Chapter 3. Integrative Group Reports

3.1 Building Equity and Capacity with Geoscience

From the beginning of the SZ4D Initiative, the importance of successfully communicating scientific understanding of subduction zones and associated hazards to the general public was recognized, as well as the need to train the next generation of scientists to conduct interdisciplinary studies to fill in gaps in our knowledge of subduction processes (McGuire et al., 2017). Because international cooperation is necessary to achieve the scientific goals, capacity building needs to be a central pillar of SZ4D. At the same time, social sciences and humanities must play a role in facilitating interdisciplinary research in SZ4D (Till et al., 2017). Moreover, the geoscience community's interest and attention to the issues of belonging, access, justice, equity, diversity, and inclusion (BAJEDI) have grown considerably since the initial vision document was created, and data have shown the lack of progress on BAJEDI issues at the doctoral level (e.g., Bernard & Cooperdock, 2018; Williams-Stroud, 2021; Beane et al., 2021). To formulate a revised, more focused scope for BAJEDI in SZ4D, a group consisting of interested participants, including both SZ4D scientists and specialists in geoscience education, public outreach, diversity, and organization structures, was formed. As this group started meeting, it became clear that the common goal of transforming the mindset of our geoscience community to embrace education, outreach, capacity building, BAJEDI, and social justice was critical to the success of the SZ4D and future scientific endeavors by the geosciences community. This group chose the name Building Equity and Capacity with Geoscience (BECG) to reflect this vision.

RESEARCH QUESTIONS

As the BECG integrative group considered how to effectively address BAJEDI within the scope of the SZ4D initiative and in doing so transform the geosciences community, we identified six research questions that can serve as an investigative outline for facilitating this change (**Figure BECG-1**).

1. How can we leverage efforts into equitable international capacity-building partnerships that improve capabilities (e.g., skills, data, software, technology, understanding) for all scientists and stakeholders involved? To what degree will these improvements be sustainable?
2. Geohazards disproportionately affect specific communities. How can improved understanding of subduction zone geohazards be used to inform and address social justice and equity issues in hazard mitigation? What considerations must be made to ensure equitable engagement of and outcomes for those communities?
3. Educational efforts that are more inclusive and have measurable learning outcomes are needed to equip and diversify our scientific community. How do we identify, develop, and implement these strategies?
4. Hazard monitoring and rapid response efforts inform decision-makers globally, requiring preparation and clear communication channels. Can we establish a distributed model of outreach by better training SZ4D community members to accomplish effective science communication, including

information during rapid response events? Would this model help the general public to better understand geohazards and risk associated with them?

5. What are evidence-based practices for interdisciplinary collaboration that break down silos and improve understanding across disciplines? How can SZ4D become a model for interdisciplinary efforts to enact equity-oriented relationships and outcomes in community science?
6. The diversity of the geoscience community has lagged behind other disciplines. What can we do in terms of BAJEDI to enact transformative change in the geoscience community? Can SZ4D be designed as a community science project to increase inclusivity and equity? How can such a broad community science project be funded equitably and enact partnerships that are mutually beneficial for all stakeholders?

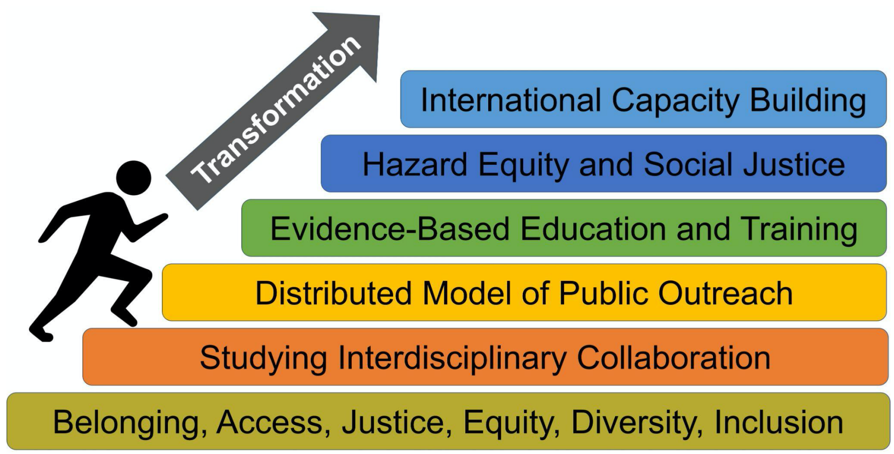

Figure BECG-1. *Research goals of the Building Equity and Capacity with Geosciences (BECG) group.*

In the following sections, we delve into the components of these six research questions, including the objectives, the primary needs, and the associated activities we suggest. This text follows our Traceability Matrices for each of the research questions.

1. International Capacity Building

A primary objective we identified is to **establish and promote best practices for cooperative international field research**, particularly in the context of SZ4D science, based on existing knowledge within and outside of geosciences. This will entail a significant amount of information gathering and a literature review of sustainable human capacity building and technical infrastructure development, considering both efforts inside and outside geoscience (e.g., Geoscientists Without Borders, Engineers Without Borders). In addition, information gathering should involve discussions with the American Geophysical Union Hazards Equity Working Group (HEWG), the NSF Partnerships for International Research and Education (PIRE) program and associated PIs, and the Thriving Earth Exchange, which specifically focuses on working with local communities. We also highlight the importance of discussions with investigators with international experience and organizations such as the U.S. Geological Survey Volcano Disaster Assistance Program

(VDAP) and international organizations such as OVSICORI-Costa Rica that have many years of experience participating in international capacity building partnerships (e.g., Lowenstern & Ramsey, 2017).

Effective partnering with scientists, agencies, and universities responsible for subduction zone science and hazard management must include intellectual property guidelines, cost sharing, field activity plans, and agreement on scientific expectations before any activities commence. A training program should be developed to enable the SZ4D community to embrace these principles. The integration of international stakeholders would be strengthened if international scientists in the geographic target region are part of the science planning and review process; this approach resembles the evaluation model of CONVERSE activities where scientists engage in planning disaster scenarios. SZ4D can also consider other funding agencies (e.g., Department of State, USAID) that could enable international science diplomacy. To strengthen international relationships, asking scientists and policymakers in the international locations about their key goals and needs, as well as science communication protocols in place, ideally during the project design phase, can ensure that we have shared goals and clear plans that will benefit the local communities. Waiting until the "last minute" to address these issues is unlikely to be successful and risks diminishing the strength of international partnerships.

The second objective is to **establish and promote best practices for FAIR** (findable, accessible, interoperable, and reusable) data among international researchers (Wilkinson et al., 2016). This objective requires not only open data and data products, but also research policies that better incentivize data sharing to improve the quality of research results and minimize the limitations for access and interpretation (Fecher et al., 2015). Establishing and sustaining FAIR practices can be difficult, but support enabling international communities to work with facilities that do this already to transmit and archive open data (UNAVCO/IRIS, IEDA). Training the community towards open data could involve supporting workshops for providers to learn, develop, and implement FAIR data practices with a supportive community. Such workshops used to be offered by institutions like IRIS but have been limited by lack of funding. Regardless, efforts should be made to work with data facilities to establish effective strategies. Despite the desire for ubiquitous FAIR data, there are clearly challenges to providing FAIR data (e.g., Tenopir et al., 2011), such as limited infrastructure that prevents access. We suggest making concerted efforts to identify what the limitations and challenges are in each situation and then seek to provide what is needed to overcome them (e.g., Boeckhout et al., 2018). Surveying individual communities very early in the relationship-building process provides important assessment of the anticipated limitations, potential for unexpected roadblocks, infrastructure needs (both short- and long-term), and human capital and compensation. *Having a clear and sustainable plan for open science is essential for interagency cooperation that can both impact hazard science and present a unified view to those outside science.*

The third objective is to **promote open, effective, bilateral communication and scientific training**. The development of multi-language communication and training opportunities is critical for effective communication and training for international partnerships. We would recommend that the SZ4D work with in-country collaborators and social scientists to develop appropriate content in effective formats and with careful cultural considerations. This can be accomplished by facilitating collaboration between physical and social scientists to learn about educational interests and context that would enhance the effectiveness of scientific communication. For example, training on instrumentation specific to in-country projects should be prepared in native languages and acknowledge the existing technology and infrastructure. A second need is to create a more inclusive training pedagogy that considers cultural context and national education systems. This effort should build upon existing resources (e.g., SERC, UNAVCO, IRIS), and should consider developing models for successful remote training.

