase costs and require more time and human resources.

Segments along the Andean margin provide a unique opportunity to control for and vary many factors related to both our research questions. The climates along the Andean forearc are controlled by macroscale atmospheric and ocean circulation, which sets up large climate differences along the subduction zone segments. The scale of the subduction zone segments is large enough to discriminate the effects of individual rupture segments and boundaries of climate systems from one another. For example, comparisons between the Ecuadorian, Arica, and Maule-Valdivia segments control for tectonic geometries, but allow variations in climate to be explored, which affects delivery of sediment to the subduction trench. Comparisons between the Arica and Pampean segments allow climate to be held fixed, while tectonic geometry could be studied. Comparisons between some parts of the Peruvian and Pampean segments might allow climate to vary in flat-slab subduction areas.

In general, the group noted that there are "gradients upon gradients" within the larger Andean subduction system, which provide a rich opportunity to build a substantial number of notional experiments.

A smaller-scale PI-driven experiment outside these regions, but that pairs with the Pampean segment in Chile, would compare it with the Peruvian segment of the Andean margin, both of which involve flat-slab subduction but have different climates. Other paired systems considered potentially fruitful include the Nankai and Cocos-Panama subduction (in the area of northern Costa Rica), where convergence rates are broadly similar, but the thickness of sediment entering the trench varies systematically between the two systems. In Nankai, the thick sedimentary section is associated with active accretion of the margin, whereas the sediment-starved Cocos Plate is not and appears to have fundamentally different upper-plate deformation kinematics. These two contrasting situations likely alter the energy budget between these subduction zones as the transfer of mass from the downgoing slab to the upper plate likewise transfers energy to the subduction zone system (Research Question 2).

The L&S working group members noted particular opportunities to draw on the investments of other countries and organizations interested in subduction zone research. For example, there is already a wealth of information from the Nankai, Mediterranean, and Hikurangi subduction zones - setting up cooperative and data-sharing agreements with Japan, the EU, and GNS New Zealand. Thus, while it is clear that the SZ4D will not be active in all of the subduction zone systems our group discussed, partnerships with international organizations have the potential to greatly expand the breadth of scientific discoveries by increasing the number of experiments we might execute.

OUTLINE OF INITIAL PLAN FOR COMMUNITY COORDINATION

The SZ4D initiative provides an exciting opportunity for the Earth surface process community to study subduction zone landscapes and seascapes. Community coordination will be especially important for the success of the L&S component of SZ4D. We regard the community as spanning engaged scientists, institutions, and domestic and international partners collectively invested in SZ4D.

To build this community, we propose a range of SZ4D L&S-level programs to promote community engagement, network building, idea exchange, and ultimately synthesis of results. An international exchange of researchers would be one such program to build capacity and collaboration among host countries. SZ4D-sponsored graduate student and faculty exchanges with international hosting countries would build lasting relationships among the global subduction-zone science community. Additionally, a wealth of information collected by the potential host country of Chile exists - and more exchanges involving international students and senior scientists would help to integrate this prior knowledge-base into SZ4D efforts. A successful international community would require partners to be co-equal investigators with access to educational opportunities for themselves and their students. Similarly, a domestic graduate student exchange program among SZ4D-supported PIs would foster the exchange of ideas and integration of research needed for a successful L&S program. The international and domestic graduate trainee exchange programs would help to coordinate PI and student-level research,

but more importantly, promises to broaden the knowledge base of student participants, expand their professional networks, and jump-start a community of next-generation leaders in subduction zone surface process science. In addition, a structured and coordinated training and exchange program would be able to acknowledge outstanding contributions to subduction zone surface process research. We envision partnering with existing public and private scientific capacity-building programs, such as those sponsored by the USAID Bureau for Humanitarian Assistance, GeoHazards International, and others.

Meetings offer another means of SZ4D L&S community building. We plan to hold annual SZ4D L&S-sponsored international and domestic workshops, webinars, conferences, and field trips to further community development. These events will have topical and planning themes with defined goals. For example, events can serve the purpose of coordinating new, ongoing, and past PI experiments and datasets, identifying new research and infrastructure needs, showcasing new studies and findings, and synthesizing results across disciplinary, organizational, and political boundaries. These events would also provide a platform to organize logistics and assess progress toward the overarching L&S science objectives. The L&S working group sees benefit in a centralized means of facilitating exchange opportunities, developing professional networks, and fostering a new scientific community.

A structure for coordination of community science is necessary to build an engaged network of participating scientists, institutes, and facilities necessary for the execution of scientific priorities, research activities, and data management. We present two end-member potential organizational structures that facilitate the SZ4D L&S notional experiments through PI-driven studies. Both organizational structures aim to maximize transparency, build community consensus on essential scientific targets, and organize PI-driven research and data streams to enable community-wide efforts to allow a successful, comprehensive synthesis of results. One coordination plan involves the identification of overarching scientific priorities needed to achieve the goals of the bigger-picture experiments. Program solicitations would be carefully tailored to stimulate PI-driven research proposals targeting the identified scientific goals. Proposals would be assessed on quality and alignment with the mission forwarded within the specific solicitation and SZ4D more broadly. The goal would be to foster a PI-driven ecosystem of science and data generation and sharing that produces the building blocks needed to realize the broader notational experiments. An alternative organizational structure focuses on building a scientific advisory group with the task of finding a consensus of scientific targets that drive decision-making and study design to ensure that each essential component of the experiment is completed. This model differs from the last in that program targets are more specific, and a broader community is engaged in building consensus on incremental science targets. In this case, the science would still be PI-driven, but program directives would be more tightly tethered to objectives defined by the community. Such a community-driven advisory structure might allow adaptation to emerging SZ4D questions and continual alignment of the investigations around community-driven science priorities.

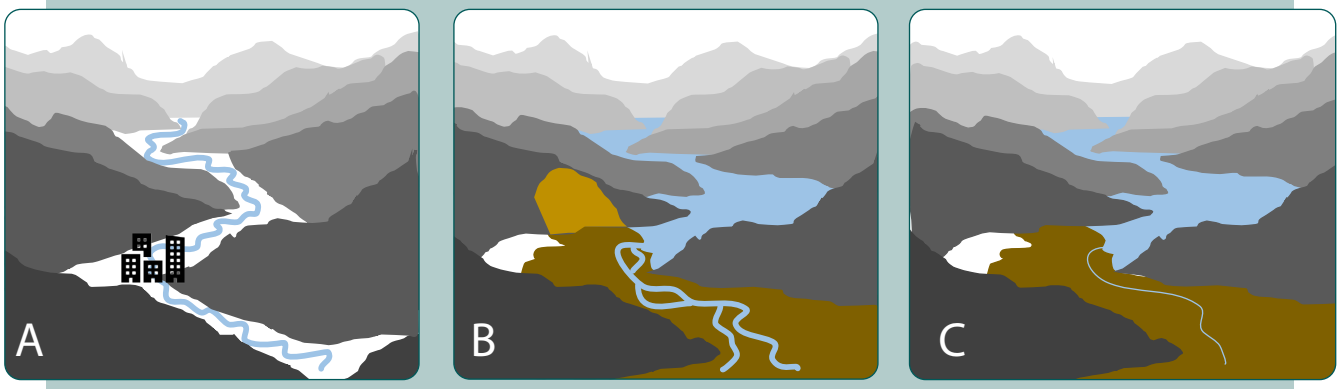
To be able to simulate subduction systems, community coordination is needed for the development, implementation, and maintenance

of large-scale technological, data acquisition, and modeling infrastructure and for analytical facility support and access. Many Tier 1 L&S SATM measurements involve terrestrial and submarine remote-sensing surveys (drones, airplanes, and satellites) with large spatial footprints. Additionally, the SurfArray ESN will require substantial facilities support to deploy, maintain, and manage data from this instrument network. These data streams require partnerships with and support for existing facilities that maintain the available expertise, equipment, and infrastructural capabilities. In some cases, these capabilities and data already exist or will soon be available (e.g., NASA-ISRO NISAR, ESA Copernicus Sentinel missions, commercial high-resolution imagery), and SZ4D partnerships could serve to facilitate and streamline data access. In other cases, data and infrastructure exist that assist in maintaining data streams, but additional SZ4D support will help expand the existing capabilities to handle the needs of L&S (e.g., USGS, OpenTopography, NASA Earthdata, IRIS, UNAVCO, CUAHSI). Finally, new technological developments and associated infrastructure are needed to integrate generated datasets across the subduction zone landscapes and seascapes (e.g., seamless merging of new and existing topographic and bathymetric data) that can be developed and maintained by partnering with existing facilities and/or by forming new organizational units within SZ4D.

Analytical data (e.g., geochronology), must be acquired and synthesized to test L&S hypotheses. Unlike many of the large, centralized data facilities that can be used to process and archive remote-sensing data, geochronologic facilities are numerous and somewhat heterogeneous in their instrumentation and protocols. Thus, SZ4D will need a vehicle to allow individual PIs engaged in SZ4D investigations to access these heterogeneous facilities in a way that maintains consistent data quality through the adoption of common protocols and standardization. We suggest drawing and expanding on existing NSF investments in EarthCube to ensure that results are comparable across labs and subduction zone segments. Through SZ4D coordination between modelers, field scientists, and geochronologists, key modeling needs will be identified and new capabilities generated for hypothesis testing using coupled subduction system models. Central to this effort is coordination and collaboration with SZ4D-MCS to help identify key science targets and modeling needs to meet L&S research objectives. Furthermore, this process can benefit from the existing groundwork for coupled surface process-geodynamic numerical model development and infrastructure provided by NSF-sponsored organizations such as the CSDMS and the CIG. Collaborations between these organizations have already led to the development of new infrastructure that is capable of more easily coupling geodynamic and Earth surface process models. L&S would ideally collaborate and integrate with these existing efforts and help inspire new modeling efforts and capabilities.

SIDEBAR 4

Landslides and cascading downstream impacts



Large seismically, climatically, or volcanically triggered landslides in mountainous watersheds commonly set off a cascade of downstream hazards (e.g., Pierson and Major, 2014; Fan et al., 2018). Long runout debris flows and avalanches destroy infrastructure far from the slope failure (**Figure S4-1A, B**)(e.g., Voight, 1990; Wartman et al., 2016), and where they encounter lakes or reservoirs produce catastrophic tsunamis (e.g., Genevois and Ghirotti, 2005; Wiles and Calkin, 1992). Landslides frequently produce dams that impound water for days to months after a landslide (**Figure S4-1B**), unleashing massive floods upon gravitational failure (**Figure S4-1C**)(e.g., Costa and Schuster, 1988). Landslides can also reroute rivers through forcing avulsions (**Figure S4-1B**) and inhibit coarse sediment transport, resulting in aggradation of 10's of meters of gravel for kilometers upstream of landslides (e.g., Finnegan et al., 2019), wreaking havoc on infrastructure and ecosystems along the river corridor (e.g., Korup, 2014). Finally, large changes in river elevation through first aggradation and then incision due to the downstream transport of debris can occur for centuries following large landslides (**Figure S4-1A,B,C**)(e.g., Stolle et al., 2019) and can impact communities >100 km away (Sarker et al., 2014).

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MAGMATIC DRIVERS OF ERUPTION

What controls the location of volcanoes and the occurrence of eruptions?

SCIENTIFIC MOTIVATION

Recent observations and innovations are fueling a new decadal effort in studying Magmatic Drivers of Eruption (MDE). Magma pathways in the crust have been observed "lighting up," with increases in seismic events prior to, between, and during eruptions (e.g., Pesicek et al., 2018) and some magma storage regions inflating and subsiding - "breathing" - over the eruption cycle (e.g., Xue et al., 2020). New petrological and geochemical studies have found that magma assembly, transport, and run-up to eruptions occur over timescales from hours to years (Costa, 2021), similar to timescales of observed volcanic unrest. Changes in gas CO_2/SO_2 measured weeks to months prior to eruption (e.g., Aiuppa et al., 2017) provide a possible signal of deep magma recharge and a new precursory data stream to integrate into physics-based forecast models (Shreve et al., 2019). High-resolution geochronology over the lifecycle of volcanoes (~ 500 ka) shows evidence for changes in eruptive behavior that is in pace with glacial cycles (Watt et al. 2013; Aubry et al., 2022).

The SZ4D MDE implementation plan is motivated by scientific discoveries and societal urgency. Globally, almost 800 million people live in regions that are directly exposed to volcanic hazards (Brown et al., 2015), and the vast majority of these regions are in subduction zone settings. The crustal magmatic systems associated with subduction zone volcanism also produce critical mineral and energy resources, as well as drive the formation and evolution of continental crust. The SZ4D initiative builds on the MARGINS, GeoPRISMS, and EarthScope programs, which were highly successful in tracing magmatic volatiles through the subduction process, imaging melt in the crust and mantle, and modeling the thermal structure of subducting slabs and the growth

of the continental crust. The new focus of MDE is on **the initiation of volcanic eruptions at subduction zones**, as we recognize that there are new discoveries to be made that connect the most hazardous volcanoes on the planet today to underlying subduction drivers. Magmas at subduction zones are volatile-rich, and thus inherently different from those in other volcanic settings. Furthermore, subduction zones are responsible for most of the subaerial eruptive activity that occurs each year. Recent work implicates the entire trans-crustal magmatic system (Cashman et al., 2017) and even the mantle in controlling the initiation of eruptions (Grove et al., 2012; Power et al., 2013; Ruprecht and Plank, 2013). Here, we propose to investigate the entire system of controls on volcanic/plutonic behavior in volcanic arcs in four dimensions (**Figure MDE-1**). By focusing on the trans-crustal magmatic system and how it links the mantle melting region above subducting slabs and the magmas and gases emitted at arc volcanoes, SZ4D will provide a fundamentally new perspective on subduction-related volcanic systems, with the goal of identifying subduction drivers and developing long-term forecasts of eruptions.

A central question motivates MDE's envisioned science activities: **How do trans-crustal processes initiate eruptions at arc volcanoes?** The trans-crustal magmatic system is instrumental in controlling eruption initiation and inter-eruptive unrest and quiescence. Processes within the trans-crustal system either prime or initiate volcanic eruptions outright or provide suitable conditions whereby intrusions and/or eruptions can be triggered by external drivers such as earthquakes or edifice collapse.

Additionally, the dynamic processes that govern the evolution of trans-crustal magma systems, including mantle magma production and the partitioning of mass and energy between volcanic and plutonic components along and across volcanic arcs, span wide temporal ranges. While eruptions may occur over short timescales at Earth's surface, their frequency and vigor may be set by processes throughout the crust and that occur over the lifetime of the volcano or longer (**Figure MDE-1**). These trans-crustal processes underpin the internal and external mechanisms that directly initiate eruptions through overpressure, tensile failure, and/or shear failure in the subsurface. These initiation mechanisms also drive eruption style, composition, eruptive volume, unrest behavior, and timescales.

This chapter is structured to follow the process developed by the SZ4D MDE working group, with input from the broader volcanology community to define:

- **Central Hypotheses** that link eruption drivers and responses at subduction zones
- **A Traceability Matrix** that identifies practical activities to support the science questions that arise from the central hypotheses
- **Notional Experiments** that are guided by Traceability Matrix activities and strategies for deployment at arc volcanoes and segments
- **Site Evaluation** that arises from an inventory of arc volcanoes and exhumed systems and the requirements of the hypotheses and notional experiments
- **Activities** that can precede field experiments
- Parallel **Laboratory and Modeling Efforts**
- **Community Coordination**

The Hypothesis Grid

MDE's central question and scientific framework can be articulated most clearly in terms of magmatic system controls and responses (**Table MDE-1**). Our ultimate goals are to identify underlying subduction drivers and develop useful eruption forecasts.

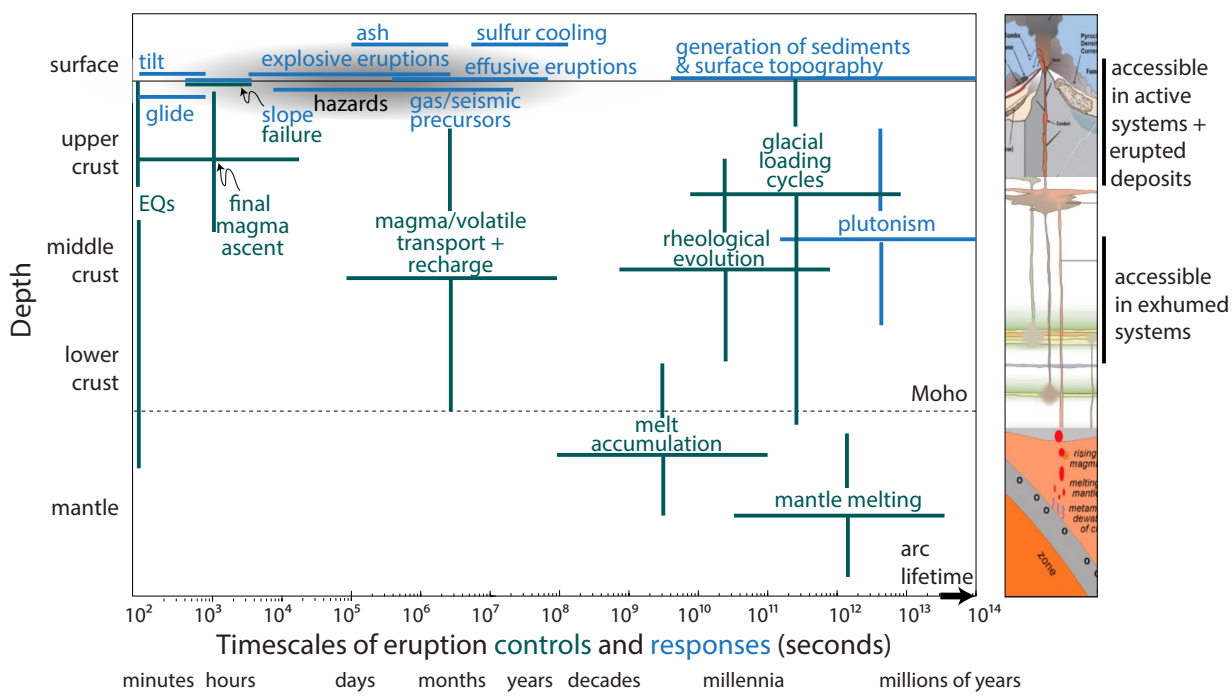
Controls on the magmatic system fall into three broad categories:

1. The supply rates of the magma and volatiles from the mantle to the crust that ultimately fuel all eruptions
2. The volume, depth, and distribution of magma that collectively define a volcano's trans-crustal system
3. The rheology and stress state of magma and surrounding crustal rocks that permit or resist magma movement

System *responses* include consideration of:

1. Eruption precursors and the run-up to eruption
2. Eruption repose, quiescence, and aborted unrest, or intrusion not culminating in eruption, which may lead to plutonism
3. Eruptive style, vigor, and duration - the output of useful forecasts

Figure MDE-1. *Processes across multiple timescales and spanning the trans-crustal magmatic system impact subduction zone hazards near the surface. The goal of MDE research is to connect the volcanic system, the trans-crustal magmatic system, and the subduction system. These systems are typically treated separately, even though they are interrelated. For example, volcanic eruptions may be initiated rapidly by influx of mafic magmas from the mantle wedge. Different trans-crustal magmatic architectures may develop as a response to different mantle magma supply rates. More broadly, arc magmatic systems may respond to and drive FEC and L&S. For example, surface processes such as glacial unloading may lead to greater decompression melting in the mantle and greater eruptive frequency. SZ4D provides the opportunity to test different hypotheses for how subduction processes across a range of timescales - from minutes to millions of years - drive magmatism and volcanism, and the hazards associated with them. The column at right is an amalgamation of three separate cartoons (from the ERUPT report, NASEM, 2017), a reflection of the lack of current integration and the opportunity for SZ4D to make novel connections by drawing on evidence from active volcanoes, erupted deposits, and exhumed arc systems in four dimensions.*



3.3 Magmatic Drivers of Eruption

The response of a magmatic system to each control depends on the state of the magmatic system (volume, depth, and magma/pressure distribution) and the mechanical properties of the host crust (rheology and stress state).

The MDE working group considered how recent findings and methodological developments have led to testable hypotheses, and had the MDE Interest Group vote on how to prioritize the resulting Hypothesis Grid. Importantly, additional hypotheses were solicited, and then groups met to discuss the most compelling and testable hypotheses, as well as synergies between them.

As a result, three main sets of hypotheses were identified:

HYPOTHESIS A | Gas and magma composition are linked to eruption precursors, run-up times, and eruption intensities

HYPOTHESIS B | Mantle magma production and supply rate are linked to the intrusive/extrusive mass budget, crustal residence time, repose time, and the evolution of crustal magmatic architecture

HYPOTHESIS C | The periods and drivers of different external eruption triggers over timescales of minutes to >100,000 years are linked

Table MDE-1. *The MDE Hypothesis Grid. Magmatic system controls and responses define a grid of inquiry and testable hypotheses.*

Magmatic System Controls	Magmatic System Responses		
	Eruption precursors and run-up time	Plutonism, intrusion, and repose	Eruption style, vigor, and duration
Supply Rates: Magma and Volatiles • What controls production rate in the mantle? • What controls recharge rate? • What controls recharge composition? • What controls volatile accumulation?	High CO_2 / S gases weeks to month prior to eruption signal deep recharge *Werner et al. (2020)* Mafic eruptions have shorter intiation times *Kent et al. (2019)*	Intrusive flux is related to extrusive flux *Till et al. (2019)* Mafic eruptions have shorter repose times *Passarelli & Brodsky (2012)*	Slow subduction is correlated with lava domes *Zellmer (2009)* Fast magma ascent results in higher intensity eruptions *Gonnermann & Manga (2012)*
Depth and Distribution of Magma • How does magma travel through the entire crust? • How deep does the volcanic system extend? • Why and where do magmas stall? • What controls storage depths prior to eruption?	Mantle can recharge during an eruption *Ruprecht & Plank (2013)* Slow vanguard ascent and staging of eruptions *Roman & Cashman (2018)* Magma systems shallow due to thermal priming *Gualda et al. (2018)*	Optimal depth of magma chamber growth *Huber et al. (2019)* Plutons focus due to thermal weakening *Ardill (2018)* Magma supply influences reservoir location *Lerner et al. (2020)*	Basaltic Plinian eruptions are sourced from shallow magma systems *Bamber et al. (2020)*
Rheology and Stress State • What controls magma density, viscosity, and volatiles? • What controls crustal rheology? • What controls the stress state of the crust? • What are the roles of slope failure and earthquakes in eruption triggering?	Rheology, tectonic stress, buoyancy control magma stalling depths *Watanabe et al. (1999)* Static stress from M≥7.5 earthquakes < 200 km away can trigger eruptions *Nishimura (2017)*	Silic magma systems have longer repose *Passarelli & Brodsky (2012)* Longer repose -> weakened crust and reduced failure *DeGruyter & Huber (2014)* Large viscous systems require an external trigger *Gregg et al. (2012)*	Extension favors calderas *Wilson et al. (1995)* Microlites growing rapidly and heterogeneously during ascent from shallow storage can cause basaltic Plinian eruptions *Sable et al. (2006)* *Bamber et al. (2020)*

HYPOTHESIS A | Gas and magma composition are linked to eruption precursors, run-up times, and eruption intensities. For example (**Figure MDE-2A**):

- High observed CO_2/SO_2 in gases (weeks to months) prior to eruption signal deep magma recharge (i.e., magma recharge drives eruption run-up time periods).
- Eruptions driven by mafic rejuvenation involve shorter initiation times than felsic rejuvenation.
- The run-up to eruption (over years or the full inter-eruptive period) involves stealth ascent, second boiling (i.e., crystallization-induced gas exsolution), and magmatic evolution to more silicic compositions.
- Outgassing efficiency during magma ascent controls eruptive intensity.

Critical scientific needs to test these hypotheses include: constraints on and models to predict magma recharge rate, especially for mafic magma; precursory time series in gas chemistry and geophysical signals; and measures of outgassing efficiency. Ideally, sensor arrays would capture events prior to, during, and after eruptions of varying intensity on many volcano targets. A large number of targets would be necessary to capture unrest and eruption at volcanoes that span a range of subduction parameters, including the subduction rate of water, sulfur and carbon, magma production rates, and upper plate stress regimes. The relevant timescales of processes are minutes to decades.

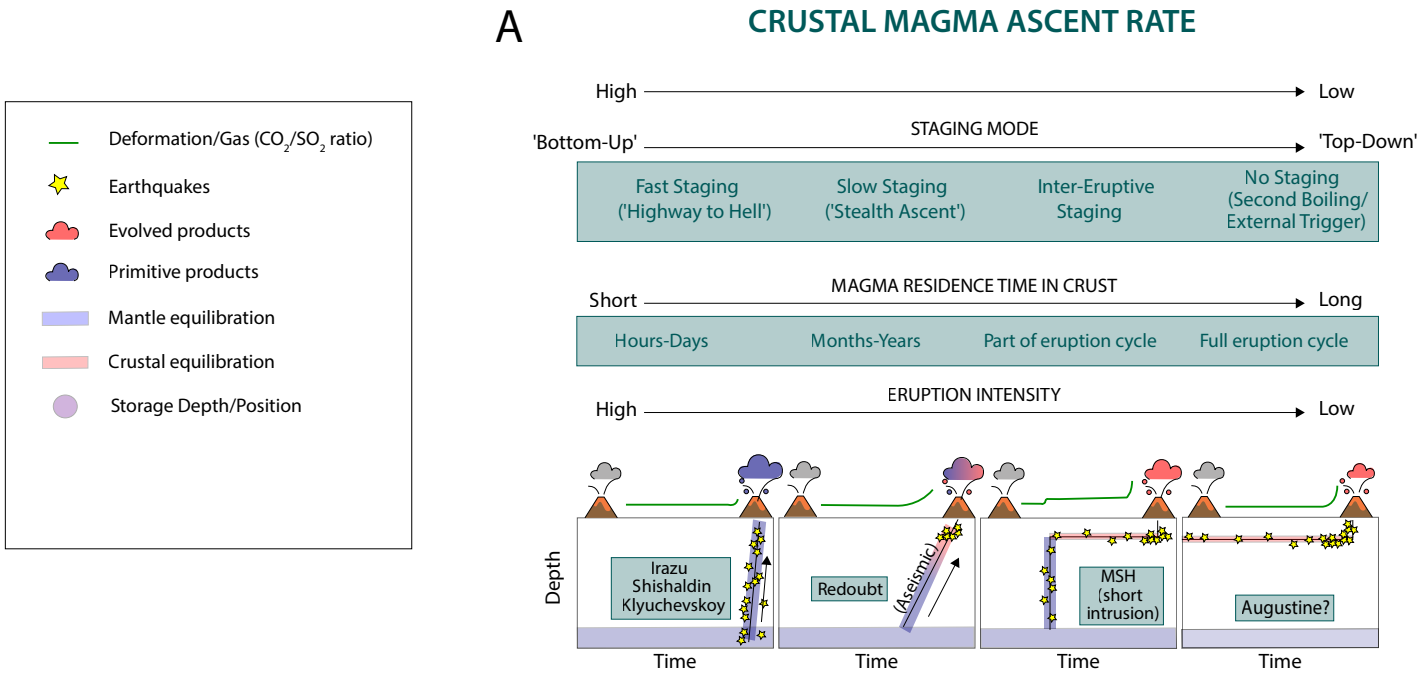
HYPOTHESIS B | Mantle magma production and supply rate are linked to the intrusive/extrusive mass budget, crustal residence time, repose time, and the evolution of crustal magmatic architecture. For example (**Figure MDE-2B**):

- High mantle-derived magmatic flux leads to shallow magma reservoirs and/or long-term progression to shallower storage depths (i.e., the "crustal ladder").
- Short magmatic crustal residence times (from the mantle to the surface in days to months) lead to high intensity, mafic eruptions.
- Mantle magma supply rate is related to subduction drivers (convergence rate, composition, temperature, and angle of the subducting plate) as well as to the state of the mantle in the wedge, ultimately connecting the structure and evolution of the trans-crustal magmatic system to underlying subduction drivers.

In order to test these hypotheses, key actions need to first be taken, including conducting high-resolution geophysical imaging of trans-crustal magmatic systems, detailed mapping and geochemical analyses of past erupted rocks, laboratory experiments, and studies of exhumed plutonic and volcanic systems on a small number of well-chosen systems that are densely instrumented and comprehensively studied for their magmatic histories. Assimilation of these various data streams within coupled thermal and mechanical models of magma intrusion and accumulation in the crust is critical to understanding the processes that control intrusive-extrusive magma partitioning over timescales of years to millions of years.

HYPOTHESIS C | The periods and drivers of different external eruption triggers over timescales of minutes to >100,000 years are linked. For example:

- Glacial unloading is an external trigger



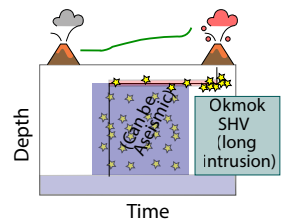
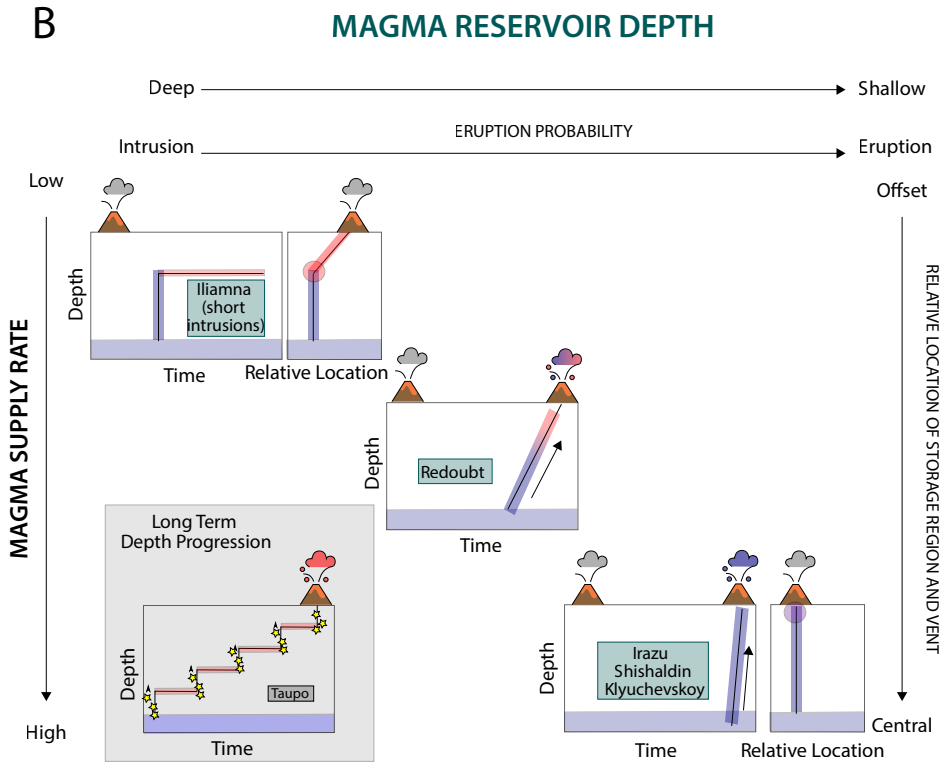


Figure MDE-2. *(A) Graphical summary of Hypothesis Set A, linking crustal ascent rate (left) to crustal staging, residence time and eruption intensity; (B) Graphical summary of Hypothesis Set B, linking mantle magma supply rate (right) to magma reservoir depth and eruption vs intrusion likelihood.*



that occurs over ~10,000–100,000 year timescales.

- Sector collapse can result from hydrothermal alteration of edifice rocks (hundreds of years) or dome growth (months).
- Static and dynamic stress triggering, as from local or teleseismic earthquakes, occurs over hours to seconds, but also requires a magmatic system that has evolved over years toward failure.

