Project Summary - Collaborative Research: Catalyzing SZ4D

Overview

Despite the global urgency to mitigate the risk from geohazards, we still have limited understanding of the fundamental drivers behind earthquakes, tsunamis, volcanic eruptions, and landslides, and thus their predictability in time and space. The SZ4D (Subduction Zones in Four Dimensions) initiative is a community-driven effort that strives to address this need directly by coordinating and enabling fundamental research on the underlying physical and chemical characteristics and processes specifically in subduction zones. The effort was identified as a high priority in the National Academy of Sciences *Earth in Time* report and has brought together 74 scientists who study earthquake, volcanic eruption, landslide, and tsunami driving processes and incorporated input from approximately 1600 participants in workshops and webinars. We focus specifically on subduction zones because these geographic regions provide the opportunity to strategically investigate multiple hazards simultaneously in locations that generate some of the largest risks to society from geological events. In addition, the geometry of subduction zones permits unusually well-controlled natural experiments that can be used to isolate and study key factors that drive geohazards.

Intellectual Merit

SZ4D seeks to answer the following questions: 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 geoscience community to embrace education, outreach, accessibility, capacity building, diversity, equity, inclusion, and social justice as critical components for the success of the SZ4D and future scientific endeavors by the geosciences community? Answering these questions will require a substantial infrastructure investment in the form of instrumental arrays accompanied by support for field, modeling and laboratory science.

The expansive vision of SZ4D needs cost estimates, time phasing and project planning in order to prepare for full submission to the Foundation and any partnering agencies. This proposal lays out a plan to accomplish this development quickly. The major components of this proposed SZ4D catalyst effort are: 1) A staffed center that will organize the work and build equity and capacity in the Geosciences (BECG) following a Collective Impact model. 2) Technical project management to realistically evaluate costs and trade-offs of the instrumentation options. 3) Preparatory work for the geological, modeling and laboratory facilities which include workshops and modest engineering design work. All of these specific activities were strategically selected because they directly affect high-priority elements of the draft implementation plan and have identifiable, tractable development needs that should be addressed prior to launch of a full SZ4D program.

Most of the work is planned in year 1 to inform a decision about proposal strategy prior to anticipated MSRI funding calls. Extended work beyond year 1 will continue the community momentum and prepare for launch of the enabling facilities through other mechanisms.

Broader Impacts

Broader Impacts of this proposal are directly woven into each activity proposed to facilitate community building around geohazards with the aim of catalyzing community engagement and science development towards a collective design of a full SZ4D program to understand hazards that threaten the lives and livelihoods of communities globally.

1. Introduction

There is considerable and justified global urgency to understand and mitigate the risks that result from geohazards such as earthquakes, tsunamis, volcanic eruptions, and landslides, particularly as these risks may intensify and evolve in a changing world. Despite this, we still have limited understanding of many of the fundamental drivers behind most geohazards, and this lack of fundamental understanding severely hinders efforts at mitigation and at predicting the occurrence and impacts of hazards in time and space. The SZ4D (Subduction Zones in Four Dimensions) initiative is a community-driven effort to address this need directly by coordinating and enabling fundamental research on the underlying processes. SZ4D brings together scientists who study the processes that drive earthquakes, volcanic eruptions, landslides, and tsunamis at subduction zones because these geographic regions provide the opportunity to strategically investigate multiple hazards simultaneously. The geometry of subduction zones permits unusually well-controlled natural experiments allowing the key factors that drive geohazards to be isolated and studied. Subduction zones also generate the largest risk to society from geological events.

Representatives from U.S. research communities that study subduction geohazards have been collaborating for the past three years in a Research Coordination Network (RCN), to turn the vision for hazards-focussed subduction zone science laid out in McGuire et al. (2017) into an actionable plan. The implementation of the SZ4D Initiative was identified as a high priority for NSF in the 2020 NASEM consensus report *Earth in Time: A Vision for Earth Sciences 2020-2030*. The SZ4D RCN is currently organized into three working groups (Landscapes and Seascapes, Faulting and Earthquake Cycles, and Magmatic Drivers of Eruption), and two integrative groups (Building Equity and Capacity in Geoscience and Modeling Collaboratory for Subduction) with a total of 74 members. Through a combination of meetings, workshops, webinars, and town halls, the RCN has engaged more than 1600 participants to identify community priorities, key observations and measurements to enable the scientific advances to better understand geohazards. These efforts led to the October 2021 release of the draft SZ4D Implementation Plan that stated the requirements for a long-term coordinated study of subduction zone hazards and a Center structure to enable it. This proposal lays out the critical initial steps to implement that plan by building the Center, initiating technical project management and nucleating facilities.

The working groups and integrative groups have synthesized community input and identified several **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 our geoscience community to embrace education, outreach, accessibility, capacity building, diversity, equity, inclusion, and social justice as critical components for the success of SZ4D and future geoscientific endeavors?

From these questions cross-cutting themes emerge. For instance, all current geohazards studies strive to establish the circumstances under which catastrophic events can be forecasted. Would additional instrumentation result in better predictions, or are there fundamental limits to what the data can tell us? For example, some volcanic eruptions already can be anticipated with sufficient instrumentation, but others are not predicted for reasons not yet understood (Winson et al., 2014). The discovery of slow slip events prior to some, but not all, M8+ earthquakes raises similar questions about our ability to predict earthquakes (Brodsky and Lay, 2014; Pritchard et al., 2020). Is the limiting factor the fundamental complexity of the system, or the lack of instrumentation close to the fault? The same questions apply to anticipating the timing and scale of mass failure.

Beyond the scientific synergies, the practicalities of studying several geohazards at a limited number of subduction zones add significant value compared to multiple individual studies. Leveraging mutually beneficial partnerships, instrumentation, data management, and capacity building can accelerate scientific advances, including unanticipated ones. In particular, a common regional focus allows development of more integrated partnerships, strategic deployment of physical infrastructure, and concerted contextual information that enables multidisciplinary interpretation. The draft report of the RCN advises a focus on Chile paired with a domestic site to leverage the power of comparative studies.