The fourth objective is to **develop sustainable funding pathways for bilateral, multinational training and exchange** programs. This objective requires seeking appropriate funding across the SZ4D organization with a model for perpetuating the training program and expanding it to other communities and countries after SZ4D. One approach could be to identify partnerships that can fund foreign students to assist with data collection (i.e., participant support), with an emphasis on supporting students from communities that are directly affected by subduction zone hazards. We suggest a potential goal of equal funding between US and International students through SZ4D support. Our community should also seek to learn lessons from how international training has worked for International Center for Theoretical Physics Geophysics Program (ICTP) and other large infrastructure projects outside geoscience (e.g., large telescopes). As mentioned before, SZ4D could benefit from developing funding partners outside of NSF, including other US agencies (e.g., USAID) and international agencies (e.g., UNESCO, ICTP, ILP).

Finally, we recognized an important objective to **minimize imperialistic or colonial methods of interaction**. This can take the form of PIs "bestowing knowledge" upon international collaborators simply as field support or as non-indigenous researchers going to locations to extract knowledge (e.g., Cartier, 2019; Wight, 2021). This objective highlights the need for our community to develop implicit bias training for international collaborations, with both general core training and location-specific considerations. The development and implementation of this training requires working with international partners, host countries, and social scientists (Nordling, 2017). SZ4D would greatly benefit from regular review of objectives and practices to identify underlying colonial attitudes and to foster growing awareness throughout the SZ4D community (Stefanoudis et al., 2021). Considering this need, we recommend that any SZ4D-sponsored field experiences or international research meetings be preceded by in-country cultural training. We also recognize the need for change in the SZ4D community to embrace multiple and alternative method models of "success." The success of SZ4D relies on developing strategies to enable and value trust and community building as part of the scientific process, instead of just focusing on research outcomes. Trust and community building takes time and is necessary for meaningful collaboration and effective hazard mitigation. This approach emphasizes the importance of planning for trust and community building at the beginning of project activities and that not fully structuring and planning for this will compromise the effectiveness of the SZ4D mission.

2. Hazard Equity and Social Justice

The first objective we identified was to **identify the local relevance of hazards in the context of subduction zone science**. The SZ4D community could significantly benefit from being better informed on the resources, local agencies, and hazard information available for specific regions of interest. To grow awareness and increase local impact of SZ4D science, we envision workshops or a series of webinars with local experts on hazards of the selected region, including accounts of previous noteworthy events and a review of what data are available, underscoring key gaps. The stronger our coordination and collaboration with local agencies monitoring hazards, the more effective our science outcomes. The SZ4D science goals should account for and be tailored to benefit the specific aims of local hazard monitoring agencies. As such, the review and prioritization of SZ4D science should legitimately involve these agencies in the process and decision-making. Successfully accomplishing this goal would mean early involvement of minoritized/marginalized groups and communities.

The second objective is to perform a more in-depth **evaluation of the impacts of various hazards on local communities**. A primary step toward accomplishing this objective is to identify the existing science knowledge gaps associated with the local hazards. This effort can be facilitated by coordinating with international and associated national hazard monitoring agencies when prioritizing the science targets, and clearly identifying key stakeholders as well as lines of communication between the stakeholders. Another requirement for reducing hazard impact is to identify community exposure and social vulnerabilities to hazards. Because this builds upon physical science research but also includes substantial regional and social insight, we recommend inviting local social services agencies and government officials to present information to the SZ4D community on community exposure to hazards. We envision this effort can also be supported by cultivating internship opportunities for U.S.-based graduate students and postdocs to work for government and social service agencies that serve affected communities. A final need for this objective is assessing which new hazard information would have the greatest impact on reducing future hazard impacts. To accomplish this objective, dedicated meetings and/or workshops with local hazard monitoring agencies, community support agencies, and civic decision-makers could help prioritize the knowledge gaps based on their perceived impact on communities. This information should then be used to revise the initial SZ4D science plan accordingly.

The third objective is to **establish best practices in hazard communication within diverse communities**. This would require partnerships between physical and social scientists, science communicators, and educators to develop and implement techniques to communicate with diverse communities early on about the research plans and results. Activities to meet this need could include science communication training workshops with topics such as "How to talk with the public about your science" and "Considerations for communicating with diverse communities." Recent research on communicating earthquake early warning to the general public has highlighted the importance of these efforts (Kamigaichi et al., 2009; Wein et al., 2016; Becker et al., 2020). These efforts indicate a need to invite social scientists and communication experts to present their findings at SZ4D meetings and conferences. Similar to the previous objective, we encourage cultivating internship opportunities for faculty, postdocs, and graduate students to work with specialists on hazard communication within diverse communities, including science communicators, education researchers, and social scientists. A critical component to aid in integrating science communication with local communities for each project is the coordination of bringing people or instruments to field settings.

The fourth objective is to **create and support an open-access risk data repository** that includes physical data, hazard inventories, and vulnerability assessments. We envision the need for a portal for data and visualization using open software such as QGIS, but work would need to be done to identify effective data formats for hazard, exposure, vulnerability and risk assessment, and to communicate risk in a consistent manner. To illustrate the latter, there were major challenges identified in the aftermath of the Kaikoura, New Zealand, earthquake where seven experts were asked to quantify risk, and no two had the same responses. We recommend collaborating with spatial scientists on the efficacy of risk data formats, software, and processing needs. Ultimately, this objective is likely to require a comprehensive hazard inventory, such that communication and collaboration with local agencies will be paramount.

3. Educational and Training Strategies

The first objective we identified is to **increase the effectiveness of training through the scholarship of teaching and learning**. The geoscience community has embraced education and outreach efforts for several decades (e.g., Edgett & Christensen, 1996; Benthien & Andrews, 2003; Braile et al., 2003; NRC, 2013). Although this has contributed to a growing set of educational materials available, collaborations with geoscience education researchers and social scientists are needed to increase the use of valid and reliable learning assessments and sharing of the overall results by instructors. We see a variety of activities that could aid this effort, including a more pervasive development of well-defined learning outcomes and appropriate assessment instruments. To enable participating instructors to share the results of this educational research requires improved support and training on how to obtain institutional review board (IRB) approval for human subject research. Ultimately, we envision that progress on this objective will be achieved by increasing the number of instructors that participate in scholarship of teaching and learning, including through national meetings (e.g., Earth Educator Rendezvous) or through local campus initiatives (e.g., faculty learning communities). SZ4D is poised to be a critical catalyst for promoting and supporting the science of learning, which can be enhanced by sustained support of collaborations with geoscientist education researchers and social scientists.