Critical scientific needs to test these hypotheses include:

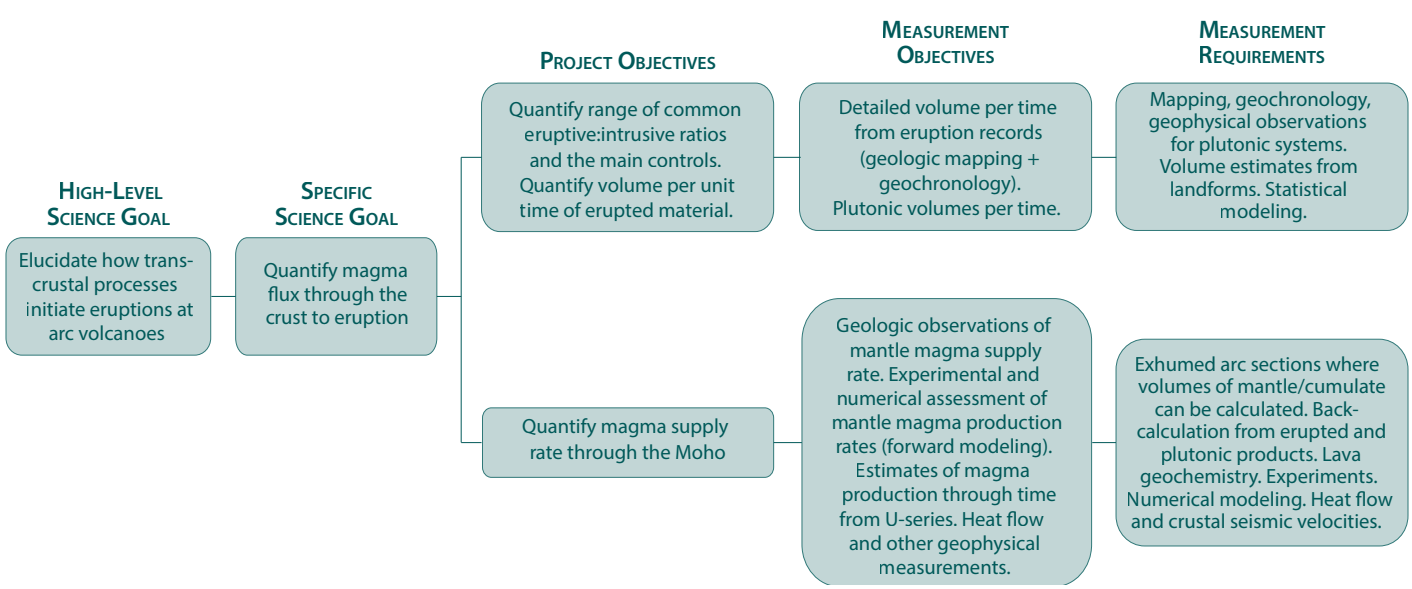
- seismic time series over the shortest timescales;
- geodetic and gas chemistry time series over medium timescales;
- and landscape, geological, petrological, and geochronological studies over the longest timescales.

Furthermore, modeling studies and analog experiments representing a wide range of timescales would constrain the effects of different crustal and magma rheologies and the dynamics of mechanical and thermal evolution. We note that this is an opportunistic hypothesis set, dependent on the nature of activity in the target region(s) during the deployment period in the case of medium- to short-range external triggers. However, as it draws on the same observations required to address Hypothesis Sets A and B, it requires minimal additional observational effort while providing key potential linkages to crosscutting themes and FEC and L&S science goals.

TRACEABILITY OF THE SCIENTIFIC QUESTIONS THROUGH PRACTICAL ACTIVITIES TO ADDRESS HYPOTHESES

The SZ4D MDE working group utilized a *Traceability Matrix* to outline how the three sets of hypotheses will be tested. The traceability matrix provides a logical framework for relating science goals, project objectives,

Figure MDE-3. *Example from the traceability matrix showing how science goals can be related to specific measurements from a variety of disciplines.*



specific measurements, and data products. This approach is useful for identifying linkages between the primary MDE hypotheses. The traceability matrix also provides an efficient way of identifying where datasets from different disciplines should be integrated. **Figure MDE-3** provides an example from the *Traceability Matrix* of how it can be utilized to connect science goals to data collection.

NOTIONAL EXPERIMENTS: INSTRUMENTAL, REMOTE SENSING, AND GEOLOGICAL EFFORTS

The science goals and measurements defined by the *Traceability Matrix* allow us to develop a set of Notional Experiments involving instrument arrays and remote-sensing observations aimed at addressing the key MDE hypotheses. Observations required to address Hypothesis Set A, such as CO_2/SO_2 in volcanic gas emissions and the number and rate of seismic events and locations, can be collected with smaller arrays of instruments (**Volcano Sensor Arrays**, **Figure MDE-4A**) and are thus feasible at a larger number of systems. Thus, for example, a hypothesized relationship between outgassing efficiency and eruption intensity can be targeted with sparse instrument deployments (e.g., seismometers, acoustic sensors, MultiGas sensors, differential optical absorption spectrometers [DOAS], Global Navigation Satellite System [GNSS] receivers), and geochemical and geological studies of recent eruptive products, coupled with a program of **Volcano Remote Sensing**, at a large number of systems that are likely to erupt within the coming decade. In conjunction with these activities, **Volcano Rapid Response Arrays** will enable the flexibility to deploy instrumentation and conduct geologic sampling on volcanoes that erupt or exhibit unrest and have the potential to address science questions.

In contrast, observations required to address Hypothesis Set B include high-resolution geophysical images of trans-crustal magmatic systems, detailed mapping/sampling and geochemical analysis of past erupted rocks, and a detailed understanding of the state of the stress regime, thickness, and thermal maturity of the crust for systems that form in response to a range of mantle magma supply rates (Katz et al., 2022). Thus, tests of Hypothesis Set B will come from detailed observations on the volume and distribution of magma accumulation, along with a complete record of eruption frequencies and volumes from the geological record (see **Exhumed Systems and Their Past Eruptive Records**).

This challenging set of observations requires dense instrumentation arrays that will only be feasible to deploy on a few carefully chosen systems (**Volcano Imaging Arrays**, **Figure MDE-4B**). Volcano remote sensing observations and modeling of, for example, deformation may also help to constrain the distribution and volume of magma accumulation.

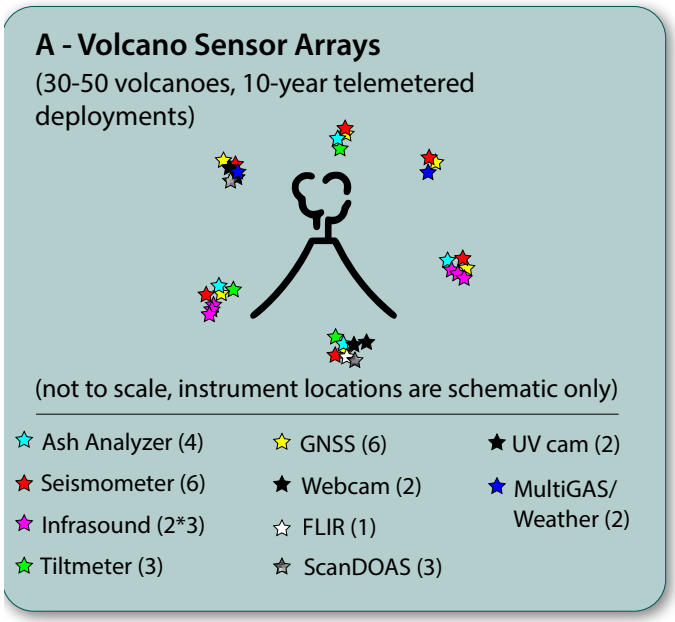
Taken together, the Volcano Sensor Arrays, Volcano Imaging Arrays, Rapid Response Arrays, and Remote Sensing observations comprise the complete **VolcArray** needed to address the three main sets of hypotheses (**Figure MDE-4**) in combination with geological, experimental, and modeling work.

Volcano Sensor Arrays

Targeted hypotheses: A and C

Proposed experiments

To investigate some hypotheses requires relatively sparse instrumentation for characterization



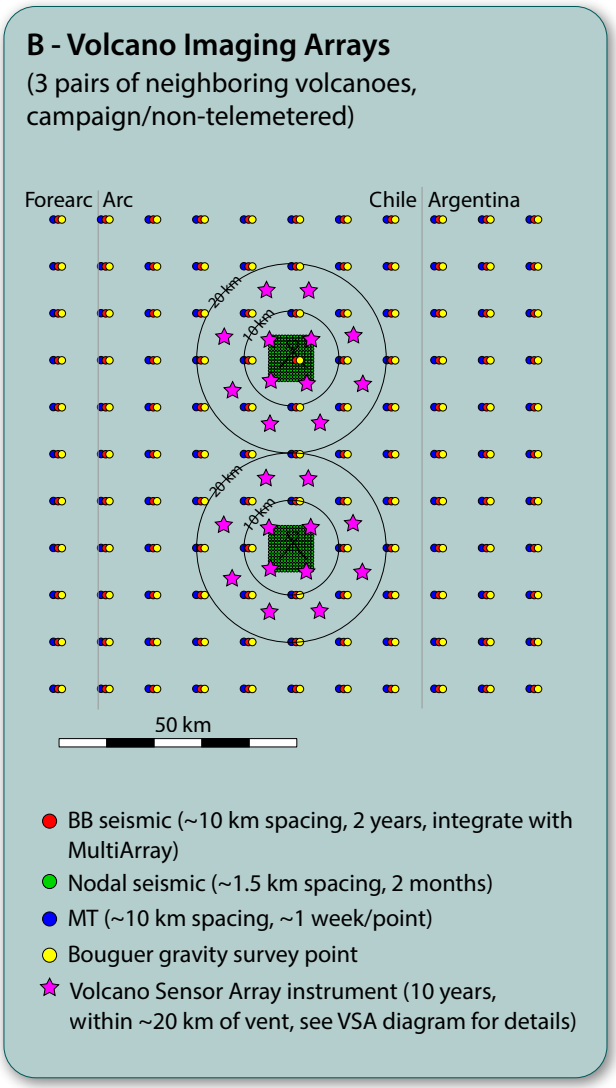


Figure MDE-4. *Schematic of VolcArray. Left panel: Schematic of the Volcano Sensor Array (VSA). Data collected by the array will be complemented with remote sensing observations, rapid response deployments, and a petrologic study of eruptive products produced during the deployment period. Right panel: Schematic of the Volcano Imaging Array (VIA). Data collected by the array will be complemented with remote sensing observations, an in-depth study of past eruption products, and quantification of mantle magma supply. Note VIAs will be co-deployed on a small number of the systems hosting VSAs.*

of unrest during various phases of the eruption cycle (**Volcano Sensor Arrays**), combined with geochemical and geological studies of eruptive products from the observation period. Such deployments are feasible at a relatively large number of systems, likely to erupt within the coming decade. The overarching goals of these experiments are to understand how gas and magma composition are linked to eruption precursors, run-up times, and eruption intensities.

ACTIVITY 1 | Instrument and remotely sense a set of restless (i.e., currently exhibiting seismicity, deformation, or degassing) or potentially active arc volcanoes with visual, thermal, gas, seismic/acoustic, and geodetic monitoring equipment to observe the evolution of the data collected in near-real time, from background state through run-up to and syn-eruption.

ACTIVITY 2 | At the same volcanoes, conduct a petrological examination of erupted rocks in order to determine the cause (e.g., mafic rejuvenation) and - using diffusion chronometry - timing of the eruption initiation event.

ACTIVITY 3 | Compare the results of both sets of studies (Parts 1 & 2), in addition to any regional seismic studies from the FEC working group, to determine whether the hypothesized correlation exists between the recorded gas and geophysical signals and the petrological timing of the eruption-initiation events.

ACTIVITY 4 | Systematically compare petrological/textural and geophysical determinations of magma storage depth and ascent rate for each event with extrusion rate and eruptive styles monitored at the vent.

ACTIVITY 5 | Develop physical models that can assimilate these different datasets (from Activities 1–4) to investigate magma transport processes to forecast eruptions. The observations from Parts 1–4 will also provide the opportunity to investigate the effects of external triggers (Hypothesis Set C) on processes at multiple timescales in magmatic and hydrothermal systems.

SCOPE | We propose to deploy a large number (30–50) of **Volcano Sensor Arrays** to observe volcanoes at different stages of their eruption cycle. The chosen volcanoes should also have different recharge magma chemistries (including mafic) and different eruptive styles. The proposed number of target volcanoes is based on the following analyses. First, if we had deployed **Volcano Sensor Arrays** at all 99 volcanoes worldwide that were degassing (Carn et al., 2017) or deforming (Furtney et al., 2018; Reath et al., 2020) over a 10-year period between 2000 and 2020, we would have observed ~30 full eruption cycles and characterized multiple eruptions that followed repose periods of one to eight years and had a Volcanic Explosivity Index (VEI; Newhall and Self, 1982) of 0–4 (**Figures MDE-5 and MDE-6A, B**). While the probability of capturing a VEI 4+ eruption during a 10-year deployment is low, should such an eruption occur, **Rapid Response Arrays** would enable rapid deployment as the eruption evolves. With 30 to 50 **Sensor Arrays** focused regionally in the Americas, we estimate a probability of ≥0.8 in "capturing and characterizing" approximately ten eruptions in a 10-year period (**Figure MDE-6**). Given the large number of proposed targets, **Volcano Sensor Arrays** could potentially be deployed incrementally, focusing first on a few volcanoes in geographic proximity to the systems chosen for **Volcano Imaging Arrays** and expanding progressively to cover all 30 to 50 target volcanoes.

Expected outcomes

1. We expect to directly characterize the relationship between magmatic processes (e.g., mafic rejuvenation) and associated gas emissions and/or geophysical signals (e.g., deformation). This would enable real-time interpretation of volcanic gas signals during future volcanic unrest, critically improving forecasting abilities.
2. We expect to establish a correlation between mafic rejuvenation as a driver of eruptions and the characteristic timescales over which it initiates eruptions.
3. We expect to identify the critical thresholds in outgassing efficiency and magma ascent rate that correspond to different eruptive behaviors.
4. We expect that any correlation between local and regional seismicity, deformation, and changes in degassing and volcanic seismicity will permit differentiation between external (stress changes on magmatic systems) and internal triggering mechanisms (mafic rejuvenation, or changes in magmatic pressure).

Volcano Imaging Arrays

Targeted hypotheses: B and C

Proposed experiments

To investigate some hypotheses requires dense instrumentation for high-resolution geophysical

imaging (Volcano Imaging Arrays), combined with detailed mapping and sampling studies. Deployments are only feasible at a handful of selected volcanoes that represent a potential range of mantle magma supply rates. The overarching goals of these experiments are to quantify magma supply rates from the mantle, the geometry of the trans-crustal magmatic system, and eruptive histories. Therefore, these systems do not need to erupt during the duration of the Volcano Imaging Array deployment, although Volcano Sensor Arrays will also be in place on volcanoes targeted for imaging for opportunistic study in case of eruption or unrest.

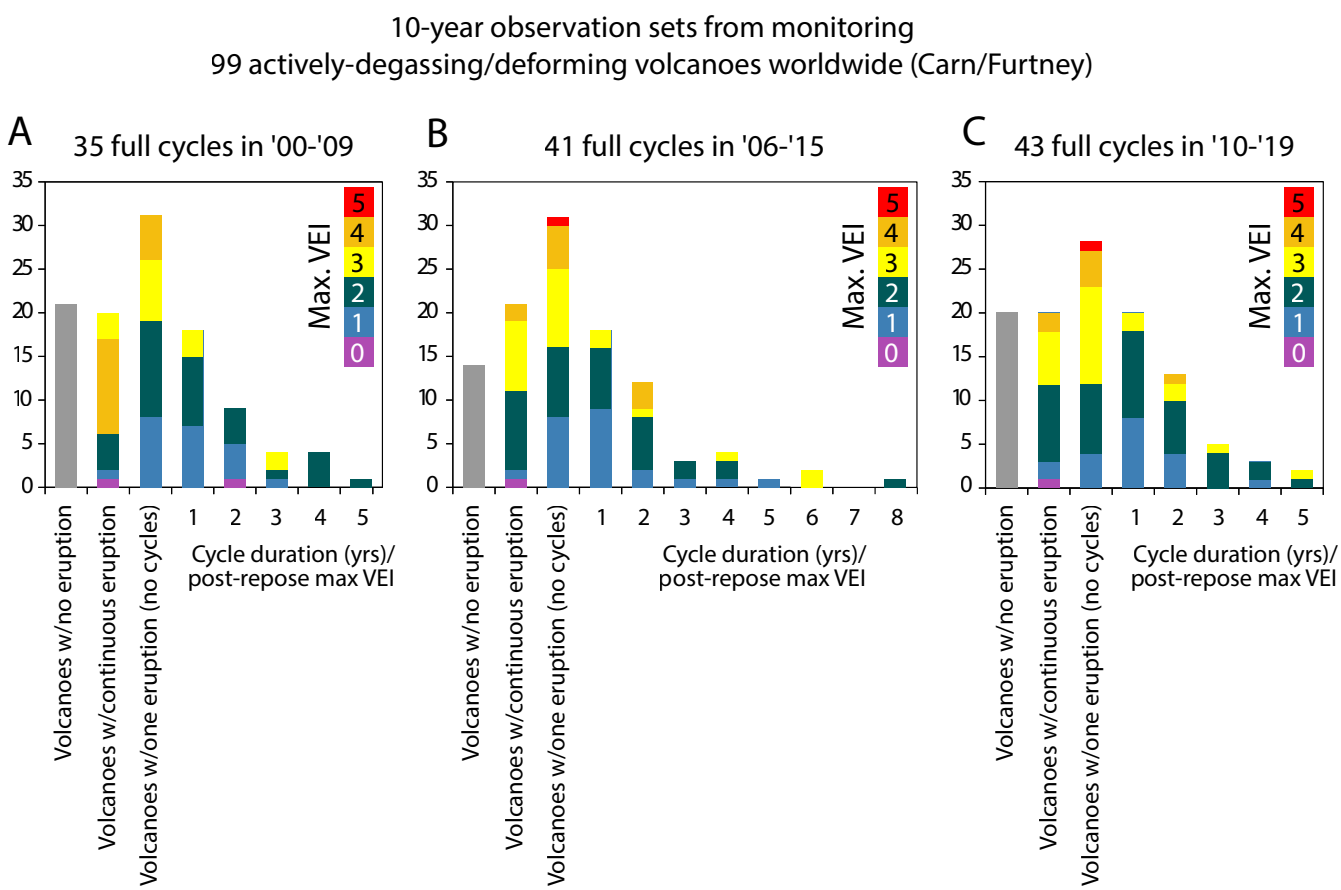
ACTIVITY 1 | Collect data that will provide constraints on mantle magma supply rate from ^3He and CO_2 flux campaigns and heat flow.

ACTIVITY 2 | Conduct extended mapping surveys and sampling of eruptive products to estimate volumes, eruption history and explosivity, and to identify parental melt compositions through geochronological, geochemical, and petrological studies.

ACTIVITY 3 | Conduct geothermobarometry and textural studies of eruptive products to constrain magma pressure, temperature, and physical properties, including timing of magma recharge.

ACTIVITY 4 | Collect images of the magma system and crustal properties along with dense observations for seismic tomography, magnetotellurics (MT), and gravimetry.

Figure MDE-5. *"Best-case scenario" for observations of eruption with Volcano Sensor Arrays. Each plot characterizes eruptive activity at these 99 volcanoes within a 10-year period (A) 2000–2009; (B) 2006–2015; (C) 2010-2019), coded by maximum VEI and repose period (cycle duration).*



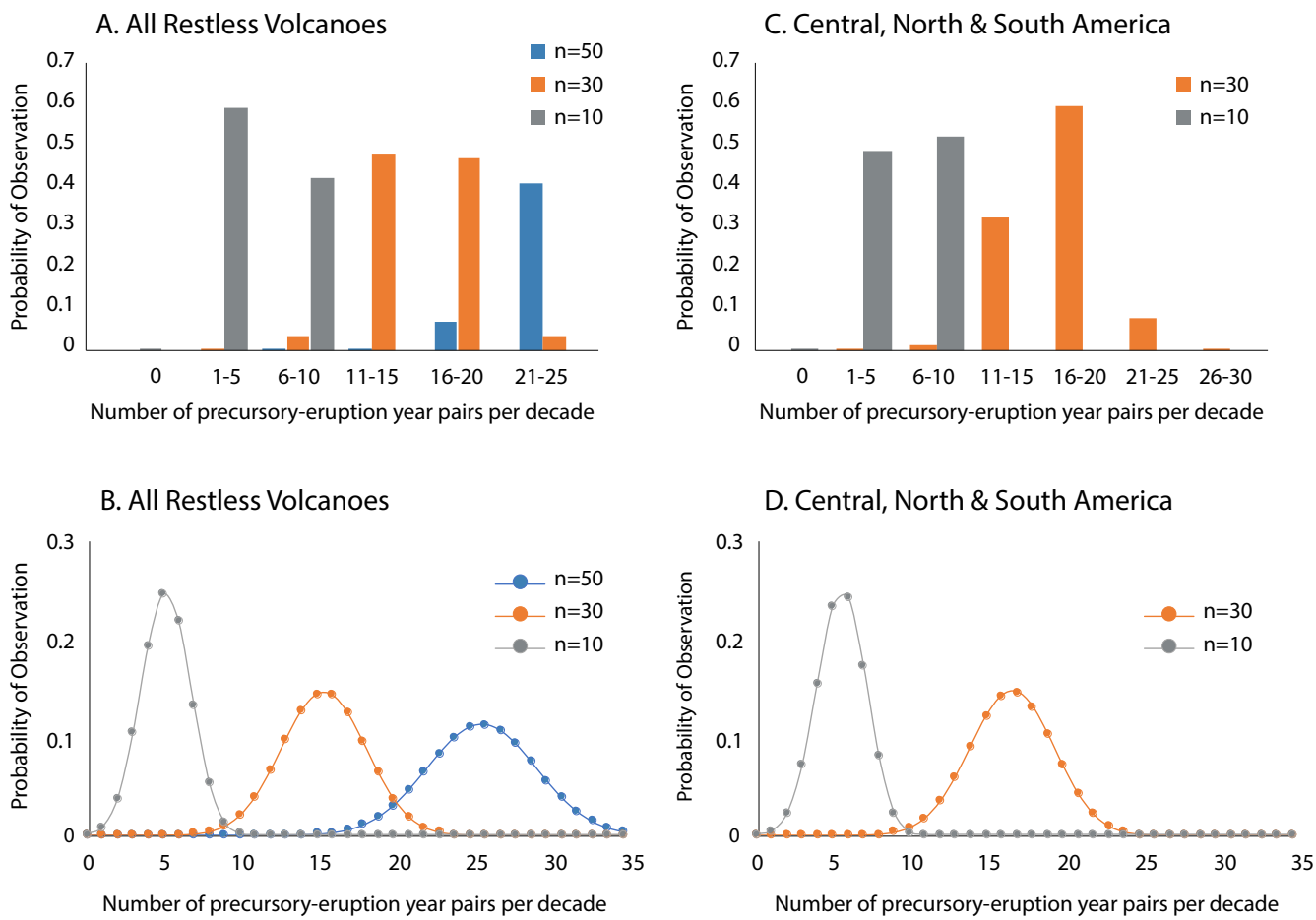


Figure MDE-6. *Calculated probabilities for n = 10, 30, and 50 Volcano Sensor Arrays observing eruption cycles for the 99 identified restless volcanoes, and n = 10 and 30 for a subset of these from North, South, and Central America (36 volcanoes). Probabilities were determined using observed eruption behavior for the 99 restless volcanoes in Carn et al. (2017) and Furtney et al. (2018) based on the decade 2000–2009. A precursory-eruption year pair is defined as a year without an eruption followed by a year with at least one eruption during this decade (such that both precursors and the eruption would be observed with the Volcano Sensor Arrays). Some volcanoes show more than one eruption cycle in this decade. Calculations use the binomial theorem for observational arrays of n = 10, 30, and 50 volcanoes. Probabilities for all restless volcanoes determined as P = (number of observed volcanoes that had ≥1 precursory-eruption year pair in the 2000–2009 decade)/(total number of volcanoes) for all volcanoes, or for the subset of volcanoes in North, South, and Central America. This is 51/99 volcanoes for the entire set of restless volcanoes and 25/36 volcanoes for North, South, and Central America. Results are shown individually for each number of eruption cycles in (B) and (D) and binned into groups of five (A) and (C).*

ACTIVITY 5 | Collect terrestrial and satellite geodetic measurements (e.g., NISAR) of deformation induced by the magma system as well as temporal changes in gravity. Activity 6. Investigate changes in seismic rate and event location. The geophysical imaging methods should be designed for observing eruptible magma and exsolved volatiles. This will require investments in instrumentation on nearby volcanic edifices that connect with strategies proposed by the FEC and L&S working groups. The observations from Parts 2–3 will also provide the opportunity to investigate the effects of external eruption triggers (e.g., glacial unloading in Hypothesis Set C) on processes at long timescales.

SCOPE | It will be important to develop experiments in at least three different island arcs: those related to slow, medium, and fast mantle magma supply rates. Furthermore, targeting proximal pairs of stratovolcanoes and nearby monogenetic centers will allow examination of variations in crustal architecture, stress, or composition at constant subduction parameters. Such a strategy could lead to targeting a pair of neighboring volcanoes at three different arcs.

Expected outcomes

1. We expect to quantitatively constrain and contrast the time-averaged and current supply rate of magma into the trans-crustal volcanic system - one of the "holy grails" of volcanology - through multidisciplinary measurements.
2. Detailed geophysical imaging of the subsurface beneath volcanoes should reveal the architecture of the magmatic system, the melt fractions in different regions, and how centralized it is relative to the edifice.
3. We will test hypotheses regarding the relationship between magma supply rate and depth-evolution of magma reservoirs.
4. We will test the relationship between magma crustal residence time and eruption intensity.

Volcano Rapid Response Arrays

Targeted hypotheses: A, B, and C

Given the goal of capturing eruption-related and external triggering phenomena inherent in Hypothesis Sets A and C, a component of the MDE implementation plan will involve rapid response to eruptions or episodes of volcanic unrest in cases when there is potential to make observations of precursory and syn-eruptive behavior, particularly for VEI 4+ eruptions or in response to major potential external triggers (large earthquakes and/or sector slides or collapses). Thus, we envision maintaining strategic caches of **Rapid Response Arrays**, ideally housed in target regions. We also plan to implement a program of routine remote sensing (see section **Remote Sensing Program** below) to detect anomalous gas, thermal emissions, and/or deformation for identifying candidate targets, and to organize protocols for rapid-response ash/lava sampling and analysis. The approaches to the development of the **Rapid Response Arrays** will be informed by the results of the CONVERSE initiative (Fischer et al., 2021).

Remote Sensing Program

Targeted hypotheses: A, B, and C

Hypothesis Sets A, B, and C all require a coordinated program of continuous and opportunistic remote sensing in addition to ground-based observations. Routine satellite observations, such as those from the upcoming NASA-ISRO Synthetic Aperture Radar (NISAR) mission (NISAR, 2018), the TROPOspheric Monitoring Instrument (TROPOMI) on board the Copernicus Sentinel-5 satellite (Theys et al., 2019), and the planned *Surface Biology and Geology (SBG) imaging spectrometer mission*, as well as observations of thermal anomalies from satellite-borne sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites (e.g., Girona et al. 2021), will provide critical information on the state of deformation and degassing at all volcanoes in target regions and will aid in early identification of rapid response targets and potential external triggers such as flank instabilities (e.g., Schaefer et al., 2017). Additional spaceborne instruments, such as the EMIT instrument on the International Space Station that measures mineral composition of wind-blown dust in arid regions, and the Nanosatellite Atmospheric Chemistry Hyperspectral Observation System (NACHOS) Cubesat-hosted prototypes, may also provide useful observations towards MDE goals. Depending on the selected target regions, MDE may develop partnerships with one or more *Geohazard Permanent Supersites* to ensure regular acquisition and processing of critical satellite data. Additionally, campaign or opportunistic airborne (e.g., lidar, aeromagnetics, aerogravity surveys) and drone-based observations can be used to complement ground-based observations in cases where safe summit access is limited.

NOTIONAL EXPERIMENTS: EXHUMED MAGMATIC SYSTEMS

In parallel with instrument deployments and field efforts related to eruptive products (**Section III**), and building on immediate scientific activities (see **section VII**), a spectrum of work on exhumed magmatic systems will be critical to testing MDE hypotheses.

Exhumed Systems and Their Past Eruptive Records

Targeted hypothesis: B

Proposed experiments

Plutonic rocks and the products of past eruptions at **Exhumed Systems** can be used to constrain magma supply rates from the mantle to the crust, magma storage conditions (e.g., depths, temperatures, volatile contents), the spatial distribution and volumes of magma, and the timescales of magmatic processes in the crust. Plutonic localities enable testing of hypotheses for how these variables influence the evolution of subsurface magmatic systems that in turn drive surface hazards.

ACTIVITY 1 | Combine geochronology, geospeedometry, laboratory experiments, and models to explore processes over a wide range of timescales of pluton assembly (millions of years to minutes, e.g., Glazner et al. 2004) and rates (e.g., mantle supply and ascent rates within the crust, longevity and periodicity of eruptible and uneruptible magmatic states).

ACTIVITY 2 | Use geobarometry to establish the structure and distribution of phases within magmatic systems, and magma within the crust through time.

ACTIVITY 3 | Conduct (hyper)-dense geochemistry analyses throughout the stratigraphy of plutons and past eruptive sequences, as well as conduct experiments on natural compositions, to assess the evolution of critical magmatic properties (e.g., volatile contents) and relationships between magmatic events and eruptions (e.g., recharge).

ACTIVITY 4 | Assess micro (crystal/pore) to macro (field) scale structural information preserved in intrusive systems to estimate processes related to magma movement (e.g., emplacement, stalling, percolation, extraction from mushes, and replenishment).

ACTIVITY 5 | Synthesize these results to place constraints on the thermal structure of the crust in time and space, and on the rate and efficiency of internal processes (phase segregation and magma transport to shallower portions of the crust). These measurements will be applied in models that address the eruptibility of magmas and incubation time for reservoir growth, which will also incorporate geophysical measurements from active systems (see Section III). They will also be important for identifying volcanic and plutonic systems that are genetically related, helping to identify the magmatic processes that result in eruptions versus those that are decoupled from them.

SCOPE | Different exposed plutons provide access to distinct levels within the crust (from 0–60 km), architectures (oceanic versus continental arcs), and inferred tectonic regimes (compressional versus extensional). Different sites have been studied to greater or lesser detail and with different methods. Given the variability in characteristics of exhumed systems, a common approach may not be appropriate for every site (as for active volcanoes). Rather, each site may have independent research needs with the goal of understanding magmatic compositional variation with depth, storage times, and magma supply rates. The scale will range from the individual plutons to a trans-crustal cross section of an exhumed arcs. The number and diversity of sites should be selected based on their utility in testing hypotheses, and proposed initiatives should build off existing datasets.

Expected outcomes

We expect to characterize the magmatic history (e.g., composition, storage depths, transit times) and state of the crust through time and their relationship to magma eruptibility, eruption periodicity, and drivers of magmatic eruptions. Comparison of this arc-scale magmatic history with long-term histories of erosion and landscape evolution will be critical to evaluating cross-disciplinary questions regarding how arc structure links to surface topography and sediment generation.

NOTIONAL EXPERIMENTS: LABORATORY AND NUMERICAL MODELING STUDIES

Laboratory Experimental Studies

Targeted hypotheses: A, B, and C

Proposed laboratory experiments

ACTIVITY 1 - volatiles | Perform new sets of volatile solubility and diffusivity experiments at magmatic conditions. While solubility laws for H_2O are well characterized, CO_2 solubility is poorly known under lower crustal conditions. The behavior of S is as yet highly underconstrained given the complex partitioning relationships that exist across multiple melt and gas species as a function of P, T, and oxidation

state. Diffusive loss/gain of volatiles from melt inclusions in various mineral phases is important for understanding the fidelity of melt inclusions for pressure estimates and their use as geo-speedometers (e.g., ascent rates). More work is also needed to fully understand the behavior of halogens and noble gases and the effect of gas fluxing (e.g., CO_2 fluxing) on melt inclusion records and gas emissions.

