Chapter 4. Synthesis

4.1 Cross-Cutting Themes

4.1.1 Cross-Cutting Science Themes

Subduction zone geohazards such as earthquakes, volcanic eruptions, landslides, and tsunamis have immense societal impact, and the Earth system that controls these catastrophic events is complex. The processes underlying subduction zone hazards operate on spatial scales from microns to hundreds of kilometers and timeframes from milliseconds to millions of years. A coordinated observational, modeling, and intellectual infrastructure is required to investigate how the different parts of the system interact with each other and better understand the processes that underlie subduction zone hazards.

The SZ4D initiative seeks to bring together researchers who study many different aspects of the subduction zone system. **No one living in a subduction zone must worry about "just" tsunamis, or "just" eruptions, or "just" landslides, why would SZ4D?** By integrating scientific discoveries from Landscapes and Seascapes (L&S), Faulting and Earthquake Cycles (FEC), and Magmatic Drivers of Eruptions (MDE), building a system-scale. physics-based framework with the Modeling Collaboratory for Subduction (MCS), and transforming the way we do science by Building Equity and Capacity in Geoscience (BECG), we have the opportunity to:

- Build statistically robust, multidisciplinary systems to investigate hazard precursors and provide forecasts of hazard likelihood
- Develop a full 4D understanding of how energy, stress, and mass move through the subduction zone system
- Establish generalized frameworks for modeling fluid flow, semi-brittle deformation, and brittle and ductile failure
- Understand how variations in climate impact geohazards along the entire subduction zone
- Develop a quantitative understanding of how an event that begins as an earthquake or a volcanic eruption will catalyze cascading, and oftentimes more damaging, hazards such as landslides, tsunamis, or lahars
- Improve how we do interdisciplinary research and collaboration in order to address the critical SZ4D themes while fostering equity and capacity building
- Learn from and engage with international partners to set up effective feedbacks between emerging local hazard science needs and SZ4D science goals
- Build collaborations with social scientists to assess (1) the past, current, and future vulnerability of local communities to subduction zone hazards, (2) the role of communities on cascading hazards, and (3) the impact of hazard forecasts on local communities
- Train the next generation of interdisciplinary researchers to tackle emergent and future grand challenges in the field

Most importantly, an integrative SZ4D approach will support efforts to funnel the above discoveries and efforts into an organized pipeline that turns scientific results into effective hazard estimates, communications products, coordinated alerts and warnings, capacity building, and outreach efforts.