A second objective would be to **increase the inclusiveness of training** for the next generation of SZ4D scientists. To accomplish this goal, our community would need to ensure that training across our disciplines meets the learning needs of trainees (postdocs, graduate students, and advanced undergraduates) and we have a better understanding of the value systems that motivate trainees. An initial step towards this objective could be the development of a needs inventory from a survey of SZ4D trainees and instructors. Similarly, an inventory of the values held by trainees would shed new light on what motivates trainees and potentially what helps them to persist in pursuing SZ4D science. To close the assessment loop, current training practices could then be reviewed and evaluated in the context of these inventories to assess whether training is meeting the needs and values of trainees and how it could be improved.

A third objective would be to **ensure trainees are properly equipped with SZ4D-specific research skills**. We identified several needs for improvement that would help to meet this objective, including: (1) improving spatial and temporal reasoning skills to handle increasingly large and detailed 4D datasets, (2) improving access to inclusive training opportunities in fieldwork settings, and (3) improving understanding of how geoscientists create and validate models (conceptual to computational) to generate new knowledge. Each of these efforts is likely to require educational research, both new studies and a review of existing literature, to make progress on these needs. In addition, we recognized the need to embed more technical training (e.g., coding or machine learning) into existing curriculum (NASEM, 2021) and encourage integration of datasets and models to build skills critical in undergraduate education (Mosher & Keane, 2021). SZ4D could energize this by motivating and facilitating reevaluation and revision of existing curriculum to meet these needs.

A fourth objective would seek to **increase the integration of societal relevance of geohazards into training**. The large-scale effort to incorporate societal relevance into educational materials and approaches via the InTeGrate project has reached over 100,000 students, providing an important resource to learn lessons and effective strategies (D.C. Gosselin et al., 2019). Increasing awareness of how SZ4D research can be used to understand and mitigate geohazards with potentially large effects on society should create motivation for trainees to pursue SZ4D science as part of their career development. In each of these cases, we envision that educational research that builds on the work of the InTeGrate project in the context of SZ4D science would help to meet these needs.

Finally, we identified that a key objective would be to **implement effective educational strategies more broadly**. Although there has been considerable growth of peer-reviewed educational materials over the past two decades, there are still obstacles to faculty instructors incorporating vetted educational materials into their teaching (McMartin et al., 2008; McDaris et al., 2019; SERC, 2012). A key pathway forward involves learning from research on professional development of geoscience instructors (e.g., Manduca, 2017). Moreover, we should seek methods to help faculty embrace findings from educational research and encourage faculty instructors to incorporate evidence-based best practices. This can be achieved by developing or fostering professional development training for instructors that would include focus on pedagogical skills and scholarship of teaching and learning in addition to the educational materials. Support for this comes from recent research indicating even one-time participation in an educational workshop with peers can lead to improved teaching by supporting a combination of affective and cognitive learning outcomes (Manduca et al., 2017). A comprehensive research review of undergraduate STEM reform strategies (Laursen, 2019) found that in geoscience, compared with other disciplines, online platforms and repositories such as the Digital Library of Earth System Education (DLESE), the Teach the Earth portal, and Pedagogies in Action have served as highly utilized supports for improving instruction. Efforts to address this objective via professional development workshops can build on and link with these repositories to share resources for learning and improving instruction more broadly. After participation in these workshops, early career scientists could be mentored by previous participants, thereby creating a cohort of knowledgeable and connected individuals who can advocate for best practice within U.S. teams.

4. Distributed Outreach Model

The first objective we identified is to **establish a model to connect SZ4D scientists with key non-scientist stakeholders**: policymakers, media, educators, and impacted populations. For the discourse to be fruitful, we need to embrace successful communication skills and training approaches, and facilitate implementation over the broad multi-institutional SZ4D community. We could then host or support a series of workshops that focus on the development of communication skills and point people to associated resources. These trainings should be constructed in cooperation with international collaborators and scientists working in hazard mitigation and rapid response efforts. To aid in the outreach skill development for SZ4D participants, it is essential to create more "attractive" opportunities for members from these different sectors to interact with one another. So in addition to providing a toolkit to enable effective communication between the different sectors, we also need to increase networking opportunities, develop incentives, and reward those who invest the time and effort. Otherwise, participation in outreach will be limited to those willing to volunteer (e.g., Edgett & Christensen, 1996; Andrews et al., 2005). An overarching need for this objective is that the efforts developed should be supported in ways that are scalable and sustainable. As such, our community should seek to develop plans and timelines for the multi-sector connections that can be sustained beyond the scope of an individual project, considering ways to integrate with ongoing activities. For example, offering networking opportunities as a component of an annual research conference.

The second objective would be to **evaluate the impacts of outreach efforts**, with a particular focus on communities most affected by subduction zone hazards. In general, there is a need for increased value on the evaluation process, which means including evaluation from the beginning designs of a project, committing to seeing the evaluation through to the end, and then planning for the time and effort required to complete it. We recommend that initial evaluations focus on understanding the strengths and weaknesses of past, similar efforts such as EarthScope and GeoPRISMS. Information collection followed by critical review could enable SZ4D to identify and apply best practices from these previous approaches and avoid some of the pitfalls. Another key need is assessment and evaluation strategies of diversity in outreach efforts. To address this, we suggest inviting BAJEDI experts to share strategies that could then be implemented by SZ4D efforts.

The third objective is to **build a portal for access to collective outreach resources that leverages and complements** without duplicating existing efforts. It is important to capitalize on platforms that already exist because geoscience is more likely than other disciplines to use collective outreach resources in commonly accessed platforms as a tool for undergraduate STEM reform (Laursen, 2019). To accomplish the curation of outreach resources, a first step would be to define the resource needs by the various audiences (e.g., K–12, general adults, stakeholders, residents in hazardous areas). Organizing the resources according to need, providing clear descriptions of the resources, and embedding essential implementation support (e.g., video clips demonstrating use) are all ways to facilitate the likelihood and ease of use. It is critical to ensure there is unobstructed access to the information such that there can be equitable distribution of the resources. Survey evaluation of the portal user experience can help to evaluate this. Moreover, we should seek a way to incentivize a portal model where the resources can be rapidly updated as new events occur. Another step would be to implement an evaluation of the contribution platform(s). SZ4D community members would be encouraged to promote the use of these resources when interacting with public stakeholders.

Finally, we recommend the development of a clear means for the broad public at large to connect with SZ4D organization and its scientists. To accomplish this, members of the SZ4D community should invest the time and effort to participate in events, conferences, and networking opportunities that create availability and strengthen connections with the general public. In addition, there is also a clear need for evaluation of how easily and to what degree the broad public is able to interact with SZ4D. Establishing data collection and information gathering strategies will be an essential component of addressing this need.

5. Interdisciplinary Collaboration

The first objective we identified was to **establish how to evaluate what a successful collaboration looks like in the SZ4D community**. Our community would need to develop a consensus on the hallmarks of a successful collaboration that accounts for the costs and benefits of collaboration. This could be pursued through the form of workshops that would seek to build consensus and a report compiled from them that describes the key elements for the SZ4D community. Another important component to this effort would be the development of a means to measure successful collaboration. This assessment could entail creating a rubric from the consensus-building workshop report and then making this broadly available and ensuring it is revised based on additional feedback. The assessment could then be applied to previous large-scale interdisciplinary initiatives in the geosciences (e.g., GeoPrisms, MARGINS) to identify the areas of prior success, obstacles to collaboration, and efforts in need of an improved approach. We strongly recommend these efforts occur at the beginning of the SZ4D initiative to guide the planning and provide early opportunities for formative feedback.

A second objective would be to **learn from the successes and failures of other communities**. This objective requires that we first identify the best practices from other disciplines outside the geosciences. We might identify best practices through a thorough review of literature in other communities and consulting with specialists on interdisciplinary collaboration. However, we envision that our community will also need to identify which aspects of the best practices from other disciplines would be relevant to geosciences and to SZ4D. The detailed nature of these contextualization likely means that best practices would need to be informed by educational research.