Answering the questions identified by the RCN will require new observations both on land and under the sea. **Three pieces of the in situ SZ4D infrastructure** (Fig. 1) are: (1) a large-scale, long-term backbone array of **amphibious geodetic and seismic instruments (MegaArray)**, with densification in key areas of interest; (2) multi-component, standardized **volcanic arrays (VolcArray)**; and (3) a set of **surface and environmental change detection arrays (SurfArray)** that image changes in Earth's surface and rainfall. These observational pieces are only meaningful if the new observations are accompanied by concerted geological studies, laboratory experiments, geophysical imaging, numerical modeling, and scientific human resource development programs to provide context and identify processes.

Figure 1. Schematic of major instrumental arrays and activities of SZ4D.

Based on the need for both the arrays and support for the accompanying studies, the **SZ4D draft implementation plan identified the need for five facilities**, which can be built to varying degrees on existing resources: (1) **Offshore Instrumentation** to enable the MegaArray and SurfArray, including 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 seismic and geodetic arrays in regions with little prior infrastructure (MegaArray). (3) Logistics and sampling in field programs that involve **Human Deployments** 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 for Subduction (MCS)** to both develop new subduction zone numerical modeling capability and provide resources for their use by the whole

SZ4D research community. (5) A **Laboratory and Sample Consortium** for the study of material properties, rheology during deformation, and phase equilibria of molten systems.

This SZ4D catalyst proposal is organized around **three major components**: 1) Section 2 describes a staffed center charged with **organizing the work and building equity and capacity in the Geosciences (BECG)** and ensuring that the multidisciplinary efforts are coordinated following a Collective Impact model. 2) Section 3 lays out the technical project management to **evaluate costs and trade-offs of the array instrumentation** options for meeting the scientific goals and necessary functions of the Off-shore and On-shore facilities. This component will largely be performed by the collaborating institutions in coordination with the SZ4D committee structure. SAGE/GAGE will handle the technical project management, Georgia Tech will model geodetic array design and URI will evaluate the high-resolution bathymetry options. 3) Section 4 outlines **preparatory work for the Human Deployment, Modeling, and Lab and Sample facilities**, which include workshops and modest engineering design work to determine costing. All of these activities were selected because they directly affect high-priority facilities and arrays of the draft implementation plan and have identifiable, tractable development needs that should be addressed prior to launch of a full SZ4D program.

Section 5 provides timelines and milestones where we identify a critical decision-point and the subsequent trajectories of the project based on anticipated funding opportunities. The proposed timeline is designed to establish resources beneficial to the community even in the absence of fully funded facilities. BECG activities and scientific exchange at the workshops will have benefits beyond SZ4D with an even greater impact should the full vision be realized.

This proposal builds on the efforts of the prior SZ4D RCN and those of the MCS RCN. The SZ4D RCN delivered a draft implementation report to the agencies in October 2021 and the MCS RCN is delivering its final report to NSF in 2022. Because of the pandemic, in-person meetings of both RCNs were delayed and a few workshops remain which will conclude the RCN activities and resources. The role of those activities and how they relate to the proposed work is explained in Section 5. A transition plan is presented in Section 2c to combine the activities and committees into a single organizational structure that appropriately represents the community with multiple opportunities for scientists to engage and drive the decision-making of SZ4D.

2. The SZ4D Science Center: A Model for Coordination and Engagement

2a. SZ4D Center Overview

Activities carried out by individual SZ4D components will be interconnected. The enterprise must be phased so that interdependent components can be executed smoothly over the lifetime of SZ4D. This coordination requires a **Science Center that can integrate the science planning** (Fig. 2).

A fundamental objective of the Center will be to maximize SZ4D's Collective Impact (CI, see section 2b.) by coordinating science integration, data products, stakeholder and partner engagement, and BECG efforts across the SZ4D community groups. These essential functions will be provided by a dedicated staff in the Center whose role will include providing logistical support to the SZ4D community and designing effective communication strategies to engage the community and develop international partnerships. The Center will interface with existing facilities to manage and leverage their resources for SZ4D data collection and will support new facilities (e.g., Human Deployments, MCS, Laboratory and Sample) as well as coordinating data management and, identifying new cyberinfrastructure needs, and facilitating access to all SZ4D data through a common data portal. The Center will also communicate regularly with NSF and other agencies (e.g., NASA, USGS, NOAA) to coordinate resources that enable SZ4D activities.

Figure 2. *Simplified organization of the advising committee structure that would be coordinated by the SZ4D Center. Numbers indicate target membership size. See Figure 3 for a detailed diagram of the larger SZ4D enterprise.*

International engagement is a critical piece of the SZ4D implementation plan, including a potential focus site in Chile. The existing RCN is organizing an in-person meeting in Chile in May 2022 that will be run through the Geological Survey of Chile with an open application process for Chilean scientists. Future international coordination will be led by the Center. To this end, we have budgeted for an in-person international meeting to be held in Potsdam, Germany, in Year 1 to coordinate current and planned complementary efforts in Chile with research groups in Germany and France.

SZ4D center administrative staff will organize virtual and in-person meetings and workshops, facilitate communication between committees and facilities, prepare and disseminate documents, and maintain the SZ4D website and mailing lists.

2b. Building Equity & Capacity in Geoscience (BECG)

As a community-driven scientific initiative, **SZ4D seeks to address major gaps in our understanding of geohazards by coordinating fundamental research and bringing together a range of historically disparate geologic sub-disciplines and scientists**. The culture of inclusion needed to accomplish this goal requires geoscience to consider a new approach. Previous similar efforts have operated in a model whereby NSF and other funders support the proposals that make the greatest impact with the least amount of resources within a limited timeframe. This "Isolated Impact" model creates minimal lasting effects on communities due to a short-term focus on rewards and costs, while motivating PIs to propose and conduct work by distinguishing their efforts from others in a culture of competition. In addition, the approach of relying on the NSF Broader Impacts criterion to build equity and capacity in the geosciences has struggled to create sustained social impact and has not leveraged evidence-based effective practices (Bozeman & Boardman, 2009; Nadkarni & Stasch, 2013).

The Isolated Impact model is not sufficient to enact the transformative change in building equity and capacity necessary to create a more cooperative and sustainable approach to conducting the science as proposed in the Implementation Plan. Instead, we will build a SZ4D Center espousing a Collective Impact (CI) framework (Kania and Kramer, 2011; 2013). CI is based on organizing a group of community members around solving specific social problems using a structured form of collaboration. It is essentially the "how" to effectively achieve a big vision (Herman, 2014). The CI methodology is increasingly recognized by experts as a necessary alternative to the Isolated Impact model (NASEM, 2020; Jolin, 2012). Previous research has shown that successful CI initiatives meet five criteria: (1) a Common Agenda, (2) Shared Measures, (3) Mutually Reinforcing Activities, (4) Continuous Communication, and (5) a Backbone Organization.

