Chapter 1. Introduction

Rationale for an SZ4D Initiative

The most devastating geohazards on Earth occur along subduction zones, where energy is focused into narrow coastal belts, mainly along thousand-kilometer-long continuous faults that generate parallel volcanic arcs and steep, unstable terrain extending hundreds of kilometers inland. Subduction zones are also locations where human populations are often concentrated and risks from devastating geohazards can be great. Although we currently have a limited understanding of the physical processes controlling the occurrence, timing, and magnitude of subduction hazards, modern data and new techniques suggest that significant progress is possible. In the past two decades, seismic and geodetic data have revealed the rich array of slip processes during an earthquake cycle as well as novel volcanic eruption precursors, and geomorphologists now have access to seascapes to complement their onshore work. The availability of new data and techniques suggest that the time is right 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 the catastrophic events to be placed in a fully four-dimensional physical context. SZ4D (Subduction Zones in Four Dimensions) 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 major earthquakes, tsunamis, volcanic eruptions, and mass movements at Earth's surface (**Figure I-1**).

Because of their special geometry, subduction zones are the best natural environments on Earth in which to isolate the processes that control variability of geohazard behavior. The interrelated physical and chemical processes that occur as one tectonic plate descends beneath another defines and ultimately controls the surface expressions of earthquakes, volcanoes, tsunamis, and landslides. There are clear variations in temperature and pressure with depth that exert first-order control on processes and thus can be studied. There are also identifiable variations laterally along the subduction zone that then become manifest in differences in geohazards (**Figure I-1**). These lateral variations range from the expected, such as variations in plate convergence rate that corresponds to the number and size of the earthquakes that occur, to the subtle, such as variations in terrestrial erosion rate that then may influence the quantity and type of magma generation. Such along-strike and depth changes in boundary conditions can be modeled, providing one of the most straightforward approaches to modeling the causes of the resulting array of earthquakes, volcanoes, and landforms.