A third objective would be to **increase successful collaboration across subdisciplines through expanded evaluation**. Inherently, successful cross-disciplinary collaboration requires improved understanding of other subdisciplines. Creating mutually beneficial opportunities for meaningful discussion between practitioners from different subdisciplines should lead to improved understanding of the techniques, philosophies, and primary needs of different subdisciplines. We contend that evaluation of whether collaborations are successful based on the criteria established in the prior two objectives will need to become more common. Current reward structures can be problematic for scientists engaged in interdisciplinary research, particularly early career researchers, because academic culture tends to focus value on specific research outputs such as primary-authored publications (Goring et al., 2014). Expanding the evaluation to recognize the value of educational outcomes, dataset creation, outreach efforts, and the application of scientific results to policy or management activities will require concerted multi-institutional effort. We propose that these evaluations be a required aspect of annual funded project reports.

The final objective would be to **increase the use of best practices to facilitate collaborations within geoscience and between geoscience and other disciplines**. This would require communication of the best practice recommendations broadly through the SZ4D community and beyond. One possible activity to achieve this would be disseminating the findings from the best practice identification process via high visibility medium (e.g., *EOS*). In addition, some aspects of the dissemination would need to be recurrent as the best practices are reviewed and adapted over time with new learning. Workshops at regular intervals could facilitate this review and revision. Another need for increasing the use of best practices would be to ensure SZ4D research meetings and conferences encourage and enable the use of best practices. This could be achieved through regular communication with conference convenors and organizing committees to share best practices, offer guidance, and advocate for implementation.

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

The first objective we identified is to **capitalize on changing demographics to increase the pool of diverse students, faculty, and professionals in geoscience**. An identified obstacle to achieving this objective is lack of access to geoscience programs for minority populations. To address this, SZ4D can provide opportunities for community college and minority-serving institution (MSI) students to participate in a wide range of SZ4D activities. Another need we identified is to develop skills for students to learn teamwork. An activity to support this need is to actively seek ways for MSI faculty and students to participate in subduction zone science via teamwork and collaboration.

A second objective is to **build mutually beneficial networks/partnerships of MSIs with traditional research institutions** (NASEM, 2019). We recognize that the links between minority serving and research institutions is currently weak, so we would recommend that the research institutions involved in SZ4D seek to develop memorandums of understanding (MOUs) with MSIs to embark on strategic partnerships. Considering that community colleges also host a large proportion of the underrepresented racial and ethnic minority population in higher education, we would also recommend that research institutions develop MOUs specifically with community colleges. There also appears to be relatively weak links between minority-focused science organizations (e.g., SACNAS, AISES, NABG) and prior interdisciplinary, multi-institutional efforts like SZ4D that limited their impact. SZ4D could improve the situation by helping to facilitate the development of MOUs with multiple minority-focused science organizations.

A third objective would be to **promote rigorous science through changing the science culture to value diverse perspectives**. Studies demonstrate that we need diverse perspectives to ask and solve important science questions (e.g., Powell, 2018), reminding us that the people who have the access to participate in SZ4D science will get to define what questions get asked and researched. Based on this, SZ4D should ensure a diverse group of scientists are integrally involved in the science planning and activities, including the funded research, the review panels, and the organizational leadership. In addition, we can encourage our community to promote studies that demonstrate the additional rigor that comes from a diverse research team (e.g., Hofstra et al., 2020).

Finally, we should seek to **increase geoscience literacy in diverse communities**. A specific challenge with this objective is that predominantly minority communities are less engaged in science or not at all (Basu & Barton, 2007). Research finds science literacy is connected to authentic uses of science in daily life, described as public engagement with science (Feinstein, 2011), so increasing geoscience literacy will be tightly tied to our outreach efforts. SZ4D can support community workshops, outreach, and educational materials to help minority communities become more engaged in the geosciences. The EarthConnections Alliance is an example of an existing effort that could be built upon. This objective remains an untapped opportunity, because minority communities can be disproportionately affected by environmental and natural hazards.

Inviting and welcoming local community members to meetings that discuss the hazards can be a starting point for the discourse.

CONNECTIONS BETWEEN RESEARCH TARGETS: COMMON NEEDS AND ACTIONS

Upon reviewing the Traceability Matrices for each research question, we identified a number of common themes among the needs and actions across the different targets. **Figure BECG-2** highlights some of these key connections. The interconnectedness indicates that the efforts of the SZ4D community should be focused on high-impact needs and activities as these will efficiently contribute to multiple targets. Some of the high-impact needs we identified include: incorporating societal relevance into SZ4D efforts, the development of new measurement methods to track progress, improved communication across different stakeholder groups, more concerted efforts to establish sustainable partnerships, developing a common agenda across disciplines, and improving access for all potential participants. Likewise, we identified a set of common activities that include: reviewing established best practices, collecting information from prior experiences, seeking to centralize resources to improve access, establishing communities of practice, offering workshops, and social science research. For example, establishing partnerships is a fundamental way to develop connections, build international capacity, and improve outreach and interdisciplinarity. When we considered the activities required to facilitate the building of partnerships, we found that review of best practices, offering workshops, and establishing communities of practice would be effective choices, similar to what we found for other primary needs.

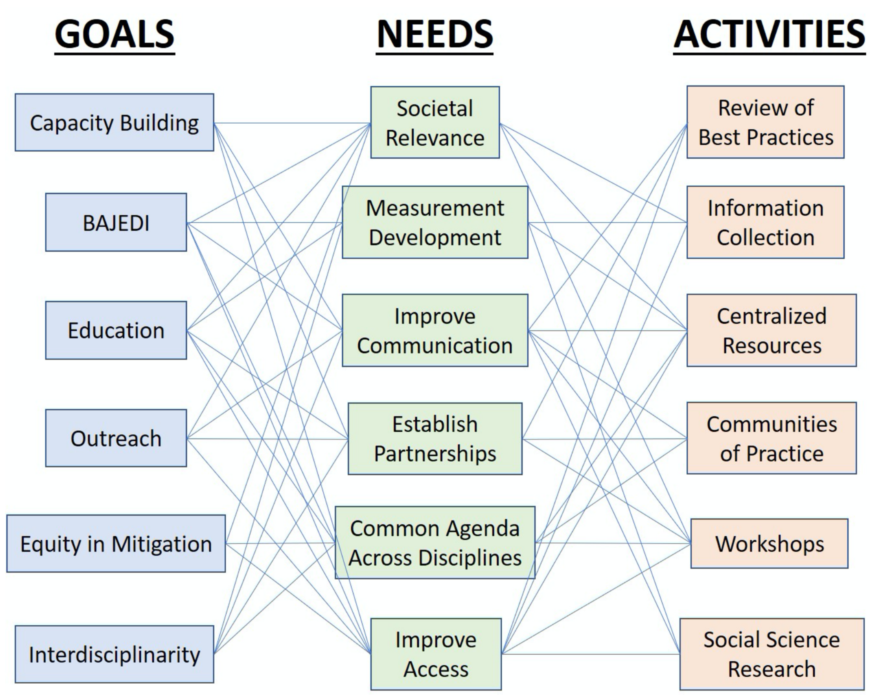

Figure BECG-2. *Diagram illustrating connections between BECG research goals, primary needs, and suggested activities.*

PHASING OF THE ACTIVITIES

Current discussions of how to coordinate activities across the different components of SZ4D involve efforts to articulate which activities depend on each other to ensure appropriate sequencing. Considering that many of the BECG activities are not dependent on instrumentation, fieldwork, or modeling efforts, it does not appear that there are as many critical sequencing dependencies as there are for the physical science activities. However, we did find that some activities have higher levels of urgency than others, and that some activities would be easier to accomplish during the middle or later stages of the SZ4D program. To help illustrate this, we have sought to construct a phased list of key BECG activities.