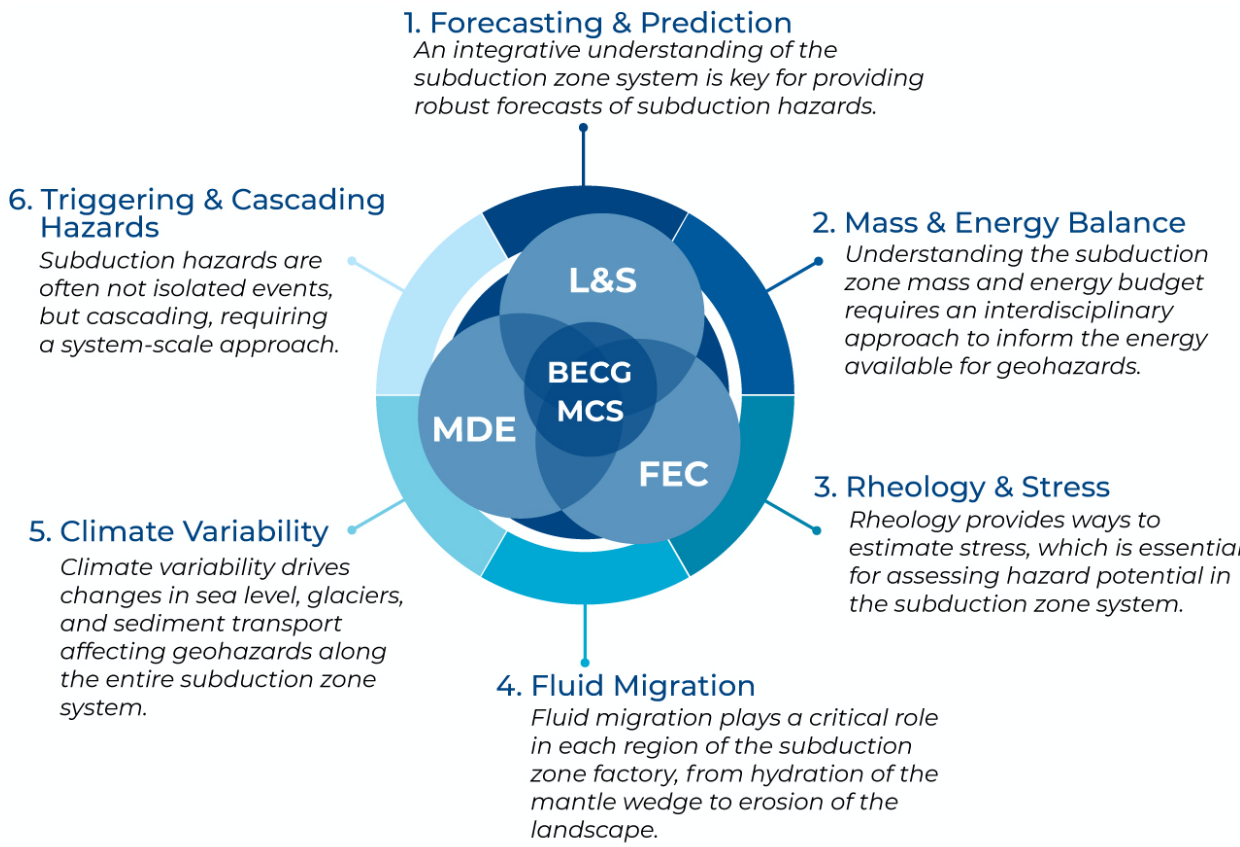

Figure CCST-1. *A visualization of six cross-cutting science themes that link together the three main SZ4D disciplinary groups, Landscapes and Seascapes (L&S), Faulting and Earthquake Cycles (FEC), and Magmatic Drivers of Eruption (MDE); and two SZ4D integration groups, Building Equity and Capacity in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

To tackle the grand challenges of subduction zone system science, we propose an integrative approach that links the understanding gained from each of the disciplinary areas through six cross-cutting science themes (**Figure CCST-1**). These six themes represent fundamental research areas that must be addressed to expand our knowledge of the subduction zone system and its geohazards. In this subchapter, we discuss each cross-cutting theme and provide examples of interdisciplinary knowledge gaps and areas for future research efforts.

1. Forecasting and Prediction. Subduction zones generate some of Earth's most devastating geohazards (e.g., earthquakes, landslides, volcanic eruptions, and tsunamis). Providing robust forecasts and warnings to vulnerable populations is critical for mitigating the potential impacts of these disasters. The concept of forecasting is simple in principle, but exceedingly difficult in execution. Ideally, a robust forecast is grounded in a thorough understanding of the entire system, its uncertainties, and how it responds as it evolves. Precursors to hazardous events (e.g., earthquake foreshocks, volcanic unrest, and slope creep) are well understood and recognizable, and there is a clear pathway to communicate scientific observations. In this framework, detailed monitoring detects activity in its early stages allowing scientists to update models and project the trajectory of the system to provide an evaluation of hazard potential. However, a forecasting strategy for subduction zone geohazards cannot be achieved while critical gaps remain in our understanding of the system and, in particular, the precursors of hazardous events. Additionally, there remains a critical need to develop model-data fusion techniques and robust frameworks for estimating how the system will evolve.

1.1 Precursors. The warning signs of an impending subduction zone hazard are very difficult to determine, and oftentimes these catastrophes occur with little to no warning. Understanding the precursory signals of an imminent disaster is critical to providing useable warnings and mitigating the effects of subduction zone geohazards. Determining precursory signals of potential hazards is a fundamental goal of the SZ4D initiative.