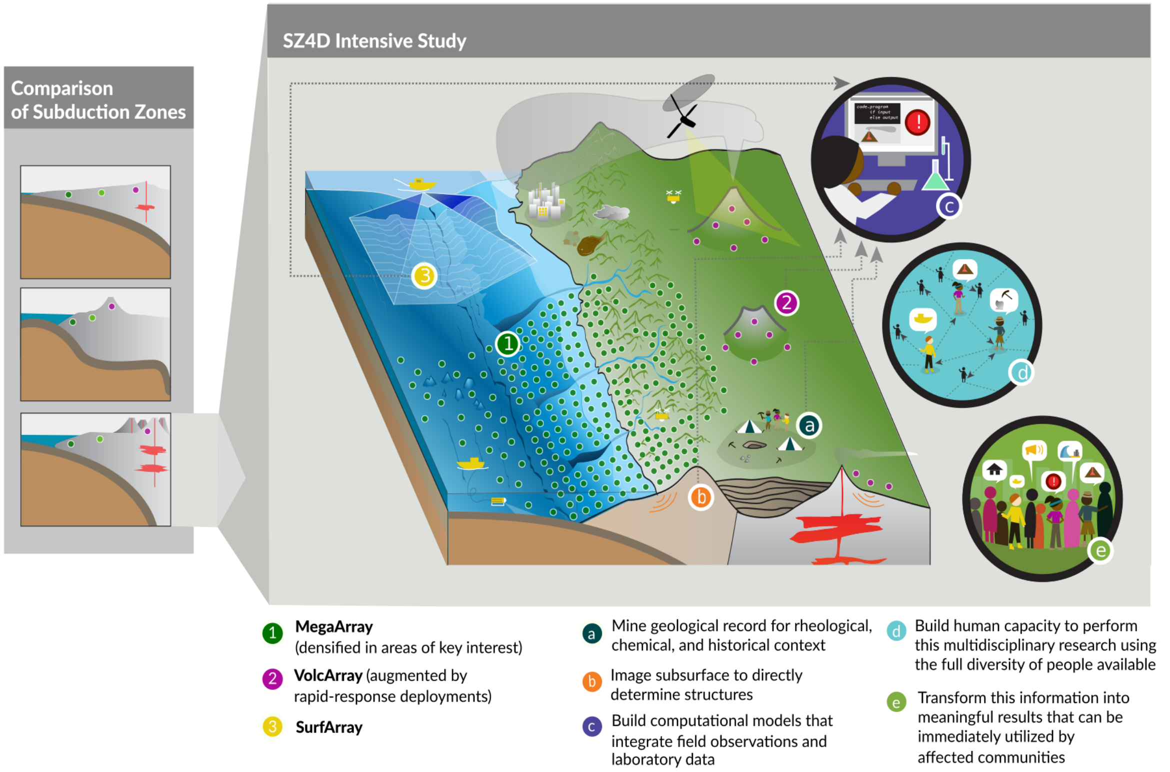

Figure I-1. *Schematic of major instrumental arrays and activities of SZ4D.*

This draft *SZ4D Implementation Plan* is the result of more than two years 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 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. It lays out a set of needed key observations and experiments that would address each scientific question and would be part of a long-term 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—from the outset and by design—promote equity and inclusion in the United States and in 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* (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 these regions. 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 U.S. research community to work together to develop a consensus plan for an SZ4D program.

The SZ4D RCN was charged with taking the broad vision laid out in the McGuire et al. (2017) report and translating it into a concrete and viable blueprint for what an SZ4D program would entail. The SZ4D initiative was also examined by the National Academies' committee that produced *A Vision for NSF Earth Sciences 2020–2030: Earth in Time* (also known as the CORES Report; NASEM, 2020). In it, the committee identified the further development and ultimate funding of SZ4D as a high-priority activity for the NSF Division of Earth Sciences.

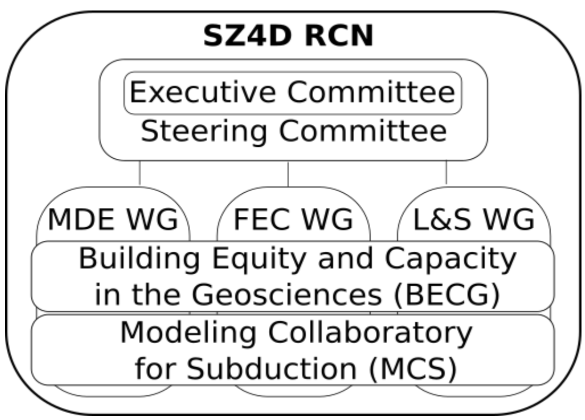

Figure I-2. *Organization chart of the SZ4D Research Coordination Network.*

The RCN has pursued the development of an SZ4D program by obtaining input from a representative cross section of the subduction geohazards research community (**Figure I-2**; **Appendix 1**). Working groups on the three core scientific themes of Faulting and Earthquake Cycles (FEC), Magmatic Drivers and Eruptions (MDE), and Landscapes and Seascapes (L&S) were identified through an open nomination and selection process. Simultaneously, two Integrative Groups were established to represent our collective strategy for building equity and capacity in the geoscience (BECG) via the SZ4D research community, and a program for creating a next-generation modeling (MCS) for subduction zone research. The 74 members of the working groups and integrative groups met continuously throughout 2020 and 2021 to build this implementation plan. Along the way, the RCN has engaged a total of over 1600 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 the past two years. The RCN also hosted 13 webinars that brought insights from experts from 11 countries. The membership of the working groups and integrative groups 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 who we represent.