The SZ4D RCN initiated these criteria and a SZ4D Center will build critical elements as the CI Backbone and work to coordinate components (1)-(4) for integration of research and BECG goals. The SZ4D Center will support individual PIs to identify and develop their projects aligned with the CI framework, including brokering training as needed. The CI approach ensures activities will be assessed by a common set of values and goals, while also providing a common language and environment for sharing successful strategies. A SZ4D Center with new communication mechanisms will lead to more effective transmission of scientific information and enable all community members to be engaged in discourse and decision making. To catalyze the construction of the CI framework, we are seeking to: 1) engage Minority-Serving Institutions (MSIs) and 2) create communities of practice to develop the CI framework. Ultimately, we envision seeking larger-scale support through the NSF INCLUDES and CTGC opportunities.

2b.1. Engaging Minority-Serving Institutions (MSIs) for Broadening Participation in SZ4D

To **build capacity for historically minoritized groups to participate in SZ4D science**, it is necessary to work with MSIs in "mutually beneficial" ways as these institutions enroll and graduate a disproportionately high share of minoritized STEM students (NASEM, 2019; NCSES, 2019). SZ4D will engage MSI stakeholders in person, both on MSI home campuses and later in a group workshop, to partner in defining the CI framework. An initial on-campus engagement is important to establish relationships that lead to workshop participation and for building sustained connections to the CI Backbone through connecting with long-term SZ4D staff who can offer centralized support which is key for mutually beneficial partnerships (NASEM, 2019). The workshop will be designed to primarily and integrally involve MSI representatives to enable honest and unobstructed communication (Ballysingh et al., 2017; Gonzales et al., 2021), helping to shape a Common Agenda that represents the perspectives of a broad range of institutional stakeholders, regions, and minoritized communities. The workshop will be modeled after recommendations made for how NSF can better support MSI capacity building (ASEE, 2020) recognizing the unique, under-resourced contexts in which HSIs often operate (Núñez et al., 2021). This effort will be aided by the fact that the lead institution (UCSC) is an MSI.

2b.2. Communities of Practice to Develop the Collective Impact (CI) Framework

The SZ4D RCN has made progress on the Common Agenda and Backbone of CI, but developing the Shared Measures, Mutually Reinforcing Activities, and Continuous Communication will take more time and concerted effort. Three overarching goals described in the Implementation Plan will enable SZ4D to exceed prior community engagement efforts: 1) **Belonging, Accessibility, Justice, Equity, Diversity, and Inclusion (BAJEDI)**, 2) **Capacity Building**, and 3) **Interdisciplinary Collaboration**. We propose to use year-long communities of practice for each goal to mold a new CI framework based on the faculty learning community model and trading zone approach to interdisciplinary scientific collaborations (e.g., Cox, 2004; Sherer et al., 2003; Shipley et al., 2016). We propose using stipend support to attract experts on these topics and ensure participants commit to achieving the goals over a longer time frame (Ward and Selvester, 2011).

The BAJEDI community of practice 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). We will identify mutually reinforcing activities for increasing access to SZ4D science for underrepresented populations, such as memorandums of understanding between partners at MSIs and traditional research institutions (NASEM, 2019). Developing effective strategies for communicating the relevance of BAJEDI efforts will be critical to recruit and retain a diverse SZ4D community. The community of practice will develop assessments for application across SZ4D as self-examination is crucial to identify and address BAJEDI issues (Velasco et al., 2021).

SZ4D provides a unique opportunity to establish equitable international capacity-building partnerships to improve capabilities (e.g. skills, data, technology, understanding) for all stakeholders involved. The Capacity Building community of practice will identify mutually reinforcing activities for cooperative international field research, sustainable human capacity building, technical infrastructure development, and FAIR (Findable, Accessible, Interoperable, and Reusable) data and research policies (Fecher et al., 2015). Efforts to minimize colonial methods of interaction will be central, including implementation of cross-cultural implicit bias training (e.g., Nordling, 2017; Cartier, 2019). Developing shared measures to assess these activities' effectiveness, efficiency, and sustainability will facilitate detection of colonial attitudes and foster awareness in the SZ4D community (Stefanoudis et al., 2021). We will aim to increase adoption 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. We 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 (policymakers, impacted populations, and media) and evaluating effectiveness of outreach with shared measures.

The Interdisciplinary Collaboration community of practice will seek to implement evidence-based practices for collaboration that break down disciplinary silos and improve understanding across subject areas. We 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 (timeline in Fig. 4), extending into research on collaboration (Collins et al., 2007).

2c. Center and Governance Structure

A Center management team, led by the PI, will **interface with the SZ4D community and partners to implement the directives of the scientific community**. Each Center management structure will be overseen by an Advisory Committee (AC, Fig. 2), sourced from within the SZ4D community. This would include ACs for the activities of the new facilities, an AC coordinating science priorities across the different disciplinary groups, and an AC ensuring integration of BECG goals via CI. In all cases, membership will be determined by an open nomination and volunteer process facilitated by a Committee on Committees (CoC). The CoC will serve as a point of contact for nominations and volunteers and will actively solicit members to ensure a diverse, balanced composition that represents the full community. CoC will combine nominations from the current committees, the community and their own work to present a slate of candidates to the Steering Committee for each term. Each member will serve a 3 year rotation, staggered to cycle a third of the committee each year. The anticipated number of members of each of the ACs is shown in Figure 2. The overall Center activities will be overseen by the Center Steering Committee, which will also facilitate communication, coordination, and resolving competing objectives between the ACs. This will be accomplished by composing the Center Steering Committee with members from each of the various ACs, via nomination of representatives by each of the ACs.

The SZ4D community recognizes its shared goals with various other entities focused on either certain aspects of subduction zone hazards or specific regions. For example, there are a variety of potential collaboration opportunities with the proposed Cascadia Region Earthquake Science Center (CRESCENT) and CONVERSE. Actively pursuing good communications with our sibling organizations as noted in the connection to partner organizations in Figure 3 is an important goal of SZ4D that will lead to our CI in the broadest sense.