ACTIVITY 2 - diffusion | Precisely determine the timescales of magmatic processes such as ascent rate, residence time, and mixing timing through new experiments to develop accurate diffusion laws as a function of P-T-X (and importantly H_2O).

ACTIVITY 3 - Geobarometers | Perform new sets of phase equilibria experiments targeted to specific arc melt compositions and trans-crustal P-T space to increase the utility of geobarometers. To understand the rate, path, and distribution of magma through the crust, it is essential to reliably determine the pressure growth history of crystals. Geobarometers for magmatic systems have been improving over the fifty years, yet they remain inaccurate when applied to crustal magmatic systems. We will complement these experiments with new fluid inclusion barometers that will significantly increase the precision of pressure constraints.

ACTIVITY 4 - Rock physics experiments on realistic and analog materials | Explore the effects of solid and multi-phase liquid rheology on magma movement, rock alteration, and changes in mechanical strength, pluton growth, and outgassing efficiency.

ACTIVITY 5 - Seismic velocity and attenuation and electrical conductivity measurements | Conduct experiments necessary to interpret geophysical images as a function of melt and bubble contents for different compositions, fractions, and geometries. Correlate the physical properties of magma with evolving mush structure in four dimensions at various temporal and spatial scales to allow extrapolation of laboratory-calibrated rheological models to geological scales that are many orders of magnitude larger than in the laboratory. Synchrotron and neutron radiation has emerged as powerful tools for characterizing the time-resolved three-dimensional distribution of mineral phases, stress states, and grain orientation in materials (e.g., Zhu et al., 2011; 2016). These technological advances provide a tremendous opportunity to develop new experimental methodologies so that evolving properties and microstructures can be quantified in operando.

Expected outcomes

1. We expect to improve current degassing models by incorporating better solubility and partitioning laws into multi-component systems. This is critical to interpreting measured volcanic gas compositions in terms of magmatic processes.
2. We expect to improve our capacity to characterize magmatic events (e.g., mixing or recharge events) and quantify the duration of residence in reservoirs and rate of ascent.
3. We expect to significantly improve our understanding of the depths at which magmas reside and better reconstruct their pressure-time histories.
4. Rock physics experiments would both improve understanding of the mechanical coupling between magmas and their host during transport and accumulation and provide more accurate models to relate

elastic and electrical properties of multi-phase magmas for geophysical inversions.

Modeling Studies (MCS)

Targeted hypotheses: A, B, and C

Numerical models integrate observations into a framework that enables testing of hypotheses. Models represent a powerful tool for exploring the physics underlying magmatic processes, making eruption forecasts, and connecting processes in active magmatic systems to the geologic record. Modeling will play an important role in testing hypotheses (see **Section III**), in developing the VolcArray design, in interpreting observational data and forecasting eruptions (**Section IV**), and in executing immediate science activities preceding array deployment (**Section V**).

The Modeling Collaboratory for Subduction Volcanic Systems Workshop took place online from September 2020 to May 2021, producing a report (Gonnermann and Anderson, 2021) that encompasses:

1. Challenges and opportunities for subduction zone volcano modeling and collaboration, and
2. A vision for how a modeling collaboratory would best advance the science objectives.

This section summarizes key outcomes of the workshop report in the context of the MDE objectives within three main pathways.

Physical/numerical model development involves both the study of novel physical processes as well as model implementation and verification/validation. Examples of poorly understood processes that could be addressed include non-equilibrium phase separation and reactive transport in magma reservoirs, the dynamics of dike ascent, controls on magma reservoir formation and eruptive vent locations/geometry, magma-groundwater interactions, and the mechanics of deep melt transport into the crust. For problems in which there is broad agreement on modeling needs and relevant physical processes, an MCS facility could support focused (open source) new code development and updating of old codes. Examples of problems that could benefit from accessible community codes and open-source model development include multiphase, unsteady conduit flow; ground deformation associated with magma reservoirs and heterogeneous, elastic, and viscoelastic rock rheology; multi-component thermal conduction; and equilibrium thermodynamics of multi-phase magmas. A volcano MCS can also organize model verification and validation to establish reproducibility standards and promote collaborative modeling practices. Model development could be supported through thematic community working groups (CWGs) to bring researchers – modelers, experimentalists, and observationalists, as well as those from other fields such as computer science or applied mathematics –- together to work on common problems, producing models and results through workshops and collaborative proposals.

Inversion and data assimilation. Inverse methods provide the critical link between data and models. Techniques vary widely, from simple optimization approaches to sophisticated Bayesian inference frameworks. An MCS could play an important role in organizing different research communities to develop frameworks for synthesizing diverse data, joint inversions, and uncertainty quantification. Data types with complementary sensitivity to structure and processes include deformation, seismicity, seismic wave tomography, electromagnetics,

gravity, geochemistry and petrology, and gas and thermal emissions.

Inverse methods and data assimilation are fast-evolving fields following the explosion of new statistical methods in data sciences. Anomaly detection and pattern recognition have been revolutionized using machine learning techniques and have benefited greatly from the quantity of freely available data. An MCS could also provide a bridge between volcano researchers, applied mathematicians, and data scientists. These collaborations could improve sensor network design, reduce non-uniqueness inherited from inversions, and provide more accurate, physics-based, forecasting frameworks.

Training and human capacity building. To advance hypothesis-driven science objectives through integrative modeling of magmatic-volcanic systems requires a critical mass of geoscientists who are skilled in model development and in the application of models. An MCS could serve as a programmatic conduit in this regard, assuring through workshops and networking (in particular, through the CWG structure) that a growing pool of modelers will be optimally positioned to collaborate with experimental and observational scientists through model development and hypothesis-driven model use. MCS can also provide training for researchers interested in learning more about specific models, including code utilization, implementation of existing codes in modern open-source formats,and the underlying physics and assumptions behind the models. These efforts are clearly aligned with the capacity building, education, and Belongining, Accessibility, Justice, Equity, Diversity, and Inclusivity (BAJEDI) goals of the SZ4D BECG Group.

SITE EVALUATION

The Notional Experiments in **Section III** will involve all aspects of the complete **VolcArray**. **Imaging Arrays** will be required at a small number (~4–6) of systems that are driven by a range of mantle magma supply rates and that have imageable trans-crustal magmatic systems and accessible volcanic histories. It is also necessary to deploy **Volcano Sensor Arrays** at a large number (~30–50) of arc volcanoes that exhibit magmatic unrest and have a history of frequent eruption or potential for near-term eruption, with the potential for augmentation by **Rapid Response Arrays** during emerging episodes of unrest. All sites should be logistically feasible (accessibility and open data are key) and involve close partnership with local observatories and academic institutions. The selected regions/sites should also be a good fit with FEC and L&S priorities to maximize logistical support and allow for crosscutting science activities.

Ideal Location Characteristics and the MDE Arc Volcano Inventory

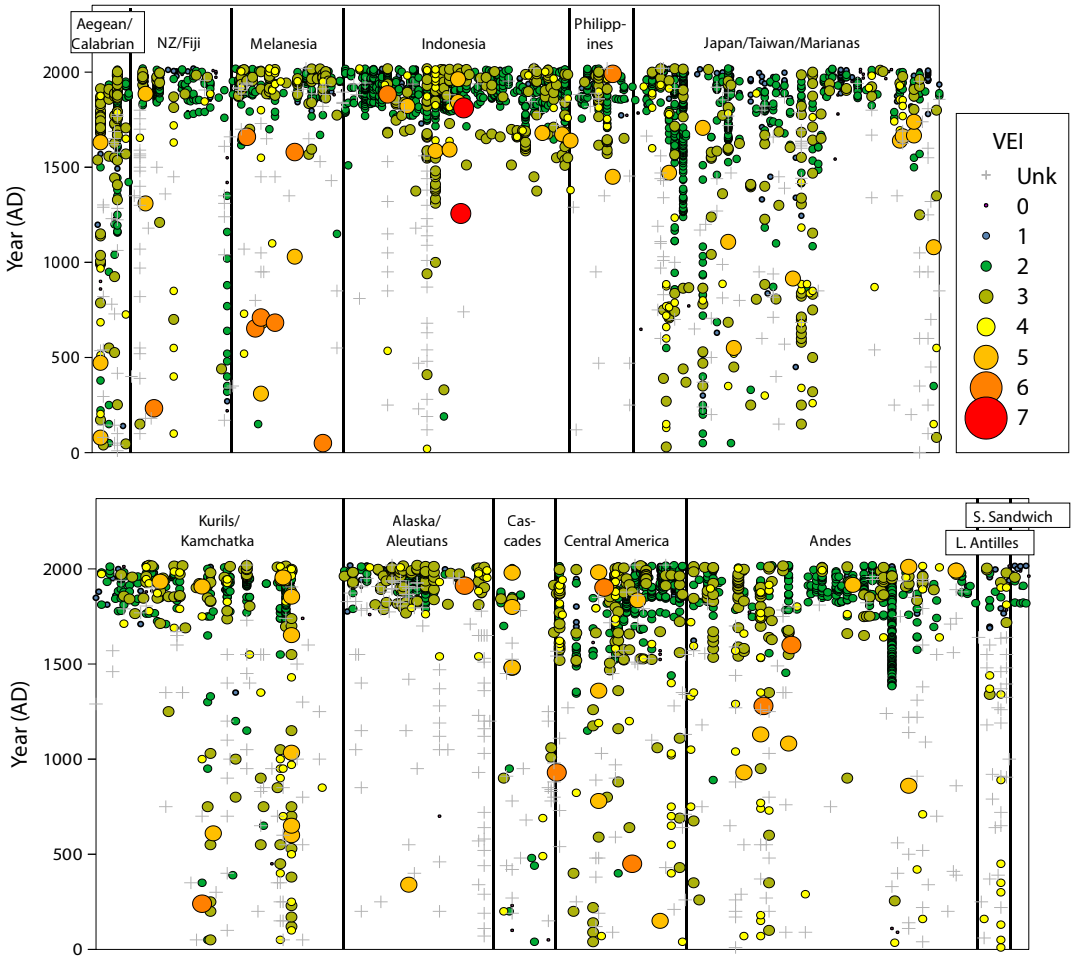
Volcano Sensor Arrays are largely aimed at Hypothesis sets A and C, with many diverse targets (~30–50). Ideal location characteristics include:

- Systems "potentially active," in that they show unrest and/or probability for eruption within the next decades. Indications of potential activity may include whether a system is actively emitting gas (Carn et al., 2017) or deforming (Furtney et al., 2018).
- Good summit access to deploy MulitGas and other gas measurement (DOAS) units year-round or with unmanned aircraft system (UAS) campaigns, for time-series characterization of gas chemistry.

- A diversity of magma chemistries, from mafic to felsic. A significant proportion of the target volcanoes should be of basaltic composition to test hypotheses as to magma initiation time, mafic recharge, and gas chemistry.
- Accessible targets, in order to deploy and maintain near-field instrumentation and to provide telemetry options for near-real-time, open data transmission.
- A subset of volcanoes with a good probability of eruption multiple times with different intensities over the observation period.
- Systems that exhibit a diversity of eruptive styles and intensity. Ideally **Volcano Sensor Arrays** would capture eruptions from VEI 1 to 4. This may require **Rapid Response Arrays** as well (see **Section IIIc**).
- Proximity to large magnitude earthquakes to test for triggering of volcanic unrest and eruption.

Volcano Imaging Arrays are largely aimed at Hypothesis sets B and C, with a small number (~4–6) of targets for intensive and integrated geological, geochemical, and geophysical studies.

Figure MDE 7. *Number of eruptions through time (past ~2000 years) per subduction zone, coded by VEI. Each vertical column represents one volcano that erupted in the Holocene; the width of data in each segment thus roughly indicates the number of different volcanoes that have been active in the Holocene (data from Smithsonian Global Volcanism Program, grouped by CAVW number; Global Volcanism Program, 2013).*



Ideal location characteristics include:

- Access to significant land area for certain key observations, such as wide-aperture seismic and geodetic deployments and InSAR. This would likely preclude island arc volcanoes, though active source imaging could also be possible offshore for submarine volcanoes. Island arc volcanoes could be included among the Volcano Sensor Arrays.
- Excellent exposures or records of past eruptive deposits should be accessible for study of volume, eruptive intensity, composition, thermobarometry, geochronometry, and geospeedometry over timescales ranging from 10^{-2} to 10^{4} years.
- Targets that span a range of mantle magma supply rates. Ideally, **Volcano Imaging Arrays** would be deployed at systems formed from high, medium and low mantle magma supply rates.
- Target volcanoes that enable tests of mantle magma supply rate as a driving parameter for the location, depth, distribution, and chemistry of the trans-crustal magma system. For this reason, magmas should not be substantially contaminated by crustal interactions (e.g., thick crust). Alternatively, variations in crustal thickness could be viewed as a critical control parameter that varies along strike in Chile.
- Co-location of some of the **Volcano Imaging Arrays** with FEC and L&S targets. This will offer the greatest opportunity for intensive study across the arc system.

To identify candidate sites that meet the above criteria, we assembled an *MDE Arc Volcano Inventory* that tabulates relevant characteristics for all of Earth's currently active volcanic arcs. The *Arc Volcano Inventory* includes both scientific and logistical considerations. Ultimately, host country priorities and expert input across the community will be critical for identifying specific target systems for both **Volcano Sensor Arrays** and **Volcano Imaging Arrays**.

Ideal Arc Segments for Volcano Sensor Arrays

Ideal arc segments for **Volcano Sensor Arrays** are those that host multiple restless volcanoes that span the full range of eruption intensity (VEI), magma type, degassing and deformation mode, unrest and eruptive style, and subduction and upper plate parameters. The primary requirement for **Volcano Sensor Array** targets is restlessness, such that multiple time series (e.g., gas chemistry, volatile flux, seismicity, and/or deformation) can be measured. A secondary target is volcanoes with the potential for eruption in the coming decades. As **Figure MDE-7** shows, regions with the largest number and VEI range of frequently erupting volcanoes (indicated by vertical/horizontal extent and size/color of dots in each region box) include Indonesia, Kurils/Kamchaka, Alaska/Aleutians (though many eruptions are of unknown VEI), Central America, and the Andes. The *MDE Arc Volcano Inventory* further indicates that these regions host a relatively large number of restless volcanoes spanning a range of magma types. Thus, for hypotheses that require capturing eruptions with a range of VI, these regions are most fertile for the deployment of **Volcano Sensor Arrays**.

Locating **Volcano Sensor Arrays** in a small number of regions or countries would enable the most efficient logistics, focused capacity building efforts, and the caching of instruments for **Rapid Response Arrays**. It would also

have the potential to link to FEC and L&S observational campaigns. A small number of regions or countries would also limit the range of subduction and upper plate variables that could be explored. Taking into account access and logistical considerations, the ideal regions for **Volcano Sensor Arrays** are Alaska/Aleutians and the Andes, with a proposed primary focus of Volcano Sensor Array deployments in Chile as the single country with the largest number and most diverse suite of potentially active volcanoes, and a secondary focus area of study in the Aleutians using data from the permanent networks maintained by the Alaska Volcano Observatory. To provide adequate coverage to address the science questions underlying Hypothesis Sets A and C, **Volcano Sensor Arrays** may extend beyond the focus subduction segments.

Ideal Arc Segments for Volcano Imaging Arrays

Volcano Imaging Arrays should be located in arcs with a range in mantle magma supply rates. However, due to the difficulty in constraining these rates, we rely on known "subduction parameters" (i.e., volatile flux, convergence rate, plate age, composition of the slab, stress state of the upper plate) such that a "representative" picture of typical arc volcanism (e.g., not in back-arc, relatively simple crustal tectonics/structure) can be formed. Below we list and evaluate candidate arcs representing a range of magma supply rates (see the *MDE Arc Volcano Inventory* for a full list). Given the necessary aperture of geophysical arrays required to image deep roots of trans-crustal magmatic systems, we note that island and submarine arcs are problematic for some types of imaging; however, others (e.g., active-source seismology) may be better suited for offshore deployment. Therefore, integrated seafloor observations may be desirable in any SZ4D target locations within island arcs.

Other considerations include imageability, logistical access, viability of international collaborations, and magma composition. The pairwise comparison between mafic (distributed volcanism) and felsic systems at any arc segment provides important perspectives. Feeble or low-volume systems are less likely to host large, easily imageable mid-to-lower crustal magma systems that would inform models of the trans-crustal system. Logistical considerations have greatly limited volcano studies in many regions and include concerns about physical accessibility, permitting, and weather. These considerations vary depending on the type of imaging involved; long-term observatories require different access than quick, low-impact studies. Operating outside the United States requires extensive coordination from international collaborators. All of these considerations vary globally and regionally.

An overarching imaging objective is to compare systems with different magma supply rates at both trans-crustal and shallow-magmatic levels. However, there are no direct measures of magma supply or production rates in the mantle. We instead rely upon proxies and secondary "subduction parameters" that may ultimately drive magma supply to guide prioritization of specific arcs. Volatile flux models depend on a variety of kinematic and thermal parameters and are important to the extent that flux melting controls input (e.g., Cagnioncle et al., 2007; Wilson et al., 2014; Zellmer et al., 2015; Cerpa et al., 2018). These parameters depend largely on thermal paths followed by the descending plate (van Keken et al., 2011).

The second major source of magma, decompression melting, is more likely controlled by the speed of corner flow, and hence convergence rate modified by wedge geometry and upper-plate thermal structure (Grove et al., 2012; England & Wilkins, 2004). Other parameters such as the stress state of the upper plate also have been hypothesized to have strong control on mantle magma production (Karlstrom et al., 2009).

Given all of these potential proxies for magma supply rate, a variety of prioritizations could be made. One "endmember" in nearly all of these proxies is Cascadia, with its very young incoming plate, slow convergence, and the likelihood that sediments and upper oceanic crust dewater before reaching subvolcanic depths. Thus, magma supply should be relatively low in Cascadia compared with other arcs. Many other subduction zones (e.g., Peninsular Alaska, Central Chile, North Japan) likely deliver substantial volumes of volatiles to sub-arc depths and drive flow at many tens of km/My rates and would be useful to contrast with Cascadia. However, proxies vary between them, with higher subduction rates in Central America or Chile than off Alaska, but younger incoming plate ages. Comparisons between Cascadia and at least two other, colder subduction zones should provide new perspectives on magma supply rate. Taking into account the above considerations as well as proposed locales for Volcano Sensor Array deployments in Alaska and Chile, we propose locating **Volcano Imaging Arrays** in Central Chile, Cascadia, and Peninsular Alaska.

Ideal Locations for Study of Exhumed Systems

Exhumed systems afford a potentially complementary record to active volcanic systems as they represent accessible deeper crustal records of the transit of magmas from the mantle to the surface. Ancient arc systems, representing both accreted oceanic and continental arc crust, are widely present in the geologic record and range in age, exposure depths, and lithologies. A handful of localities represent nearly complete arc crustal sections, preserving depths from the crust-mantle interface to surface volcanic and sedimentary rocks, and have been extensively studied (e.g., Talkeetna arc, Kohistan arc). Other localities may only preserve a record of magmatic activity within a restricted depth range (e.g., Southern Alisitos Arc). To aid in assessment of candidate sites that meet the above criteria, we assembled an inventory of *Global Exhumed Arc Plutonic Sections* that tabulates relevant characteristics (age, range of depth exposed, lithologies, and whether a complementary, coeval volcanic section is present) for all known localities.

Desired Attributes

The choice of localities that can be used to address the three sets of hypotheses defined in Section I will depend on considerations such as their lithologies, age ranges, availability of prior information, and geologic contexts. Multiple localities will be used to test the hypotheses. The chosen sites could serve as comparisons between active systems, or could potentially be used to relate active processes observed by the VolcArray to those taking place at depth using exhumed, ancient analogs of these systems. For example, many arcs display variability in terms of magma supply rate (e.g., Sierran Arc). Comparing crustal residence times, magmatic compositions, and storage depths during "high"- and "low"-magma supply time periods is an example of a specific study that could be undertaken. In addition, localities

preserving both contemporaneous plutonic and volcanic records could be particularly useful for connecting observations of plutons to samples of volcanic products. The *Global Exhumed Arc Plutonic Sections* highlights potential study localities (e.g., Talkeetna, ancient Cascades, Southern Alisitos, Fiordland, Famatina, Sierran) that are well characterized and are useful archives of the deep crust, but potential study sites are not meant to be limited to those listed. Prior characterization (in terms of chemistry, geochronology, modeling, etc.), while useful, is not required. Sites could also be selected to coordinate field experiences and logistics with **Volcano Sensor** and **Imaging Arrays** on active systems (e.g., in South America or Cascadia)

IMMEDIATE SCIENCE ACTIVITIES THAT CAN PRECEDE SZ4D DEPLOYMENTS

Results from work on existing data and samples, along with key experimental and modeling efforts, will be essential for guiding details of future SZ4D deployments and ultimately achieving the main goals of MDE. These efforts include using petrologic studies, laboratory experiments, geophysical studies, and physical models to:

1. Constrain the architecture, composition, and thermodynamic state of both active and extinct magmatic systems;
2. Establish new observational tools for use in future experiments;
3. Tie together geophysical and petrological data to create broadly self-consistent constraints on magmatic systems; and
4. Develop robust numerical modeling frameworks that can assimilate diverse data, make predictions about observations, and explore the phenomenology of magma transport processes. Each of these activities is directly linked to the MDE hypotheses.

Legacy Instrumental Data and Mapping Studies

Depending on the selected region(s), years to decades of campaign or continuous data may be available for systematic reanalysis in light of MDE science questions and observational objectives. Assessment of existing data (e.g., from campaign or continuous seismic, GNSS, and gas monitoring instruments, and from remote-sensing observations), and previous studies (e.g., geologic, heat flow, $^3He/^4He$, CO_2 flux surveys/maps) are thus critical immediate science activities to guide detailed site selection and experiment planning, to provide baselines for MDE deployments, and to provide initial constraints on mantle magma supply rates.

Samples from Prior Eruptions

Existing samples that are currently housed in repositories and individual research collections can be studied to constrain the architecture, composition, and thermodynamic state of arc magmatic systems at present and through time. Similarly, studies to examine intrusive-extrusive relationships in magmatic systems are necessary and can be conducted using existing samples. Specifically, applying well-established petrologic tools (e.g., geothermobarometers, hygrometers, phase relations, geochemistry, geochronology) to these samples will constrain pressures, temperatures, compositions, depth, average repose times, melt extraction efficiency, and eruption initiation mechanisms of magmas and magma storage regions of prior eruptions

(Hypothesis Sets A and B). Few such studies have been systematically undertaken for a whole arc, or even an arc segment, especially for active systems. However, such information is critical for understanding the evolution and current state of the crust and magma storage at both active and inactive systems. For example, only 27 of the 99 "restless" volcanoes that are emitting SO2 and/or actively deforming (Carn et al., 2017; Furtney et al., 2018) have had enough petrological data collected to provide estimates of magma storage pressures and temperatures. These efforts to collect new, and synthesize existing, data for target volcanoes will be critical in contextualizing field measurements made with the **Volcano Sensor** and **Imaging Arrays**.

Laboratory Experiments

Laboratory experiments are an essential tool for furthering our understanding of magmatic processes in arcs, can be used as a starting point to address MDE hypotheses, and can inform the design and deployment of field experiments. Experiments will be critical in constraining the P-T-X-H_2O-CO_2 conditions of magma storage. For example, laboratory exploration of phase equilibria in P-T-X space can provide more context and more precise estimates than geothermobarometers for a targeted system. Only six of the 99 "restless" volcanoes mentioned above have been subjected to detailed phase equilibria experiments, highlighting the need for this work. Such experiments will be particularly useful for the active magmatic systems chosen for comprehensive 4D study using **Volcano Imaging Arrays**. Similarly, experiments that constrain the pressure-composition controls on volcanic gas CO_2/SO_2 ratios are critical for interpreting gas time series that will be measured using **Volcano Sensor Arrays** and relating them to processes at depth and accompanying geophysical time series. Additionally, the development of improved geothermobarometers and calibrations of crystallinity-temperature relationships will be needed to extract information about the state of the magma from erupted samples and can precede instrumental deployments.

Currently, there is a dearth of experimental data on petrophysical properties and rheological behaviors of volcanic mushes and country rocks. The mechanisms (e.g., over-pressure, chemical instability) by which magma and volatiles coalesce and erupt are unclear. Can over-pressured magma rupture volcanic mushes? If so, what are the key parameters that control the transition from ductile flow to brittle fracture? Rock physics experiments are needed to provide realistic magma and host rock rheologies that can be incorporated into models of magma movement and eruption forecasting, as well as to develop constitutive models relating geophysical parameters (e.g., elastic moduli, electrical resistivity) to the thermodynamic state of the imaged magma body.

Numerical Modeling

Modeling is essential to tie together field observations (petrology, geodetic, and geophysical inversions) and to build a framework for investigating the evolution of magmatic systems over a range of time and length scales. Pre-deployment modeling efforts can also be leveraged to design and guide the instrumentation and data integration strategies. Mechanical modeling allows assessment of the response of the magmatic system, defined by petrological, laboratory experiment, and geophysical datasets and subject to assumed governing equations as well as numerical implementation approaches, to different rates of magma supply and magma composition. Past and present

signals of unrest can be combined to hindcast and forecast the conditions that may initiate an eruption and link active volcanic processes with the geologic record. The Modeling Collaboratory for Subduction will provide a framework for addressing common modeling challenges between working groups of SZ4D, community code development, and training support.

COMMUNITY COORDINATION PLAN

Clear plans for community-wide science and outreach coordination are critical to the success of SZ4D. In an SZ4D survey of the volcanology community, 85% of respondents identified a multidisciplinary, community-driven effort like SZ4D as important for understanding subduction zones. However, in the same survey, about half of the respondents identified the US academic volcanology community as 6/10 or less in terms of organization. Evidently, there are both broad agreement on the need for an initiative like SZ4D to understand integrative questions like subduction zone hazards and significant challenges in building organizational capacity within the MDE-aligned community. Indeed, the *National Academy of Sciences ERUPT report* (NASEM, 2017) highlighted improved organization and coordination as major goal. Fortunately, in the wake of the ERUPT report, several linked efforts such as the Community Network for Volcanic Eruption Response (CONVERSE) RCN and MCS have forged a clear path toward enhanced community coordination. We will build on the successful coordination plans from these efforts to develop MDE- and SZ4D-wide science coordination plans.

Key lessons from CONVERSE regarding rapid response (see **Section IIIc**) include a transparent organizational structure with science advisory committees to ensure an open application process for sample and data collection, sample distribution, and other fieldwork. For example, one-page proposals were solicited from the community for proposed field campaigns and access to samples from the Kilauea 2020 eruption. These proposals were evaluated by a scientific advisory committee that worked closely with the observatory (Fischer et al., 2021). Also important are clear and consistent protocols for data and sample handling, and the accessibility and equitable representation in decision-making across communities, career stages, and nationalities. The interest and high participation rates in CONVERSE and MCS activities suggest they represent the starting point for a successful blueprint for coordination across SZ4D, with the overall goal of more interdisciplinary and stronger scientific results.

SUMMARY OF KEY SCIENTIFIC AND BROADER OUTCOMES

A major metric for the success of the SZ4D initiative is the extent to which it will enable the subduction zone science community to address questions and hypotheses that would not be accessible absent the scale and integration of the SZ4D effort. The motivating hypotheses for the MDE community relate the mantle supply of magma to the trans-crustal magmatic system and ultimately to volcanic hazards at the ground surface. Testing these hypotheses will build an improved understanding of how volcanoes work, with implications for hazards and forecasts along subduction zones. More broadly, the SZ4D effort will build organizational, infrastructure, and training capacity across the volcano science community.

Links to MDE Tracability Matrix and Databases

- *Traceability Matrix*
- *MDE Arc Volcano Inventory*
- *Global Exhumed Arc Plutonic Sections*

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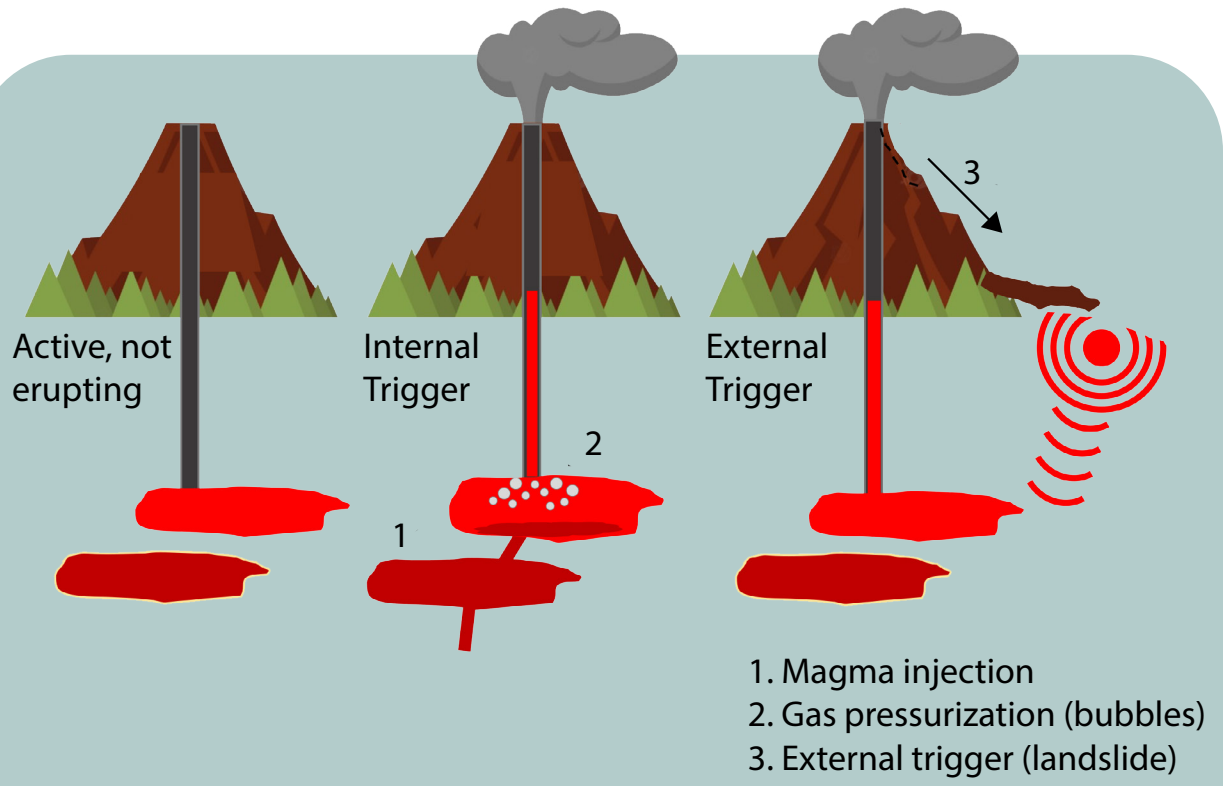
SIDEBAR 3

What drives a volcanic eruption?



Volcanic eruptions are triggered by both internal processes (from within the magma or magmatic system) and external process (e.g., landslides, earthquake). The most common mechanism for triggering eruptions in arc settings is deeper, hotter magma entering a shallower magma storage region, but eruptions can also be initiated by buildup of gas pressure related to crystallization. One open question volcanologists are trying to constrain is how much time will elapse between the triggering event, and the physical eruption.

BUILDING EQUITY AND CAPACITY WITH GEOSCIENCE

For a more inclusive science community and a broader understanding of geohazards to address social justice and equity issues in hazard mitigation

SUMMARY

Early in SZ4D discussions, the community recognized that an initiative of this scale and scope afforded the opportunity to implement a carefully considered slate of activities to ensure the program's long-term "broader impact." Concepts discussed coalesced into two parallel and complementary themes:

1. To better communicate scientific understanding of subduction zones and associated hazards to the public, and
2. To train a new generation of researchers to answer key science questions about subduction processes using interdisciplinary approaches (McGuire et al., 2017).