The working groups and integrative groups initially focused on developing science questions. These initial discussions led to refinement of the research questions and key observations throughout 2020, during which direct community input was solicited through a series of webinars. Based on this community input, as well as input from the other working groups, each working group refined its research questions and key measurement requirements continuously throughout 2020 and 2021. Once a framework was established, the questions were mapped onto requisite activities and instrumentation through traceability matrices. The groups then developed notional experiments that captured key activities. In parallel, the RCN developed an inventory of subduction zones globally that allowed regions to be assessed for their appropriateness for these notional experiments. The working groups and integrative groups then combined their requirements and recommendations for geographic regions and developed a phased plan of experiments and activities (**Figure I-3**).

This process resulted in the production of a draft document by each of the working and integrative groups, which identified the key research questions, the measurements required to address them, the types of experiments that might be used to test specific hypotheses derived from the research questions, and the places where these experiments might be carried out. These draft reports were cross-reviewed by each of the working groups to highlight the scientific questions and measurement requirements that spanned the larger subduction zone science community. Finally, these reports were released for community feedback to ensure that the documents represent the entirety of scientific opinion as to what the most important scientific questions are, and the instrument and modeling networks we will need to study them.

The reports of each of the working groups are in Chapter 2 of this report and those of the integrative groups are in Chapter 3. The working groups and integrative groups initially worked independently to ensure a broad discussion that accurately captured the scientific needs. Chapters 2 and 3 purposefully preserve disciplinary preferences and priorities to maintain transparency of the full process. Later, the RCN worked to integrate and synthesize those plans. The common themes of Chapters 2 and 3 are synthesized in Chapter 4. In particular, Chapter 4.1 highlights common scientific and technical needs. Chapter 4.2 reconciles the geographic requirements and makes recommendations on geographic focus. Chapter 4.3 presents a draft organizational and governance structure.

This draft is the initial compilation of the RCN's activity that is being disseminated broadly for comment. Individual working group and integrative group chapters (2 and 3) have been publicly posted with multiple virtual and written forums for comments and discussion; however, this document represents the first synthesis of the work, including the products of cross-cutting committees devoted to developing common themes and structures across the RCN.