In FEC, two overarching questions drive discussions for forecasting an impending event:

- *Do distinctive precursory slip events or distinctive foreshocks occur prior to large earthquakes?*
- *What causes either foreshocks or precursory behavior?*

Unfortunately, there remains significant ambiguity surrounding the pre-rupture behavior of faults, and there does not appear to be a universal spatial or temporal pattern governing precursory behavior (e.g., Bürgmann, 2018). As such, recognizing and understanding migratory foreshock sequences as well as precursory slow slip remains a critical outstanding challenge (e.g., Pritchard et al., 2020).

Similarly questions regarding precursors are key to forecasting volcanic unrest. In MDE, two overarching questions include:

- *Are there key precursory signals of an impending volcanic eruption?*
- *What processes trigger volcanic eruption?*

Unrest signals such as surface deformation and increased seismicity have shown potential for providing early warning of a volcanic system transitioning into an eruptive state. However, global investigations evaluating surface deformation signals for eruption likelihood resulted in more false positives than true positives, 29 vs. 25, respectively (Biggs et al., 2014). An investigation of seismic precursors for ~30 years of eruptions from the Aleutian Arc found that using seismic precursory signals to forecast eruption worked well for volcanoes with long repose intervals (>15 yrs) or large eruptions—forecasting 10 out of 14, (a ~29% false negative rate) (Cameron et al., 2018). However, for small eruptions (VEI ≤ 2) with short repose intervals, only 7 out of 45 eruptions (~84% false negative rate) were successfully forecasted using seismicity data (Cameron et al., 2018). During this time period, 23 unrest events were classified as unrest without eruption and one event was classified as a false alarm, resulting in a 25% false positivity rate. Progress in forecasting volcanic eruptions will not be made without a better understanding of the key precursory signals and the mechanisms that trigger eruptions.

From the L&S perspective, large landslides share the precursory signals of volcanic eruptions and earthquakes, such as microseismicity and increased ground motion, but also respond to large storm events. Not all large storms trigger landslides, but the precipitation rate, duration, and cumulative precipitation amount have been shown to correlate with increases in landslide events. The first L&S overarching question encompasses forecasting though understanding the myriad feedbacks and processes that contribute to mass transport:

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

For example, what are the fundamental controls on the initiation and runout of landslides, turbidity currents, liquefaction, and other surface processes, including those influenced by earthquake and volcanic events? With monitoring of existing or ongoing slope failures and measuring meteorological, environmental, and surface deformation characteristics, we can make further progress on understanding the mechanics of slope failure and the conditions that promote or suppress periods or events with elevated landslide activity. Combined with the development of new, accurate, and efficient physics-based models of slope failure, these measurements can perhaps improve "landslide forecasts" and maybe even identify precursory signals detectable from remotely sensed time-series data for large slope failures or large-scale event-triggered landslides. Furthermore, improved understanding via measurement and model developments related to sediment transport in the aftermath of a large sediment generation event (e.g., widespread landsliding) can enhance flood prediction modeling. For example, in the aftermath of a catastrophic landsliding event, a hazard cascade develops as the liberated sediment migrates downstream in the years to decades after the initial event. This sediment can aggrade and fill previously deep river valleys, decreasing the threshold discharge for flooding. Improving our ability to simulate this hazard cascade will lead to better flood hazard forecasts for downstream communities following a catastrophic landslide event.

1.2 Model-Data Fusion. Model-data fusion remains a critical need in all aspects of the SZ4D program. The Modeling Collaboratory for Subduction (MCS) is uniquely poised to fill this critical computational gap and provide a physics-based framework for combining the multi-temporal, multi-spatial, multidisciplinary observational and laboratory datasets proposed by the SZ4D initiative. Inversion techniques such as adjoint methods allow for multi-data stream inversion and investigation of long timescale system evolution (e.g., Spasojevic et al., 2009; Zhou & Liu, 2017; Zhou et al., 2018). Advancements in near-real-time statistical data assimilation will be essential for testing hypotheses for hazard precursors and triggering mechanisms, to guide instrumentation deployments and to interpret observations. Progress in model-data fusion is needed to develop the next generation techniques for subduction zone geohazard forecasting and deal with very large volumes of diverse data from centralized and distributed sources (e.g., earthquake recordings, satellite observations, GNSS measurements). Furthermore, the development of a computational resource for subduction zone data assimilation will enhance and support the interoperability of data and software and enable integration and collaboration across different subduction scientific domains.