To develop these themes, in early 2021, SZ4D scientists and specialists in geoscience education, public outreach, diversity, and organizational structures joined to form the Building Equity and Capacity with Geoscience (BECG) integrative group. Since then, BECG has researched a range of programs and activities to consider how SZ4D could be transformative for US students and faculty, international participants, and communities directly affected by subduction hazards. BECG explored topics beyond traditional broader impacts education and outreach efforts, including international capacity building, best practices for conducting interdisciplinary research (Till et al., 2017), and factors that have long undermined belonging, access, justice, equity, diversity, and inclusion

(BAJEDI) in the geosciences (e.g., Bernard and Cooperdock, 2018; Williams-Stroud, 2021; Beane et al., 2021). Additionally, BECG consulted the social science literature and compiled the learned best practices from our community to aid in the development of a list of broader impact activities that support the science goals identified by the other SZ4D working groups and integrative groups. BECG formulated the following six primary areas where SZ4D should concentrate their broader impacts efforts:

1. Building capacity for international collaborative research, training, and data sharing;
2. Promoting hazard equity and social justice;
3. Supporting evidence-based education and training;
4. Increasing effectiveness of public outreach;
5. Strengthening interdisciplinary collaboration; and
6. Improving BAJEDI.

From these six areas (**Figure BECG-1**), BECG developed six research questions to frame its discussions concerning how SZ4D could motivate changes within communities located in subduction zones settings and within the geosciences community, both in the United States and internationally.

In the next sections, we delve into the components of these six research questions, including suggested objectives, primary needs, and potential activities. This text follows our *Traceability Matrices for each of the research questions*. The remaining sections of this chapter propose a framework and an implementation plan for meeting these objectives and needs.

RESEARCH QUESTIONS

International Capacity Building

RESEARCH QUESTION 1: How can we leverage efforts into equitable international capacity-building partnerships that improve capabilities (e.g., skills, data, software, technology, understanding) for all scientists and stakeholders involved? What do we need to build into our programs to make these improvements sustainable?

To address questions associated with international capacity building, a primary objective is to **establish and promote best practices for cooperative international field research**, particularly in the context of SZ4D science. This will entail extensive information gathering and a literature review of sustainable human capacity building and technical infrastructure development in the geosciences. A key principle for effective partnering with scientists, agencies, and universities responsible for subduction zone science and hazard management is establishing the elements of equitable cooperation, such as intellectual property guidelines, cost sharing, field activity plans, and agreement on scientific expectations before work starts. Training of US-based SZ4D participants and close engagement with all international stakeholders (policymakers, scientists, and educators) from the start of the planning process can ensure that we have shared goals and clear plans that will benefit the local communities.

The second objective is to **establish and promote best practices for FAIR (findable, accessible, interoperable, and reusable) data among international researchers** (Wilkinson et al., 2016). SZ4D must ensure its data and data products are openly accessible, but it can also put in place policies that better incentivize data

sharing from other entities to improve the quality of research results and minimize the limitations for access and interpretation (Fecher et al., 2015). This will entail active, organized dialog early on to understand needs and to convey FAIR data practices that have been collectively developed over the last several decades within US and international research communities. The SZ4D Center will be positioned to leverage the experience of its constituent groups to help new partners overcome potential limitations (e.g., infrastructure, human capital) and other challenges (e.g., Boeckhout et al., 2018; Tenopir et al., 2011). Having a clear and sustainable plan for open science is essential for interagency cooperation. It can both impact hazard science and present a unified view to those outside science.

The third objective is to **promote open, effective, bilateral communication and scientific training**. The development of effective multi-language communication and training opportunities is critical for developing and maintaining international partnerships. SZ4D should work with in-country collaborators, existing educational offices, and social scientists to develop appropriate content in effective formats and with careful cultural considerations. This can be accomplished by facilitating collaboration between physical and social scientists to learn about educational interests and context that would enhance the effectiveness of scientific communication.

The fourth objective is to **develop sustainable funding pathways for bilateral, multinational training and exchange programs**. Achieving this objective requires seeking appropriate funding across the SZ4D organization with the goal of perpetuating the training program and expanding it to other communities and countries after SZ4D. One approach could be to identify partnerships that can fund foreign

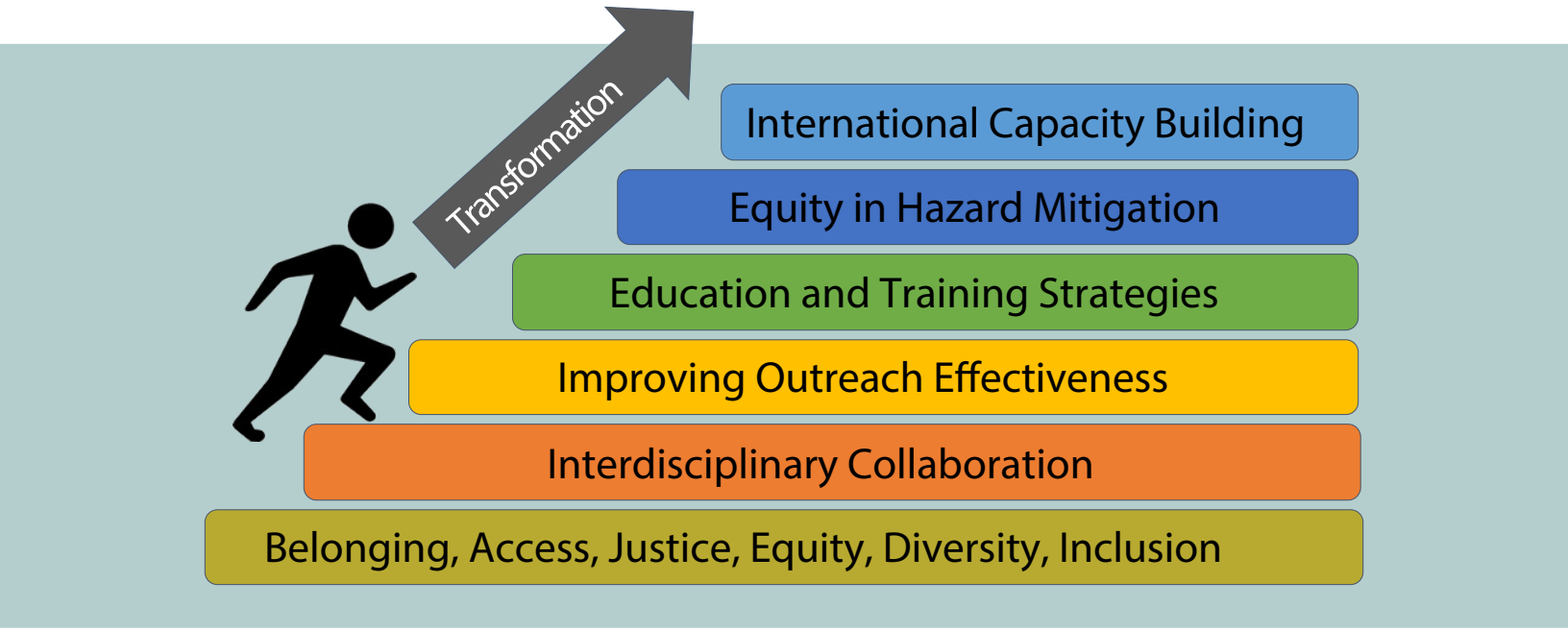


Figure BECG-1. *Research goals of the Building Equity and Capacity with Geosciences (BECG) group.*

exchange of students to assist with data collection, with an emphasis on supporting students from communities that are directly affected by subduction zone hazards. A potential SZ4D goal is to provide equal funding to US and international students.

Finally, we recognize an important objective is to **minimize imperialistic or colonial methods of interaction**. Such interactions can take the form of PIs "bestowing knowledge" upon international collaborators, in that the PIs simply need field support to accomplish the research while resisting any intellectual contribution or PIs "extracting knowledge" from their Indigenous populations and giving no credit to their contributions or any prior research done in-country (e.g., Cartier, 2019; Wight, 2021). Our community must work with international partners, host countries, and social scientists (Nordling, 2017) to implement cross-cultural and implicit bias training for international collaborations, including general core training and location-specific considerations that grow awareness toward underlying colonial attitudes embedded in traditional interactions (Stefanoudis et al., 2021).

Equity in Hazard Mitigation

RESEARCH QUESTION 2: Geohazards disproportionately affect specific communities. How do we translate improved understanding of subduction zone geohazards into products that can be used to inform and address social justice and equity issues in hazard mitigation? What considerations must be made to ensure equitable engagement of and outcomes for those communities?

The first objective seeking to address equity in hazard mitigation is to **strengthen ties with local hazard monitoring and emergency management agencies to maximize the local impact of subduction zone science**. The SZ4D community could significantly benefit from being better informed about the local agencies, resources, and hazard information available for specific regions of interest. To facilitate communication and strengthen relationships, we envision workshops and webinars conducted collaboratively with local experts that discuss the region's hazards, provide accounts of previous noteworthy hazard events, discuss geographic variations in exposure, and review what data are available. Specifically, we recommend inviting local agencies and government officials as well as nonprofit organizations working in these areas to discuss community vulnerabilities to hazards and which new hazard information would have the greatest impact on mitigating future risks. As the SZ4D community becomes more informed about locale, we envision SZ4D science will evolve to prioritize targets that address local needs in conjunction with intellectual merits.

The second objective is to **establish best practices in hazard communication within diverse communities**. This goal goes well beyond improving public outreach and requires establishing partnerships between physical and social scientists, science communicators, practitioners from nonprofits working on the ground, and educators to develop and implement techniques to communicate with diverse communities about the research plans and results. Activities to meet this need could include science communication training workshops with topics such as "how to talk to the public about your science" and "considerations for communicating with diverse communities." Recent research on communicating earthquake early warning to the general public has highlighted the importance of these efforts (Kamigaichi et al., 2009; Wein et al., 2016; Becker et al., 2020),

and indicates a need to invite social scientists and communication experts to present their findings at SZ4D meetings and conferences. Similar to the previous objective, we encourage cultivating internship opportunities for faculty, postdocs, and graduate students to work with specialists on hazard communication within diverse communities, including science communicators, education researchers, and social scientists. The ability to communicate our science effectively to local communities for each project will facilitate bringing researchers and instruments to field settings.

The third objective is to **support the creation of an open-access risk data repository** that includes physical data, hazard inventories, and vulnerability assessments. A portal for visualizing the integrated information would improve the ability for SZ4D researchers to recognize high vulnerability areas and critical gaps in hazard information. While the development of this repository is likely beyond the current capabilities of the SZ4D community, SZ4D should aspire to initiate its development through collaboration and advocacy. We recommend engaging with spatial scientists to learn more about the efficacy of risk data formats, software, and processing needs. Ultimately, the SZ4D community should consider ways to contribute to a comprehensive hazard inventory, which would rely on communication and collaboration with local agencies.

Educational and Training Strategies

RESEARCH QUESTION 3: Educational efforts that are more inclusive and have measurable learning outcomes are needed to equip and diversify our scientific community. How do we identify, develop, and implement these strategies?

A first objective in the SZ4D educational effort is to **ensure trainees are properly equipped with SZ4D-specific research skills**. There is consensus that trainees need to improve their:

1. Spatial and temporal reasoning skills to handle increasingly large and detailed 4D datasets,
2. Ability to work in large-scale fieldwork settings such as the human deployments proposed to collect critical SZ4D data, and
3. Capability to create and validate models (conceptual to computational) to generate new knowledge.

SZ4D is poised to be a catalyst for promoting the science of learning, which can be enhanced by sustained support of collaborations between physical scientists and education researchers. In addition, we recognize the need to embed more technical training (e.g., coding or machine learning) into existing curricula (NASEM, 2021) and encourage integration of datasets and models in order to build skills critical in undergraduate education (Mosher & Keane, 2021; Nyarko & Petcovic, 2022). SZ4D could energize this by motivating and facilitating reevaluation and revision of existing curriculum to meet these needs.

A second objective seeks to **increase the integration of societal relevance of geohazards into training**. This is inspired by the large-scale effort to incorporate societal relevance into educational materials and approaches via the *InTeGrate project* (Gosselin et al., 2019). InTeGrate created classroom-ready, peer-reviewed activities where students work hands-on with the complex, interdisciplinary challenges at the intersection of the Earth system and society. SZ4D is well positioned to create materials that can be used to teach about the risks of geohazards, with potentially large positive effects,

especially on communities within subduction zone regions. Exposing students to how SZ4D seeks to address geohazards also has the potential to inspire students to pursue SZ4D science as part of their career development. SZ4D should follow the collection, development, testing, and dissemination strategy demonstrated by the InTeGrate project to share its scientific findings through new educational resources.

A final key objective is to **implement effective educational strategies more broadly**. Although there has been considerable growth of peer-reviewed educational materials over the past two decades, faculty instructors still need to overcome obstacles to incorporating vetted educational materials into their teaching (McMartin et al., 2008; McDaris et al., 2019; SERC, 2012). A key pathway forward involves learning from research conducted on the professional development of geoscience instructors (e.g., Manduca, 2017), which indicates we should seek methods to help faculty instructors to incorporate evidence-based best practices. This can be achieved by developing or fostering professional development training for instructors that would include a focus on pedagogical skills and the scholarship of teaching and learning in addition to the training on educational materials developed with associated with SZ4D science. SZ4D should embrace professional development workshops as a means to disseminate new teaching materials and contribute to a cohort of knowledgeable and connected individuals who can advocate for best practices and the scholarship of teaching and learning.

Improving Outreach Effectiveness

RESEARCH QUESTION 4: Hazard monitoring and rapid response efforts inform decision-makers globally, requiring preparation and clear communication channels. What strategies for science communication would enable people to better understand geohazards and risks associated with them?

To address research questions associated with outreach, the first objective is to **connect SZ4D scientists to key non-scientist stakeholders** using evidence-based approaches to successful science communication. A step toward achieving this would be to support a series of workshops or a community of practice, attended by members of the SZ4D community, that focuses on the development of effective communication strategies. Materials for these trainings would be formulated in cooperation with international collaborators, nonprofit groups, and scientists working in hazard mitigation and rapid response efforts. Once the communication plan is finalized, it would be distributed to the broad, multi-institutional SZ4D community for implementation. An overarching principle is to support outreach efforts in ways that are scalable to large populations, are sustainable beyond the scope of an individual project, and can be integrated with ongoing activities.

The second objective is to **evaluate the impacts of outreach efforts**, with a particular focus on communities most affected by subduction zone hazards. PIs must commit the time and effort to evaluate an outreach project from its very beginning through to its completion. The evaluation of outreach projects could be facilitated using in-place nonprofit, nongovernmental groups that have experience with the particular issues concerning development and deployment of outreach campaigns. Initial evaluations should focus on understanding the strengths and weaknesses of past efforts such as EarthScope and GeoPRISMS, including both those led by PIs and those initiated by SZ4D Center staff. Information collection followed

by critical review could enable SZ4D to identify and apply best practices from these previous approaches and avoid some of the pitfalls. Another key need is to assess and evaluate outreach strategies aimed at increasing diversity. To address this need, BAJEDI should invite experts to share strategies that could then be implemented by SZ4D efforts.

The third objective is to **build a single portal that provides open access to collective outreach resources** that leverages existing, widely used platforms without duplicating them. A first step toward reaching this goal is to define the resource needs by the various audiences (e.g., K–12, general adults, stakeholders, residents in hazardous areas). Then, we will survey existing resources and organize them according to need. To increase the likelihood the resources would be used, we will provide clear descriptions of each resource and embed essential implementation support (e.g., video clips demonstrating use). Evaluation of the portal experience through user surveys will allow us to make improvements. Moreover, we will incentivize a portal model where the resources can be rapidly updated as new events occur.

Interdisciplinary Collaboration

RESEARCH QUESTION 5: What are evidence-based practices for interdisciplinary collaboration that break down silos and improve understanding across disciplines? How can SZ4D become an exemplar for interdisciplinary efforts to enact equity-oriented relationships and outcomes in community science?

The first objective for this set of research questions is to **collectively decide on SZ4D goals for successful interdisciplinary collaboration**. BECG identified a set of goals for consideration:

1. Develop innovative new ideas and construction of new knowledge,
2. Increase publications with authors from different disciplines,
3. Increase numbers of grant proposals and funded projects with PIs/co-PIs from different disciplines,
4. Involve disciplines less common in subduction zone research,
5. Train early career researchers with multidisciplinary understanding and more transferable skill sets, and
6. Share methodologies and data between different disciplines.

After collective goals are established through broad community input, the second objective is to **incentivize the tracking of information related to the interdisciplinary collaboration goals**. The data collection process will be important for investigating whether progress is being made. Identifying the specific data collection process will be clearer once the goals have been decided. Nevertheless, it appears reasonable to consider short surveys of the SZ4D community at regular intervals, possibly during SZ4D-sponsored research conferences or workshops. A fully online survey sent to the whole community could potentially collect information from a broader swath of participants. This is an example of a BECG data collection strategy that should be done in an scientifically ethical and accountable way. It should go through an Institutional Review Board (IRB) approval process to help ensure the results are presentable and publishable.

A third objective is to **follow strategies from prior work for facilitating successful interdisciplinary collaboration**. NASEM (2005) offered

recommendations for stakeholder categories (e.g., researchers, posdocs, graduate students, undergraduates) that provide guidance to SZ4D. Of note is that research team leaders should bring together collaborators early in the process to work toward agreement on key issues and ensure that participants strike a balance between contributing to and benefiting from the team. In addition to the categorical recommendations, SZ4D governance structures should include diverse representation and scientists from different disciplines. The working group structure has embraced this approach as they are focused on research questions as opposed to specific disciplines.

A final objective is for SZ4D to **acknowledge the potential disadvantages of interdisciplinary collaboration and decide how to address these issues**. Some of the potential disadvantages (e.g., Goring et al., 2014) for SZ4D to address are:

1. A decline in first-authored publications in the short term that can be significantly damaging to early career researchers,
2. Lower perceived "credit" for publications that have longer author lists,
3. Higher risk of innovative projects inspired by cross-fertilization,
4. The increased time it takes to learn other disciplines to have meaningful knowledge transfer, and
5. The power dynamics that can occur with researchers at different career levels.

While it would be difficult for SZ4D to influence current reward structures in academia that focus on first-authored publications, SZ4D can provide guidance to help early career researchers make decisions about interdisciplinary collaborations and how to showcase their positive outcomes if they decide to pursue them (e.g., Gewin, 2014). Overall, SZ4D will need to identify and implement strategies to address issues of interdisciplinary collaborations to be more equitable.

Belonging, Access, Justice, Equity, Diversity, and Inclusion (BAJEDI)

RESEARCH QUESTION 6: The diversity of the geoscience community has lagged behind other disciplines. What can SZ4D do in terms of BAJEDI to enact transformative change in the geoscience community? How do we design SZ4D to increase inclusivity and equity in our science endeavors? How can such a broad community science project be funded equitably and enact partnerships that are mutually beneficial for all stakeholders?

The first BAJEDI objective is to **capitalize on changing demographics to increase the pool of diverse students, faculty, and professionals in geoscience**. Census data clearly indicate the rising diversity of the US population, but NSF has recognized the "Missing Millions" of women and minorities from the science and engineering workforce (NSB, 2020). Likewise, recent research identified that racial diversity in geoscience doctoral degrees have not increased over several decades (Bernard and Cooperdock, 2018). Racial diversity has increased for geoscience undergraduate degrees but has occurred at a very limited number of institutions (Beane et al., 2021). An obstacle to broadening diversity is lack of wide access to geoscience programs for minority populations. One way SZ4D can help address this deficiency is to provide opportunities for minority-serving institution (MSI) students to participate in SZ4D activities. Another option would be for MSI faculty to become involved in SZ4D activities

that they could then share with their students. It will be important to learn about BAJEDI strategies that have been successful at MSIs.

Considering the options MSIs present for engaging a more diverse community in SZ4D, a second objective is to **encourage the building of mutually beneficial networks/partnerships between MSIs and research institutions involved in SZ4D** (NASEM, 2019; NCSES, 2019). While some of the research institutions involved in SZ4D are MSIs themselves (e.g., Arizona State University, University of California Santa Cruz, University of California Davis, University of Houston, University of New Mexico, University of Texas El Paso, University of Washington), most are not. Establishing relationships between SZ4D institutions and interested MSIs has the potential to provide new opportunities for both sides. However, forging new relationships requires trust, so the use of memorandums of understanding (MOUs) between geoscience departments at paired institutions is recommended to help describe the commitments in working together. MOUs could outline the range of opportunities each institution intends to offer (e.g., hosting, information exchange, training workshops), along with the expected timeline. In seeking to develop relationships with specific institutions, SZ4D should also work with minority-focused science organizations (e.g., Society of American Chicano and Native American Scientists [SACNAS], American Indian Science and Engineering Society [AISES], National Association Black Geologists [NABG], GeoLatinas, National Association of Geoscience Teachers at 2 Year Colleges [NAGT2YC]) that can provide guidance based on prior experience and their knowledge of the communities involved.

A third objective is to **promote rigorous science through changing the science culture to value diverse perspectives**. Studies demonstrate that we need diverse perspectives to ask and solve important science questions (e.g., Powell, 2018). They remind us that the people who have the means to participate in SZ4D science will get to define what questions get asked and researched. Based on these studies, SZ4D should ensure a diverse group of scientists are integrally involved in science planning and activities, including the funded research, the review panels, and the organizational leadership.

Finally, we seek to **increase geoscience literacy in diverse communities**. Research finds science literacy is connected to authentic uses of science in daily life (Feinstein, 2011). We recommend that SZ4D outreach efforts support community workshops and supply educational materials that provide information about local geohazards to help minority communities understand the risks and become more engaged with the geosciences (Basu and Barton, 2007). This engagement is important, as minority communities are often disproportionately affected by environmental and natural hazards. The *EarthConnections Alliance* is an example of an existing effort that we could build upon

CONNECTIONS AMONG RESEARCH GOALS: COMMON NEEDS AND ACTIVITIES

The traceability matrices allowed BEGC to identify a number of common needs and activities across the different BECG research goals. The needs showing relationships to the largest number of goals suggest they should

be SZ4D community priorities and addressing them would have the greatest impact. Similarly, the activities most commonly identified to address needs should be prioritized for SZ4D investment. **Figure BECG-2** highlights the most commonly identified needs and activities and illustrates the key connections between the goals, needs, and activities.

The next section describes how the key elements of a successful Collective Impact model directly meet the most common needs identified by the BECG traceability matrix process.

AN OVERARCHING FRAMEWORK TO ACCOMPLISH THE RESEARCH GOALS: COLLECTIVE IMPACT

Kania & Kramer (2011) proposed the Collective Impact (CI) idea, in which a group of people from different sectors commit to a common agenda for solving a specific social problem using a structured form of collaboration. CI has quickly grown in popularity (Kania & Kramer, 2013) and has been recognized by the White House Council for Community Solutions as an important framework for progress on social issues (Jolin, 2012). In contrast with CI's collaborative approach, the isolated impact approach occurs more commonly as single entities try to make the most impact with the fewest resources. Isolated impact often results from grantors seeking to satisfy a specific goal when allocating funds: support the proposals that make the greatest impact with the fewest resources, within a limited timeframe that does not align with the pace of typical institutional change. This traditional system produces efforts that often have minimal lasting effects on communities due to a short-term focus on rewards and costs, and it motivates proposers to focus on distinguishing their efforts from others. In fact, studies indicate relying on the Broader Impacts criterion of NSF proposals to accomplish social impact is flawed (Bozeman & Boardman, 2009; Nadkarni & Stasch, 2013). We thus contend that the goals and objectives outlined in this chapter cannot be accomplished through physical science PIs proposing individual social impact efforts as addenda to proposals primarily focused on physical science research. Instead, **SZ4D PIs should be envisioned as playing a role in a larger cooperative effort that is seeking to accomplish long-term broader impacts through a CI framework**. The SZ4D community sees CI as an opportunity for transformative change, enhancing our ability to create more sustainable, positive outcomes to education and outreach efforts and BAJEDI issues within the geoscience community.

Previous research has shown that successful CI initiatives typically meet five criteria that together produce the alignment necessary to make meaningful and sustainable progress on social issues (Kania & Kramer, 2011). The first is a **common agenda**, in that all participants have a shared vision for change that includes a common understanding of the problem and a joint approach to solving the problem through agreed upon actions. The second is a **shared measurement system**, in which there is agreement on the ways success will be measured and reported with key indicators by all participating organizations. The third is **mutually reinforcing activities** that engage a diverse set of stakeholders, typically across multiple sectors, in a set of differentiated activities that combine together to form a coordinated plan of action. The fourth is **continuous communication** that involves frequent interaction over long

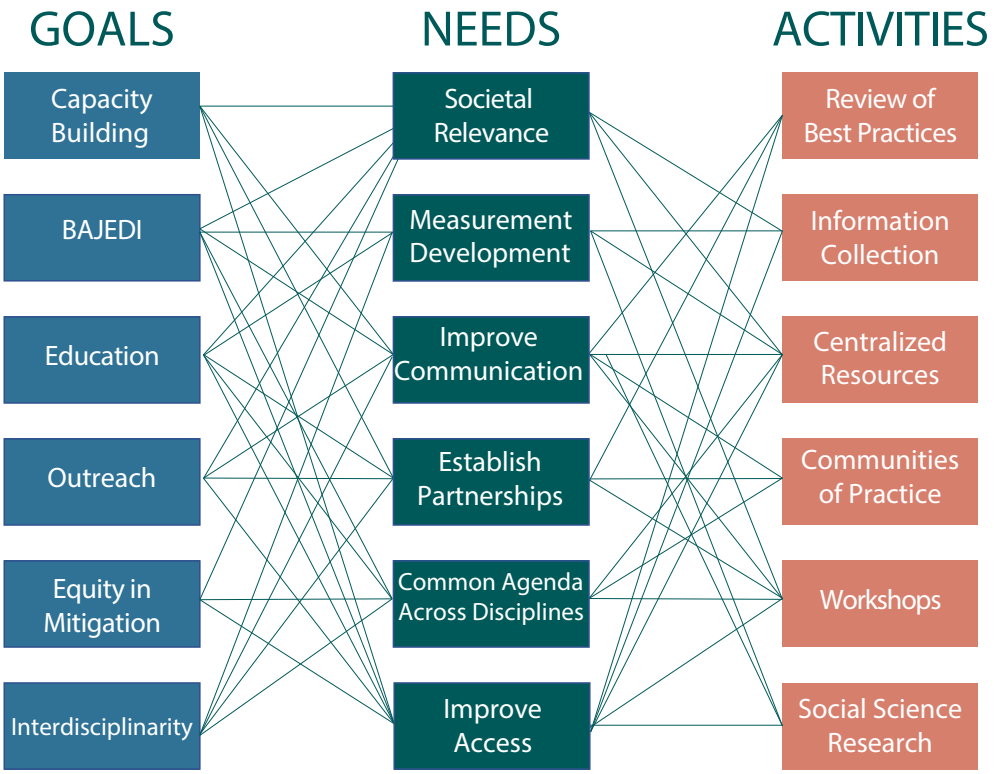


Figure BECG-2. *Diagram illustrating connections between BECG research goals, primary needs, and suggested activities. The overlapping connections illustrate how implementing an activity can meet several needs and how progress on a need can help several goals.*

periods among key players within and between organizations to build trust and encourage ongoing learning and adaptation. The fifth is a **backbone organization**, where independent staff provide ongoing support. The backbone staff and volunteers play several roles to move the initiative forward: guide strategy to match vision, support aligned activities, facilitate shared measurement practices, build public will, advance policy, and mobilize funding (Turner et al., 2012). If these five criteria can be met, the successful result observed involves cascading levels of linked collaboration (**Figure BECG-3**).

We are encouraged that SZ4D working and integrative group efforts have already made progress on the first CI criterion by agreeing on a common agenda with a shared vision. We have established the most important research questions through collective discussion and then vetted them through multiple town halls and all hands meetings with larger portions of the SZ4D community. The chapter draft review process, June 2021 All Hands Meeting, and Catalyst Proposal review process gave the SZ4D community an opportunity to review and provide feedback on the proposed approach of defined needs and suggested activities to answer the research questions. This process has strengthened our common understanding of SZ4D's scientific agenda and support for building a CI framework. The remaining CI criteria are less well developed in SZ4D efforts up to this point, but we find remarkable alignment between the CI criteria and the critical needs independently identified by BECG (**Figure BECG-2**). Finally, the need for backbone organization as a CI criterion indicates that SZ4D should be prepared to support several staff members to coordinate and sustain BECG activities.

We should note that CI is not a magic elixir and that several criticisms of this framework have been made (Wolff, 2016; Wolff et al., 2017). In particular, CI has been criticized as promoting a top-down model that doesn't sufficiently engage those most affected by the issues in shared decision-making. However, we believe that several BECG goals address this issue by focusing on BAJEDI, international partnerships, and inclusiveness throughout strategies for community engagement. Nevertheless, the criticism is a reminder that SZ4D, with the guidance of BECG, would need to be open and available for all to participate and influence the direction.

Implementing a CI framework for SZ4D activities will help transform the mindset of our geoscience community to embrace education, outreach, capacity building, belonging, access, diversity, equity, inclusion, and social justice as critically important for the success of the SZ4D scientific endeavors.

IMPLEMENTATION PLAN AND PHASING

The open review and comment period for the draft Implementation Plan in 2021 gave the broader SZ4D community an opportunity to provide feedback on the goals, needs, activities, and Collective Impact framework proposed by BECG. BECG also received feedback from NSF on the initial draft of the report.

BECG considered all of the feedback and used it to help construct a defined work plan for implementation that focused on five areas with the greatest opportunities:

1. Establishing and sustaining partnerships with key communities,
2. Shepherding communities of practice for social change,
3. Cordinating existing and new international capacity building efforts,
4. Improving education and training by strengthening relationships between SZ4D and key partners, and
5. "Matchmaking" between PIs and BECG efforts.

To organize the projected supporting activities by topic, expected timeline, and key parts of SZ4D responsible for the effort, BECG developed a preliminary *phasing spreadsheet*. This spreadsheet uses the phasing described in **Chapter 5.3**, highlighting activities from the RCN, proposed activities for a two-year catalyst Phase 0, and then estimates activities for Phase 1 (1–3 years), Phase 2 (~10 years), and Phase 3 (~5 years). Please refer to **Chapter 5.4** on Program Structure and Governance for details on the key parts of SZ4D that will be responsible for accomplishing BECG's vision.

Establishing and Sustaining Partnerships with Key Communities

Key to SZ4D's success is building partnerships with national and international organizations that monitor natural hazards, as well as with marginalized communities that are often the most affected by hazards. As a first step, during Phase 0, SZ4D will meet with MSI faculty and students on MSI home campuses and later in a group workshop, with the goal of engaging in mutually beneficial dialogue to define a common agenda for implementing BECG's vision. In particular, SZ4D needs to learn from MSIs what BAJEDI looks like at their institutions so that other SZ4D institutions can implement those practices to increase BAJEDI in our community. Meeting people on campus will be important for communicating SZ4D's

commitment to establishing relationships and provides opportunities to simply listen to MSI faculty and staff. The goal is for this dialogue to lead to workshop participation and sustained connections between MSI faculty and SZ4D staff (NASEM, 2019). The workshop will be designed to foster honest and unobstructed communication between MSI and SZ4D representatives (Ballysingh et al., 2017; Gonzales et al., 2021). It will be modeled after recommendations made for how NSF can better support MSI capacity building (ASEE, 2020).