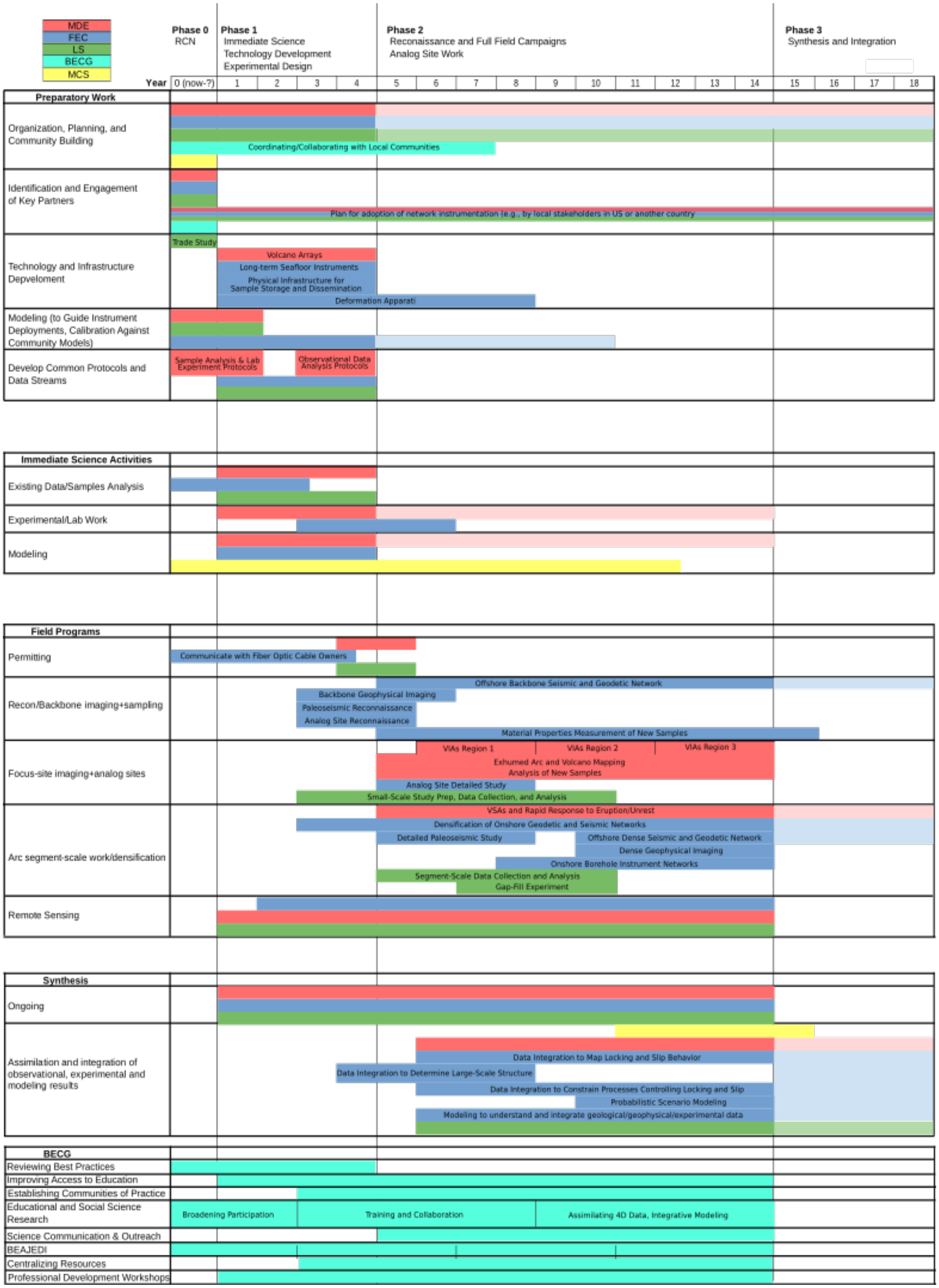

Figure I-3. *Proposed phases of SZ4D implementation. (Link to high resolution version)*

SCIENCE PLAN OVERVIEW

Chapter 2 outlines the critical questions associated with geohazards that have been formulated by each working group. A key general theme emerges: forecasting and predicting geohazards is desirable and is currently achievable to varying, limited degrees. Forecasting is a mature field that probabilistically anticipates hazard or risk empirically. The closely related study of prediction focuses on scientific hypotheses of future behavior and is more akin to hypothesis testing. Scientific prediction can be fully deterministic or stochastic 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 towards assessing the physics-based predictability and the presence or absence of precursory behavior. Some volcanic eruptions can be forecast based on observable increases in earthquake rates, deformation, or gas emissions, but others elude such approaches. Is the difference merely a matter of deploying sufficient instrumentation to detect subtle signals or are there fundamental differences in process that need to be elucidated? Earthquake prediction is even more elusive, despite the fact that theory and laboratory experiments commonly show precursory processes, and intriguing field-scale observations of possible precursors have been made in recent years. Is the difference between nature and the model systems simply a matter of insufficient observations or of fundamentally different processes that are not yet understood? For landslides, theory also suggests that we should be able to anticipate the timing and scale of mass failure based on environmental and topographic data, yet observations thus far have not yet shown that this understanding is correct. Is the problem merely lack of adequate measurement of the controlling variables or is the process intrinsically stochastic? And once initiated, sediment produced by these landslides may, in some cases, modify downstream rivers in predictable ways that may change flooding hazards. Observing the detailed sequence of these changes will help us predict mass transport events that might produce cascading effects downstream that augment other geohazards for decades following the original event. Once this knowledge is established, we need to understand how local hazards agencies can successfully utilize forecasts while delineating the limits of prediction to ensure equity in mitigating hazards.