Over the past decades, significant progress has been made in statistical data assimilation. The seminal sequential data assimilation technique, the Kalman Filter (Kalman, 1960) and its updated Extended Kalman Filter (Kalman & Bucy, 1961), have been successfully applied in the field of geophysics to model colored noise sources in surface deformation data and investigate transient signals along faults and at active volcanoes (e.g., Segall & Matthews, 1997; Aoki et al., 1999; McGuire & Segall, 2003; Miyazaki et al., 2003, 2011; Fukuda et al., 2004; J. R. Murray & Segall, 2005; Ohtani et al., 2010; Anderson & Segall, 2013; Dalaison & Jolivet, 2020). The more recent Ensemble Kalman Filter (EnKF) addresses the computational costs and linearization issues inherent to the Kalman filter and Extended Kalman filter (Evensen, 1994). The EnKF has recently been adapted and successfully implemented to forecast volcanic unrest and investigate eruption precursors (Gregg & Pettijohn, 2016; Bato et al., 2017, 2018; Zhan & Gregg, 2017; Zhan et al., 2017, 2019, 2021; Albright et al., 2019). Other sequential data assimilation techniques such as multi-objective Evolutionary Data Assimilation (EDA) have also been successfully implemented for investigating the near-real-time evolution of nonlinear systems (e.g., Dumedah, 2012, 2015; Dumedah & Coulibaly, 2014; Dumedah & Walker, 2014).

Advancements in model-data fusion are key for understanding system evolution, improving data analysis, and developing the next generation of forecasting approaches. The progress made in the fields of climate modeling, hydrology, and physical oceanography provide an important jumpstart that will greatly benefit the SZ4D initiative. However, there is still significant work to be done.

2. Mass and Energy Balance, Hazardous events both respond to and impact the distribution of mass and energy within subduction zone systems. Each of the working groups has elements of mass and energy balance within their research questions. Here, we highlight several outstanding research questions that demonstrate the role that an integrated SZ4D effort can play in understanding the distribution of mass and energy that drive earthquakes, tsunamis, landslides, and volcanic eruptions.

Mass transport near Earth's surface via landslides and sediment transport responds to and also drives deeper processes in the crust within two-way feedback systems. The L&S group asks the following question:

- *What are the feedbacks between subduction zone earthquakes and volcanic eruptions, and sediment generation and transport across landscapes and seascapes?*

Deep crustal processes can dramatically modify the landscape and impact mass transport where large storms are infrequent (e.g., Bruni et al., 2021). For example, **Figure CCST-2A** shows landslides that were triggered by shaking from the 2018 M 6.6 earthquake in Hokkaido, Japan; the hillslope vulnerability was elevated due to saturated conditions related to typhoon Jebi a few days before the earthquake (e.g., Yamagishi & Yamazaki, 2018). In another example, the roughness of the subducting slab can impact incision and uplift rates of the landscape (Ramírez-Herrera et al., 2021). Explosive volcanic eruptions can change the landscape in the days after the eruption as ejected material is reworked and transported through the drainage network, but the eruption will also continue to impact sediment flux for decades due to stripped vegetation. Our ability to forecast terrestrial and submarine mass wasting hazards requires establishing the role of both landscape-impacting storms and solid Earth processes at a range of timescales.

At the same time that solid Earth processes can affect surface mass transport, sediment transport over short and long timescales can affect earthquakes and volcanic eruptions. On short timescales, for example, **Figure CCST-2B** shows the iconic landslide that triggered the 1980 eruption of Mt. St. Helens by unloading the magmatic system (e.g., Belousov et al., 2007). On longer timescales, transport of sediment to the trench can impact coupling and plate velocity (Behr & Becker, 2018). The section below on the Impacts of Climate Variability describes more ways that sediment loading affects the subduction zone interface, for example, by stabilizing the interface beneath forearc basins (Fuller et al., 2006). Understanding the interplay of surface and subsurface systems requires innovative integration of datasets at a wide range of time and spatial scales.