One of the initial tasks of this proposal is to transition from the current RCN to a Center structure. This requires refreshing and expanding the representation of the community without disrupting the successful current trajectory of SZ4D. Consequently, we will begin forming the ACs to guide the development of new facilities (Offshore, Onshore, Human Infrastructure, Laboratory and Sample) and the maturation of MCS. Current SZ4D RCN Working and Integrative Groups will be maintained to provide input to the Science and Collective Impact ACs.

To ensure continuity, a final, in-person all-hands RCN meeting, planned before the proposed transition in August 2022 and followed by a full community meeting in November 2022.

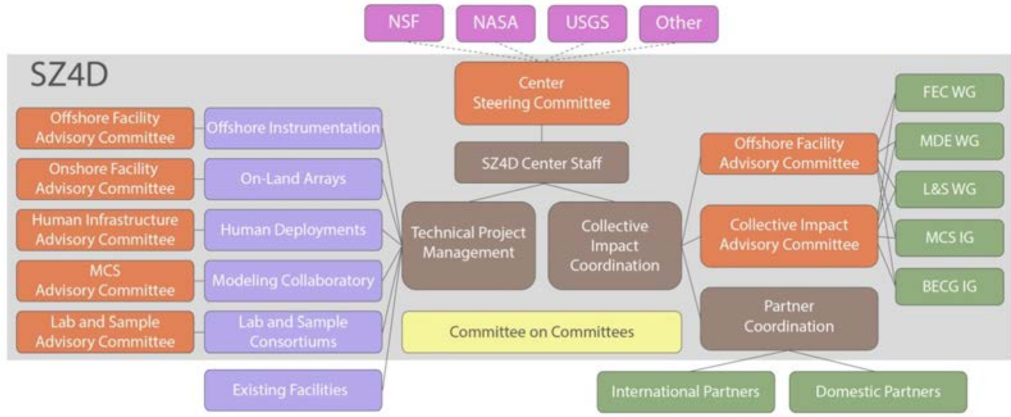

Figure 3. *Organizational structure of the central elements of the SZ4D Center (brown); Advisory Committees (orange); Facilities (purple); Community Groups, Working Groups (WG), and Integrative Groups (IG) (green); funding agencies (pink); Committee on Committees (yellow). Gray marks the extent of the SZ4D community.*

3. Array Design Activities

MegaArray, VolcArray, and SurfArray are at the heart of SZ4D. Each requires extensive instrumentation and has specific development needs before proceeding to implementation. The work in this section is designed to focus on the arrays and their associated facilities (Facilities 1-2 as described in the introduction). Section 3a details technical project management which will cover costing and implementation phasing for all three arrays. Two of the arrays (MegaArray and SurfArray) have significant technical knowledge gaps that will be addressed in distinct design activities as described in Sections 3b-c.

3a. Technical Project Management

A key goal of this catalyst proposal is to **build a realistic budget model and phasing plan for the acquisition and operation of instrumentation described in the SZ4D draft implementation report**. A budget model will be developed for the instrumentation aspects of SZ4D that allows cost estimates to rollup, and preserves the selection of different assumptions in quantities or cost values. Once the instrumental observations are specific, the dependencies in time phasing of activities will be incorporated into a high-level plan. This will include estimates of technical readiness or preparatory phases and integrated plans for maintaining and operating the arrays.

These technical project management needs require staff support and the collaborating SAGE/GAGE Facilities on this proposal will perform this part of the planning effort. The collaborators will build a budget model that will help identify a range of project cost estimates, given a particular set of assumptions and the relative costs of different aspects of the initiative. The second step is to build a time phased plan that identifies long-lead developments, tasks contingent on another task or processes. The budget model and project execution readiness will be used to inform whether the next phase should be an MSRI-1 (design phase) or MSRI-2 (implementation phase). Recognizing there are a multitude of scientific, technical, and funding considerations involved, a high-level timeline that is consistent with the technical plan will be an important component of planning the next phase of this project.

The budget model includes several steps, each based on iterative communication with the committee structure (Fig. 3) as well as narrower focus groups of subject matter experts. To date, the SZ4D community has worked to identify observations needed for the science objectives, with some specific suggestions for what instrumentation should be included. The budget model will need to quantify the target number of each type of sensor or instrument, along with a range of quantities and unit costs. The cost estimates will include equipment for enclosures, power and communication systems that can be specific to the deployment environment, anticipated methods of deployment and long-term operation. As cost estimates are rolled up, the value of each observation to the objectives will be weighed in by the scientific stakeholders and community. The budget model will also include instrumentation that has never been produced or deployed at scales envisioned here, and instrumentation with highly complex deployment logistics (e.g., helicopters on volcanoes, seafloor instrumentation). These will increase uncertainty in cost and schedule estimates. We will also include anticipated costs for receiving, testing, and integration of instrumentation elements into deployable systems.

Choosing what instrumentation to acquire has strong dependencies on operational aspects, including power and data telemetry. In addition to acquiring equipment and operating it, tasks associated with the deployment or installation and with servicing and data recovery will also be considered. These costs will be included in the budget model with flexibility to explore the implications of where these costs lie in the construction phase or operations phase of the initiative. Costs for long term maintenance (such as monitoring of instrumentation performance for state of health, command and control, telemetry performance, security updates and the servicing of operating instrumentation) will be estimated with considerations on how well integrated such activities are across the diverse sets of instruments and disciplines. The costs associated with servicing and data recovery for the offshore component will depend on instrumentation choices (e.g., communications and endurance), and will need to consider the costs of national and international vessels in close collaboration with potential national/international partners.

The time phased plan development will focus on the technical readiness of desired observational capabilities and on the anticipated integration of deployments. Instrumentation may take many months to be delivered, or to integrate between suppliers into deployable packages. Incorporating work-flow or data-flow elements necessary for large scales of operation, often take design alterations and experimentation to optimize.

In summary, the SZ4D community will work through the committee structure with the SAGE/GAGE Facility staff to identify choices in specific instrumentation – their quantities, deployment configuration, and operations model. Cost range estimates will be associated with each. Communications will be facilitated through the SZ4D Program Manager and involve regular, iterative virtual committee meetings. The budget model and project execution readiness will be used to inform the decision-making on the appropriate next phase of the project as discussed in the timeline and milestone section of this proposal (Sect. 5).