In addition to forecasting and prediction, five other cross-cutting themes were identified (**Figure I-4**). Mass transfer couples the subduction system and hazardous events and involves the transformation of energy from one form to another. Therefore, it is important to unravel the **mass and energy balance** of the subduction zones. Observations of deformation generally measure strain, yet predictive understanding of processes requires knowledge of stress. The connection between stress and strain is the domain of **rheology**, which is essential to all facets of the SZ4D effort. **Fluids** provide the fastest mode of transport across the system and exert first-order control on geohazards in both 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.

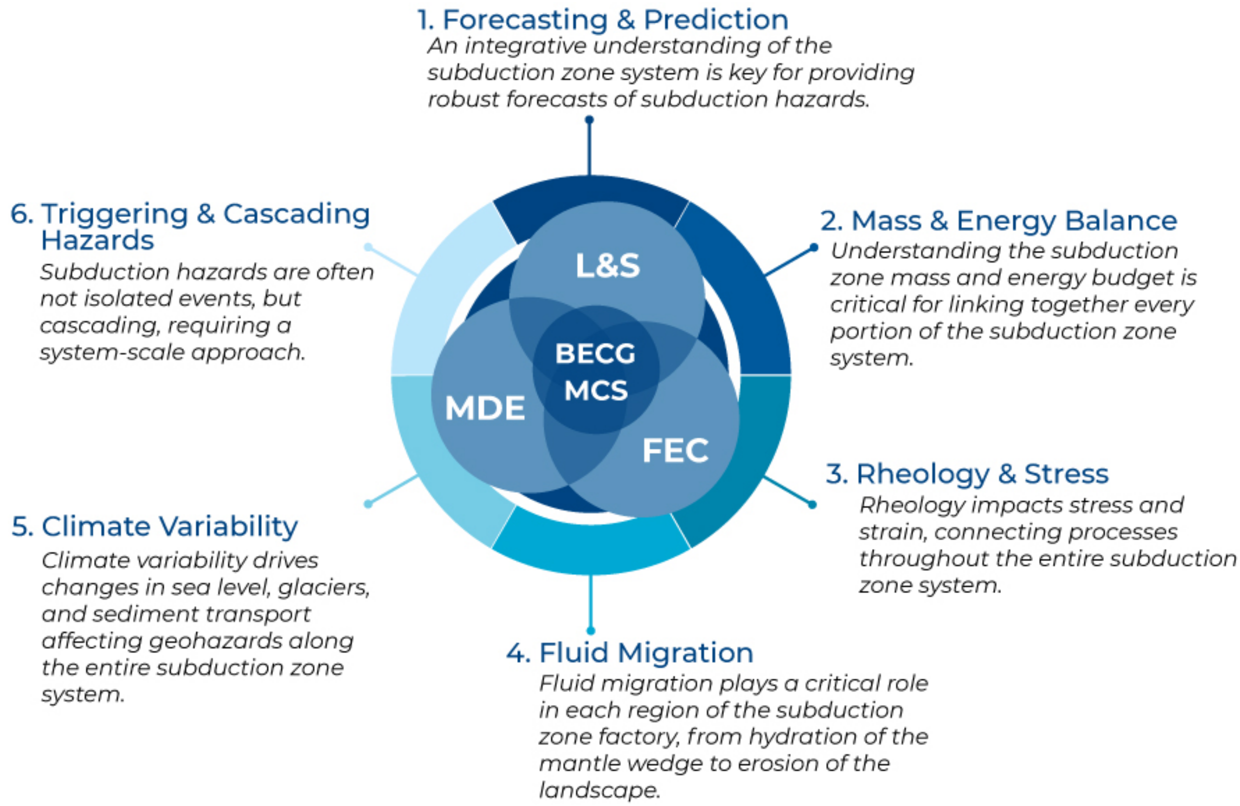

Figure I-4. *A visualization of six cross-cutting science themes that link the three main SZ4D disciplinary groups, Landscapes and Seascapes (L&S), Faulting and Earthquake Cycles (FEC), and Magmatic Drivers of Eruption (MDE); and two SZ4D integrative groups, Building Equity and Capacity in Geoscience (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.*

These cross-cutting issues discussed in Chapter 4.2 of this report demand a serious observational effort. In particular, SZ4D requires field instrumentation in the form of: (1) an array of **amphibious geodetic and seismic instrumentation (MegaArray)** that spans an entire ~500 km-long segment and is densified in critical areas, (2) **volcano arrays (VolcArray)** of standardized, multiparameter volcanic instrumentation packages, and (3) **surface and environmental change detection arrays (SurfArray)** that image changes in Earth's surface and rainfall.