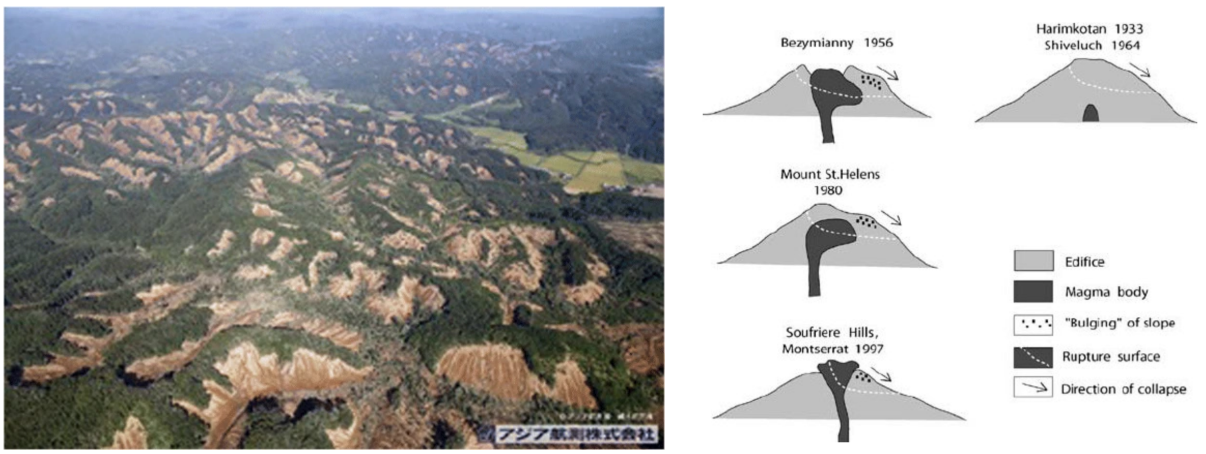

Figure CCST-2. *(A) Aerial photo of landslides triggered by shaking from the M6.6 2018 Hokkaido, Japan earthquake (from Yamagishi & Yamazaki, 2018). (B) Sketches illustrating the role of landslides in facilitating lateral blasts at Bezymianny, Mount St. Helens, Soufrière Hills and Montserrat, where magma bodies were shallower than Harimkotan that did not have a lateral blast. (Taken from Belousov et al., 2007)*

The subduction zone mass budget also considers interesting and unanswered questions about how mass transport within the crust impacts hazards. For example, sediments at the trench become entrained along the subduction interface so that the nature and the rate of sediments transported to the trench might affect how slip occurs along the megathrust (e.g., Lamb & Davis, 2003; Brizzi et al., 2020). The section below on the Impacts of Climate Variability describes many ways that sediment impacts slip modes, which is central to the FSE research questions. Subducting sediments also contribute volatiles that can migrate from the slab through the volcanic system. One of the overarching goals of the MDE experiments is to quantify magma supply rate from the mantle and determine its impact on the resultant volcanic activity and volcanic hazards. For example, what can volatile flux measured at volcanic systems tell us about mass flux from the mantle, ascent rate, and potential eruptive intensity (e.g., P. J. Wallace, 2005; L. M. Wallace et al., 2021)?

Mass transport within the subduction zone system is one element of the system's energy budget and can contribute to the energy available to drive destructive earthquakes, landslides, tsunamis, and volcanic eruptions. When the rate of energy input to the subduction system exceeds the rate of energy output, the system accumulates energy, which is then available to drive hazardous events. The size of a hazardous event depends on how much energy is in the system. While knowledge of the stress state might tell us how close the system is to failure, additional information is needed to forecast the size of that failure. We measure earthquake magnitude in energetic terms and the volcanic explosivity index (VEI) characterizes the volume and height of ejecta that comprise kinetic energy of the eruptions. It makes sense to consider the energy budget when assessing hazard potential.