3b. MegaArray Design

As described in the Draft SZ4D Report, offshore observations of subduction zone behavior and structure are particularly important given that most active portions of the fault systems lie below the submerged part of the margin and near-fault measurements are required to track the seismicity, geodetic coupling and transient slip. Faithfully **characterizing the spectrum of seismic slip behavior over a ~500x500 km region for a decade is scientifically required and will need a historic offshore observational effort; this is the prime goal of the MegaArray**. Dedicated resources are required to determine density, configuration and requisite instrumentation for the geodetic and seismic components of megarray for both an earlier backbone phase baseline and a second phase of detailed observations.

3b.1 Geodesy

Our goals are to **establish logistically and financially rational approaches to making seafloor geodetic measurements that provide resolution sufficient to answer core**

scientific questions for the FEC component of the SZ4D program. This requires 1) Optimizing network design to resolve changes in large-scale fault coupling across the seismogenic zone. Down-dip variations in coupling at a scale of ~40 km are thought to control persistent asperties across seismic cycles and the tendency for large earthquakes that may rupture to the trench. The network design will account for features of candidate SZ4D sites as well as intrinsic resolution and instrumental limitations. 2) Optimizing network design to resolve transient events; by identifying slow transients at the scale of larger geologically and seismically resolvable features along the megathrust interface and characterizing possible precursory transients comparable to ones prior to the 2011 Tohoku and 2013 Iquique events. Satisfying these criteria requires constraints on slip for a large range of magnitudes and durations (weeks to years). However, to evaluate interactions in the system, and to best constrain the modes of slip in space and time, spatial resolvability for different mechanisms of slip should be similar.

For an initial phase of instrument deployment, we will establish an initial backbone set of stations to define larger-scale features with patch-size resolution at 80-100 km. During the second phase of denser observations, transients and coupling should be resolved for a characteristic length of 20 km within the first 50 km of the trench, and 40 km characteristic length closer to and below land. For transients, our preliminary estimates are that a slip of 5 cm over 2-weeks is needed. For interseismic coupling, backslip/slip on the order of 1-2 cm/yr are needed. These numbers will be refined through this work.

To constrain the mode of slip across the megathrust we aim to characterize behavior from the trench downward and beyond the interface that defines the extent of the seismogenic zone. This will identify regional controls by the megathrust on seafloor displacement and tsunami generation. To evaluate transient slip behavior, we aim to resolve offshore events occurring over days to months that constitute precursory activity associated with some very large earthquakes, and to detect and resolve the behavior of slow-slip on the scale of geologically and seismically resolvable structures near trench.

To evaluate the design constraints for resolvability and cost, we request support for a project scientist and senior graduate student to undertake resolution tests to inform geodetic array design. We will use model-parameter information obtained from the weighted model resolution matrix, e.g. Menke (2012), weighted by error and cost (Sect. 3a) relative to existing networks (including land and offshore stations). The method shares features with those described in Blewitt (2000), Kyriakopoulos and Newman (2016) and Sathiakumar et al. (2017). For any model geometry, we will determine the weighted model resolution increase obtained from the addition of a specific instrument type and noise level. We will evaluate combinations of *a priori* densely-spaced networks to determine network subsets that can maximize resolution.

Modeling will start with half-space and layered-earth models (Okada, 1985; Wang et al., 2003), followed by Finite-Element models for more complex behavior if necessary. All methods are either directly incorporated in *GTDef* (Murekezi et al., 2020a,b), or can be included through ingestion of Green's functions (Kyriakopoulos and Newman, 2016, Williamson et al., 2017). While GNSS-Acoustic and seafloor pressure have been considered the most likely approaches for measuring coupling and SSEs, we will also evaluate other instrument types, including borehole pressure and tilt, optical fiber strainmeters, and direct-path acoustics, to determine their capability and relative value for an SZ4D deployment. The initial development will be for Chile, and either Cascadia and Alaska, depending on the SZ4D community focus.

3b.2 Seismology

A parallel effort is required for the seismology component of MegaArray to **determine the types of sensor(s), sensor installation, and optimal array design**. The MegaArray needs to have the capability to 1) characterize the spectrum of seismic slip, from microseismicity to low-frequency earthquakes; 2) record large earthquakes on scale; and 3) be used for geophysical imaging of subduction zone structure. Possible sensors include broadband and intermediate period seismometers, short-period ‘nodes’, strong motion instruments, absolute pressure gauges, and new technologies such as Distributed Acoustic Sensing (DAS). Other considerations are the duration and mode of sensor installation (e.g., shielding, burial); the latter is important for recording strong ground motions in shallow, fluid-rich sediments. Geodetic needs, such as absolute pressure gauges (APG), and the ability to include other geophysical or oceanographic sensors, which are important for identifying and suppressing non-tectonic signals (e.g., Muramato et al., 2019) and may benefit other scientific communities. We also need to determine the optimal array design for both the phases of the MegaArray: the earlier “backbone” phase and the latter densification. This array design needs to be informed by predictions from numerical modeling and closely coordinated with a parallel effort for seafloor geodesy. Finally, other important considerations include the water depths of instrumentation and the mechanisms of data recovery. Possible data recovery methods include acoustic and optical modems for ocean-bottom seismometers or immediate data access for cabled systems; a plan for servicing and data retrieval also needs to be closely coordinated with other offshore components, and guided by the priorities of local stakeholders.

We propose an integrated set of tasks to determine the technical specifications and array design of the seismic part of the MegaArray. 1) A series of virtual workshops to clarify the data needs for characterizing different types of seismic signals based on existing observations, numerical modeling and experiments, learn from previous and current deployments, identify any critical knowledge gaps and determine strategies to address them, and gauge the priorities of national and international partners. Each workshop will include ~20-25 people to enable focused discussions. Virtual workshops will allow for international participation, which is essential to engage stakeholders near potential deployment sites and to learn from previous/ongoing international efforts. These workshops will be organized by an ocean bottom seismic committee, which will be formed by members of the FEC working group, the MCS, and other community members. 2) Support for a Project Scientist to gather information on the capabilities of different sensors and other instrument components to inform decisions on technical specifications, which requires a review of literature and technical reports from manufacturers, and targeted analyses of existing datasets. Likewise, array design needs to be informed by resolution and detectability tests, review of the results of previous arrays, targeted data analyses on the performance of previous and existing arrays, and the predictions of numerical models. This individual will work closely with the ocean bottom seismic committee to delineate and prioritize these activities, which will also be guided by outcomes from the virtual workshops. 3) Finally, MegaArray design needs to be informed by the costs associated with instrumentation and the operation and management of the array (See Sect. 3a). Together, these activities will provide the information necessary to map out the next steps in planning MegaArray.