<u>Phase 0. Establishing Shared Goals, Reviewing Best Practices, Broadening Participation</u>

- Learn from local communities
- Connect local experts with prospective PIs to establish shared goals
- Inventory the needs/values for trainees
- Review best practices for capacity building and collaboration
- Research how to broaden participation
- Conduct workshops on implicit bias, international fieldwork
- Establish MOUs between MSIs and research institutions

<u>Phase 1. Researching While Building Mechanisms for Training, Collaboration, and BAJEDI</u>

- Research how to improve field training, interdisciplinary collaboration
- Improve access to skill-building workshops
- Coordinate and collaborate with local hazard agencies
- Recruit MSI scientists
- Identify limitations to providing FAIR data
- Review best practices for outreach

<u>Phase 2. Improving Training, Expanding Access, Diversifying Collaborations</u>

- Revise training
- Offer student internships
- Provide multilingual versions of training
- Develop communities of practice to diversify collaborations
- Conduct workshops for data providers to adjust to changing data
- Increase sharing of learning assessments
- Increase participation in scholarship of teaching and learning

<u>Phase 3. Assessment, Dissemination, and Building for the Future</u>

- Offer professional development for instructors
- Pursue effective science communication and outreach
- Research handling of 4D big data, model construction
- Evaluate interdisciplinary collaborations
- Assess progress on BAJEDI

AN OVERARCHING FRAMEWORK TO ACCOMPLISH THE RESEARCH GOALS: COLLECTIVE IMPACT

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

Previous research has shown that successful collective impact initiatives typically meet five criteria that together produce the alignment necessary to make meaningful and sustainable progress on social issues (Kania & Kramer, 2011). The first is a **common agenda** in that all participants have a shared vision for change that includes a common understanding of the problem and a joint approach to solving the problem through agreed upon actions. The second is a **shared measurement system** in which there is agreement on the ways success will be measured and reported with key indicators by all participating organizations. The third are **mutually reinforcing activities** that engage a diverse set of stakeholders, typically across multiple sectors, in a set of differentiated activities that combine together to form a coordinated plan of action. The fourth is **continuous communication** that involves frequent interaction over a long period of time among key players within and between organizations to build trust and encourage ongoing learning and adaptation. The fifth is a **backbone organization**, where ongoing support is provided by an independent staff. The backbone staff tend to play several roles to move the initiative forward: guide vision and strategy; support aligned activity; establish shared measurement practices; build public will; advance policy; and mobilize funding (Turner et al., 2012). If these five criteria can be met, the successful result observed involves cascading levels of linked collaboration (**Figure BECG-3**).

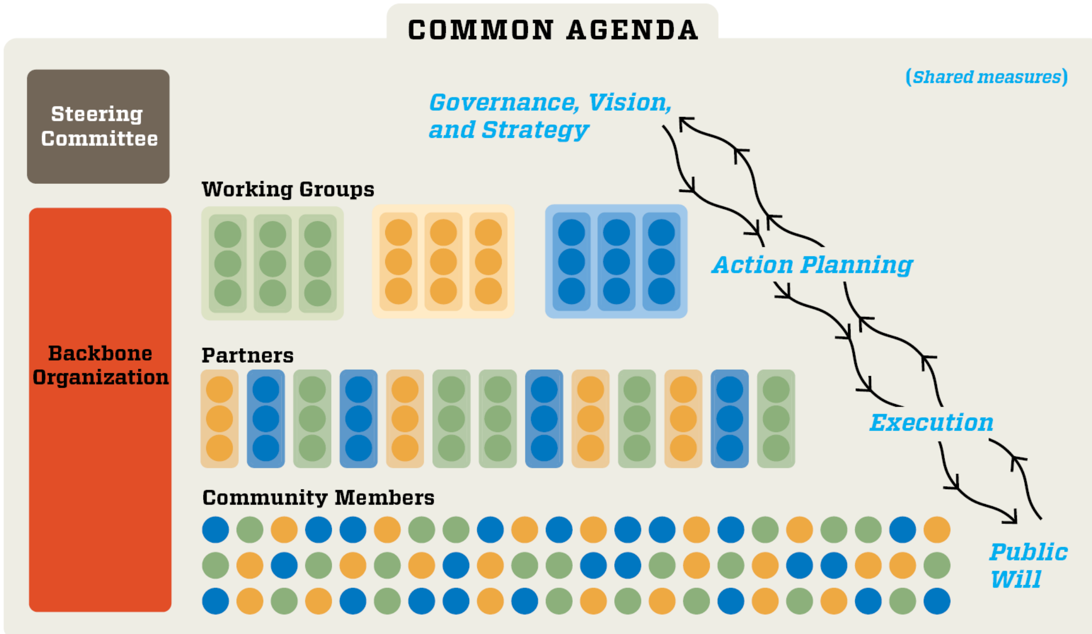

Figure BECG-3. *Cascading levels of collaboration that are observed with a successful Collective Impact framework. Figure from Kania & Kramer (2013).*

We are encouraged that the efforts of the BECG integrative group have already made progress on establishing a common agenda with a shared vision for change. This is based on establishing the most important research questions through collective discussion and then vetting these through multiple town halls and all hands meetings with larger portions of the SZ4D community. We anticipate that the draft review process will give the SZ4D community an opportunity to review and provide feedback on the proposed approach of defined needs and suggested activities to answer the research questions. This process will strengthen a common understanding of SZ4D's agenda. The second criterion for successfully achieving CI is building a shared measurement system, as outlined in both the development of measurement instruments in our defined needs and in information collection for this purpose in the suggested activities (**Figure BECG-2**). We also highlighted improving communication in our most prominent needs, which would support the fourth criterion of continuous communication. Workshops and communities of practice were highlighted as key activities, which could serve as mutually reinforcing activities if they involve a diverse group of stakeholders and are coordinated to fulfill a common action plan. Finally, the need for backbone organization for successful CI indicates that SZ4D should support an independent staff member to coordinate BECG activities.

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

In response, contributors to the CI model have continued to revise the framework (e.g., Harwood, 2014; Cabaj & Weaver, 2016), most recently incorporating community aspiration, inclusive community engagement, and movement building. This shift seeks to unlock the power that comes from acting like an organization, but thinking like a movement (Etmanski, 2016). In a movement-building approach, the emphasis is on transforming systems to create a more receptive climate for new ideas to take hold and embolden system leaders to act based on grassroots sentiment. We see this as the best pathway forward: conveying this concept through the implementation of a CI framework for SZ4D BECG activities will facilitate transforming the mindset of our geoscience community to embrace education, outreach, capacity building, belonging, access, diversity, equity, inclusion, and social justice as critically important for the success of the SZ4D scientific endeavors.

3.2 Modeling Collaboratory for Subduction

The Modeling Collaboratory for Subduction (MCS) is a novel community- and model-building effort to advance subduction zone science. It was envisioned in the Boise Subduction Zone Observatories report (McGuire et al., 2017), and this chapter highlights the key points that have arisen from broad community discussions as part of the NSF-funded MCS Research Collaboration Network (RCN) in operation since 2018. The MCS RCN led to a series of community workshop discussions, summarized in detailed workshop reports at https://www.sz4dmcs.org/ (Wada et al., 2019; Dunham et al., 2020; Wada & Karlstrom, 2020; Gonnermann et al., 2021). Additional workshops are scheduled for the remainder of 2021, and results from all of these MCS RCN efforts will be synthesized in a separate MCS report by the end of 2021.