Growing a trusted network of community partners to regularly communicate critical information on geohazards is fundamental to SZ4D broader engagement. Based on literature review and discussion with experts (e.g., Kozo et al., 2020), we will **develop a "Partner Relay" model, where SZ4D will partner with emergency management agencies and a network of trusted community organizations, including locally operating nonprofit, non-governmental organizations that regularly work with targeted populations**. Although we initially considered a more distributed model for outreach that would train SZ4D community members to communicate directly with the general public, BECG identified expertise and research that indicates science communication and outreach is more successful when delivered by trusted organizations (Fischhoff, 2013; Weingart & Guenther, 2016). Thus, SZ4D will focus on providing key takeaways and science messaging to trusted community agencies, who will then relay this critical information to the general public. This approach will also enable SZ4D to accomplish more equity-oriented engagement and strategies for preparing bi- and multilingual communities for natural hazards and risks associated with them (Kozo et al., 2020). Based on its initial work, BECG will develop a prioritized list of agencies and organizations to target during Phase 0 so that SZ4D can begin establishing partnerships. Additional follow-up will include identifying key community vulnerabilities and determining how SZ4D might better convey information to the groups. The results of these meetings would be compiled and shared with the SZ4D community.

Training the SZ4D community in best practices for interdisciplinary and international collaboration and awareness of BAJEDI issues will be central to partnership development. For example, to help ensure success of the 2022 SZ4D National Meeting in Chile, BECG developed cultural competency training and offered it to all US participants before the meeting. BECG will continue to develop and implement these training sessions on a regular basis to build trust, stay connected, and promote and encourage sharing of resources, ideas, and inclusive strategies across the partnerships.

Shepherding Communities of Practice for Social Change

Studies of the physical processes of solid Earth geohazards can make limited contributions to hazard risk mitigation. Research indicates that disasters are a result of natural hazards interacting with social structures (e.g., Kelman, 2018), and misinterpreted scientific results may have deleterious effects on communities in the event of a disaster (e.g., Albris et al., 2020; Alexander, 2014).

During Phase 0, SZ4D will establish several **communities of practice** (CPs, i.e., groups of people who share common interests or goals). Each CP will include people from its diverse network of disciplines, institutions, stakeholders, communities, and nations, bringing multiple perspectives to bear on the challenges faced

by SZ4D. During Phase 0, year-long CPs will gather groups of physical and social scientists to build components of the CI framework for SZ4D. The CPs will target three of the BECG research goals:

1. BAJEDI,
2. Capacity building, and
3. Interdisciplinary collaboration.

Stipend support will be used to attract both physical and social science experts and to ensure participants commit to achieving the goals over a longer timeframe (Ward & Selvester, 2011). Financial support also honors the importance of this work and encourages its participants to engage with one another and with the project in more purposeful ways. Participation and formative and summative assessment of the outcomes will be monitored. Outcomes will be presented to SZ4D governance for decisions about implementing recommendations.

Initial Community of Practice Descriptions

The **BAJEDI CP** will build on the MSI workshop to identify opportunities for increasing the pool of diverse students, faculty, and professionals in SZ4D (e.g., Powell, 2018; Hofstra et al., 2020). The CP will identify mutually reinforcing activities for increasing access to SZ4D science for underrepresented populations. To recruit and retain a diverse SZ4D community, it will be critical to develop effective strategies for communicating the relevance of BAJEDI efforts to everyone in the SZ4D community. The CP will develop rubrics to assess the effectiveness of the various BAJEDI efforts across SZ4D, as self-examination is crucial for identifying and addressing BAJEDI issues (Velasco et al., 2021).

SZ4D provides an exceptional opportunity to establish equitable international capacity-building partnerships to improve capabilities (e.g., skills, data, technology, understanding) for all stakeholders involved. The **Capacity Building CP** will identify mutually reinforcing activities for cooperative international field research, sustainable human capacity building, technical infrastructure development, and FAIR data and research policies (Fecher et al., 2015). Efforts to minimize colonial methods of interaction will be central, including continued development of cross-cultural implicit bias training (e.g., Nordling, 2017; Cartier, 2019). The CP will also consider strategies to increase adoption of and participation in the scholarship of teaching and learning to improve training efforts. Measures for assessing whether trainees are properly equipped with SZ4D-specific research skills will be developed in collaboration with geoscience education researchers. The CP will also focus on outreach strategies for understanding geohazards and associated risks by identifying mutually reinforcing activities to connect SZ4D science to key non-scientist stakeholders and evaluating effectiveness of outreach with shared measures.

The **Interdisciplinary Collaboration CP** will seek to implement evidence-based practices for collaboration that break down disciplinary silos and improve understanding across subject areas. The CP will establish a consensus set of key elements in a successful interdisciplinary collaboration, accounting for both costs and benefits, and develop methods to assess and improve SZ4D collaborations (Goring et al., 2014). This will build on a review of best practices and common obstacles of prior community efforts being compiled by the SZ4D RCN, extending into research on collaboration (Collins et al., 2007; Lenfle & Söderlund, 2019).

There are **compelling recent examples that SZ4D can use to model its CP approach**. The ShakeAlert® Earthquake Early Warning (EEW) Joint Committee for Communication, Education, Outreach, and Technical Engagement (*JCCEO&TE*) is a vibrant international effort that, over six years, has assembled a broad spectrum of practical resources, tackled difficult questions, and provided great insight into the social systems that are inherent to hazard mitigation. Over the same period, the NSF GEO Directorate has sponsored BAJEDI-themed grant programs (GOLD, GOLDEN) to foster organizational diversity and transformation and has increasingly required the inclusion of social scientists in efforts to diversify the culture of science (Posselt et al., 2019). SZ4D will follow this lead in recruiting and compensating experts in equity-centered higher education to design CI components of SZ4D from the very beginning stages.

Coordinating Existing and New International Capacity Building Efforts

Through its effort during the RCN stage, SZ4D is now positioned to leverage, coordinate with, and complement existing international capacity building activities, especially those relevant to a South American focus site. We will use workshops to **bring existing groups/leaders together to identify similarities and differences in current efforts and identify gaps where there are opportunities for new initiatives/developments**. SZ4D will organize one-day "add-on" workshops of opportunity associated with established community meetings (e.g., AGU, EGU, GSA, SSA, IUGG, LACSC, SAGE/GAGE). These meetings of opportunity are an efficient way to entrain new participants, including early career investigators, build relationships with international partners and stakeholders, share experiences, and plan/coordinate specific capacity building activities. SZ4D will strive to support virtual meeting options to encourage participation of groups that are unable to travel; this option became available during the COVID pandemic and was used for Special Interest Group meetings with themes on international collaboration held at the 2021 (fully virtual) and 2022 (hybrid) SAGE/GAGE community workshops.

The SZ4D Center will **facilitate regular meetings between both SZ4D governance and SZ4D project principal investigators to prioritize needs and develop opportunities** for capacity building efforts. SZ4D communications with Chilean and Argentine collaborators and with other international partners has made us aware of the needs and challenges facing local stakeholders. These international relationships also provide SZ4D governance with a foundation for coordinating project execution with specific SZ4D PIs. SZ4D governance will cultivate and engage its contacts at both international and domestic sites to broker sustainable project plans from PIs that maximize the impact of their work. SZ4D will continue to reinforce the use of FAIR practices across all SZ4D data and data products, building off models developed by IRIS, UNAVCO, and IEDA, and extending into other communities. SZ4D has helped to initiate conversations between data providers in the United States and Chile for this purpose.

A fundamental element of capacity building is bringing people together to work in the same space. SZ4D will **provide funding to support travel and SZ4D staff coordination to enable bi-directional international student/postdoc exchange programs**. The initial focus will be on developing an **international network focused on subduction geohazards (SZNet)**, with the

Cascading Levels of Collaboration

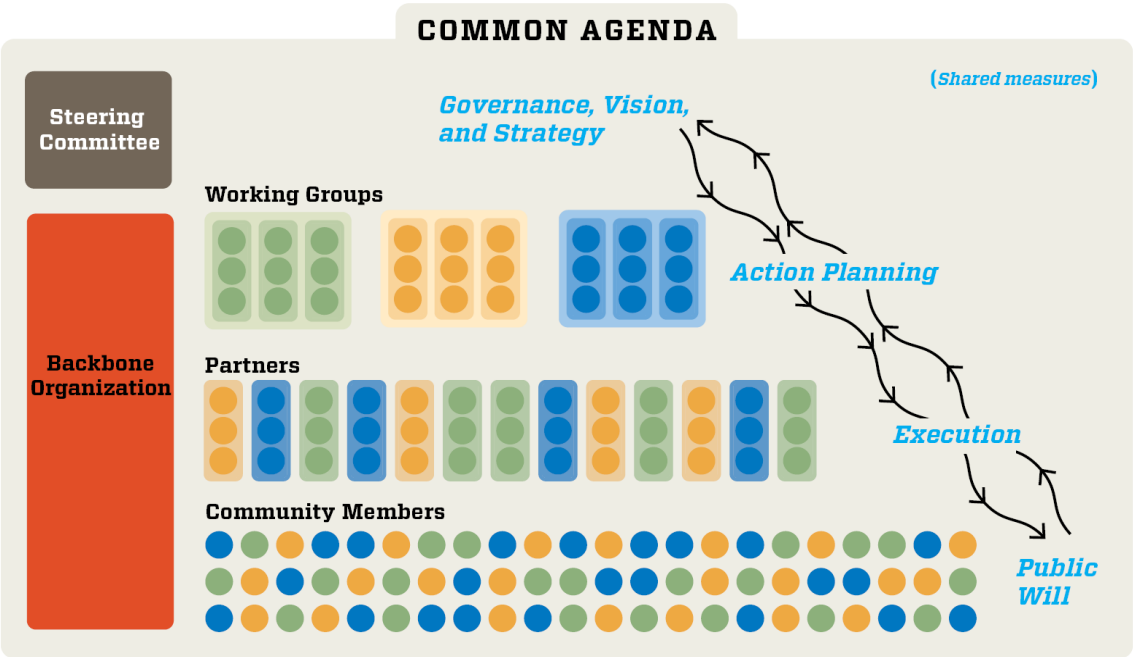


Figure BECG-3. *Cascading levels of collaboration that are observed with a successful Collective Impact framework. Figure from Kania and Kramer (2013).*

goal of fostering a cadre of early career scientists who can synthesize information from different subduction zones and who have a diverse set of international contacts. The NSF AccelNet program can facilitate international training and exchange of students and postdocs within SZNet. We expect that groups like SZ4Grads will participate in SZNet as well as channel awareness to their own networks. Funding for SZNet would enable a variety of activities, spanning in-person fieldwork collaborations to travel to an institution in the United States, Chile, or other countries participating in SZNet to conduct sustained, collaborative research. SZ4D PIs would also be encouraged to consider different levels of experience, including summer/winter break research experiences for undergraduates, utilizing student cohorts and dedicated mentorship, similar in style to UNAVCO's and IRIS's summer undergraduate internship programs. These interactions will benefit from a continued emphasis on cultural training, implicit bias, and equitable models of collaboration to avoid imperialistic and colonial interactions (e.g., Cartier, 2019; Wight, 2021).

Any new capacity building activities must **leverage existing resources to develop a sustainable model** beyond the sunset of SZ4D. Capacity building has been facilitated by a variety of academic, monitoring, and philanthropic organizations (e.g., *IRIS International Development*, *Volcano Disaster Assistance Program*, *Earthquake Disaster Assistance Team*, *Geoscientists Without Borders*, *Engineers Without Borders*) distributed in the United States and internationally. SZ4D will engage with these groups to learn from their experiences and, ideally, collaborate on shared opportunities. In particular, we would like to better align and learn from academic groups that our community has some familiarity with already, including the Earth

Observatory of Singapore and the International Centre for Theoretical Physics in Trieste, Italy. In addition, through SZ4D's strong connection with the USGS, we will draw from its significant expertise from its Volcano Disaster Assistance Program (e.g., Lowenstern & Ramsey, 2017) and Earthquake Disaster Assistance Team to navigate the complexities of in-country capacity building with hazards applications. Throughout this process, SZ4D will continue to engage with and learn from complementary efforts such as the AGU-sponsored *Hazards Equity Working Group* and *Thriving Earth Exchange*.

Lastly, a key practical consideration for SZ4D will be the **translation of all associated educational/training materials** as they are developed, to broaden and maximize their utility. With a primary international site in Chile, Spanish and Indigenous language translations will be the first-order product and will be able to provide immediate impact to other stakeholders throughout Latin America. This effort will initially focus on scientific and educational products, such as topical scientific or research presentations, public outreach presentations, synthesis reports, methodology or field practice training materials, technical workbooks, and classroom lessons, and will build upon existing resources (e.g., SERC, UNAVCO, IRIS). In cases where material is being developed from scratch, Native language participants recruited from SZ4grads and elsewhere could be supported to participate in the development of educational content and subsequent translation. We will continue to establish connections in the research and teaching communities in Latin America to ensure that our products have meaningful applications and to provide opportunities for feedback. We will also use partnerships with other international groups, especially those working in other parts of the developing world and in regions with subduction processes and associated hazards (e.g., Indonesia), to determine how best to adapt these products to wider audiences. As appropriate, we will work with local experts to factor in cultural context and national educational standards in the development of training pedagogy and to ensure that any classroom-specific material is appropriate.

Improving Education and Training by Strengthening Relationships between SZ4D and Key Partners

An essential part of the SZ4D mission is to freely share its scientific findings and advances in research methods and technologies, and nurture and sustain the reciprocal relationships it will build within the research community as well as the communities where it does research. SZ4D should proactively contribute to **formal education** (at universities, colleges, and K–12 schools), to **informal (public) education and interpretation** (at museums, science centers, and parks and preserves), and to the **training and professional development** of a diverse cadre of new and experienced scientists and educators alike. Many in the SZ4D community already have accrued valuable experience in one or more of these realms that can help guide SZ4D educational strategies. However, there are numerous organizations with ongoing educational efforts that SZ4D should seek to partner and coordinate with, including the National Association of Geoscience Teachers (NAGT), National Earth Science Teachers Association (NESTA), National Science Teachers Association (NSTA), Science Education Research Center (SERC), and the education divisions of AGU and GSA, as well as affiliated scientific organizations such as the EarthScope Consortium, OpenTopography, Computational Infrastructure

for Geodynamics (CIG), Community Surface Dynamics Modeling System (CSDMS), USGS, NASA, NOAA, and State geological and hydrological surveys. During the first phase of SZ4D, we will organize a workshop with representatives from these organizations to establish partnerships and plan activities with the SZ4D community. PIs and instructors will be encouraged to contribute presentations at regular large conferences and in smaller workshops and short courses specifically focused around teaching and training. Coordination with organizations such as SERC for the **curation of educational resources** will also be essential to ensure the efforts persist beyond the timescale of individual research projects.

SZ4D staff and a rotating set of PIs will offer **topical summer institutes** that focus on incubating research to address SZ4D science questions. These institutes will be based on the successful model established by CIDER Summer Programs. CIDER places a strong emphasis on intensive teamwork on a specific research problem to foster communication across disciplines and scientific generations while also providing mentorship and new research opportunities for the next generation of solid Earth scientists.

The breadth of SZ4D's planned activities also provides an opportunity to investigate best practices in geoscience education. Educational research will be needed to evaluate optimal training strategies for developing:

1. Spatial and temporal reasoning skills to handle increasingly large and detailed 4D datasets,
2. The ability to work coherently in large-scale fieldwork settings such as the human deployments proposed to collect critical SZ4D data, and
3. The capability to create and validate models that reveal essential new information. An SZ4D Science Program should also support complementary geoscience education research that investigates strategies to improve how we equip SZ4D students and postdoctoral researchers.

"Matchmaking" Between PIs and BECG Efforts

SZ4D's CI framework will facilitate scientists working together across disciplines rather than in parallel on individual projects. For this effort to be successful, we need structures that foster, support, and reward impactful collaborations whose efforts span both scientific and broader impacts.

All topical SZ4D workshops will bring together participants from a wide range of disciplines and at various career stages. **Each topical workshop will highlight professional development programming that fosters successful approaches for research program development and collaboration** (e.g., Youtie & Boseman, 2014).There will be a focus on early career researcher attendance so that we can reinforce the benefits of interdisciplinary collaboration in an academic culture that tends to focus value on specific research outputs such as primary-authored publications (Goring et al., 2014). We will establish mentorship structures for these participants to leverage as they develop discipline expertise but with an eye toward interdisciplinary applications.

To facilitate PI engagement in impactful broader impacts projects, we need to **build a system where PIs can contact SZ4D in the proposal planning stage to ask for assistance in developing broader impact strategies that align with and leverage existing BECG**

efforts and resources. SZ4D staff can identify potential connections, share points of contact, and facilitate dialog. Because the SZ4D staff will be maintaining a database of local scientists and other potential collaborators, they would be able to help PIs make connections within the areas of geographic focus. For example, the application and attendance information collected as part of the 2022 SZ4D national meeting in Chile provides a starting point for SZ4D to establish connections with local scientists based on shared interests.

By maintaining a **publicly accessible database that highlights activities and collaborations, PIs can explore how their efforts fit into a broader context**. To provide an accurate view of BECG efforts, the SZ4D database should seek to include activities that are funded through a SZ4D science program and those that are funded by other programs, agencies, and governments that are related to SZ4D research questions. This information can be collected in two ways:

1. Proposals requesting additional research funding will be contingent on providing information on previous, ongoing, and planned BECG efforts, and
2. All workshop participants will be required to provide information on their BECG efforts with their registration.

Opportunities for collaboration presented by the database can be highlighted in SZ4D communications to encourage participation.

While elements of these approaches have been used by other science centers, such as the Southern California Earthquake Center, we are not aware of any organization that has provided mechanisms to foster and assess collaborative capacity building efforts to this extent. To help ensure equity on this new pathway, SZ4D will annually assess the balance of ongoing broader impacts efforts and recruit collaborative endeavors for critical, underrepresented activities. The committee approach, drawing from a wide cross section of the community and stakeholders, offers a broader-based platform to make connections outside of the traditional modes of collaboration. It is SZ4D's intent that the collaboration development strategies will successfully transform how we create and sustain equitable collaborations that will serve as models for future efforts within geosciences.

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MODELING COLLABORATORY FOR SUBDUCTION

TOWARD AN INTEGRATIVE COMMUNITY FRAMEWORK FOR SUBDUCTION ZONE MODELS

The Modeling Collaboratory for Subduction (MCS) is a community- and model-building effort to advance subduction zone science. The MCS group was envisioned as a core component of the Subduction Zones in Four Dimensions (SZ4D) initiative in the *Boise Subduction Zone Observatories report* (McGuire et al., 2017). Given the novelty and ambitious scope of MCS and SZ4D, their planning efforts were subsequently funded as separate RCNs. In April 2022, the MCS and SZ4D RCNs officially joined under the overarching SZ4D umbrella, and MCS will become one of the core facilities and activities of SZ4D. The MCS RCN supported a series of community workshop discussions that are summarized in detailed workshop reports (Wada et al., 2019; Dunham et al., 2020; Wada & Karlstrom, 2020; Gonnermann et al., 2021). This chapter highlights the key points that arose from these workshops, planning efforts in conjunction with the SZ4D working and integrative groups, and broad community discussions. Specifically, this chapter focuses on the structure and implementation of MCS; the detailed scientific objectives of the MCS group are woven into the individual working group chapters.

The objective of MCS is to create new kinds of physics-based models for subduction zone hazards and apply them to understand fundamental physical processes, guide instrumentation

deployments, interpret observations, and assess predictability of hazards. Specifically, MCS activities will be built around the following overarching objectives:

- Construct models that link subduction zone state and long-term margin evolution to the character and predictability of event occurrence.
- Integrate observational constraints into models, while simultaneously using models to define optimal observational strategies.
- Build physics-based, predictive models for volcano, earthquake, and geomorphic systems that are spatially and temporally coupled.
- Build a diverse and equitable community of scholars who are well versed in modern modeling tools.

At a more granular level, the MCS group will work toward addressing the science questions posed by the SZ4D working groups. The individual working group chapters describe the modeling tools required to achieve their goals and identify specific areas where MCS input will be needed for success.

From the outset, MCS will integrate physics-based modeling and discovery into the observational and laboratory efforts of SZ4D, rather than following the more typical sequence in which modeling is used only after data collection. In this way, modeling will be employed not only for interpreting datasets, but in the planning and design of observational deployments. As new observations come online, data streams will be assimilated into models to assess the "state" of megathrust and volcanic systems, recognizing that long-term processes and geologic/geophysical context can play key roles in shaping individual rupture or eruptive events. MCS will employ adjoint models and physics-enabled machine learning and artificial intelligence approaches that fully leverage the new datasets being collected. In this way, we seek to transform how large-scale Earth programs are conducted and enhance what they can achieve in terms of advancing solid Earth systems science.

In the context of MCS, "model building" is a means to validate new physical descriptions, make predictions based on simplified theoretical approaches, and develop numerical models that can be used to explore the general role and interactions of fundamental processes in controlling system behavior (i.e., for the physics-based discovery of emergent phenomena). Numerical modeling can also be integrated with laboratory experiments or analog physical models to facilitate the up-scaling of laboratory results to large-scale natural systems.

In addition, MCS seeks to build more complex, "applied," and regionally "realistic" models that can fully assimilate both structural information (e.g., from geophysical imaging and geology) and time-dependent sensor data streams (e.g., from seismometers and geodetic sensors) from global subduction zone observatories (**Figure MCS-1**). One exciting new direction in this regard is the development of adjoint models based on full or reduced-order physical models, as well as physics-enabled machine learning techniques, the combination of which have the potential to inform real-time hazard assessments alongside more traditional inversions of multi-sensor data.

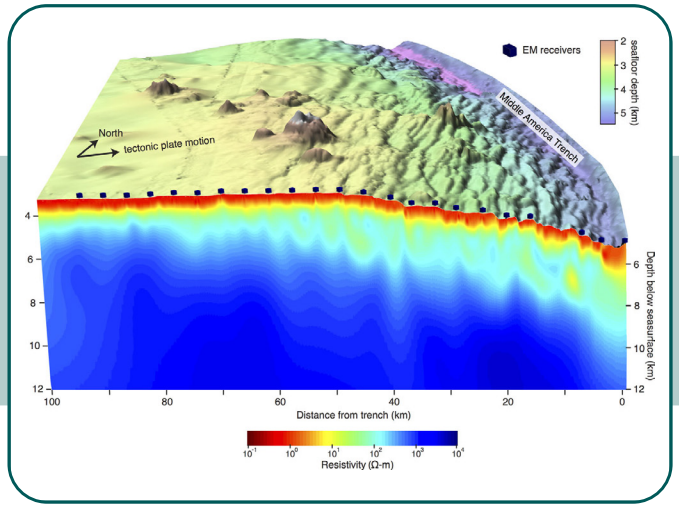
Such new approaches are needed to consistently interpret constraints on the general workings of earthquakes, volcanoes, and surface processes in subduction zones; to identify knowledge

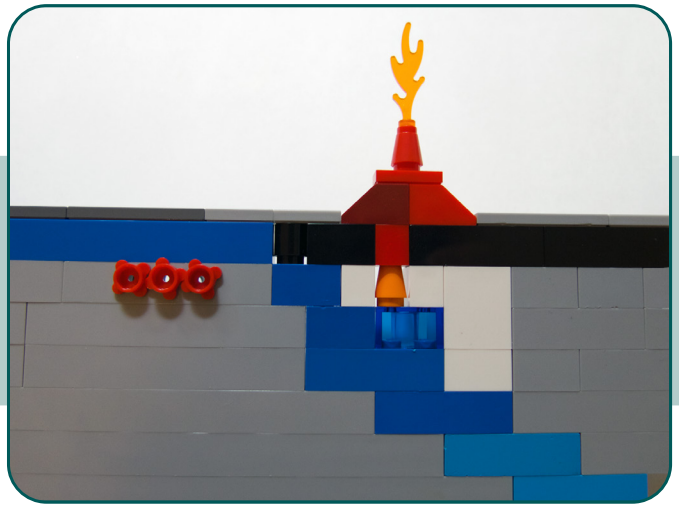
gaps in our physical models; and to define optimal observational strategies to reduce uncertainties. Construction of the relevant tools will require extensive validation and verification efforts, which have the added benefit of pushing forward quantitative standards for modeling and inversion across earthquake and volcano science, generally (e.g., SCEC). On the decadal timescale, MCS will lead to the new fundamental science and operational approaches that are needed for quantifying, and possibly forecasting, earthquake, tsunami, landslide, and volcanic hazards.

The modeling envisioned by MCS will be advanced through SZ4D's ambitious plan for new observational infrastructure in Chile and complementary sites in Cascadia and Alaska. The new data streams from MegaArray, VolcArray, and SurfArray will be used to inform and test models, leading to further model refinement and possibly incorporation of additional physical processes. Moreover, it is clear that subduction zones on Earth are diverse in terms of their tectonic setting and/or current stage within their volcanic or earthquake cycles. To advance subduction zone science, it is therefore imperative to also integrate observations from other regional laboratories outside of SZ4D's primary focus sites to arrive at a globally validated physical understanding.

MCS is envisioned as a new SZ4D core facility that can serve to support the development of such a framework and provide a home for sustained interactions between modelers, experimentalists, and observationalists. Sustained efforts are crucial because we do not yet know how to assemble complete models of earthquakes, volcanoes, and landslides. MCS can provide and assimilate building blocks to test alternative physical descriptions and identify the most important processes in controlling system behavior, providing the glue between studies of subduction zones through geologic time and current activity. Moreover, MCS can support global subduction zone research communities, including the local stakeholders, as well as international and domestic observatories in different stages

Figure MCS-1. *Concept of a modular, building- block-based framework for physics-based modeling provided by the MCS to explore general physical processes and to create regionally specific subduction zones modes, for example, to interpret real-time sensor data for system "state." Left: Electric conductivity structure for Central America (from Naif et al., 2015).*





of their implementation, helping to support cross-disciplinary and cross-site collaborations. Model-based cross-validation is needed to quantitatively link insights from the Chilean observatory, as well as other international efforts, to hazard and risk settings of domestic societal concern for the United States.

Further, while any successful study of subduction zones requires an appreciation of their physical and geologic diversity, it also requires acknowledging the importance of fostering a diverse scientific community to perform these studies. MCS presents a novel opportunity to help establish computational approaches as alternative entry pathways for underserved and underrepresented communities into the geosciences. Such efforts will complement more traditional training and community-building efforts to empower computational scientists with the interdisciplinary tools they need to be successful. Together with extensive, sustainable, equitable, and coordinated outreach and teaching efforts (e.g., to enhance quantitative literacy in K–12 students and undergraduates), MCS and the computational geosciences, in general, can contribute greatly to efforts to build a better and more diverse community of geoscientists. This important theme is further explored in the BECG chapter. MCS will play a large contributing role in initiating and supporting belonging, accessibility, justice, equity, diversity, and inclusion (BAJEDI) efforts within SZ4D, as well as partner with aligned efforts such as Computational Infrastructure for Geodynamics (CIG), Community Surface Dynamics and Modeling System (CSDMS), and Cooperative Institute for Dynamic Earth Research (CIDER) domestically and internationally.

COMMUNITY-DEFINED MCS DESIGN GOALS

Through the workshops and community engagement sponsored by the MCS RCN, key design goals were defined in order for MCS to achieve the guiding objectives described above. The community emphasized the need to create new pathways for discovery, based on investments in human and computational infrastructure and that are supported over timescales longer than a typical grant cycle. The MCS RCN workshop reports describe these community-defined design goals in significant detail. Here, we highlight the common themes that crystallized from these community discussions among observationalists, experimentalists, and modelers. Specifically, the community recommends that MCS should:

- Support the development of new physics-based forward models to study geologic hazards associated with subduction zones. Model development in these efforts should be guided by the science objectives of the SZ4D working groups with priorities defined by community input.
- Support sustained exchange between computational, observational, and laboratory subduction zone scientists within SZ4D and the broader community through workshops, hackathons, and shared model building. Specifically, this scientific exchange can be realized through regional and process-focused research groups.
- Support model and modeling framework tool development and validation/verification exercises, with a mix of centralized and distributed approaches, based on continuous community input and guidance,

and supporting both community-based and PI-driven code development, as well as centralized framework efforts.

- Support the documentation and usability of codes through tutorials, cookbooks, and workflow examples to allow the use of models for both teaching and research applications.
- Support SZ4D operations by storing and disseminating data-derived products, such as community structural models, and serving as a repository for inverse and forward modeling and data analysis tools from all disciplines involved in SZ4D.
- Support access to computing resources, which will empower scientists with different backgrounds and institutional support, and broaden and democratize participation in leading-edge, data-driven, high-performance and cloud computing within the solid Earth sciences.

While striving to achieve these goals, MCS should be strategically guided by principles such as:

- Providing validated, flexible, robust, well-documented, and efficient open-source codes with inherent consideration of multi-physics, cross-scale, adjoint approaches, and uncertainty quantification.
- Embracing the guiding principles of open science and FAIR (findability, accessibility, interoperability, and reusability) data practices with standardized output formats.
- Empowering the widest and most diverse representation of the community, equitable representation of all voices and supporting active international collaboration.

For many problems a range of alternative, possibly competing, modeling approaches are needed. Thus, when possible, MCS should support modular workflows (**Figure MCS-1**) rather than a single "consensus" approach for how the physics of subduction should be modeled. Model components can then be verified and benchmarked first to ensure that codes tackle the subsystem components involved in the coupled multi-scale, multi-physics problems correctly and efficiently. Moving toward validation (i.e., ensuring that the overall physical representations - the coupled subduction models - are the right ones), codes must simulate interactions across scales and explore coupled physical processes. For this, the more general framework must be tested as widely as possible both at the SZ4D sites and through the integration of data from different regional subduction zones, laboratory experiments, and other natural laboratories.

Lastly, to be successful, MCS must ensure tight collaboration between computational and applied math experts and domain scientists, as well as close exchange between modelers, experimentalists, and observationalists. The latter includes supporting modeling and model construction by observationalists and appreciation of data analysis and laboratory experiments by modelers, in the spirit of empowering interdisciplinary research.

In summary, MCS should serve as a computational science facility for SZ4D, providing the most versatile tools possible while pursuing the goal to create physical models for subduction zone hazards. Of course, MCS will not operate in isolation. The science objectives overlap with several agencies (NSF, USGS, NASA, NOAA) and community organizations (e.g., CSDMS, CIG, Volcanology hub for Interdisciplinary

Collaboration, Tools and Resources [VICTOR]), and existing and possible future earthquake centers in the United States. There are also clear links with a number of international partners, such as the Center for Excellence in Solid Earth (ChEESE), an initiative to bring cutting-edge solid Earth high performance computing (HPC) enabled codes closer to hazard applications. MCS will strive to work collaboratively within this constellation of computational centers, leveraging existing infrastructure, while trying not to duplicate efforts.

DATA-DRIVEN COMPUTATION

The MCS is the natural home in SZ4D for data-driven computational approaches, such as deep learning and other machine learning (ML) methods that have seen significant geoscience applications in recent years. These advances are relevant to all components of SZ4D and have utility for researchers working with geophysical, geochemical, geologic, and experimental data and models. MCS combined expertise in physics-based and data-driven computation will ensure a holistic approach of SZ4D modeling and data-analysis efforts. SZ4D will both leverage existing ML techniques and develop new ML approaches in its data assimilation and modeling efforts. Specifically, MCS will utilize ML in the following ways:

1. ML data processing pipelines are adept at event and signal detection, association, location, and automatized interpretation. MCS will build and utilize these workflows to analyze real-time data collected from the on- and offshore instrumentation. Such information can be leveraged to determine seismicity distributions and fault structure as well as image magma plumbing systems and trans-crustal magma transport. MCS will also explore ML-enabled denoising, which is expected to be important for data from ocean bottom seismometers, high-rate geodesy, and other noisy data streams such as volcanic gas emissions.

2. ML-enabled workflows could be applied to rapidly process and reduce real-time multiparameter MegaArray, SurfArray, and VolcArray data for rapid, physics-based data analysis. For example, such ML workflows are now standard in hydrograph modeling. In seismology, observables such as first arriving P- and S- waves from large magnitude earthquakes can be linked to earthquake source time functions to facilitate event identification, analysis, and direct prediction of hazards such as shaking intensity and tsunami amplitudes.