3c. High-Resolution Bathymetry for SurfArray

Understanding how soil moisture, routing of runoff and density currents initiate and facilitate mass transport across subduction-zone land- and sea-scapes requires a seamless, high-resolution depiction of the on-land, near-shore, shallow water, and deep water morphology of the solid-earth surface. To achieve this objective, we need to **develop technologies, sensor networks, and workflows to produce a continuous, high-resolution (≤ 1 m postings) description of the solid-earth surface across an entire subduction zone system**.

Mature technologies such as Airborne Laser Swath Mapping (ALSM) and green-Lidar ranging exist for imaging Earth’s onland and near-shore topography at high resolution. Likewise, high-resolution bathymetry within shallow water (< 80 m) has been collected along much of the United States coastline. However the widespread collection of high-resolution, deep-water bathymetry still constitutes a technological challenge and represents the main barrier to achieving the required seamless, high-resolution dataset. Nonetheless, there are several recently developed technologies that promise to enable the collection of the key information needed to probe Earth's land- and sea-scapes in deep water. To this end, we propose to conduct a trade study to identify the optimum mix of systems and sensors to collect high-resolution bathymetry (better than 1m resolution) over one or more large sections of subduction zone (~1000 km length). This scale of high-resolution bathymetric survey would exceed previous academic or commercial ventures and thus requires a thorough and deliberate investigation of technologies and methodologies that could accomplish the task efficiently and economically. The study will provide a cost/benefit analysis based on the mapping output vessel requirements and cost. This analysis, for example, will examine operational schemes such as single, long-endurance of autonomous underwater vehicles (AUVs) deployed from shore; towed systems deployed from uncrewed vessels; and multiple AUVs deployed simultaneously from a single crewed vessel. We will bound the analysis to operational concepts already demonstrated at sea, but novel and developing concepts will be noted in an appendix for consideration.

The trade study will be guided by requirements (e.g., mapping area, mapping resolution, desired data types) defined by an SZ4D-sponsored workshop designed to engage end-users and experts. To provide context to the analysis, a suitable subduction zone will also be identified and used as the "target". Having a natural feature to plan against will help identify operational pros and cons of the different systems, sensors, and operational concepts. For example, systems can have varying degrees of maneuverability that can greatly affect mapping performance in steep terrain; by considering each system in a real subduction zone these differences can be identified and highlighted.

Potential systems (e.g., AUVs) are more than just a host for a mapping sensor and can carry a suite of oceanographic and geophysical sensors. This study will identify all of the sensors available on each system, the resultant type and resolution of data and potential additional sensors that may be added with varying levels of effort/cost. We will estimate the level of effort required to process each data type (including seafloor mapping data) prior to any analysis, as it is expected to represent a non-trivial effort for successful surveys.

The project will solicit the expertise housed at U. of Rhode Island - Graduate School of Oceanography who have extensive experience as users and developers of AUV systems.

4. Facilities in Support of Field, Modeling and Laboratory Science

The instrumental arrays are necessary, but not sufficient, to support efforts to understand subduction zone geohazards. The observational data can only make sense if investments are made in the field, modeling and laboratory studies that are used to connect processes to data. These interpretative activities also need facility support. This section of the proposal describes the efforts necessary to launch these efforts.

4a. Human Deployments: A Facility in Support of Field Geology

SZ4D represents an important opportunity to **rethink approaches to field geology and sample collection** – a need that cuts across all the planned SZ4D science goals. Currently, most geological field campaigns are organized by small groups, who duplicate logistical efforts associated with travel, lodging, permitting, purchasing and/or shipping of field equipment. This approach minimizes coordinated planning, both among PIs and, in foreign countries, with international collaborators, and results in increased effort and cost. It also creates barriers to participation for scientists without a pre-existing collaboration network, limiting diversity. As a result, academic terrestrial field geology can fall behind other groups in terms of coordinated logistical support, continued public availability of data and metadata, and archiving of physical samples. Communities such as the USGS, IODP, OPP, continental drilling initiatives, and marine geology cruises provide useful models for scientific integration that may be considered in implementing field-based geology as part of SZ4D.

Creating support for terrestrial-based field science as a facility is potentially one of the most transformative aspects of SZ4D. To start planning this facility, we propose a series of webinars and a workshop supported by SZ4D Center Staff to explore the needs of field-based scientists and to develop a plan for coordinated facility support for field activities as part of SZ4D. Webinars that precede the workshop will range from individual science areas to community wide information sessions on the proposed facility, leading up to the workshop itself, which will focus on crafting a vision and implementation plan for the facility. Post-workshop webinars will be used to finalize an implementation plan for the facility. To maximize attendance, the workshop will be coordinated with a major conference, such as the Geological Society of America national meeting, and funds will primarily be used to support attendance by early career scientists and other key stakeholders. Topics covered at the workshop will include pre-field work preparation, field activities, and post-field work support and science discussions of potential sites.

4b. Modeling Collaboratory

The Modeling Collaboratory for Subduction (MCS) component of SZ4D is a community- and model-building effort to advance subduction zone science. The objective of MCS is to **create new kinds of physics-based models for earthquake, eruption, and other geohazards at subduction zones, and apply them to understand fundamental processes, guide instrumentation deployments, interpret observations, and assess hazards**. The goal is to embed geodynamic modeling as an integrated part of the observational and laboratory efforts of SZ4D from the outset, rather than the more typical sequence in which modeling follows data collection. In this way, MCS can ensure model-data fusion across the phased SZ4D effort, provide physics-based frameworks for combining multi-temporal, multi-spatial, multidisciplinary observational and laboratory datasets, and help plan and design instrumentation arrays to ensure that data collection is optimized to address the primary SZ4D science questions.