The objective of the MCS is to create new kinds of physics-based models for earthquake and volcano-related hazards at subduction zones and apply them to understand fundamental processes, guide instrumentation deployments, interpret observations, and assess hazards (**Figure MCS-1**). Specifically, the MCS would be built around the following guiding questions:

- How do we construct models that link subduction zone state and long-term margin evolution to the character and probability of event occurrence?
- How can we best integrate observational constraints into models, while simultaneously using models to define optimal observational strategies (e.g., to reduce uncertainties)?
- How can we build physics-based, predictive models for volcano, earthquake, and geomorphic systems that couple across time and space?
- How can we build a diverse and equitable community of scholars?

At a more granular level, the MCS will work toward addressing the key science questions posed by the SZ4D working groups. All three working groups explicitly highlight modeling as an important tool in addressing their science objectives. For example, the Landscapes and Seascapes (L&S) working group argues that a new generation of coupled models that incorporate elastic and inelastic deformation at short and long timescales, surface processes, and fluid flow are required to simulate active processes in the forearc of subduction zones. Similarly, the Faulting and Earthquake Cycles (FEC) working group calls for the development of coupled simulations that connect regional models of stress and deformation, faulting, earthquake sequences, and aseismic slip to study megathrust rupture dynamics and resulting tsunamigenic potential. Lastly, the Magmatic Drivers of Eruption (MDE) working group highlights the need for data assimilation in models of the magmatic-volcanic system in order to investigate magma migration processes that can lead to actionable hazard forecasts for volcanic eruptions. Thus, the need for physics-based modeling facilitated by the MCS is woven directly into the fabric of the SZ4D science plan.

A key goal of the MCS is to integrate geodynamic modeling into the observational and laboratory efforts of SZ4D from the outset, rather than the more typical sequence in which modeling is used only after data collection. In this way, modeling will be employed not only for interpreting datasets, but in the planning and design phase of observational deployments. As observational deployments come online, data streams will then be assimilated into models to assess the "state" of megathrust and volcanic systems. The MCS will employ adjoint models and physics-enabled machine learning and artificial intelligence approaches that fully leverage the new datasets being collected. In this way, we seek to arrive at a transformational change in how large-scale, Earth programs are conducted in general and to enhance what they can achieve in terms of advancing solid Earth systems science.

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

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

Such new approaches are needed to consistently interpret constraints on the general workings of earthquakes, volcanoes, and surface processes in subduction zones, to identify knowledge gaps in our physical models, and to define optimal observational strategies to reduce uncertainties. Eventually, the MCS will lead to the new fundamental science and operational tools that are needed for quantifying, and possibly forecasting, earthquake, tsunami, landslide, and volcanic hazards.

Besides scientific discovery, integration of a new kind of modeling effort into SZ4D and the wider solid Earth community has numerous additional benefits, from training and interdisciplinary workforce development, to increasing the return on investment of new instrumentation and observational efforts by means of optimal experimental design.

It is clear that subduction zones on Earth are diverse in terms of their tectonic setting and/or current stage within their volcanic or earthquake cycles. To advance subduction zone science, it is therefore imperative to integrate observations from different regional laboratories to arrive at a globally validated physical understanding. The MCS is envisioned as a new SZ4D facility that can serve to support the development of such a framework and provide a home for sustained interactions between modelers, experimentalists, and observationalists.

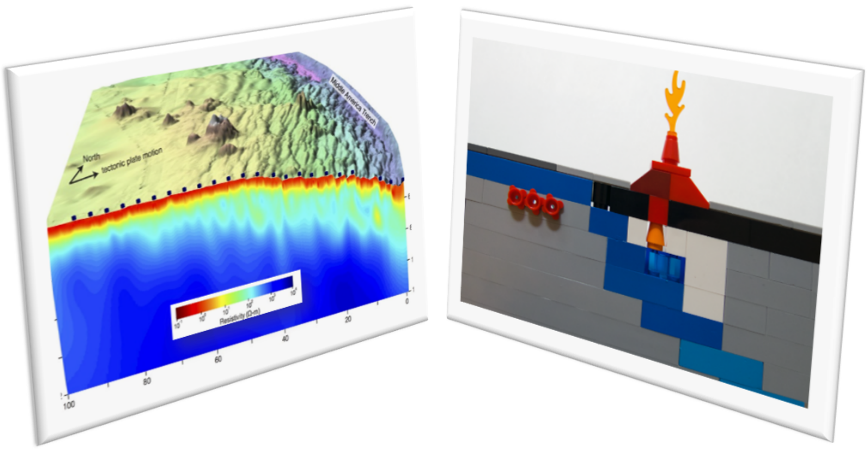

Figure MCS-1. *Digital Twin concept of a modular, building- block-based framework for physical modeling provided by the MCS to explore general physical processes and to digitally mirror regionally specific subduction zones, for example, to interpret real-time sensor data for system "state." (left) Conductivity structure for Central America from Naif et al. (2015).*

This is crucial because we do not yet know how to assemble complete models of earthquakes and volcanoes. The MCS can provide the building blocks to test alternative physical descriptions and identify the most important processes in controlling system behavior. Moreover, the MCS can support global subduction zone research communities, including the local stakeholders, as well as international and domestic observatories in different stages of their implementation, helping to support cross-disciplinary and cross-site collaborations. Crucially, model-based cross-validation is needed to quantitatively link insights from international infrastructure investments to hazard and risk settings of domestic societal concern for the United States.

Further, while any successful study of subduction zones requires an appreciation of their geologic diversity, it also requires acknowledging the importance of fostering a diverse scientific community to perform these studies. Perhaps the greatest long-term opportunity presented by the MCS is to establish computational approaches as alternative entry pathways for underserved and underrepresented communities into the geosciences. Such efforts will complement more traditional training and community-building efforts to empower computational scientists with the interdisciplinary tools they need to be successful. Together with extensive, sustainable, equitable, and coordinated outreach and teaching efforts (e.g., to enhance quantitative literacy in K–12 students and undergraduates), the MCS and the computational geosciences, in general, can contribute greatly to efforts to build a better and more diverse community of geoscientists. This important theme is further explored in the Building Equity and Capacity with Geoscience (BECG) chapter, and the MCS will play a large contributing role in initiating and supporting belonging, accessibility, justice, equity, diversity, and inclusion (BAJEDI) efforts within SZ4D.

MCS DESIGN GOALS

To achieve these ambitious scientific and community goals for the MCS requires an extensive and continued effort in supporting computational geoscience. We need to create new pathways for discovery that are based on investments in human and computational infrastructure and that are supported over timescales longer than a typical grant cycle (**Figure MCS-2**).

MCS RCN reports are available for the community workshops on the Megathrust, Volcano, and Fluid Transport components of the subduction zone problem (https://sz4dmcs.org), with an additional implementation workshop planned for links with Landscapes and Seascapes in the fall of 2021. However, clear and common themes have already crystallized from these extensive community discussions among observationalists, experimentalists, and modelers.