3. Finally, there are opportunities to utilize and leverage the complementary strengths of ML and HPC applications. The promising results of ML methods for extracting information from large datasets can be complemented with physics-based modeling to address concerns about reproducibility and physical inconsistencies for hazard and early warning applications. For example, ML can be used to speed up forward computation and extract control parameters from complex systems. Another example is that ML could be combined with results from high-resolution simulations to reduce the required forward computations for sensitivity analysis and uncertainty quantification, and for exploring optimal experimental design.

Given that the initial planning phase of the MCS RCN was focused primarily on physics-based modeling, it will be important to carry out similar

efforts for data-driven computational science applications like ML in the next phase of SZ4D. Workshops and other community-building activities are needed to identify community needs, opportunities for open-source software development, and training and educational activities.

MCS IMPLEMENTATION PLAN

To fully realize the MCS design goals described above and to support the overall SZ4D effort, we envision an MCS center that will support both centralized and distributed PI-driven modeling and science. The center will support centralized efforts spanning community code development, verification and validation exercises, training through tutorials and hackathons, and the development of community models and workflows for integration of models with data streams from SZ4D and international partners. Furthermore, the center will support distributed, PI-driven modeling and science by providing computational resources (e.g., programmer support, computational hardware allocations, planning support for focused workshops) as part of competitive proposals submitted to the SZ4D science program.

The MCS center's efforts can be divided broadly into science and operations as shown schematically in the organizational structure in **Figure MCS-2**. The center's science agenda will be set by the MCS Integrative Group in coordination with the SZ4D Collective Impact Committee; the chair of the MCS Integrative Group is also a member of the SZ4D Collective Impact Committee. These committees will set priorities for code and model development efforts, workshops, training, and other activities. The execution of these activities will be the responsibility of the MCS facility. The MCS facility staff is comprised of

- The MCS Director, a member of the SZ4D Operations Committee, who oversees the facility operations and serves as PI on proposals to support the facility.
- The MCS Program Manager, who handles day-to-day operations of the facility and handles administrative aspects of the facility such as workshop organization.
- The MCS Outreach Coordinator, who oversees capacity building activities, in coordination with the SZ4D BECG group when appropriate. It is possible that this position would be combined with the Program Manager during the initial stages of MCS until responsibilities grow beyond what a single person could manage.
- Programmers, who support centralized and PI-driven code and community model development and data integration/assimilation efforts.

MCS, in coordination with the SZ4D Collective Impact Committee and the working groups, will help to create and support the regional and process-specific focus groups described in the **Community-Driven MCS Design Goals** section above. These groups will initiate and sustain collaborations between observationalists, experimentalists, and modelers to tackle the SZ4D science questions and integrate constraints from geophysical, geological, and experimental data.

The MCS facility will also support community code development and verification and validation exercises. In many cases, these efforts will be pursued in partnership with existing and/or proposed organizations such as the CIG, CSDMS, VICTOR, and earthquake and geohazard centers

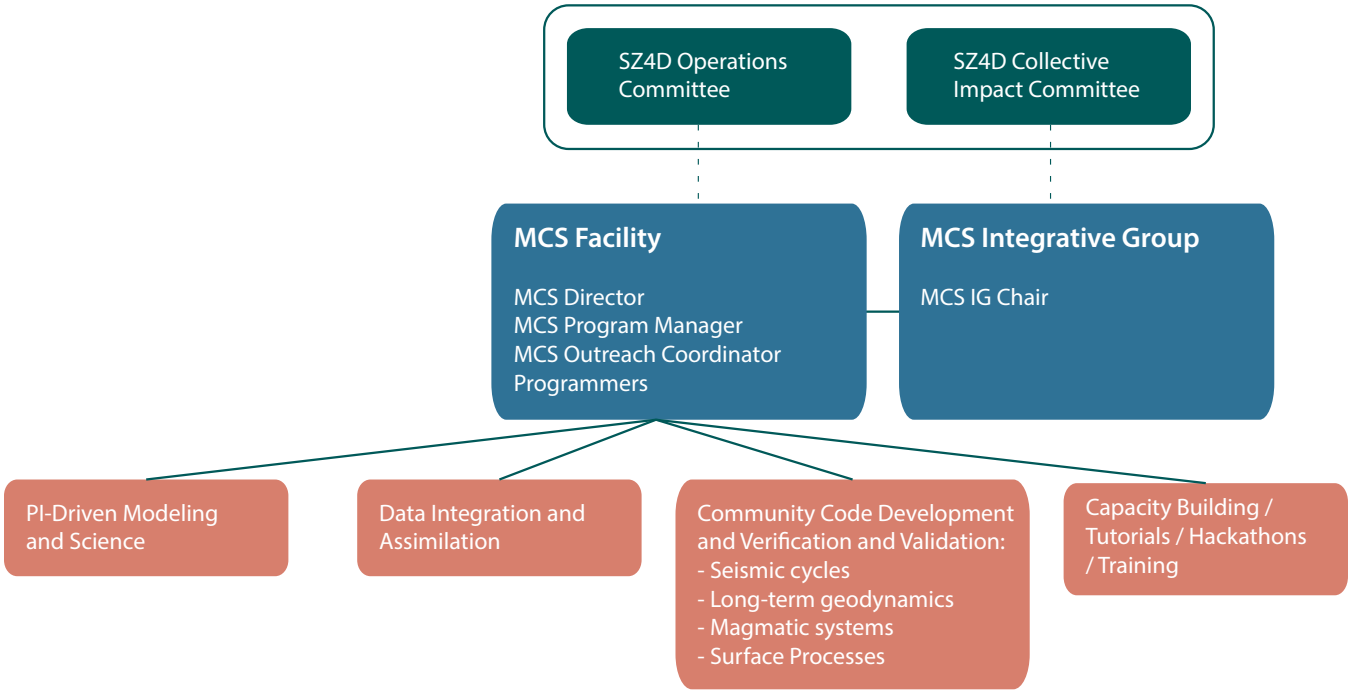


Figure MCS-2. *MCS organizational structure. Yellow boxes illustrate the two main components of the MCS: operations (MCS Facility) and science (MCS integrative group). The MCS integrative group, in coordination with the SZ4D Collective Impact Committee, will set priorities for code and model development efforts, workshops, training, and other activities performed by the MCS Facility. The orange boxes denote the activities that will be performed by the MCS Facility.*

emerging from the NSF Centers for Innovation and Community Engagement in Solid Earth Geohazards program.

As evident from the working group chapters, the current state of community modeling efforts, open-source community codes, and hence the modeling needs of each community are highly variable across disciplines. Some groups have prioritized updating widely used, but relatively simple, software packages for specific model components (e.g., forward and inverse volcano deformation models, phase equilibria calculators) to modern languages and user interfaces. Others prioritize development of open-source community codes for solving complex problems (e.g., seismic cycle modeling) or coupling existing codes into multiphysics modeling workflows (e.g., combining earthquake rupture and ground motion models with landslide and debris flow models). Across all communities there is a common need to integrate forward modeling (of either full-physics models or more computationally efficient reduced order approximations) with various data streams, through either inversions or data assimilation.

A key to this vision is for MCS to provide direct and sustained, science-driven funding for modeling and community code development activities. This vision contrasts with the operations of other existing computational facilities, such as CIG or CSDMS, which currently have minimal funding allocated to new model/code development. CIG prioritizes curating and disseminating existing software and providing training in software development best practices. This makes CIG a natural partner to MCS for certain community code development projects such as seismic cycle modeling. Furthermore, CIG maintains existing codes that can be used to address some SZ4D science questions (e.g., Aspect for long-term geodynamics and deep magma migration, PyLith for crustal deformation

modeling). Similar to CIG, but focused on surface processes, the CSDMS supports computational modeling by engaging the community, encouraging the development of computational tools and protocols, and promoting education; it does not invest significant funds in new code development. In particular, the CSDMS hosts a large discoverable model repository of open-source codes compiled from the community. The CSDMS then develops and supports flexible frameworks to couple different codes together, allowing complex systems models to be assembled from modular building blocks. VICTOR is a smaller effort than either CIG or CSDMS, supporting models for ash dispersal, lava flows, and other volcano-related problems from the vent upward. There is currently no community organizational structure for developing crustal magma transport models, so the deeper focus in SZ4D'S MDE working group is thus complementary to VICTOR and potentially provides a template for advancing modeling of magmatic systems generally. Lastly, we anticipate synergies and collaborations emerging with earthquake and geohazards centers in the coming years.

In many cases, MCS-driven community code development will be pursued by the MCS facility programmers under the supervision of the MCS Director. However, it is crucial to balance this effort, which will necessarily be based upon consensus-driven science, with distributed, PI-driven model and code development. This is essential to support a diversity of ideas and approaches and to engage all interested members of the community. We envision that funding for PI-driven research will come from the NSF SZ4D Science Program, ideally through a proposal-based mechanism to obtain MCS resources such as MCS programmer time, computational hardware allocations, and planning support for focused workshops. This could be done in a similar manner to requests for seismic or geodetic support from other core facilities (e.g., the Earthscope Consortium). Resource allocation decisions would then be made by the MCS Steering Committee in coordination with the MCS Director and SZ4D CIC.

Another component of the MCS facility will be a Data Portal/Hub. Whereas the actual data from SZ4D activities will reside at the EarthScope Consortium and other facilities, the SZ4D community requires a Data Portal/Hub to house derived products such as community models, software repositories, and workflows that facilitate access to data and integration with models. We will leverage expertise from existing computational infrastructure programs and collaborate with other community centers (such as those listed above) and workflow archiving efforts to make basic data and data product infrastructures interoperable.

The capacity building activities, overseen by the MCS Outreach Coordinator in conjunction with the BECG group, will aim at recruiting, training, and supporting a diverse group of scientists with skills that bridge geosciences, computational science, and scientific computing. These activities will include the training programs described above but could also include fellowship programs for graduate students and postdocs. The trainees would reside with PIs and benefit from being part of a cohort coordinated through the MCS center, for example, by participating in yearly hackathons, workshops, training in software development best practices, and mentoring activities.

PHASING

Having laid out the Design Goals and Implementation Plan for MCS, we now propose a phased approach to realizing this vision. The

MCS phasing is deliberately synchronized with similar phasing in the other components of SZ4D. Phase 0, the planning phase, is culminating with the release of this report. **Figure MCS-3** summarizes the MCS phasing plan, which is framed in two parallel efforts focusing on data-stream integration and process-based modeling.

PHASE 1 focuses on the design and development of technology (including modeling and data integration software) needed to collect and interpret data from the SZ4D deployments. The MCS facility (**Figure MCS-3**) can start immediately with a Director, Program Manager (who will also serve temporarily as Outreach Coordinator), and Steering Committee. Process and regional focus groups can be initiated. Community engagement through workshops will refine the model and code development priorities beyond those identified in past MCS workshops and summarized in the MCS workshop reports and working group chapters. The MCS facility can begin hiring programmers to initiate code development, initially in a centralized manner on community codes, and broadening to support PI-driven efforts once the NSF SZ4D Science Program begins. MCS will also compile and assemble existing constraints from regional laboratories (especially Chile, Cascadia, and Alaska) and begin assembling structural and, when possible, dynamic models. These modeling efforts will be geared toward exploring optimal configurations for instrumentation arrays. Plans for the MCS Data Portal/Hub will be refined and work will begin on developing workflows for data integration and assimilation. Training efforts should also begin, which could include fellowship programs for graduate students and postdocs if funding is available.

	Phase 1	Phase 2	Phase 3
Data-Stream Integration	- Use existing tools/methods to guide instrument deployment - Test/develop infrastructure to link models to incoming data streams - These tools have known limitations and approximations	- Integrate data streams into community structure models for use in simulations and hazard assessment	- Continued improvement of high volume data-stream integration with software - Continued refinement of community structure models for use in simulations and hazard assessment
Geophysics/Hazard Process-Based Simulation	- Observation-motivated model development - Incorporation of new processes and/or physics - Identify/develop new numerical approaches & tools	- Comparison of existing and newly developed codes to assess differences & improvements - Transition to new codes for data streams - Expand problem applications (e.g., geometry, 3D vs. 2D, time, physics) - Fully benchmark new codes - Link or embed in more general codes - Begin documentation / training activities	- Well-tested community codes - Fully benchmarked - Scaled-up to full application - Ready to apply to multiple questions, regions, etc.. - Community-supported through documentation, hackathons, workshops, etc.

Figure MCS-3. *Phasing diagram for MCS activities.*

PHASE 2 spans the decadal-scale observational effort. Model and code development efforts will continue, with some codes now being ready for region-specific modeling and data integration. Insights from PI-driven efforts will be incorporated into community codes. Training efforts will focus on broadening user access to include observational and laboratory scientists through tutorials, hackathons, and cookbooks. This will likely require hiring a separate MCS Outreach Coordinator. Fellowship programs should begin, if they have not already. The MCS facility will deploy the Data Portal/Hub, which will include workflow and ideally also cloud-based portals to run forward and inverse models, for both idealized and region-specific problems, and to integrate data from the SZ4D arrays. Community input based on data-integrated modeling will be used to refine hypotheses, identify knowledge gaps, and improve observational strategies.

PHASE 3 synthesizes observational data with newly developed models and experimental constraints to answer the SZ4D science questions. Community model and code development efforts will reach maturity with regard to data integration capabilities and accessibility through the Data Portal/ Hub for use by the community. PI-driven efforts will continue to explore alternative hypotheses and interpretations of SZ4D data.

We are at the cusp of achieving a new level of insight into subduction zone science and hazards, training the emerging next generation of computational subduction scientists, and elevating computational geoscience approaches to a true partnership with observational and laboratory approaches in general. Achieving this paradigm change requires bold investment and could be the beginning of a new area in solid Earth geoscience.

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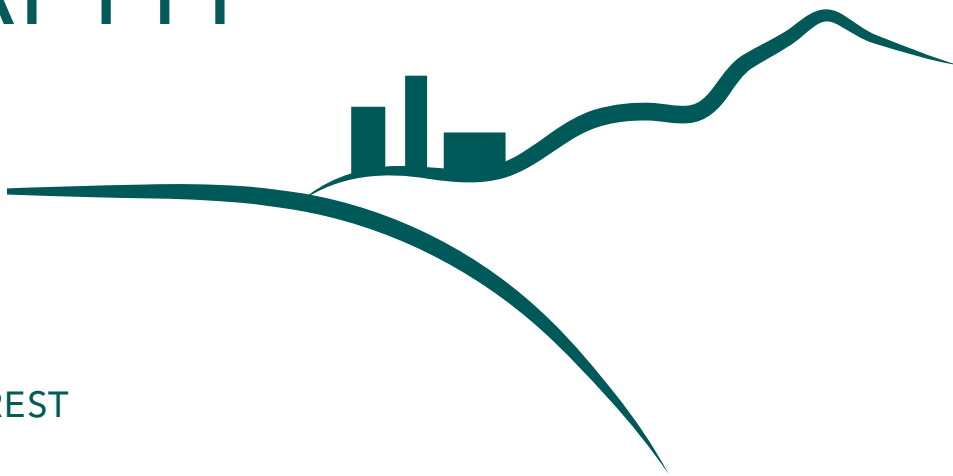
GEOGRAPHY



Identifying SZ4D Regions of Special Interest

The main goal of the SZ4D initiative is to improve understanding of how the different components of subduction zone systems interact to produce and magnify geohazards. An integral piece of this effort is to obtain new observational data on earthquakes, tsunamis, volcanoes, and mass wasting. It has become clear that dense, consistent, long-term instrumentation along with high-level data management is key to making major advances in this area.

Our geographic needs require a hybrid approach to data collection. The FEC and L&S working groups identified technical requirements that include focused, dense arrays, while the MDE working group identified the need for a more distributed approach to data collection at volcanoes. As discussed in this chapter, for both scientific and practical reasons, to maximize scientific gain will require focusing a majority of resources on one or two regions. This geographical focus will be augmented through the development of a coalition of countries that will conduct collaborative subduction zone studies and leverage existing similar efforts at subduction zones around the world. These endeavors will enable comparisons among subduction zones and the generalization of the results of focused study.

We implemented a process, described below, to determine the best locations to seat a subduction-zone observatory that was capable of addressing the research questions of all working and integrative groups. From this activity, we found that a comparative approach to subduction-zone science, in which different subduction-zone segments could be variously instrumented and activities performed, was required to meet SZ4D objectives. The SZ4D umbrella RCN identified three primary locations that included one international site (Chile) and two domestic sites (Alaska and Cascadia).

In addition, the RCN identified the need to establish connections between efforts in other, complementary subduction zones (e.g., Japan, Central America, northern South America) to form a network-of-networks that spans subduction zone science.

SUMMARY OF REGIONAL FOCUS NEEDS

The SZ4D effort has identified the need for a backbone array of amphibious geodetic and seismic instrumentation (MegaArray), a volcano array (VolcArray), and surface and environmental change detection array (SurfArray), in addition to the complementary imaging and geological work. These efforts require a physical presence in particular regions of the world.

The modeling, geological analog, and experimental efforts are required to place the observations from the primary arrays in context, where boundary conditions from a specific region can be determined from known geometries and histories. All of these components can be tied together by concrete observations gathered in a geographic context.

As described in the Introduction to this document, the SZ4D working groups used traceability matrices to identify common science needs for all of the science questions, including the high-priority characteristics of study areas. An inventory of subduction zone segments was also collated so that individual regions could be systematically assessed for their relevance to the scientific priorities. Each group individually weighed the relative value of the segments and then met to balance needs. Those discussions led to the logic presented in this chapter.

COOPERATION WITH INTERNATIONAL PARTNERS

For all regions that are being heavily considered for components of SZ4D field activities, it is essential that, from the beginning, US and in-country colleagues establish clear and open communication. This is necessary to identify the priorities of all stakeholders, cultural differences and sensitivities, established local scientific knowledge, and existing usable infrastructure and resources. Likewise, we must identify mutually beneficial aspects of the project, including research products, application for improving infrastructure and mitigating risk, and capacity building. Cooperation will necessarily extend beyond countries in which infrastructure is developed as a part of SZ4D to include other subduction-impacted nations that can benefit from and provide perspectives to our planned activities.

THE VALUE OF COMPLEMENTARY SITES

Isolating variables is a difficult problem in the observational sciences. The most effective strategy is to form a set of comparison sites that differ in only a few, scientifically interesting ways. For instance, comparisons of fast and slow subduction zones where overlying plate composition are comparable would be useful for determining the role of plate convergence rate in controlling the style of earthquake rupture. This subductology[1] approach has yielded insights into past reviews of extant data but has not been utilized extensively as a deployment strategy.

[1] *"Comparative Subductology" was coined by Uyeda (1982) as a process of grouping subduction zones according to their geometric, geodynamic, and chronologic properties in order to study the correlation of these factors with subduction zone dynamics.*

Subductology as a part of SZ4D can leverage major international efforts for some key observables. The SZ4D 2020–2021 International Webinar Series highlighted some of these efforts: Japan, Taiwan, and Cascadia already have existing seafloor cables that are providing rich datasets that should be thoughtfully complemented with any new instrumentation.

KEY GEOGRAPHY REQUIREMENTS

Scientific Requirements

Each working group developed key scientific requirements. First, the paired experimental design advocated by the L&S group requires comparison subduction zone systems in which particular factors could be regarded as fixed, while a limited number of other factors varied. The **four essential site characteristics** required to carry out L&S's notional experiments and hypothesis testing included:

1. At least some proportion of the site must include subaerial forearc exposure (free of ice);
2. Observational constraints must exist or *be acquirable* at suitable sites; and
3. At least some portion of the sites must include rocks with minerals amenable to geochronology and thermochronology such as quartz, apatite, and zircon. Once subduction zone segments meeting these conditions were identified, a pairing of segments in which independent variation in specific factors of interest (e.g., plate convergence rate) were mapped onto the L&S notional experiments to determine the optimal pairing of subduction zone segments.

MDE Hypothesis Sets A and C will require decade-long, multiparameter characterization of inter-eruption and eruption behavior at a large number (~30–50) of arc volcanoes that exhibit magmatic unrest (active degassing, deformation, and/or seismic unrest), have a history of frequent but not continuous eruption and some prior characterization, and represent a diverse range of volcanic activity. MDE Hypothesis Set B will require geophysical imaging of trans-crustal magmatic systems and characterizing the eruptive history in detail at a small number of representative volcanoes (two per arc) in three arcs (the two SZ4D complementary sites and an additional arc segment) that represent fast, intermediate, and slow convergence. For the six target volcanoes, critical requirements are access to significant land area for certain key observations, such as wide-aperture seismic and geodetic deployments and InSAR and excellent and accessible exposures or records of past eruptive deposits for study of volume, eruptive intensity, composition, thermobarometry, geochronometry, and geospeedometry. MDE also aims to study exhumed sites that represent ancient analogs to concurrently studied active systems. Sites where crustal residence times, magmatic compositions, and storage depths during "high-" and "low-" flux time periods could be characterized are ideal. In addition, localities that preserve both contemporaneous plutonic and volcanic records could be particularly useful to connect plutonic observations to volcanic products.

The ideal sites for the FEC component would possess the following characteristics:

1. Known large and active faults in overriding and downgoing plates;
2. High convergence rates;

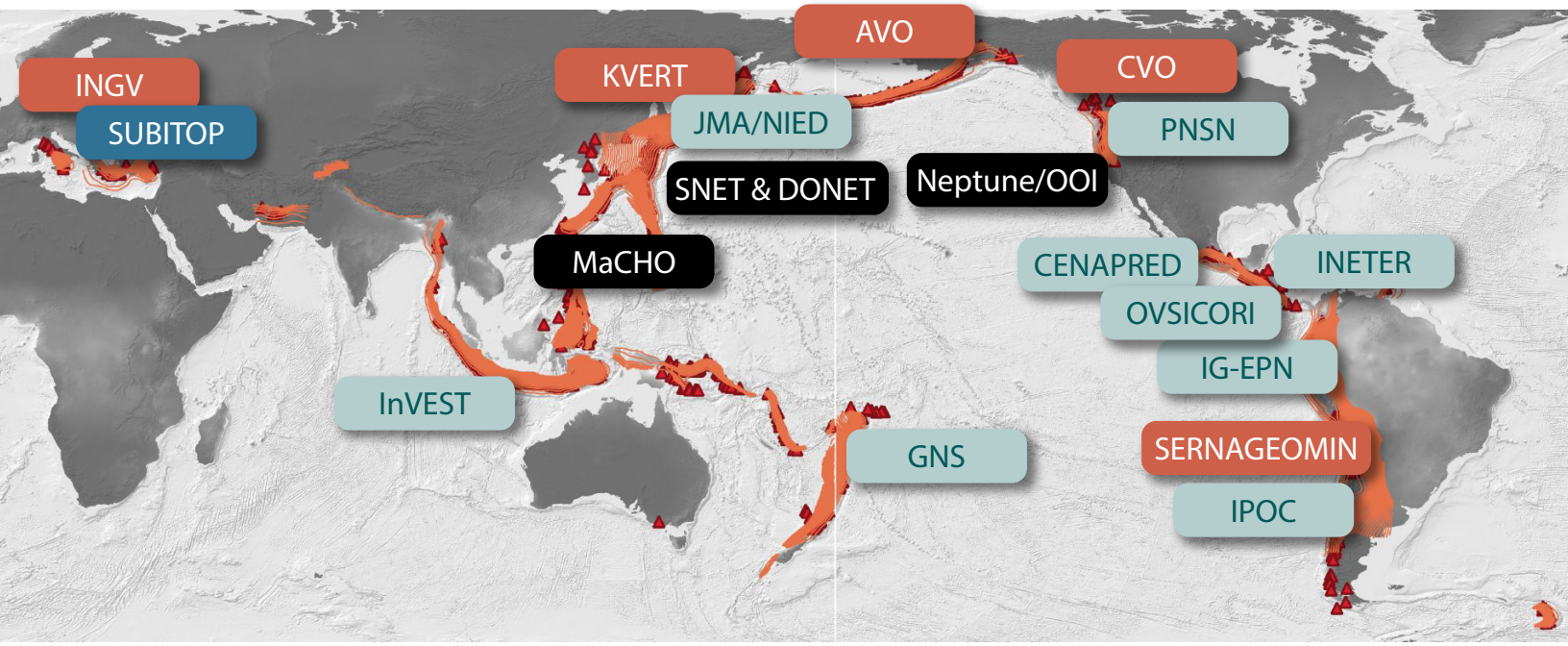
3. Known slow slip events;
4. High seismicity rates;
5. Known strong gradients in coupling along strike;
6. Known tsunamigenic event;
7. Preserved history of fault slip, earthquakes, and tsunamis; and
8. Evidence of a large earthquake that ruptured the entire seismogenic zone.

Because the overarching goal of FEC is to understand when and where along the seismogenic zone large and damaging subduction zone earthquakes occur, a fundamental requirement is that study sites are known to be capable of producing such large earthquakes. Seismic coupling is also a significant factor for all four FEC science questions; the degree to which the plates are locked is an overriding theme that affects all aspects of the seismic cycle as well as the related landscape and volcanic processes. High seismicity rates and convergence rates are favorable for observing subduction zone behavior over a decadal timescale (FEC Science Question 1). There is a preference to be late in the seismic cycle, if possible, to increase the chance of observing precursory behavior before a large earthquake (FEC Science Question 3). To capture the relevant spatial scales of large subduction zone earthquakes, study areas must span at least ~500 km along strike.

Logistical Requirements

A touchstone of the SZ4D is to enable large-scale, multidisciplinary interaction among scientists who have deep knowledge of the field context. This ambition requires taking a high degree of safety precautions for a large number of scientists who may visit the region either

Figure G-1. *Examples of regions and networks with existing instrumentation in subduction zones. Colors indicate network type. Orange: Volcano. Green: Combined earthquake and volcano. Blue: Landscapes. Black: Submarine observatory.*



directly as part of SZ4D or in complementary projects. Therefore, any region that has serious, ongoing, well-documented security concerns should not be a focus of SZ4D field efforts. The US State Department Travel Advisory list provides a useful compilation of security information. Any region that is at level 3 or 4 on this list for non-COVID reasons at the time of a proposal submission cannot be a field site (We have an understanding that COVID-related travel concerns will be reduced by the time SZ4D is first implemented.) Scientists from those regions will hopefully still be able to contribute to SZ4D through work in selected focus sites and through comparisons with other subduction zones. The establishment of a practical limit based on the federal guidelines is simply a matter of establishing a common, objective standard for work that involves a substantial number of participants traveling to the region utilizing federal funding.

As SZ4D will likely be primarily federally funded, data collected as a part of the project must be open access and consistent with NSF and other agency policies. Therefore, any collaboration internationally will need to proceed only if such open data release is permitted.

THE GLOBAL PORTFOLIO

Multiple regions of the world already have significant instrumentation and scientific focus on subduction zone processes (**Figure G-1**). Observational SZ4D efforts should complement previous and ongoing major investments. Of particular note are the major offshore cabled observatory efforts in Japan, Taiwan, and Cascadia. These significant investments should guide the technological and scientific choices of complementary sites elsewhere. Similarly, major volcano instrumentation at a blend of academic and government observatory sites informs strategic choices of study regions that can be selected to fill gaps while also leveraging prior work that establishes context for future measurements. Landscape studies have not historically had major infrastructure initiatives with a few exceptions such as the EU Horizon 2020 SUBITOP project and the long-standing efforts in Taiwan. The seascape is even a more recent focus of effort, and new work by the USGS and others in Cascadia and Alaska is beginning to show the value of regional efforts.

Critical to achieving SZ4D's scientific goals is building a global portfolio of instrumentation and activities that the international scientific community can draw upon. This strategy requires first developing a coordinated global network of subduction zone observatories to share technologies, data, and insights. Informal interactions between scientists and observatories exist, but the global portfolio would benefit from more regular and formal structures for technology, data, and human exchange.

Improving the global portfolio also requires strategic use of SZ4D resources to carefully select geographic regions that complement existing efforts. Complementary efforts should avoid redundancy, and thus SZ4D resources would not be well spent in areas that are already instrumented at the cutting edge of current technology, like Japan. Complementary efforts should also build on extant regional knowledge and data in order to maximize the potential gains over the relatively short timescale (few decades) of our work. Areas that have had little or no previous study probably should not be the primary focus of our efforts. For instance, the Scotia arc is geologically interesting, but has insufficient baseline data for a concerted effort in the next decade.

The requirement for a long subduction zone segment that is logistically feasible eliminates several other geologically significant areas from consideration. Security concerns in parts of Mexico, Indonesia, and Central America make it difficult to define a continuous segment that would meet both the scientific and practical requirements of the project.

PROCESS TO IDENTIFY REGIONS OF SPECIAL INTEREST

With these operational requirements and constraints in mind, the SZ4D RCN implemented a multi-step process to identify regions of special interest. Through detailed discussions, the working group and cross-cutting group members jointly identified sites suitable for filling gaps in our fundamental understanding of the particular geohazards, as well as sites where knowledge gained can be used to inform and reduce domestic risk from geohazards.

As a first step, discussions among the entire SZ4D RCN weighed the pros and cons of various geographic areas, including both domestic and international sites. Following several days of discussion, participants were provided with a global map of potential subduction zone sites. On those maps, they could select two locations (according to priority) that might satisfy the joint needs of the different working and cross-cutting groups. This exercise was not a vote, but instead was an informal assessment of the level of convergence on geographic sites by the working group members following the days of conversations. The density of selected areas, as well as the correspondence between sites selected by individual members, is shown in **Figure G-2**.

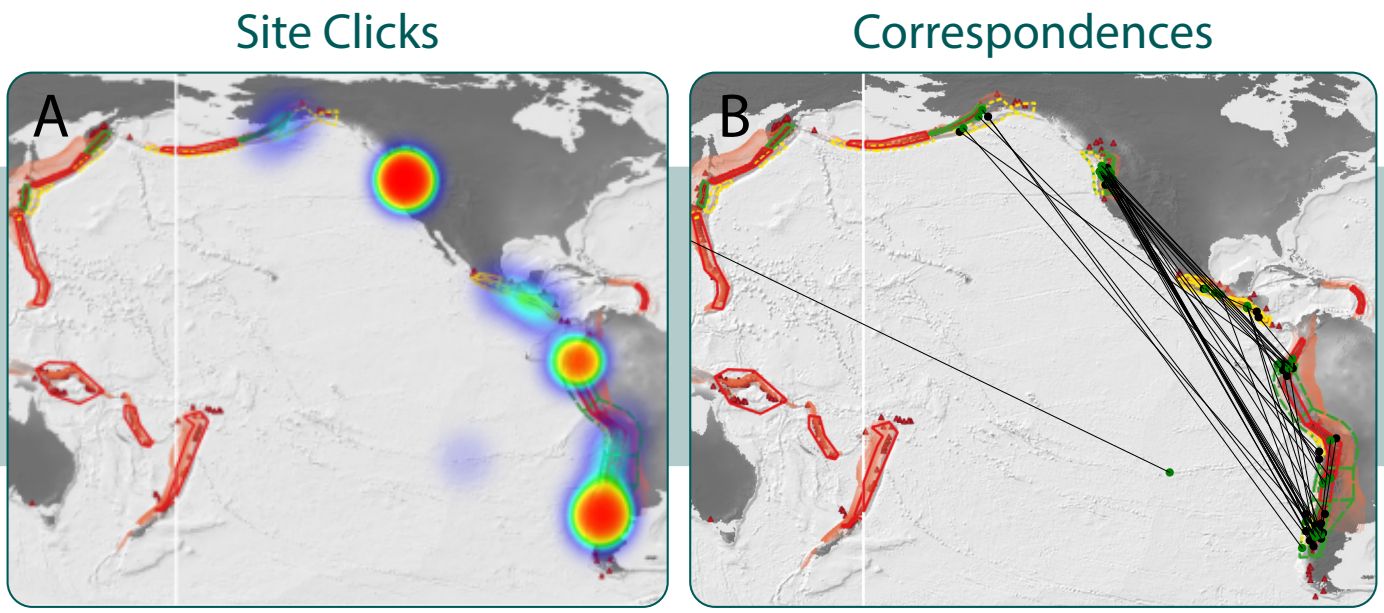


Figure G-2. *(A) Heat map of SZ4D RCN selected sites following the discussion of site characteristics, disciplinary needs, and overall site suitability. Areas that display more prominently in red show a higher density of selections. (B) Correspondences between sites selected by individuals. Each line segment links the two sites selected by each individual.*

The results of this exercise identified two main areas of convergence: Chile (24 selections total, with 16 of these selections rated as the first priority, while eight were selected as a second priority) and Cascadia (22 total, with six of these selections rated as the first priority, while 16 were rated as the second priority).The most frequent paired prioritization was between Chile and Cascadia (12 participants identified this combination, with nine calling out Chile as a first priority, and three calling out Cascadia as a first priority). The main conclusion from this exercise was that the SZ4D RCN required both an international and domestic site when designing the SZ4D efforts, and ideally these sites would provide complementary comparisons. When posed with the question, "Should the SZ4D target complementary international and domestic sites?," 41 out of 42 members of the SZ4D RCN membership voted "yes." When asked "If there is an international site, should Chile be the primary focus?", 37 out of 42 members voted "yes." Thus, there appeared a strong consensus to find complementary international and domestic sites, and of the international sites, Chile was the strong favorite. This information allowed the SZ4D RCN to identify "Regions of Special Interest," which are documented below.