While the code development efforts of the MCS will be targeted toward SZ4D science questions, there are clear overlaps with existing NSF-funded computational centers. In particular, the Computational Infrastructure for Geodynamics (CIG) and the Community Surface Dynamics Modeling System (CSDMS) serve modeling communities with interests in subduction zone dynamics. While CIG and CSDMS foster code development and training with a less directed science focus, many of their existing computational tools may serve as excellent starting points for MCS development efforts. In addition, their collective knowledge of best practices for open source well-documented code development, training and community engagement are vital resources.

The MCS RCN plans to use its remaining funds to convene a small workshop to bring together the leadership of CIG and CSDMS to discuss how best to leverage existing computational infrastructure, areas of potential synergy, and ensure that efforts are not duplicated. In addition, the planning phase of the MCS RCN identified the following areas for additional community input: (i) surface process - volcano interactions, (ii) integration between laboratory rock mechanics and modeling efforts, and (ii) slow slip. Workshops on these topics will be held virtually with support of the SZ4D Center staff or in-person in conjunction with other SZ4D meetings.

4c. Laboratory and Sample

Answering the SZ4D science questions requires the development of new experimental rock deformation capabilities. **Rheology is a cross-cutting theme of SZ4D**, but existing equipment fails to measure rheology at the relevant pressure, pore fluid pressure, and strain-rate conditions. The activities outlined here **will allow the experimental community to coordinate and propose new technical capabilities**, and will require funds for in-person and virtual workshops and consultation with engineers for preliminary equipment designs. We plan to hold a series of virtual workshops over the spring and summer of 2022 culminating with an in-person workshop after the Gordon Research Conference on Rock Deformation in August of 2022. Once the workshops are complete, the specifications will be used to contract initial design work and costing with an engineering firm to evaluate technical feasibility.

Laboratory science forms a key component of all three Working Groups, and the technical and human infrastructure required to do the science cross-cutting the Working Groups. We envision a coordinated network of laboratories that would facilitate SZ4D to achieve its scientific goals and promote new creative collaborations, increase accessibility and participation in laboratory science, and share costs to increase impact. With support of the SZ4D Center staff, we plan a community-wide virtual workshop and in-person discussions of the laboratory network at the *Experimental Rock Deformation* workshops and the SZ4D community meeting.

Collaborative field geology and experimental studies are integral to all of the SZ4D working groups and will require the coordination, storage, and distribution of physical samples. During the planning stage, we need to determine the scope and infrastructure needs for sample storage and this will require input from the broader field and experimental communities. To facilitate these conversations, we will hold a virtual workshop as well in-person discussion sessions during the proposed *Human Deployment* and *Experimental Rock Deformation* workshops as well as the SZ4D community meeting.

5. Timeline and Milestones

The timeline for the planning process is driven by funding opportunities. In broad outlines, the Center and BECG work (Sect. 2) is continuous throughout the project period (Fig. 4). Existing RCN funding allows for staffing through December 2022, and this proposal continues the staffing for an additional 3 years. The array design work must be accomplished in time for an anticipated MSRI call in late 2022, and thus section 3 work is within the first year. It is anticipated that the section 3 work most directly affects facilities 1-2 described above. Section 4 work is designed to launch facilities 3-5 and can be extended into year 2 to be aligned with the anticipated calendar of opportunities.

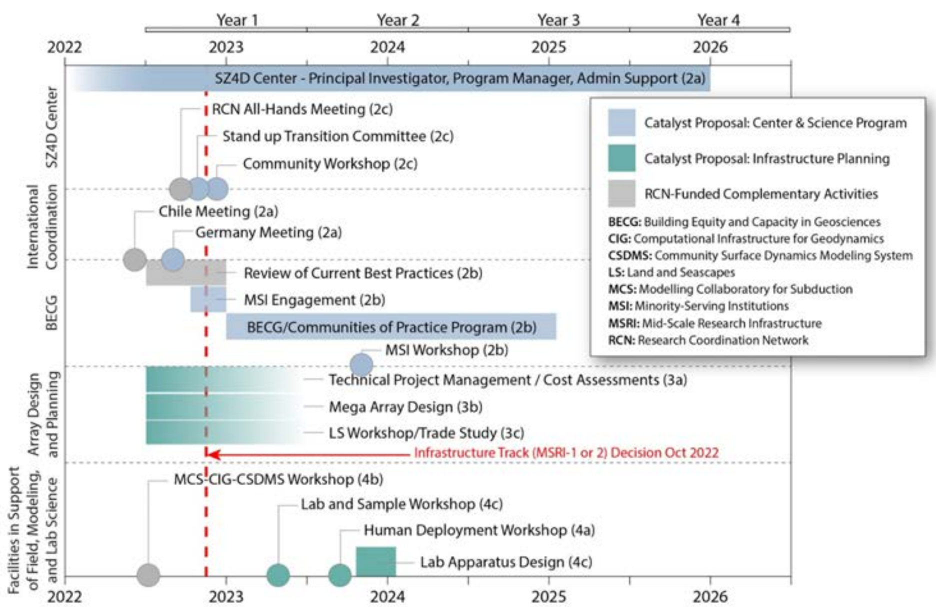

Figure 4. *Timeline of activities in this proposal (blue and teal) and relationship to complementary RCN-funded activities (gray). Numbers in parentheses correspond to sections in this proposal.*

Year 1 includes two milestones as shown in Fig. 5: launching the committee structure according to the Collective Impact principles (See Sect. 2) and defining the appropriate

Infrastructure Phasing Track (a or b in Fig. 5) which determines whether we will target the 2022-2023 solicitation for an MSRI-1 Design Phase or MSRI-2 Implementation phase. The timing of the solicitation cycle demands that this decision be made in October 2022.

The key criterion for the October 2022 decision will be the degree to which the scientific questions articulated in the implementation report can be answered by technology that is currently extant and viable at the cost level allowed by the MSRI program. If technology has been identified that convincingly answers one or more of the bulleted questions in the introduction at the appropriate cost level, an MSRI-2 proposal will be submitted. Assessing the degree to which the technology can answer the questions will require the use of the traceability matrices from the draft implementation report that break down the larger issues into sub-questions with specific data needs. The budget model will constrain costs and timing on these identified data needs which will then inform the decision. Ultimately, the proposal submission decision rests with the SZ4D Steering Committee. By design, the committee will be refreshed with an open procedure as described in Section 2 prior to the decision point.