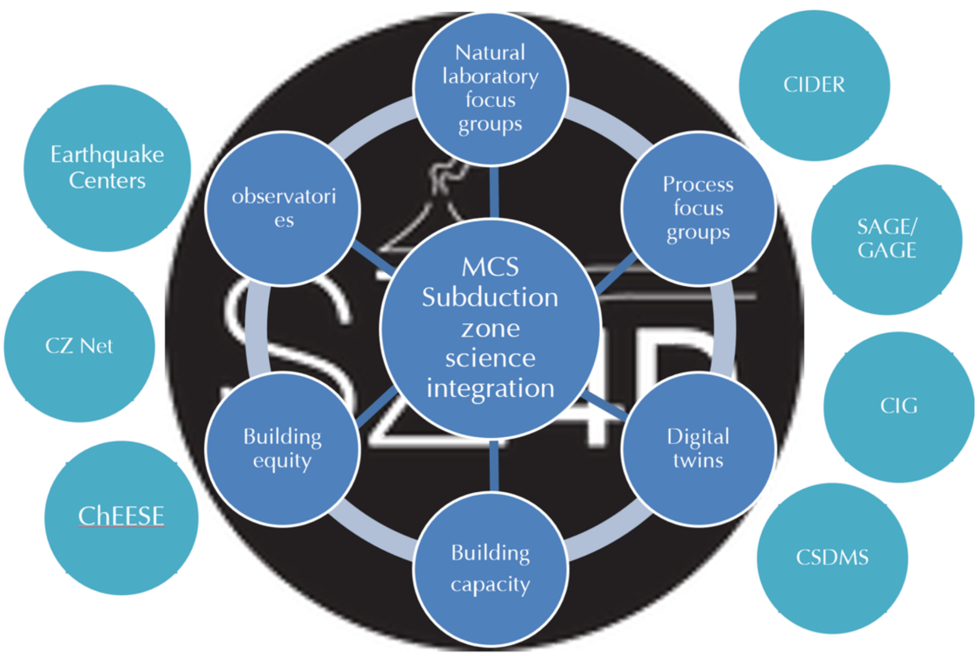

Figure MCS-2. *Immediate objectives and organizational components of the MCS within the SZ4D context and example partnerships within the wider community.*

Specifically, in terms of its design goals, the community recommends that the MCS should:

- Support the sustained exchange between computational, observational, and laboratory subduction zone scientists within the SZ4D and the geodynamics community at large through workshops, hackathons, and shared model building.
- Support SZ4D operations through community structural model storage and serve as a repository for inverse and forward modeling and data analysis tools from all disciplines involved in SZ4D.

- Support both interdisciplinary subduction process-focused working groups, as well as groups studying specific regional laboratories and case histories, such as volcanic eruption and earthquake sequence scenarios.
- Support continued model and modeling framework tool development and benchmarking exercises, with a mix of centralized and distributed approaches, based on continuous community input and guidance, and supporting both community-based code development, as well centralized framework efforts (like tools and databases linking observables with transport properties).
- Support access to computing resources, empower scientists with different backgrounds and institutional support, and broaden and democratize participation in leading-edge, data-driven, high-performance and cloud computing within the solid Earth sciences.

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

- Putting model component *verification* and benchmarking first, making sure that codes tackle the subsystem components involved in the coupled multi-scale, multi-physics problems correctly and efficiently.
- Studying interactions across scales and exploring coupled physical processes, while moving toward *validation* (i.e., making sure that the overall physical representations—the coupled subduction models—are the right ones). For this, the general framework has to be tested as widely as possible by the integration of different regional subduction zone settings and natural laboratories.
- Recognizing that a range of alternative, possibly competing, modeling approaches are needed and that, when possible and appropriate, support modular workflows made out of modular building blocks (**Figure MCS-1**) rather than a single "consensus" approach for how the physics of subduction should be modeled.
- Ensuring close collaboration between computational and applied math experts and domain scientists, as well as close exchange between modelers, experimentalists, and observationalists. The latter includes supporting modeling and model construction by observationalists, and appreciation of data analysis and laboratory experiments by modelers, in the spirit of empowering transdisciplinary research.
- Providing flexible, robust, well-documented, and efficient open-source codes with inherent consideration of multi-physics, cross-scale, adjoint approaches, and uncertainty quantification.
- Developing a range of codes with tutorials, cookbooks, and workflow examples to allow the use of models for both teaching and research applications.
- Embracing the guiding principles of open science and FAIR (Findability, Accessibility, Interoperability, and Reusability) data practices.
- Empowering the widest and most diverse representation of the community, equitable representation of all voices and supporting active international collaboration.

In these efforts, the MCS is not operating in isolation, but is meant to serve as a science hub for SZ4D (**Figure MCS-2**) and beyond, providing the most versatile tools possible while driven by the goal to create physical models for subduction zone hazards. The MCS science objectives overlap with several agencies (NSF, USGS, NASA, NOAA) and community organizations (e.g., Community Surface Dynamics and Modeling System [CSDMS], and Computational Infrastructure for Geodynamics [CIG]), and existing and possible future earthquake centers in the United States. There are also clear links with a number of international partners, such as ChEESE, an initiative to bring cutting-edge solid Earth high performance computing enabled codes closer to hazard applications.

On the training and capacity building side, SZ4D will be driven by a collective broader impact perspective, and the MCS can also usefully partner with efforts in terms of training pursued by organizations such as SAGE/GAGE, Cooperative Institute for Dynamic Earth Research (CIDER), CIG, and CSDMS.

Unlike the seismological or geodetic communities, supported by SAGE/GAGE, the computational solid Earth geosciences do not yet have a dedicated, comprehensive, and science-question independent computational infrastructure (e.g., "CAGE") to rely on, but moving into such a future, there are many mutually beneficial opportunities for partnership with efforts such as CIG or CSDMS. Their scope and capabilities are, however, distinct from the MCS, which is an unprecedented effort as discussed next in terms of implementation examples.

DRAFT IMPLEMENTATION

Figure MCS-3 portrays a few specific examples for some of the MCS model building blocks. They would include fully verified component tools for subsystems that the MCS would immediately help develop by supporting community-driven developments, centralized programming efforts by MCS center personnel, and hybrid approaches such as working with programmers "on loan" to PIs outside the center. The focus here is on the challenging geodynamic modeling applications identified by the earthquake, volcano, and surface process communities within SZ4D as key first steps to take to accelerate science integration and model building.

These blocks could consist of smaller bricks of well-tested components. They could also subsequently be assembled into even more complex assemblies, such as for regional natural laboratories (**Figure MCS-3**) or reassembled for a range of related problems outside subduction zone science. While the overarching strategy of the MCS is to develop modular modeling blocks consisting of ideally interchangeable, smaller bricks (e.g., different solvers for a visco-elastic model with fluid flow), we recognize that full modularity and coupling of bricks may not be feasible or desirable for some problems, at least in the near term. Many of the multi-physics problems we seek to explore do indeed require what is known as "tight" coupling, for example, at the solver level, and hence dedicated, specialized, and highly optimized codes. In these situations, the brick-based approach may not be tractable, and we will instead focus on developing more specialized blocks (e.g., at the level of the examples in **Figure MCS-3**). However, for all development, we will make sure that those lead to well-benchmarked codes that are accessible to the community, not just for download but also by means of well-documented cookbooks and example applications.