Hazardous events involve the transformation of energy from one form to another (**Figure CCST-3**). For example, slip events transform stored internal energy to seismic shaking, breakdown energy, and frictional heat (e.g., Aben et al., 2019). Similarly, landslide and sediment transport kinetic energy derives largely from gravitational potential energy. These examples highlight the critical role of gravitation potential and internal work, which are conservative terms, in storing energy that drives hazardous events. These events release other forms of energy (e.g., heat and ground shaking) that are lost to the system. Gravitational potential energy can be estimated from topography and estimates of material density; however, internal work, which is the product of stress times strain (e.g., Meade, 2013; Cooke & Madden, 2014), is more difficult to estimate and provides opportunities for future investigation. For example, x-ray tomography of triaxial experiments permit direct and detailed observation of deformation during fault growth that informs the evolving internal work as microcracks coalesce (McBeck et al., 2020). These tomography experiments and a wealth of field data (e.g., Barnhart et al., 2020) highlight that damage associated with fault growth is inelastic so that not all internal work is recoverable. To address our critical knowledge gap about the degree of inelastic deformation, the L&S working group posits:

- *How much permanent deformation is absorbed in the upper plate of the subduction zone and what factors control this?*

The internal work provides energy for permanent deformation such as pressure solution, microcracking, crystal plasticity, and metamorphism/metasomatism (e.g., Meade, 2013; Vora & Morgan, 2019). Estimating the internal work available to drive hazards requires better constraints on how energy is consumed by a wide range of deformation processes within the upper plate. SZ4D efforts to collect data on the rates of energy input and output, gravitational potential energy, internal work, heat flux, and other energy inputs will provide critical constraints on the energy available for earthquakes, landslides, and volcanic eruptions.

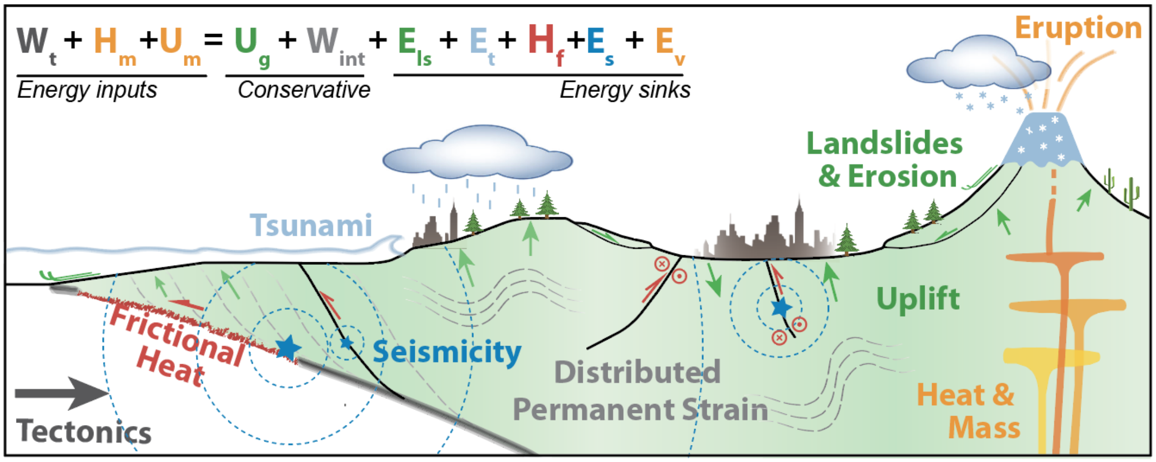

Figure CCST-3 *Schematic first-order energy budget of the entire subduction zone. The inset equation outlines in the energetic inputs (W_t - tectonic work; H_m - heat; U_m - gravitational potential energy from mass in/out of the system), conservative energy terms (U_g - work of uplift against gravity; W_{int} - internal deformation work) and energetic sinks that are lost to the system (E_{ls} - kinetic energy of sediment transport; E_t - tsunami energy; H_f - frictional heat of earthquakes; E_s - seismic shaking and E_v - heat and kinetic energy of volcanic eruptions). Understanding the relationships between subduction zone processes provides information about the energy available within the system to drive damaging hazards.*

Calculating the energy budget requires knowledge of the heat flux, strain, and the stress within the system. Heat flux, topography, and strain are generally directly observable, but stress state is much more difficult to estimate. In order to constrain the stress, we may need to use numerical models and we need to know the rheology of the system at a range of pressures, temperatures, and strain rates.