The MSRI solicitation enumerates multiple criteria for funding, most of which are already addressed by the SZ4D research planning process, e.g., “potential to deliver cutting-edge research infrastructure that provides capabilities not otherwise available.” The critical missing piece is criterion 4 of the proposal call, which is technical readiness. The work plan in Figure 4 is designed to allow assessment of readiness at the October 2022 checkpoint. If the technology required to meet the traceability matrix data needs does not currently meet the criteria for evaluation readiness as outlined in the current MSRI-2 solicitation, then an MSRI-1 proposal will be prepared to fill in the design gaps.

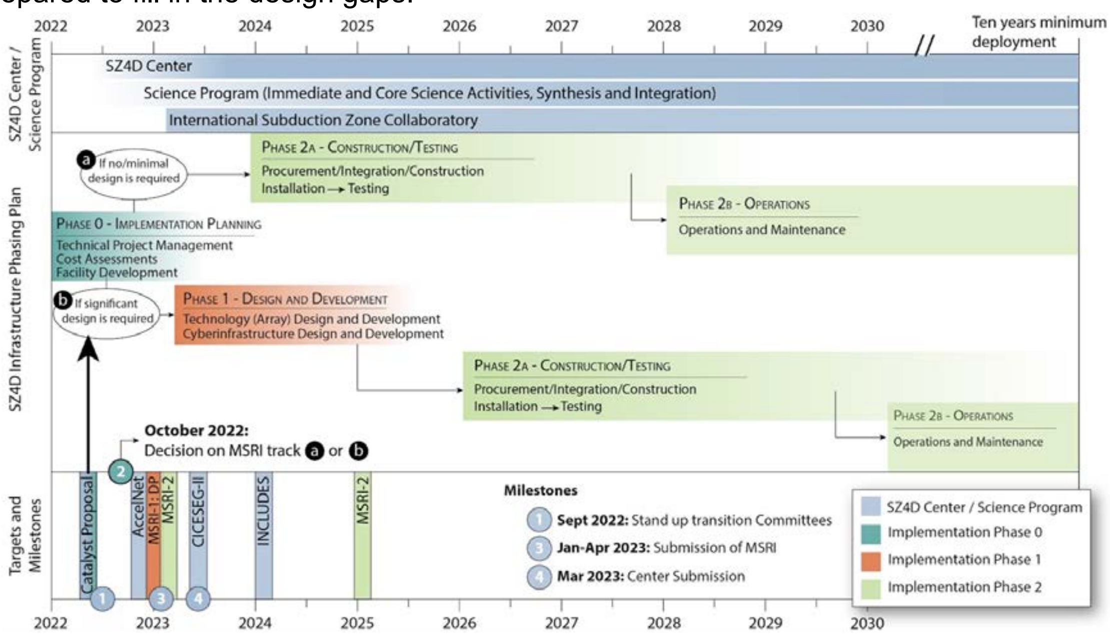

Figure 5. *Timeline and milestones for SZ4D Implementation, including trajectories based on MSRI decision-point (milestone 2). Potentially relevant funding solicitations noted for reference (MSRI: Mid-Scale Research Initiative; INCLUDES: Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science; CICESEG: Centers for Innovation and Community Engagement in Solid Earth Geohazards; AccelNet: Accelerating Research through International Network-to-Network Collaborations).*

Broader Impacts

The broader impacts of this work are: (1) building equity and capacity for geosciences, as described in Section 2, (2) creating the groundwork for new infrastructure and technical capabilities that will enable the research in subduction zones as described in Sections 3-4 and an improved understanding of geohazards that affect millions of lives and livelihoods.

Results from prior funding

E. Brodsky: EAR-1761987, *Aftershock Productivity in Context of Rupture Kinematics.* $313k, 6/2018-5/2022. Intellectual Merit: This grant works to combine the information from kinematic slip models with the detailed pattern and timing of aftershocks. A secondary goal is to examine aftershock productivity in tectonic context utilizing end-member cases. Broader Impacts: The award has supported graduate students K. Dascher-Cousineau and R. Garza-Giron, and an Israeli collaboration. Publications: Dascher-Cousineau et al. (2020a,b), Liu et al. (2019), Garza-Giron et al. (2018), Wetzler et al. (2019).

A. Newman: EAR-1447104, *Recoupling the Megathrust: Evaluation of the Transition from Postseismic to Interseismic Behavior in Nicoya Costa Rica.* $336k, 3/2015–2/2019. Intellectual Merit: Using GPS and seismic data following the Mw 7.6 earthquake to capture the transition to interseismic behavior. Broader Impacts: Fostering US/Costa Rica collaboration and funding a female PhD student. Publications: Kyriakopoulos and Newman (2016), Yao et al. (2017), Hobbs et al. (2017, 2019).

A. Soule: OCE-1357216, *Collaborative Research: Elucidating Conduit, Eruption, and Pyroclast Transport Dynamics of Large Silicic Submarine Eruptions.* $278,746; 11/2014-11/2019 (1y NCE). Intellectual Merit: The project documented the products from the 2012 eruption, estimated volumetric eruption rate of a large submarine silicic eruption. Publications: Carey et al. (2018), Manga et al. (2018, 2019), Fauria et al. (2017, 2018), Jones et al. (2018), Mitchell et al. (2018, 2019), Ikegami et al. (2018), Murch et al. (2019a,b). Broader Impacts: Supported six PhD Students and several undergraduates. The results of the research were disseminated by NPR Science Friday, BBC, Wired, and local radio and print outlets.

R. Woodward: EAR-1261681 & EAR-1851048, *Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE).* ($158,380,277; 10/1/2013–9/30/2018) and ($52,888,880; 10/2018–9/2023). Intellectual Merit: Supports operation and maintenance of facilities and instrumentation for research and education in seismology and the Earth sciences, including the Global Seismographic Network, the Portable Array Seismic Studies of the Continental Lithosphere, and the USArray component of the EarthScope program, and archives and freely distributes data from all IRIS facilities. Broader Impacts: IRIS programs encourage careers in the Earth sciences, and inform the public of current earthquakes. These awards support hundreds of PI-led experiments every year with equipment/training, provide data to tens of thousands of scientists world-wide, and reach hundreds of thousands of people via outreach.

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