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

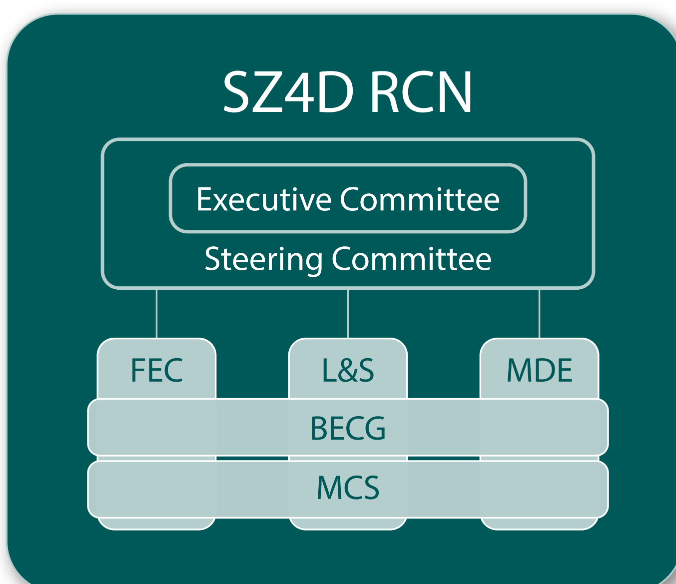


Figure I-1. *Organization chart of the SZ4D Research Coordination Network (RCN). Disciplinary groups: L&S: Landscapes and Seascapes, FEC: Faulting and Earthquake Cycles, and MDE: Magmatic Drivers of Eruption; SZ4D integration groups: BECG: Building Equity and Capacity with Geoscience, and MCS: Modeling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

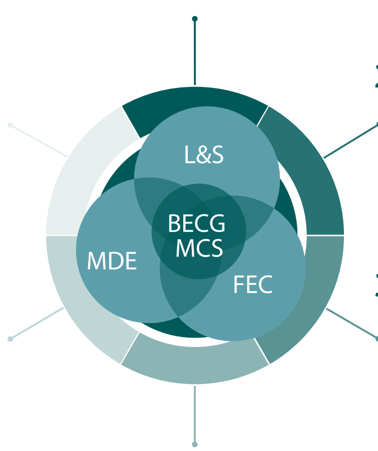
The overarching objective of SZ4D is to gain insight into the fundamental physical and chemical processes that underpin geohazards at subduction zones. **Chapter 2** outlines the critical geohazard-related crosscutting themes that span all of the working groups. One of the key emerging themes is forecasting 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.

References

McGuire, J.J., T. Plank, et al. 2017. *The SZ4D Initiative: Understanding the Processes that Underlie Subduction Zone Hazards in 4D*. Vision Document Submitted to the National Science Foundation. The IRIS Consortium, 63 pp. https://www.sz4d.org/_files/ugd/66466d_c5202b9573e1413eb006995304a4b274.pdf

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