Data from these instrument arrays can only be sensibly interpreted and utilized with complementary efforts to: (1) mine the geological record for rheological, chemical, and historical context; (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 meaningful knowledge that can be utilized immediately by the affected communities. Items 1 and 2 are addressed within the working groups plans (Chapter 2). Item 3 is addressed by the integrative group on modeling (Chapter 3.2), resulting in a recommendation for a facility devoted to this issue. 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 in Geosciences integrative group has formulated a plan (Chapter 3.1) that includes specific activities that will foster international capacity building, hazard equity and social justice, education and training, distributed outreach, interdisciplinary collaboration and increase diversity, and equity and inclusion. The key needs would be met through a coordinated effort involving community engagement, social science and education research, and centralizing resources. The SZ4D community would participate in a cooperative network seeking to accomplish long-term, sustainable broader impacts that would improve capabilities for all scientists involved.

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 4.3, facility support is necessary in several key areas. (1) **Seafloor Arrays**, including the MegaArray and SurfArray. This substantial effort and new facility in terms of scope includes dedicated support for seismic and geodetic instrument pools, collection of high-resolution bathymetry, 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 volcano arrays (VolcArray) with satellite telemetry for near-real-time data collection; environmental observing networks for landscape and deformation sensing (SurfArray), and deployable arrays for rapid response in regions with little prior infrastructure (MegaArray). (3) Logistics and implementation of field programs that involve **Deployment of Humans** as the primary observational instruments to collect systematic, standardized data (e.g., paleoseismology, framework mapping, samples for geochronology, geochemistry, and petrology). (4) A **Modeling Collaboratory** to both develop new subduction zone physical models and provide resources for their use by the whole SZ4D research community (students, postdocs, researchers). (5) A **Laboratory Experimental Consortium** for the study of material properties, rheology during deformation, and phase equilibria of molten systems.

The scale and scope of the proposed comprehensive program requires a carefully phased approach, outlined here and via a draft timeline (**Figure I-3**). SZ4D has already begun with Phase 0 activity, identifying data availability that addresses the scientific themes and the gaps therein, beginning to scope the necessary technical developments, scientific workforce needs, and an SZ4D-specific approach to capacity building based on belonging, access, justice, equity, diversity, and inclusion (BAJEDI) principles by reviewing best practice and comparing outcomes of similar community-based efforts to identify promising approaches to broadening participation. Upon the launch of an SZ4D program, we envision that Phase 1 will constitute a multi-year effort to develop technology to meet later scientific needs while simultaneously pursuing pilot-reconnaissance-level field efforts and modeling activities, and developing the detailed experiment designs and analytical protocols. Phase 2 will encompass the decadal-scale full-fledged deployment of field campaigns to comprehensively observe and analyze subduction systems. The arrays will be guided by and in turn guide model development and laboratory/experimental 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 hazard prediction is clearly desirable. Current approaches to eruption and landslide prediction are empirical; earthquake prediction remains beyond our grasp. New observations suggest a richer suite of processes is responsible for each of these hazards, but capturing the signals with sufficient fidelity for understanding has been elusive. The investment in SZ4D will revolutionize our understanding of subduction zone geohazards by providing dense, continuous, standardized data designed to be readily integrated into an interpretive framework. This framework will in turn provide the needed physically based foundation to assess the extent to which predictions of earthquake, volcanic, landslide, and tsunami hazards are possible.