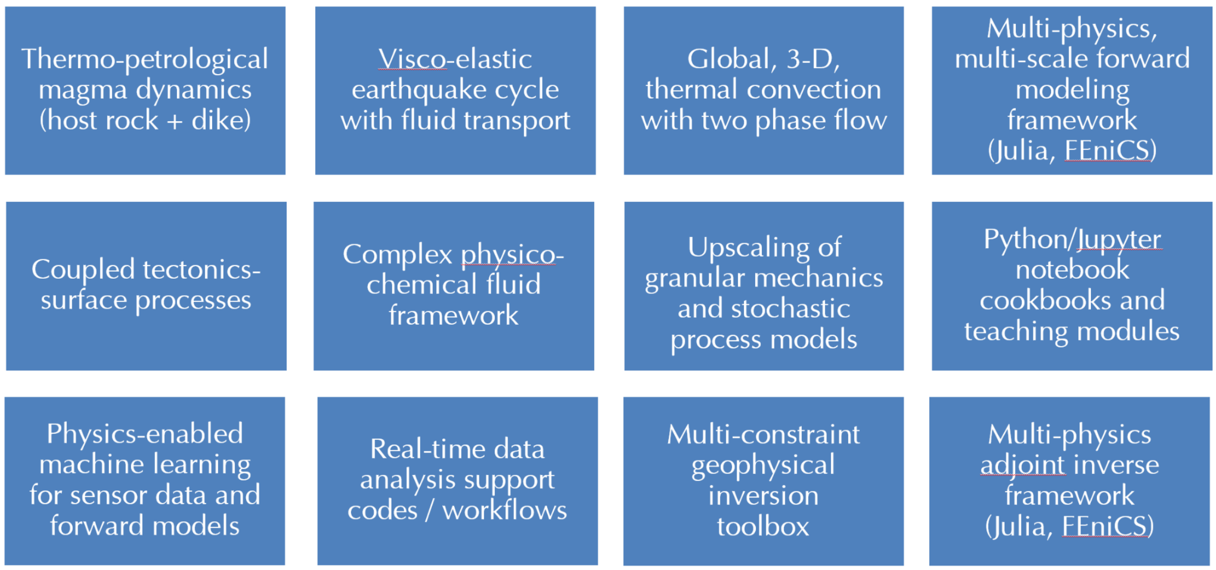

Figure MCS-3. *Example building blocks an MCS might develop to support fundamental and regionally applied subduction zone hazard modeling. Each block would include multiple bricks, for example, the visco-elastic earthquake cycle set might include fluid solver, solid solver, and friction solver bricks.*

MCS COMPONENTS

Figure MCS-4 shows how the MCS infrastructure and capabilities can be compartmentalized to achieve the previously mentioned goals. To fully realize our objectives—advance integrative subduction zone science with a large footprint in capacity building; enhancing diversity; empowering a wider subset of the solid Earth community in the use of high-end HPC and cloud computing; and contributing to geoscience education from K–12 to college levels—requires these components and more.

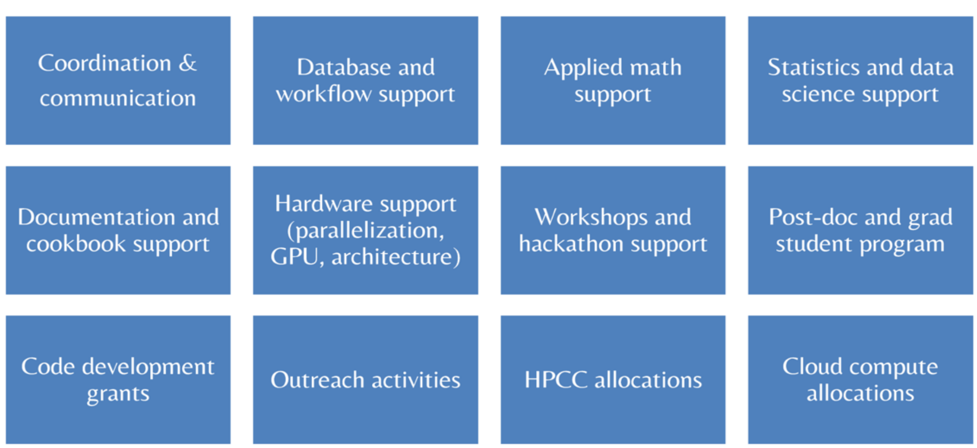

Figure MCS-4. *Example capabilities as well as human and computational infrastructure components of an MCS.*

At a minimum operational level, the MCS requires the following capabilities:

- Support for workshops, hackathons, and training for continued collaboration between observationalists, experimentalists, and modelers
- Repositories for models (time-independent geological and geophysical data) for SZ4D and other natural laboratories, as well as for primary and derived data product workflow
- Repositories for code documentation, cookbooks, and teaching material
- A dedicated program manager/coordinator
- A community-sourced and engaged science planning committee made up of modelers and observationalists

Such activities are crucial, and previous, long-term community efforts have shown, for example, that even the construction of community structural (e.g., seismic velocity, fault) models as well as automating and fully documenting secondary and tertiary data product workflows can be challenging. Existing expertise could be leveraged here, and collaborating with other community centers and workflow archiving efforts might suffice to make basic data and data product infrastructures operable.

However, to achieve a transformational advance, we must go beyond these basic capabilities and invest in continued model and community development. To achieve these more ambitious goals, the MCS requires:

- Support for multiple programmers (e.g., with HPC, applied math, visualization, database focus) at a central facility and make these individuals available to the community through a competitive grant process
- Issuing of subawards for distributed, but coordinated code development (outside of, or a dedicated component of any core SZ4D science program) or MCS needs to be supported by a long-term science plan and allocated program budget with competitive proposal review at NSF.

Only by providing these key pieces of infrastructure to the SZ4D community will the MCS be able to achieve the vision described above and go beyond prior community efforts in solid Earth computational sciences. Lastly, an ideal MCS would also include the following elements:

- Access to compute allocations, portals, and cloud workflow systems
- Support for a postdoc program in which postdocs reside with PIs, but benefit from being part of a cohort coordinated with the center, for example, by means of participating in yearly hackathons and workshops, as well as more sustained opportunities for training
- Support for competitive and inclusive graduate fellowships, with a focus on entraining new and underrepresented members to the geoscience community from diverse backgrounds

The components needed for the transformative advance described above can only be realized through sustained investment in a new computational facility. Such a facility would house a community code development team lead by a group of computational scientists. An MCS office would facilitate community engagement throughout workshops, hackathons, postdoc and graduate fellowship programs, and DEI initiatives. Lastly, PI-driven science would be supported through a competitive grant process allowing individual researchers to both leverage the computational resources of the MCS and contribute to the development of new community codes.

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

PHASING

What we can do right away: Start building a center, form a community-based planning process, hire programmers, start workshop and postdoc programs, and define and refine immediate code development tasks (in-center development, external grants to PIs, focus on open source and common standards, but not only community codes). Compile and assemble existing constraints from regional laboratories, assemble structural (static models). Compare those for key SZ4D sites with derived data products. Define specific regional sub-problems in coordination with FEC, LS, and MDE working groups, including modeling geared toward exploring optimal configurations for volcano and earthquake instrumentation based on existing and newly designed modeling codes. Use insights for experimental design (e.g. seismometer placement given asperity modeling; where/how to co-locate WG components). Assess community access to computing and training, work toward equitable participation with BECG.

Framework and codes supported after five years: Complete initial code development tasks. Develop a set of teaching and research codes and cookbooks. Initiate a summer school program. Train observationalist and laboratory scientists in code use and work on enhanced cookbook models. Refine codes depending on observationalist use. Complete storing house for inverse code and inverse frameworks. Reassess optimal solution strategies, focus on high-performance, cross-scale code development for adjoints and UQ. Complete first round of verification exercises. Define more ambitious benchmarks. Continue grant program to PIs and develop new code. Establish portals to run both forward and inverse models and hackathons and tutorials to broaden model use by non-specialists. Commence work on time-dependent adjoints and explore feeding real-time data to regionally adapted models using actual observatory data and synthetic tests. Assess tool useability and impact of training exercises. Reassess access to computing and portal/cloud strategy. Use modeling tools to refine hypotheses, identify knowledge gaps, and improve observational strategies.

Integration of real-time data streams (10 yr): Complete realtime tests for different earthquake and volcano settings. Quantify uncertainties for regional settings, and for general process models. Formalize cross site validation. Assess the degree to which earthquake and volcano systems need to be modeled across spatio-temporal scales to assess state and provide eruption and rupture scenarios. Provide fully realized regional workflows, while continuing grant program to PIs and new code development. Reassess experimental and observational strategy to reduce uncertainties. Reassess capacity building and training efforts.