3. Rheology and Stress. When subduction zone hazards initiate, potential energy is rapidly converted into strain in the solid and fluid Earth. A detailed understanding of how this transformation occurs is of interest to each SZ4D working group. While each group will focus on specific questions, experiments, and theoretical frontiers that are important to their particular problem, there are at least five key cross-cutting areas of interest.

Modeling **the boundary between viscous and brittle deformation at high temperature and strain rate** is a key overlap between the MDE and FEC groups:

- *How does magma travel through the entire crust?*
- *What mechanical properties control the rate and maximum magnitude of intraslab earthquakes?*

Intraslab earthquakes dominate the shaking hazard in cities like Seattle and Anchorage (Petersen et al., 2014, 2019) and result from the frictional failure, and possibly localized melting, of the oceanic plate's subducted crust and mantle (Peacock et al., 2002; Kelemen & Hirth, 2007; Andersen et al., 2008; John et al., 2009; Hosseinzadehsabeti et al., 2021). For instance, the 2001 M6.8 Nisqually earthquake created over $1 billion in damage through Seattle and the Pacific Northwest as the result of a few meters of slip in the subducted slab. This faulting occurred at temperatures in the range of 700°C but was contained within the brittle core of the slab (Kao et al., 2008).

A frontier of experimental rock mechanics involves understanding the dynamic weakening of lower crustal and mantle rocks. Much of this work is done with rotary shear apparatus that can reach high slip rates and temperature (e.g., Di Toro et al., 2010). This same strain-rate and temperature regime is key for understanding magma stalling depths (Watanabe et al., 1999; Annen, 2008; Huber et al., 2019), volcanic dome emplacement (Kendrick et al., 2014), and the precursory signals and triggers of volcanic eruptions (e.g., Gregg et al., 2012, 2018; Parisio et al., 2019; Zhan & Gregg, 2019; Browning et al., 2021). Consequently, many recent experiments done to understand the rheology of volcanic systems (e.g., Smith et al., 2009) use the same apparatus as those aimed at understanding high temperature, large slip earthquake rupture (Kendrick et al., 2014; Niemeijer et al., 2011). The MDE and FEC groups both propose suites of laboratory experiments, thermal and geodynamical model development, and backbone and Volcano Imaging Array observation networks to enable physics-based forecasts of future earthquake magnitudes or eruptions requires, advancing our understanding of high temperature and high strain-rate deformation.

3.1 Forearc Inelastic Deformation: Both the L&S and FEC groups require a better understanding of how inelastic deformation in the forearc occurs.

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

Plastic failure of the overlying sediments may accentuate tsunami excitation and contribute to building topography on geologic timescales. This phenomenon is particularly important at accreting margins like Cascadia. Plastic failure of the accretionary wedge during megathrust earthquakes can increase seafloor uplift by a factor of three or more and cause it to peak closer to shore (Wilson & Ma, 2021), increasing tsunami excitation and potentially decreasing the time till the first waves reach shore. The building of forearc topography during megathrust ruptures is both an energy sink that affects the propagation of an individual rupture and a significant part of the overall energy budget on geologic timescales. Understanding how forearc topography is built during earthquakes and subsequently modified by submarine and lacustrine landslides, turbidity currents, and coastal erosion and deposition will require collection of comprehensive baseline and repeat topography and bathymetry datasets for both the L&S and FEC groups as a fundamental constraint and input into models of these hazards. Seafloor geodesy studies will quantify the strain field during large earthquakes and identify zones of faulting. Onshore uplift rates will be constrained by thermochronology, cosmogenic nuclides, and geochronology studies. Collectively, this set of activities will all feed into clarifying the conditions (e.g., rheologies of the upper plate, the faults within it, plate convergence rate and/or obliquity) that govern inelastic forearc deformation and their role in the overall energy budget.

3.2 Upper Plate Strength/Rheology. Upper plate strength/rheology influences all three groups, as it controls erosion rates, magma migration through the crust, and the occurrence of shallow earthquakes in the overriding plate, which often dominate hazards in cities like Portland, Oregon (Petersen et al., 2014; 2019), and Santiago, Chile (Hussain et al., 2020).