REGIONS OF SPECIAL INTEREST

Chile

The Chilean subduction zone possesses nearly all of the high-priority scientific attributes identified by the SZ4D working groups. Factors such as slab dip, convergence rate, and climate vary systematically along the subduction zone, which allows many natural experiments to be carried out along a single subduction zone system. Rapid convergence leads to abundant seismic, volcanic, and landslide activity. The Chilean subduction zone experienced the largest instrumentally recorded earthquake in 1960 and many >M8 earthquakes since then, and it has 96 volcanoes with eruptions in the Holocene, and 33 discrete eruptions have been recorded in the twenty-first century. This significant exposure is constantly being assessed and characterized by in-country governmental organizations, and so scientific discoveries made by the SZ4D have a clear pathway to implementation in applied sciences through partnerships with these organizations. The opportunities presented by the Chilean subduction zone have produced efforts that have been ongoing in the region for decades with onshore and temporary offshore instrumentation. Importantly, there is a robust community of geohazards scientists working in Chile in both academic and national observatory settings. This community has developed internal networks and also built international collaborations with German, French, American, and other partners to develop instrumentation that was well situated to capture some of the most significant earthquakes in the early twenty-first century. The 4500 km of continental subduction zone encompassed in a single country make it globally unique. International collaborations have also produced a backbone of moderate-resolution bathymetry for much of the margin, allowing collection of high-resolution bathymetry in targeted areas. Significant onshore and offshore passive and active seismic imaging has been done over the last two decades, which can be strategically complemented by SZ4D efforts. Chilean and Argentine networks span the entirety of the subduction zone system and have enabled a substantial amount of on-the-ground domestic and international data collection to take place

over the last 40 years. Opportunities may be present in Chile both on and offshore to complement the existing efforts.

Cascadia

The Washington and Oregon margins have the largest associated risk of any domestic subduction zone and thus deserves special attention. The societal implications associated with a major volcanic eruption or the ground shaking and tsunami associated with the eventual magnitude 9 earthquake weigh heavily on the region. Also, funded infrastructure (OSU-UW CoPes Hub) allows SZ4D activities to impact resilience efforts, which is a primary objective of the BECG efforts. The fact that science can be translated into on-the-ground, domestic risk and resilience efforts makes this site particularly appealing. Additionally, accessibility provided by this domestic site makes it an ideal area where many of the aspirations of the SZ4D BECG efforts can be implemented.

Scientifically, the Cascadia subduction zone possesses some attributes that are favorable for addressing scientific questions of L&S and MDE. Significant along-strike variability in volcanism, including erupted volumes, differ by a factor of two between the southern and northern portions of the arc. Also, Cascadia hosts major changes in the partitioning of volcanism between intermediate and silicic-dominated central volcanic edifices and fields of more mafic and dispersed monogenetic centers. The high coupling and known slow slip events are favorable for some FEC goals, but the slow convergence rate and low seismicity rates make Cascadia a suboptimal region to address many of the FEC science questions, particularly those concerning the relationships between earthquakes and other slip behavior and precursory behavior. Consequently, this region lends itself best to a subset of approaches, such as paleoseismology, geophysical imaging, deep-time study of onshore fault systems and relatively quiescent but diverse volcanoes, and slow slip and tremor.

There is a wealth of existing data that can be leveraged for studies of Cascadia and comparisons to other subduction zones, including seismic data from the Cascadia Initiative, onshore/offshore active and passive seismic imaging (including the recent acquisition on a synoptic 2D deep penetration seismic reflection/refraction dataset along the margin), magnetotelluric profiling, bathymetric mapping, extensive subareal high-resolution topographic mapping, lava geochemistry, and onshore/offshore geological studies. There are also abundant opportunities for collaborations with other US organizations, including the USGS, which is emphasizing Cascadia within its subduction initiative. The ideal study strategy is thus to combine a study of Cascadia with a faster subducting analog that can provide the information on human timescales that will ultimately be important to interpreting and predicting the future behavior of the United States' most prominent subduction zone.

Aleutians/Alaska

The Aleutians/Alaska (AA) subduction zone has frequent and diverse eruptions and frequent earthquakes, and thus some sections of this ~2000 km-long subduction zone were considered favorable study areas by the FEC and MDE. For the FEC, the history of large earthquakes, variations in coupling, rupture history, and seismicity off the Alaska Peninsula make this region an attractive possible target for study; one segment was thought to be relatively late in the seismic cycle. The occurrence of a series of large interplate earthquakes here in 2020–2021

has released some of the stored energy, potentially complicating one of the appeals of this location. The region has a rich diversity in arc structure and tectonics, sediment and volatile influx feeding primary magma generation, and crustal magma differentiation processes, with the resulting outcome the production of a complete range in eruption styles from its diverse volcanic centers. However, this region is problematic for the L&S group due to the recent glacial history, which makes many aspects of required geochronology problematic, and the lack of an extensive subareal forearc with which to study important geohazards such as landslides and flooding. The focus of their work requires a substantial exposed land surface. For all groups, the remote location and challenging weather are present hurdles.

An advantage of the AA subduction zone for the MDE and FEC is that it is a relatively well-studied system with abundant existing geochemical data. Geophysical imaging and bathymetric data have been acquired in some areas, particularly off the Alaska Peninsula, but coverage is not uniform owing to the size and remoteness of this subduction zone. As with Cascadia, there are significant opportunities for collaborations with other US entities, including the Alaska Volcano Observatory, the Alaska Earthquake Center, the USGS, and NOAA's National Tsunami Warning Center.

PRIORITIZATION OF INSTRUMENTATION AND ACTIVITIES WITHIN THE REGIONS OF INTEREST

The identification of "Regions of Interest" satisfied the requirement of complementary international and domestic sites. However, the question of how to most effectively allocate resources between the "Regions of Interest" to address the SZ4D science questions required additional, subsequent discussions. During these discussions, it became apparent that the types of resources needed would vary between the different areas, because some areas would require the construction of extensive instrumentation networks, while others contain an observational backbone that is already in place. In this sense, some sites may require extensive instrumentation, while others would require science activities (such as field study, modeling, outreach) that would leverage and augment existing instrumentation to answer the SZ4D science questions. For this reason, the SZ4D RCN members considered the "Regions of Special Interest," in terms of how instrumentation and activities might be partitioned between the different sites to maximize their utility in answering the SZ4D science questions.

After a series of discussions focused on needed (and existing) observational capabilities and activities, a questionnaire was used to gather participants' opinions on how to allocate priority for instruments and activities between these three potential sites and thus to assess convergence between all disciplinary working group members. Each participant was given a total of 10 (integer) points for instruments, and 10 (integer) points for activities. These points could be allocated to each of the three "Regions of Special Interest" for each category (instruments versus activities). Forty-two participants performed this allocation, the results of which are summarized in **Table G-1**.

While there was some variability in how instruments and activities would be allocated between the different sites that depended on the specific working or cross-cutting group,

Site	Disciplinary score weighted for number of participants in each group		FEC		MDE		L&S	
	Instrumentation	Activities	Instrumentation	Activities	Instrumentation	Activities	Instrumentation	Activities
Chile	6.9	5.1	6.4±1.7	4.9±1.1	7.1±1.8	5.2±1.3	7.2±1.4	5.1±0.8
Cascadia	2.2	3.6	2.3±1.2	3.3±1.2	2.0±1.1	3.3±1.3	2.3±1.3	4.2±1.0
Alaska/Aleutians	0.9	1.3	1.3±1.3	1.8±1.2	0.9±0.8	1.5±1.3	0.5±0.7	0.7±0.8

Table G-1. *Results of exercise to prioritize instrumentation and activities between the Regions of Special Interest*

there was a remarkable consistency in the allocation between respondents, despite the disparate objectives and needs of the different groups. This informal questionnaire indicated a broad, and consistent agreement that instrumentation should be dominantly deployed along the Chilean subduction zone (6.9), and that a lesser investment of instrumentation should be allocated to Cascadia (2.2) and Alaska (0.9). On the other hand, participants allocated activities more evenly between the sites (Chile: 5.1, Cascadia: 3.6, Alaska: 1.3). Thus, the SZ4D RCN appeared to favor heavy instrumentation investment at the international site, whereas activities should be carried out across both domestic sites, as well as within the international site. In this way, existing investments in domestic instruments could be leveraged to provide the comparative information that will be necessary to answer the SZ4D science questions.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

Key to the success of the SZ4D initiative is selecting an appropriate set of sites where the phenomena identified in the science questions are best studied. We carried out a process that first ruled out inappropriate sites (based on the presence / absence of factors that prevented one of the working groups from addressing their science questions, and logistical consideration of safely working in a region). We then compiled the properties of possible subduction zone segments to identify those that best met the needs of each working and cross-cutting group, and compared the segment properties to isolate factors of interest. The SZ4D RCN also noted that the science questions would be best answered by comparing an international site to one or more domestic sites. Using the compilation and constraints, we identified three Regions of Special Interest: the Chilean, Cascadian, and Alaskan subduction zones. The SZ4D RCN strongly and clearly favored deployment of the bulk of instrumentation along the Chilean subduction zone system, while science and outreach activities were best performed at all three Regions of Special Interest. In this way, the SZ4D envisions the deployment of the proposed arrays along the Chilean subduction zone, but science will be carried out both internationally and domestically to leverage existing domestic infrastructure and to provide direct impact to domestic hazard assessment priorities.

DATA AND TECHNICAL SYNERGIES

Building partnerships for an integrative SZ4D

The study of subduction zone seismic, volcanic, and mass-movement geohazards can greatly benefit from a research strategy that includes building upon existing international partnerships and leveraging instrumentation and facilities, cyberinfrastructure and data management, and capacity-building activities that are common to all geohazards research. By pursuing a common regional focus, SZ4D can develop partnerships with international scientists and organizations, strategically deploy shared physical infrastructure, and collect contextual information, such as geologic mapping and geochronology, that enables multidisciplinary interpretation of geohazards. Shared mechanical processes, geography, and modes of interacting with societies to promote hazard mitigation all require partnerships to create the potential to significantly advance geohazards research.

PARTNERSHIPS

The geographic focus of SZ4D requires the fostering of new, and expanding of existing, partnerships. International collaborations are complex and require significant investment to establish diplomatic, cultural, and physical connections. Thus, SZ4D will take advantage of active scientific ties where possible. This is particularly true when a capacity-building effort is involved, as described in the **Chapter 4.1 Building Equity and Capacity with Geoscience** of this report and summarized below.

COMMON INSTRUMENTATION AND FACILITIES

The science pursued by individual working

groups share many common physical infrastructure needs, including a network of in situ observational technologies, 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 collaboratory to lead integration of data with cross-scale, and process models for improved understanding of the entire system dynamics (as described in the **Chapter 4.2 Modeling Collaboratory for Subduction**).

During the first part of the twenty-first century, rapid technological advances have enabled us to observe subduction zone phenomena in four dimensions with unprecedented temporal and spatial resolution. From trenches to volcanoes, we envision future research to include a suite of field-deployed, quasi-permanent sensing systems to collect time-series data on active processes. The suite may include seafloor geodetic (acoustic-GPS and pressure) and seismometry elements in a network, ideally with real-time (or at least minima-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. At the volcano scale, new synthetic aperture radar (SAR) missions such as the NASA-ISRO SAR (NISAR) mission with weekly coverage will greatly enhance deformation measurements and should be supplemented with a suite of multidisciplinary ground-based instrumentation. Access to certain facilities, even if not necessarily dedicated solely to SZ4D, will be critical to enable these envisioned observational 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, and autonomous underwater vehicle (AUV) and/or remotely operated vehicle (ROV) access. 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. SZ4D also needs 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.

The different components of MegaArray, VolcArray, and SurfArray may strongly overlap with one another in some geographic configurations. These overlapping needs are strongest in the case of onland instrumentation, which constitutes a combined instrument array that we refer to as the **Multidisciplinary Multihazard Array (Multi^{2}Array)**. The main components of the Multi^{2}Array would consist of shared multi-purpose seismic networks, surface-deformation observing systems, and high-resolution surface imaging programs. First, all three disciplinary working groups require onland seismological observations: FEC requires a set of backbone onland seismometers to detect activity of forearc faults and to resolve seismicity along portions of the subduction megathrust; MDE requires a dense distribution of seismometers in a broad area (20–100 km

diameter) around targeted volcanic systems, along with sparse networks of proximal seismometers (within ~5–10 km of vents) at a larger number of volcanoes; L&S requires instrumentation throughout the forearc and volcanic arc to detect and potentially locate large mass failures such as landslides and debris flows. Second, onland GNSS-derived surface deformation measurements are a cornerstone of answering each group's priority research questions: FEC requires densification along potentially active, slipping structures throughout the forearc region; MDE requires dense geodetic networks around targeted volcanic edifices; and L&S requires a broad distribution of GNSS measurements. Third, all groups require high-resolution topographic and optical imaging of Earth's surface: FEC to detect and characterize active faults and folds of the forearc; MDE to detect changes in volcanic craters and other portions of the edifice that accompany unrest; and L&S to identify areas where mass-transport events may be generated and the changes these events may produce downstream of these features. Institutional data collection campaigns and drone-based imaging missions are needed by all three groups to resolve changes in Earth's surface resulting from subduction-zone geohazards. Together, these joint needs encapsulated in the Multi^{2}Array provide several advantages over isolated, individual disciplinary networks - they are more cost efficient due to the repurposing of observations for the characterization of different hazards, which allows strategic densification of measurements in areas where studied phenomena may be best resolved, and they provide a common set of observations to further multidisciplinary investigations of how these sets of processes may interact with one another to produce cascading hazards across the subduction-zone system.

Finally, all working groups outlined work that will result in the collection of geologic samples. These physical samples will need to be stored and distributed to the community for analyses. Community reference materials and standards will also require storage and distribution upon request. Shared facilities will ensure uniformity in how samples and their metadata are stored and handled.

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 relationships between deformation, pore fluids, and chemical reactions. A gap in experimental capabilities exists across much of the seismogenic zone, including the very region where slip transitions from seismic to aseismic, requiring new equipment and approaches to access these critical conditions. 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.

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, from the minutes to years of magma ascent recorded in the chemical zonation of volcanic crystals, 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.

COMMON CYBERINFRASTRUCTURE AND DATA MANAGEMENT

Data management and data discovery tools are crucial parts of a community infrastructure. Interdisciplinary science can only thrive when the entire geoscience community can access and utilize data from all disciplines, which in turn requires suitably packaged data streams and a data infrastructure to ensure the availability, accessibility, and open distribution of the products of the entire effort. This level of interoperability requires dedicated, professional data managers along with carefully designed and maintained software. Searchable datasets 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 International Ocean Discovery Program (IODP) should be seamless with SZ4D data management systems. Communication about the datasets 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.

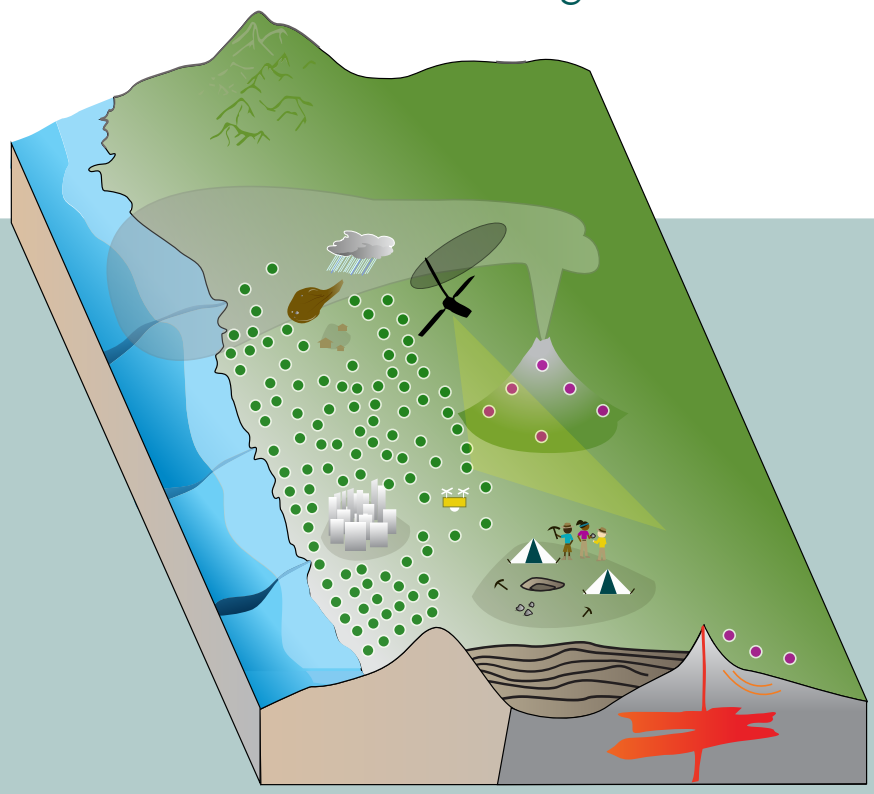
CAPACITY BUILDING ACTIVITIES

Capacity building encourages international scientific partnerships, with the intention of transferring skills, data, technology, and expertise. A shared SZ4D capacity-building effort will align with scientific targets in both emerging and developing countries in order to sustain physical infrastructure, train scientists, understand hazards, and build resiliency. Given the global importance of the subduction zone hazards, their scientific diversity, and the need to study them in multiple locations, a capacity-building effort is both a societal imperative and a scientific necessity that can yield transformative outcomes on all fronts.

A successful SZ4D program will lead to scientific discoveries and applications that would otherwise not be possible. The combined physical and intellectual infrastructure will enable observations in 4D that would otherwise not get collected. 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.

SIDEBAR 5

Multi²Array: An integrated subduction-zone geohazards observatory



We envision the MULTIhazard, MULTIdisciplinary Array (Multi²Array) as being comprised of a unified observational array designed to capture the integrated effects of seismic shaking, volcanic unrest, mass failures, and surface transport. The Multi²Array enhances the observational needs of the disciplinary groups by deploying instruments in a geometry in which core observations for some applications serve as far-field observations for others. Additionally, such an integrated network will likely save cost by situating instruments in areas where they are well configured for multiple applications and equipping these multi-purpose networks with common data processing, storage, and transfer mechanisms. The Multi²Array is designed to include instruments that can be leveraged by all three disciplinary efforts (FEC, MDE, L&S), and so consists of only on-land portions of the Mega, Volc, and SurfArrays deployed in a common geographic region.

PHASING

A phased approach for successful implementation

The scale and scope of the proposed comprehensive program requires a carefully phased approach to implementation, outlined via draft timelines (**Figures P-1 and P-2**).

PHASE 0 | Through activities supported by the SZ4D RCN, SZ4D has already largely completed **Phase 0**, including:

- Developing this Implementation Plan,
- Identifying available data that address the scientific themes and data gaps that need to be filled,
- Scoping the necessary technical developments and scientific workforce needs, and
- Developing an SZ4D-specific approach to capacity building based on belonging, access, justice, equity, diversity, and inclusion (BAJEDI) principles.

PHASE 1 | Detailed experiment designs and analytical protocols, technology, and facility and data center support will be developed to meet later scientific needs while SZ4D simultaneously pursues pilot reconnaissance-level field efforts and modeling activities. We also anticipate the initiation of a Science Program and program of Community Engagement during **Phase 1**.

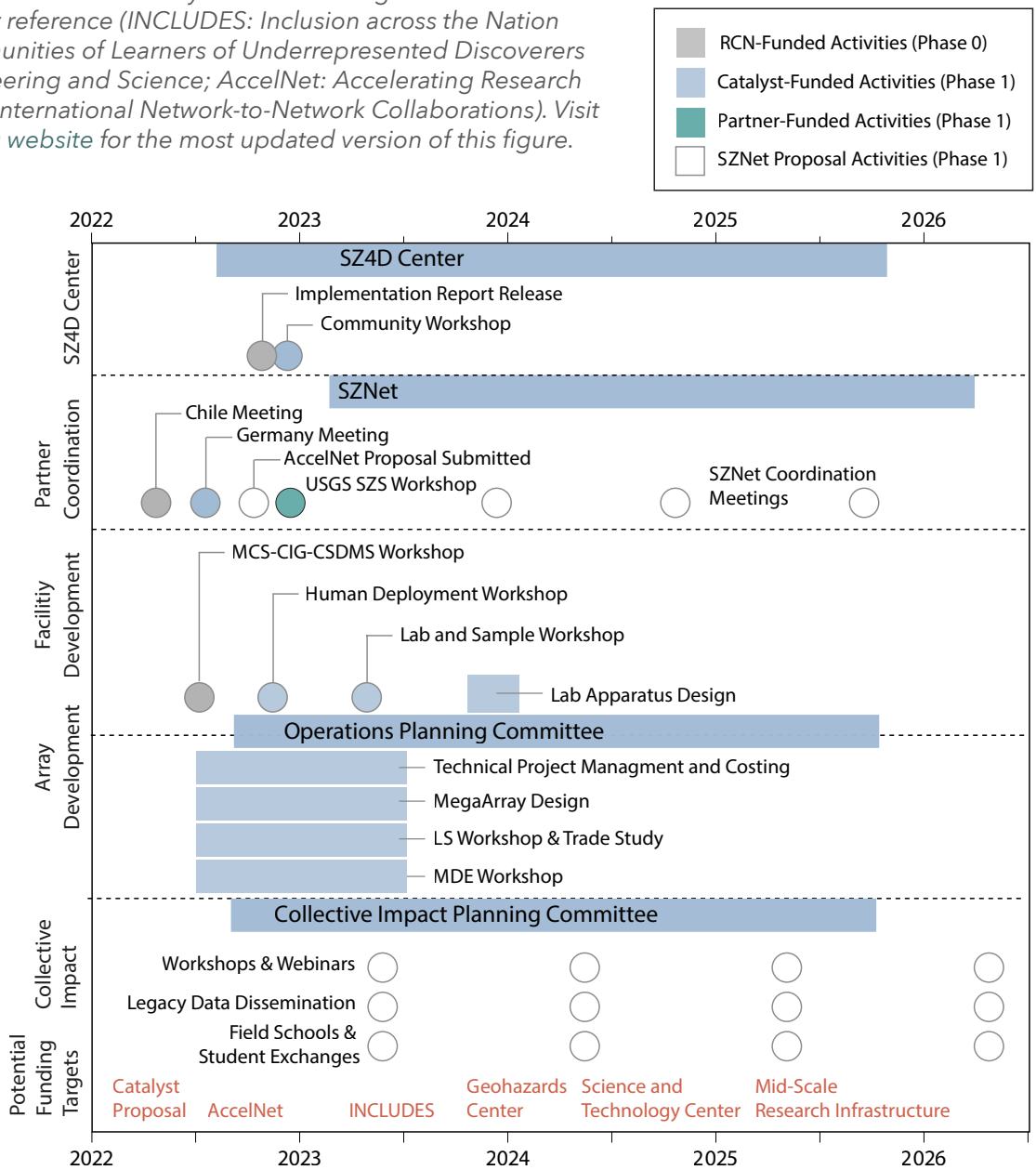
PHASE 2 | Decadal-scale field campaigns (Arrays) will be conducted, with support from the SZ4D facilities and data center, to collect the comprehensive observations needed to analyze subduction systems and their geohazards. The arrays will be complemented by and coordinated with decadal-scale field efforts. The arrays will also be guided by, and in turn guide, model development and laboratory research. A Science Program will support specific and synthesis research activities in coordination with a program of Community Engagement.

PHASE 3 | Final results from all SZ4D activities will be analyzed and synthesized and reported to the community through peer-reviewed publications and SZ4D reports.

Funding milestones largely drive the timeline for transition between phases. Successful funding for implementation of the full infrastructure program will mark the transition into **Phase 2**. The transition to **Phase 3** will occur ten years or more after the start of **Phase 2**.

Major categories of activity in **Phases 1-3** include Facility Development and Operation, Data Management, Community Infrastructure/Arrays, Community Field Efforts, Science Program Activities, and Community Engagement. A list of specific activities under each category is illustrated in **Figure P-2** (additional details can be found in **Chapters 2 and 3**).

Figure P-1. *Timeline of Phase 0 and 1 activities for SZ4D Implementation. Potentially relevant funding solicitations noted for reference (INCLUDES: Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science; AccelNet: Accelerating Research through International Network-to-Network Collaborations). Visit the SZ4D website for the most updated version of this figure.*



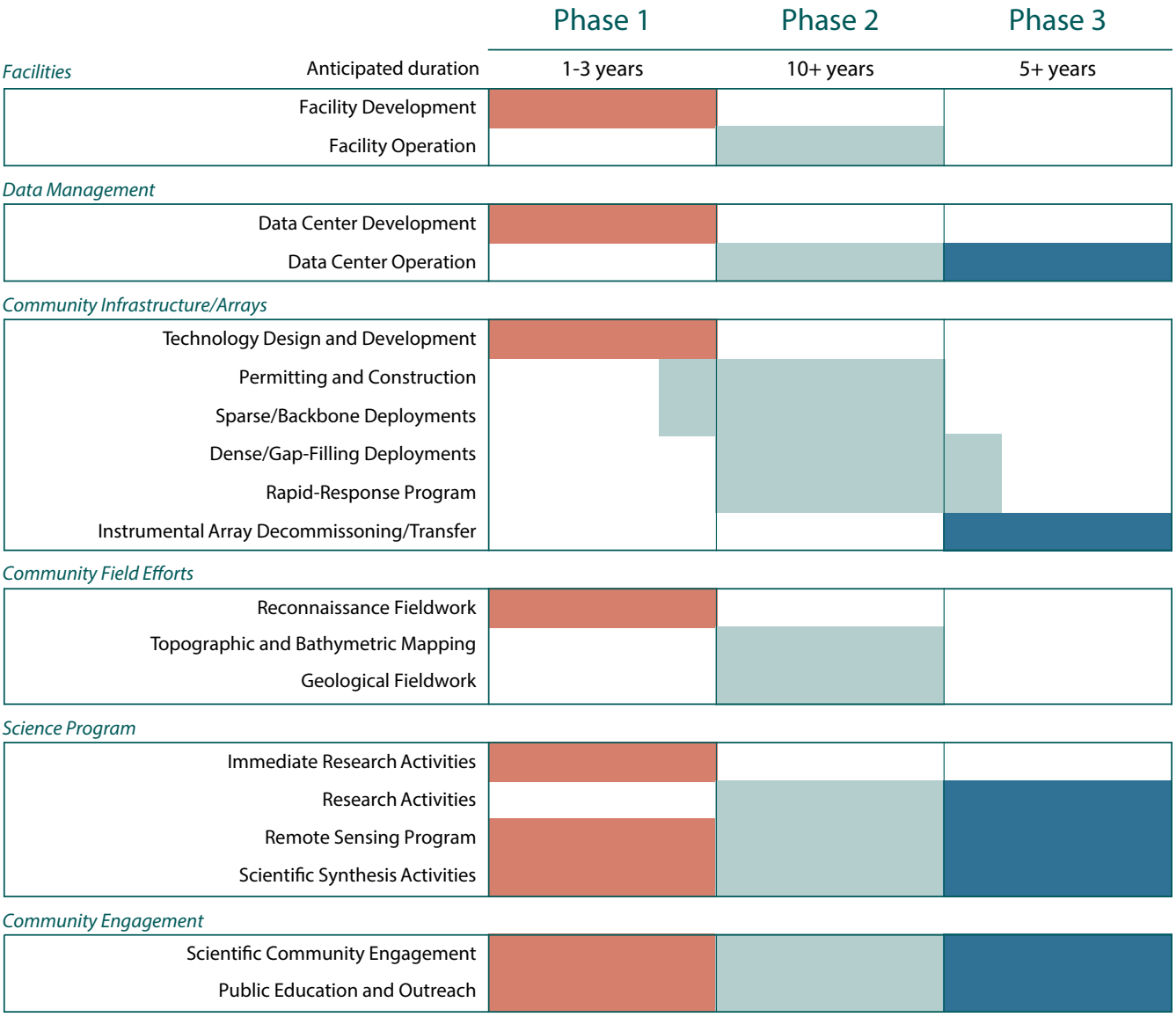


Figure P-2. *Timeline of major activities in SZ4D Phases 1-3. See this chapter and chapters 3 and 4 for additional details.*

PROGRAM STRUCTURE AND GOVERNANCE

Moving SZ4D forward, together

To achieve SZ4D's ambitious goals requires management and governance structures capable of:

1. Efficiently and effectively supporting significant **infrastructure**, including instruments deployed in the field and in laboratories, open access to near-real-time data, a Modeling Collaboratory and other new SZ4D consortia, and deployment of scientists to make critical, systematic measurements
2. Enabling and inspiring **innovative research** supported by proposal-driven funding, including seed funding
3. Coordinating across the SZ4D disciplines, focus sites, and crosscutting themes; coordinating with funding agencies; implementing a collective impacts model across all communities to ensure maximum societal impact; evolving the SZ4D program as needs change and unforeseen discoveries and circumstances arise; communicating back and forth with international, operational, and stakeholder partners; and executing community governance.

The proposed model for these management and governance structures would provide guidance to and independent oversight of three major SZ4D components:

1. A **Center** that manages and coordinates SZ4D Facilities,
2. Five **Facilities** that provide support for instrument development, acquisition, deployment, and data management, and
3. A **Science Program** at NSF whose mandate would be to identify the most promising SZ4D-centered research projects through a merit review process.

SZ4D CENTER AND GOVERNANCE

To ensure successful execution of the SZ4D initiative, a governance structure will be established to guide program evolution, evaluate progress, coordinate all involved communities, ensure information transfer, and foster partnerships for SZ4D. Oversight bodies and the envisioned management structure will coordinate the program at all levels, enabling the community to build the required SZ4D intellectual infrastructure and to create a program that is greater than the sum of its parts.

A proposed transitional governance structure designed to meet current SZ4D needs has been developed and implemented based on community and facility feedback (**Figure SG-1**). This initial structure is simple, consisting of a Steering and Executive Committees that oversee the work of the SZ4D Center. These two committees are guided by input from three working groups and two integrative groups plus two planning committees. In the transitional structure, committee members play more than one role (e.g., Executive Committee members also serve on the Steering Committee, working and integrative group chairs also serve on Steering Committee). Below we describe in more detail the transitional committee structure charges.

Governance

Committee on Committees (CoC)

The CoC develops slates of candidates for the committees (orange) and the working and integrative groups (green) defined in **Figure SG-1**. It combines nominations from each committee, volunteers from the community, and scientists identified by the CoC's own deliberations to ensure diversity balance by discipline, institution, and demographics. Committees, as well as working and integrative groups, can include both domestic and international members. The CoC recommends slates of candidates for each of the committees and working and integrative groups to the Center Steering Committee, as well as co-chairs for each committee and group. Three-year terms will be staggered such that each year the CoC will recommend a slate with a target of two-thirds current members and one-third new members. The CoC targets ranges in membership numbers (described below), but is empowered to adjust as necessary to maximize participation in SZ4D. Target size is 5-10 members.

Center Steering Committee (SC)

The SC coordinates and oversees all SZ4D activities. The SC is also charged with overseeing the general operations of SZ4D, including ensuring a suitable meeting calendar, effectively using the budget to forward SZ4D goals, and resolving competing objectives between the Collective Impact Advisory committee and the working groups. Major strategic decisions will be brought to and made by the SC. All proposals committing SZ4D staff and facilities must be approved by the SC.

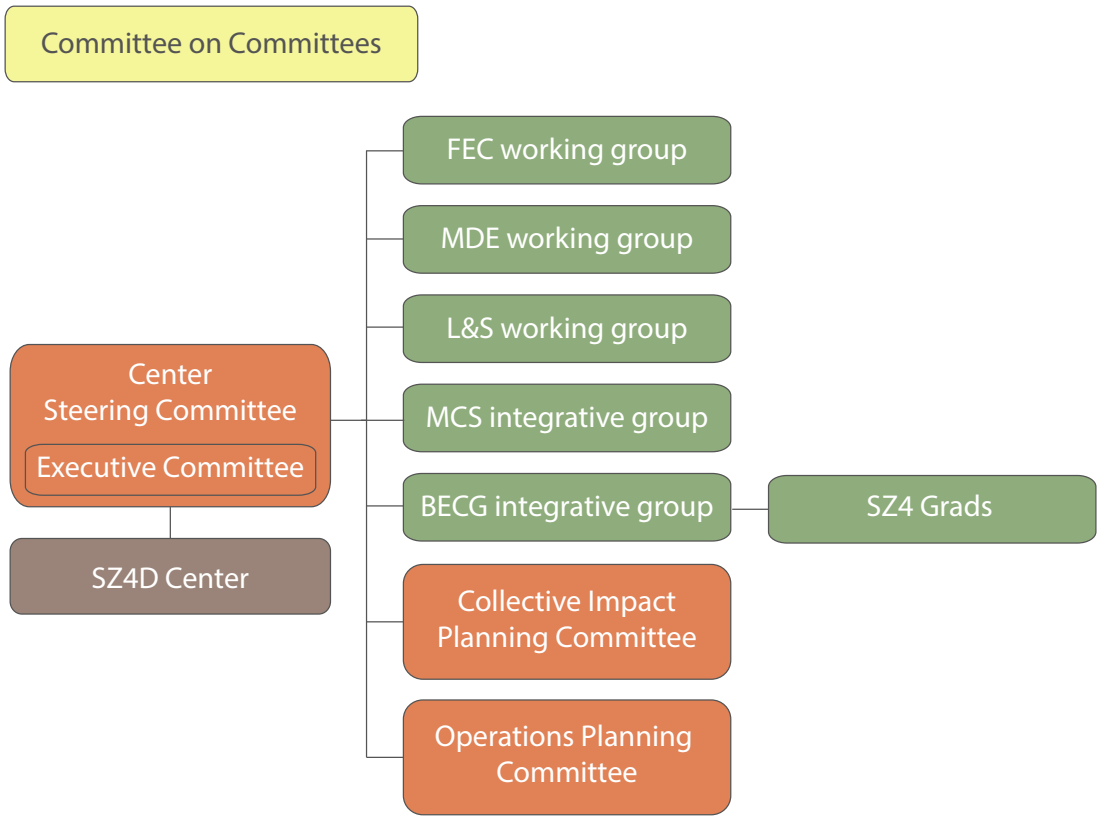


Figure SG-1. *Organizational diagram showing the SZ4D Transitional Committee Structure. The transitional structure retains the working and integrative Groups (green boxes), while adding a Collective Impact and Operations Planning Committee. All of these entities inform the Center Steering Committee that oversees the SZ4D Center. The Committee on Committees is an independent entity tasked with populating the membership of the committees and working and integrative groups.*

The current SC approves committee and working and integrative group nominations provided by the CoC. The SC assigns liaisons to all other committees from the SC membership. The target size of the SC is 15-20 members. The SC Chair is responsible for running SC meetings, serving as a point of contact for external partners and agencies, organizing and facilitating agenda-setting for SZ4D, and chairing the Executive Committee.

Executive Committee (ExCom)

A subcommittee of SC serves as the ExCom, which meets more frequently than the SC and curates information for SC decisions. The ExCom is charged with developing and coordinating strategies, responding to funding opportunities, and pursuing potential partnerships. ExCom and its members may also serve as points of contact with agencies and international partners as needed. During the transition period, the ExCom will initially retain its current membership and will institute staggered terms of three years to refresh its membership as SZ4D grows. The PIs of the SZ4D Catalyst proposal retain ex officio roles as long as Center activities are covered under that grant. Future Center PIs would assume the same ex officio roles. The target size of the ExCom would be six members.

Collective Impact Advisory Committee (CIC)

The CIC supports scientific priorities and broader impacts by monitoring SZ4D scientific and capacity building activities and advising the SC

on ways to better meet SZ4D's Collective Impact goals, such as redistributing resources. The CIC is composed of representatives from each of the active members of disciplinary communities, Integrative Groups, and Facility committees. Expertise in science relevance to agencies beyond NSF are included in this committee (e.g., NASA, USGS, NOAA). Co-chairs of the CIC will regularly report to the SC. The target size of CIC is 15-20 members.

Operations Planning Committee (OPC)

The OPC oversees SZ4D operational needs. Initially, the OPC is charged with providing scientific guidance for the design of five facilities that would support:

1. Offshore instrumentation,
2. Onshore instrumentation,
3. Field programs that require human deployment,
4. A modeling collaboratory, and
5. Experiments and sample archiving.

The OPC will work to develop the necessary proposals to support the new infrastructure. As the SZ4D Facilities are created and become operational, it is expected that the OPC will create separate oversight committees for each of them. Target membership is 15-20, with a balance of expertise relevant to the five envisioned future facilities. Expertise in data management may also be critical to the work of this committee. Members will have staggered three-year terms.

Working Groups and Integrative Groups

During the transition period, the working groups (FEC, L&S, MDE) and integrative groups (BECG, MCS) will maintain activity with refreshed memberships. These groups are viewed as representative of the community and should consult regularly with members of the community to assure alignment between community needs and SZ4D actions. The target size for each working and integrative group is 15-20 members.

Additional ad hoc subcommittees of specialized expertise may be convened by any committee as necessary as SZ4D moves to a fully built configuration. Once funding for a particular activity is secured, the SC should discuss appropriate ex officio roles for the activity's PI.

Management

The **Executive Director** of the SZ4D Center will be directly accountable to the Center Steering Committee. This structure distances the management and execution of the specified scientific directions and priorities from the governance that defines them. The SZ4D Center's full-time, professional staff will provide continuity, accountability, points-of-contact, direction, and management for the program.

We also anticipate that data needs may emerge that are not defined at the outset of the new SZ4D facilities and are described below. Additionally, a nimble, event-based rapid response capability may be required to capture the phenomena we wish to understand as part of SZ4D. Because there are many potential responses and data types, we have designed a Critical Data Collection mechanism to direct resources to the appropriate facilities and entities in the event that novel data must be collected rapidly, or activities must be performed to guarantee that all of the pieces of the SZ4D project fit together properly. This Critical Data Collection mechanism will be overseen, and actions approved, directly

by the Center Steering Committee. These scientific needs will be communicated to the Executive Director, who will then determine the appropriate facilities and entities to task with Critical Data Collection. This mechanism is intended to enable the identification and collection of emergent data needs that require flexible allocation of resources to combinations of facilities and entities, while guarding against a Center-based ad hoc science funding program.

INFRASTRUCTURE AND FACILITIES

SZ4D will require both new facilities and partnerships with existing facilities. A combination of new and existing facilities will support instrument development (e.g., seafloor), establishment of instrument networks (e.g., volcano sensor arrays), field deployments of instruments on land and at sea, and data collection that requires people as the primary observational instruments (e.g., paleoseismology and volcano chronology). New consortia are envisioned, such as the Modeling Collaboratory for Subduction and the Laboratory and Sample Consortium, to meet SZ4D objectives. The specific facilities that are essential for supporting SZ4D research include:

- Newly designed **offshore** seismic, geodetic and other instrumentation, instrument pools, mobilization teams, and marine vessels (crewed and autonomous) for deployment, service, and rapid response near the site(s) of dense deployment. The US solid Earth community has not previously attempted an offshore subduction zone observatory of this scope and duration. This seafloor facility must have the capability to respond rapidly (hours to days) to both problems and opportunities and hence implies dedicated personnel and seagoing resources.
- Newly designed **on-land arrays**, including volcano arrays with satellite telemetry for transmitting data in near-real time; environmental observing networks for landscape and deformation sensing; deployable arrays for rapid response in regions with little prior infrastructure.
- Support (e.g., for logistics, sampling instrumentation, and analyses) for field programs that involve **deployment of humans** as the primary observational instruments to collect systematic, standardized, critical data inclding paleoseismology, framework mapping, sampling and analysis for geochronology, geochemistry, petrology. This could also involve opportunities for student training, graduate and postdoc support, capacity building, and REU programs.
- **Modeling Collaboratory for Subduction** to develop new physics-based models and data-driven computation for subduction zones and to provide resources for their use by the whole SZ4D research community including students, postdocs, researchers.
- **Laboratory and Sample Consortium** for the study of material properties and rheology during deformation and phase equilibria of molten systems, including analog modeling and infrastructure for archiving samples collected as part of the SZ4D effort.

Management of the new facilities would ultimately fall under the SZ4D Center to ensure coherent data collection and coordination throughout the duration of SZ4D (**Figure SG-2**).

However, each of these facilities needs ready access to scientific expertise and a granular level of oversight of each's activities. Thus, each facility component is expected to be associated with its own advisory committee, whose membership would be determined through the Committee on Committees process, and whose members would serve fixed terms. These advisory committees would report to the Science Advisory Committee (**Figure SG-2**). The rotating composition of the Facilities' Advisory Committees would allow broad participation in the scientific oversight process, while providing continuity to the direction of the facilities. As described above, the scientific activities of the facilities would be coordinated through representative membership on the Center Steering Committee to maximize scientific impact and efficiency throughout the lifetime of the SZ4D project.

In addition to these new facilities, it may be beneficial to expand the capabilities of existing facilities and consortia, leveraging their expertise to support the collection and distribution of new and novel instrument networks and datasets. For many objectives, SZ4D is anticipated to partner with existing or forthcoming facilities or organizations, such as managing seismic and geodetic data with the Earthscope Consortium, acquiring high resolution elevation data from Open Topography, or collecting geochronologic data with the National Consortium for Geochronology. Additionally, many organizations successfully manage field deployment of on-land seismic and geodetic instruments, including the EarthScope Consortium (ESCO, successor to IRIS/UNAVCO) and the USGS Earthquake Hazards Program. Organizations specializing in geophysical data archiving and real-time access to data are NASA-JPL, IRIS/UNAVCO, and the USGS Earthquake Data Centers and Volcano Observatories. For experimental petrology, geochemistry, and structural data archiving and access, Library of Experimental Phase Relations (LEPR), ENabling Knowledge Integration (ENKI), GEOchemistry of the Rocks of the Ocean and Continents (GEOROC), Interdisciplinary Earth Data Alliance (IEDA), PetDB, and Strabospot are excellent examples of existing database efforts. The National Consortium for Geochronology is a natural partner for the acquisition and archiving of geochronology data. High-resolution topography and bathymetry data are acquired, archived, and shared through the National Center for Airborne Laser Mapping (NCALM), 3D Elevation Program (3DEP), OpenTopography, Marine Geoscience Data System, and IEDA. The Ocean Bottom Seismic Instrument Center (OBSIC) group will be essential in coordinating the design and implementation of ocean bottom seismometer components, as will other marine operators such as the University-National Oceanographic Laboratory System (UNOLS) and the International Ocean Drilling Program (IODP). It will be imperative to partner with international organizations for major field deployments (e.g., within Chile, as an example, Southern Andes Volcano Observatory [OVDAS], SERvicio GEOlógico MINero [SERGEOMIN], and many universities). Curation of physical samples and experiments will be necessary for coordinated efforts, and CONVERSE, the Smithsonian Institution, and IEDA are already developing new models. Existing centers such as Computational Infrastructure for Geodynamics (CIG), Community Surface Dynamics Modeling System (CSDMS), and the Southern California Earthquake Center (SCEC) are valuable partners for code development, training and hosting thematic workshops. To maximize the impact of SZ4D in hazard mitigation, partnerships with

the World Volcano Observatories (WOVO), the USGS Hazards program, Volcano Disaster Assistance Program (VDAP), Global Earthquake Model (GEMS), and the National Oceanic and Atmospheric Administration (NOAA) tsunami early warning centers will be vital.

Figure SG-2 displays the fully constructed SZ4D organizational structure,including the core committee, more detailed facility oversight committees, and central elements of the SZ4D Center. The diagram also illustrates connections to funding agencies that would enable a SZ4D Science Program.

SZ4D SCIENCE PROGRAM

A critical part of the success of SZ4D is support for proposal-driven research, as it invites innovation and exploration of new techniques and approaches and provides an access point that is open to the widest PI community. All proposal-driven research would address SZ4D Building Equity and Capacity with Geoscience goals (see **Chapter 3.1**), thereby ensuring maximum impact of SZ4D science on society. Proposal-driven research needs could be met by convening an SZ4D Science Panel at NSF and other agencies. The panel would be guided by peer review, consistent with agency practice and independent of SZ4D governance. The panel scope could be directed with open RFPs that focus on certain science problems, focus areas, or integration activities at different points along the SZ4D timeline, as guided by the SZ4D Center. Proposals could range from multi-PI, multidisciplinary projects to single-PI projects. A dedicated SZ4D Seed Funding program could serve as an on-ramp to SZ4D, especially for early career scientists. Another mechanism for entraining and retaining early career scientists would be supporting SZ4D graduate fellowships, postdocs, and CAREER-type grants.

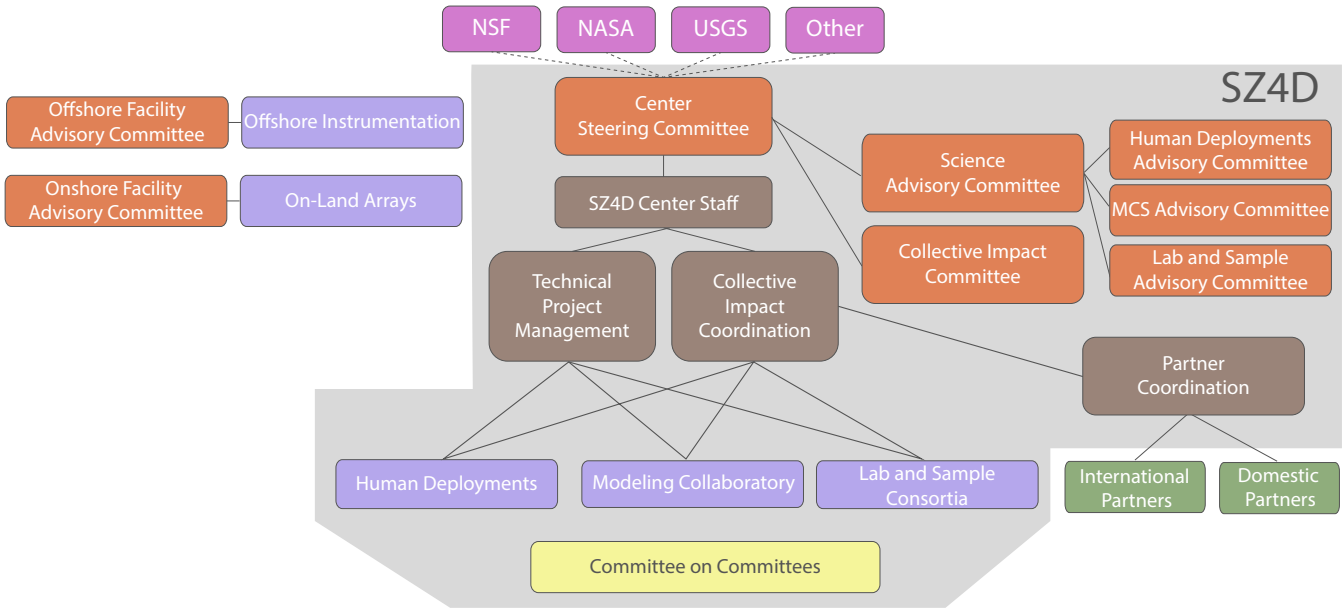


Figure SG-2. *Organizational structure of the fully constructed SZ4D Center (brown); Advisory Committees (orange); Facilities (purple); International and Domestic Partners (green); funding agencies (pink); Committee on Committees (yellow). Gray marks the extent of the SZ4D community.*

APPENDIX I-1

SZ4D RCN MEMBERS

Geoff Abers	Cornell University	MDE
Colin Amos	Western Washington University	L&S
Kyle Anderson	US Geological Survey	MCS
Pete Barry	Woods Hole Oceanographic Institution	MDE
Beth Bartel	Michigan Tech University	BECG
Noel Bartlow	University of California, Berkley	FEC
Susan Beck	University of Arizona	FEC
Thorsten Becker	University of Texas, Austin	SC, MCS
Mark Behn	Boston College	ExCom, SC, MCS, L&S
Magali Billen	UC, Davis	MCS, FEC
Ben Black	The City College of New York	MDE
Emily Brodsky	UC, Santa Cruz	ExCom, SC, FEC
Danny Brothers	United States Geological Survey	L&S
Mike Brudzinski	Miami University of Ohio	ExCom, SC, BECG
Claire Bucholz	California Institute of Technology	MDE
Roland Bürgmann	University of California, Berkley	SC, FEC
Jackie Caplan-Auerbach	Western Washington University	BECG
Simon Carn	Michigan Tech University	MDE
Chuck Connor	University of South Florida	MCS
Michele Cooke	University of Massachusetts, Amherst	BECG, L&S
Juliet Crider	University of Washington	L&S
Stephen DeLong	US Geological Survey	L&S
Eric Dunham	Stanford University	SC, MCS , FEC
Alison Duvall	University of Washington	SC, MCS , L&S
Tobias Fischer	University of New Mexico	MCS

Noah Finnegan	UC Santa Cruz	L&S
William Frank	Massachusetts Institute of Technology	FEC
Andy Frassetto	IRIS	SC, BECG
Melodie French	Rice University	SC, FEC
Alice Gabriel	Scripps Institution of Oceanography	MCS , FEC
Sean Gallen	Colorado State University	SC, L&S
Joan Gomberg	United States Geological Survey	L&S
Helge Gonnerman	Rice University	MCS, MDE
Karen Gran	University Minnesota, Duluth	L&S
Trish Gregg	University of Illinois	MDE
Matt Haney	US Geological Survey	SC, MDE
Jenna Hill	US Geological Survey	L&S
George Hilley	Stanford University	ExCom, SC, L&S
Mong-Han Huang	University of Maryland	L&S
Chris Huber	Brown University	MDE
Shaul Hurwitz	US Geological Survey	MDE
Kaj Johnson	Indiana University, Bloomington	MCS
Leif Karlstrom	University of Oregon	SC, MCS , L&S
Adam Kent	Oregon State University	SC, MDE
Eric Kirby	Oregon State University	L&S
Eric Kiser	University of Arizona	MDE
Jared Kluesner	US Geological Survey	L&S
Nicole LaDue	Norhern Illinois University	BECG
Pete LaFemina	The Pennsylvania State University	MDE
Thorne Lay	UC, Santa Cruz	FEC
Jeff McGuire	US Geological Survey	FEC
Kristin Morell	UC, Santa Barbara	SC, L&S
Yves Moussallam	Lamont-Doherty Earth Observatory	MDE
Carolina Muñoz-Saez	University of Nevada Reno	MDE
Madison Myers	University of Montana	MDE
Samer Naif	Lamont-Doherty Earth Observatory, Georgia Tech	FEC
Andrew Newman	Georgia Tech	SC, BECG, FEC

Nathan Niemi	University of Michigan	L&S
Anne-Marie Núñez	Ohio State University	BECG
Summer Ohlendorf	NOAA/National Tsunami Warning Center	FEC
Ayla Pamukcu	Stanford University	MDE
Charlie Paul	Monterey Bay Aquarium Research Institute	L&S
Jon Perkins	US Geological Survey	L&S
Terry Plank	Lamont-Doherty Earth Observatory	SC, MDE
Beth Pratt-Sitaula	UNAVCO	BECG
Christine Regalla	Northern Arizona University	FEC
Diana Roman	Carnegie University	ExCom, SC, MDE
Demian Saffer	University of Texas Institute for Geophysics	FEC
Steven Semken	Arizona State University	BECG
Donna Shillington	Northern Arizona University	SC, FEC
Joann Stock	California Institute of Technology	L&S
Danielle Sumy	IRIS	BECG
Amanda Thomas	University of Oregon	MCS
Christy Till	Arizona State University	SC, BECG, MDE
Harold Tobin	University of Washington	ExCom, SC, FEC
Aaron Velasco	University of Texas, El Paso	BECG
Daniel Viete	Johns Hopkins University	FEC
Ikuko Wada	University of Minnesota	MCS
Janet Watt	US Geological Survey	L&S
Rick Wessels	US Geological Survey	MDE
Lisa White	UC, Berkeley	BECG
Doug Wiens	Washington University	SC, FEC
Rob Witter	US Geological Survey	FEC
Heather Wright	US States Geological Survey	MDE
Brian Yanites	Indiana University	L&S
Wenlu Zhu	University of Maryland	MDE

Appendix FEC-1

FEC TRACEABILITY MATRICES

Traceability matrices show the linkages between:

1. The scientific question (Column A),
2. The broad categories of information required to address the question (Columns B–C),
3. The specific information needed to address the question (Column D), and
4. The observations, models, and experiments needed to provide specific information (Column E), which form the columns of the matrices.

The rows of each matrix list the required information and activities. Activities are color coded by category (e.g., geodesy, geology) to illustrate the breadth of interdisciplinary activities required to tackle the questions and common needs between scientific questions. The contents of this matrix are informed by discussions within the working group and feedback received from the community through surveys and town hall meetings and from other SZ4D working groups.

We describe an example from the *traceability matrix* for Question 2 to illustrate our process (**A-FEC-1**). A prerequisite for understanding controls on the speed and mode of slip in space and time is information on the speed and mode of slip itself, including in earthquakes and slow slip events. Shoreline-crossing seismic and geodetic arrays are required to provide constraints on the full range of present day slip behavior and geodetic coupling from the trench to the downdip transition to aseismic creep (e.g., **Figure FEC-5**). Paleoseismology, geology, and historical records of earthquakes are needed to explore the deeper history of where and when large earthquakes and tsunamis have occurred and for longer-term deformational processes to provide context for current behavior. Differentiating between the theories that have been proposed to explain variations in slip behavior requires constraints on materials, fluids, and structures along the plate boundary at a range of spatial scales, including the frictional properties of material along the plate boundary, heterogeneities along the plate boundary at a range of scales, and/or variations in pore-fluid pressure (e.g., Segall et al., 2010; Hawthorne and Rubin, 2013; Skarbek et al., 2012; Ando et al., 2012; Fagereng & den Hartog, 2016; Zhu et al., 2020). Differentiating between these competing explanations of what controls slip behavior thus requires constraints on materials, fluids, and structures along the plate boundary at a range of spatial scales. Seismic reflection/CSEM imaging can provide constraints on heterogeneity in plate boundary properties and indirect constraints on porosity and pore-fluid pressure at scales of tens to thousands of meters (e.g., **Figure FEC-6**), while drilling of subduction zone

fault materials or studies of exhumed megathrusts onshore are required to characterize the composition and structure of fault zone materials, finer-scale heterogeneity, and fluid-rock interactions (e.g., **Figure FEC-7**). Experimental studies on subduction zone materials are needed to determine the material properties that control slip processes and will require advancements in the range of pressures, temperatures, pore pressures, and strain rates that can be accessed in the laboratory. Numerical modeling will both illuminate the parameters that need to be observed and evaluated and synthesize observations and experiments for a comprehensive understanding of controls on subduction zone behavior.

Appendix FEC-2

PHASES OF THE SZ4D FEC EXPERIMENT

Phase 0 (Preparatory Work and Refinement of Implementation Plan)

1. Infrastructure assessment and experiment planning
   a. Assessment of existing seismic and GNSS instrumentation infrastructure, including quality, accessibility, and openness of data
   b. Focused modeling effort to inform optimal design of experiments to achieve necessary resolution
2. Organization and planning
   a. Strengthen existing and establish new international and domestic connections and initial capacity building, access, data and science sharing agreements with international partners for potential target site(s)
   b. Clarify the likely synergistic relationship between SZ4D efforts with hazard estimation and warning goals in potential observatory regions

Phase 1 (Analysis and Synthesis of Existing Data and Continued Planning Activities)

1. Data assessment and compilation
   a. Synthesis and assessment of existing constraints on subduction zone history and behavior, including from seismic and tsunami catalogs, regional earthquake source parameters, slow slip locations and behavior, tide gauge and DART data, local surveys for historic events, and tsunami source area estimates
   b. Synthesis and targeted reprocessing of prior geophysical imaging results from onshore and offshore active and passive source seismic, magnetotelluric, controlled source electromagnetic data, and bathymetric data
   c. Synthesis of existing geologic, paleoseismic, and paleotsunami data from in situ and exhumed analog sites
   d. Assembly and synthesis of existing data on material properties (friction, elastic properties, hydraulic properties) and fault structure (from both in situ and exhumed systems) to inform models and identify gaps

e. Summary of region-specific modeling efforts such as simulations of regional models of stress and deformation, faulting, earthquake sequences and aseismic slip, and megathrust rupture dynamics and tsunamigenic potential and deformation

f. Begin to develop cyberinfrastructure and data processing capabilities in conjunction with partner organizations to ensure efficient use of large datasets collected in Phase 1 and Phase 2

2. Technology development

a. Instrument developments for long-term seafloor and potentially subseafloor deployments

b. Development of experimental apparatuses that fill critical gaps in pressure, temperature, pore pressure, and strain-rate space

c. Modeling based assimilation, fusion, and analysis of Phase 0 "big data"

d. Develop modeling strategies for optimal observational and experimental design to help define the highest impact observational efforts in the lab and field

e. New modeling development capable of integrating multiple types of observables of different precision to constrain multi-scale and multi-physics modeling, in coordination with the SZ4D Modeling Collaboratory

3. Reconnaissance Work

a. Conduct reconnaissance investigations of potential subduction analog sites coordinated between field geologists and experimentalists

b. Conduct reconnaissance investigations of geologic and paleoseismic slip histories for upper plate crustal faults (onshore and offshore)

4. Organization and Planning

a. Begin discussions with potential offshore fiber optic cable owners about potential use for monitoring and warning

Phase 2a (Backbone Constraints)

1. Data acquisition

a. Slip Constraints

i. Establish a backbone geodetic network for characterizing deformation and locking at a nominal resolution of 100 km x 50 km along-strike and downdip, which requires a similarly spaced, staggered network of GNSS-A stations. In the near-trench region, where deformation can be much more localized, transitions between coupled and slipping zones may be missed due to spatial aliasing

ii. Deploy a broadly distributed (~50 km spacing), amphibious network of seismic and electromagnetic stations, and use passive source imaging, to enable initial characterization of earthquake and slow slip behavior offshore

iii. Densify onshore geodetic and seismic stations. GNSS sites should have a nominal

spacing no less than the depth to interface at that location (>~40 km near coast of most environments). Near-coast GNSS should be designed for real-time tsunami monitoring. Densification of onshore seismic networks should include arrays for improving offshore earthquake detection and location

iv. Determine and acquire available viable L- and C-band SAR data for time-series interferometry, identifying large-scale deformation, with localizations associated with surficial processes and upper-plate dislocations. Establish continued collection of SAR data from available satellites

v. Conduct reconnaissance investigations of onshore paleoseismic sites for subduction megathrust slip histories

b. Process Constraints

i. Take measurements of materials recovered from previous drilling and sample collection, or those that serve as priority representative materials for fault and wall rock

ii. Collect linear MT/broadband seismic profiles with ~20 km instrument spacing for imaging large-scale subduction zone architecture and broad-scale seismicity patterns, collocated with active source seismic lines.

iii. Collect multibeam swath bathymetry and acquire deep-penetration 2D active source seismic reflection and refraction data (at maximum of 50 km spacing) as well as heat flow probe data

iv. Collect high-resolution bathymetry along coastal areas

2. Synthesis and modeling

i. Integrate geodetic, seismic, and paleoseismic data to map locking and slip behavior

ii. Integrate geophysical imaging, heat flow,, and geology to determine subduction zone architecture and properties

iii. Combine architecture, physical property, and slip information to constrain processes controlling locking and slip

iv. Include new information on subduction zone structure and processes in probabilistic scenario modeling to estimate expected future slip behavior. Use numerical models to explore data sensitivities and provide uncertainties based on the intermediate-resolution data to guide installation of new sites in Phase 2

3. Technical Development

a. Continue to develop cyberinfrastructure and data processing capabilities in conjunction with partner organizations to ensure efficient use of large datasets collected in Phase 1 and Phase 2

b. Continue to develop and refine seismic and geodetic instrumentation based on the results of the backbone deployment, in preparation for Phase 2

4. Organization and Planning
   a. Develop and coordinate the physical infrastructure needed to share, analyze, and archive geologic and experimental samples
   b. Upgraded/reinforced on-land GNSS stations (where available) for longevity, communications, and site stability. Create a plan for long-term maintenance and data collection, archiving, and reduction
   c. Design the dense amphibious seismic/geodetic deployment for Phase 2

Phase 2b (Targeted, High-Resolution Constraints)

1. Observational
   a. Slip Constraints
      i. Informed by early results and modeling, densify the GNSS-A and ocean-bottom seismic/pressure network to capture high-fidelity features of coupling, seismicity, and slow slip. This may include deployment of fiber optic cable for distributed acoustic sensing (DAS) analysis
      ii. Continue updates to land-based GNSS and seismic networks as needed (e.g., to enable high-rate (10 Hz) GNSS, augment land-based GNSS/seismic stations with strong motion for capture of earthquake rupture signals)
      iii. Install onshore borehole observatories to capture transients in slip, hydrogeology, or strain
      iv. Instrument faults in the overriding plate with geodetic, seismic, and strainmeter sensors, as needed
      v. Continue collection of all available SAR data
      vi. Conduct paleoseismic investigations of long-term megathrust and crustal fault slip histories
   b. Process Constraints
      i. Use repeat-track multibeam bathymetry surveying in cases of shallow fault slip
      ii. Collect high-resolution geophysical images in regions of interesting slip behavior. Deploy a dense array of seismic nodes and combined OBS/OBEM instruments for active and passive source seismic and passive MT imaging. Conduct a 3D seismic reflection survey, and s dense controlled-source electromagnetic survey
      iii. Conduct geologic and experimental investigations of subduction zone analogs and inputs, including both onshore and offshore samples
2. Interpretation
   a. Analyze all new and existing observations on subduction zone behavior and structure
   b. Experiments will continue to inform modeling and geologic characterization to ensure that

necessary measurements are being made and correctly understood/applied. Experimental plans will evolve in response to emerging observations

c. Validate and calibrate data-centric modeling tools against larger community models. Modeling tools will be built to assimilate emerging high-resolution observations (e.g., rapid on-demand analysis). Models will be built to explore which theoretical developments and constraints are necessary to interpret sensor network data streams

Phase 3 (Synthesis)

1. Interpretation
   a. Integrate results from all components to address science questions
   b. Conduct targeted data analysis, modeling, and experiments to address key questions that arise during synthesis
   c. Integrate new results from SZ4D work into regional hazards frameworks in collaboration with local stakeholders
2. Organization and planning
   a. Develop plans for adoption and continued operation of SZ4D networks as appropriate

November 2022

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