Key questions from all three working groups that require quantifying the stress field and strength of the overriding plate include:

- *Where do magmas stall?*
- *How do other subduction zone faults (outer rise, forearc, and hazardous slab) and earthquakes interact with the plate boundary?*
- *How much permanent deformation is absorbed in the upper plate of the subduction zone and what factors control this?*

For example, inelastic deformation within the upper plate in the form of deformation fabrics (e.g., cleavage and folding) can consume greater energy than that released by earthquakes or used for uplift against gravity within the fold and thrust belts of the accretionary wedge (e.g., Meade, 2013; McBeck et al., 2020). As inelastic deformation reduces stored internal work, the system has less energy available to drive earthquakes and volcanic eruptions. Better understanding of the rheology of pressure solution (e.g., Niemeijer et al., 2002; Gratier et al., 2013; Pluymakers & Spiers, 2015), microcracking (e.g., Gratier et al., 1999; Vora & Morgan, 2019), crystal plasticity (e.g., Kronenberg et al.., 1990; Mares & Kronenberg, 1993), and metamorphism/ metasomatism within the upper plate under a variety of strain rate and fluid conditions can better inform the energy consumed by inelastic deformation. While the megathrust is likely weak in many locations due to fluid pressure and mineralogy, the overriding plate is strong enough to support mountain ranges, volcanic edifices, and often a rotated stress field relative to the incoming plate. Paleoseismic studies of upper plate faults, SAR acquisitions, and backbone monitoring networks will all contribute to quantifying the stress, strength, and strain distribution in the overlying plate, often in the inland regions where population density is highest and hazards from shaking, landslides, and eruptions overlap spatially.

3.3 Rheology of Granular Flows. The rheology of granular flows governs turbidites, landslides, debris flows, pyroclastic flows, lahars, and perhaps some aspects of earthquakes.

- *What are the fundamental controls on the initiation and runout of landslides, turbidity currents, and volcanic mudflows?*
- *What controls seismic radiation from these events?*
- *How does rheology change throughout the evolution of a particular flow?*

The evolution of the governing rheology during an individual landslide/debris flow has long been recognized to be a complex process dependent on fluid pressure within the flow (Iverson, 1997, 2003; Iverson et al., 1997). While lahars contain a larger fraction of solid material than debris flows, their rheological evolution is complex due to the fluid component (Vallance & Iverson, 2015). Similarly, pyroclastic flows can be governed by granular flow rheologies that involve complex interactions between the gas and solid components (Dufek, 2015). The complex interplay among seasonal climate/rainfall variations also affects our ability to model and predict the onset of motion in slow-moving landslides (Finnegan et al., 2021). Recently, models suggest that collisional impacts between grains within a fault zone during rupture as an alternative mechanism to frictional sliding to explain the incoherent nature of high-frequency radiation in the near-field of earthquakes (Tsai et al., 2021). The theoretical models that underlie these studies of lahars, landslides, pyroclastic flows, and earthquakes are deeply related creating a fundamental overlap in SZ4D and the MCS component in particular. Many of the hazards described by granular flow are infrequent and difficult to observe but overlaps between different SZ4D components may improve the available datasets. For instance, FEC backbone arrays both onshore and offshore can help monitor for submarine landslides and turbidites (Fan et al., 2020; Gomberg et al., 2021), which may lead to rapid response bathymetric surveys by the L&S group.

4. Fluids and Fluid Migration. The distribution of fluids, fluid migration, and the interaction between fluids and solid materials play critical and far-reaching roles in subduction zone processes and thus in the seismic, volcanic, landslide, and other hazards that occur in subduction zone systems. Integrative research into these processes is critical for graining a fundamental understanding of how subduction zone systems work and the interplay of these processes in the development of hazards.

All the individual working group chapters in this report emphasize the critical and ubiquitous role of fluids in subduction zones, including controlling the nature of behavior of the megathrust and other important faults, influencing the rheological response of the crust to seismicity and volcanism, impacting magma transport and eruption hazards and facilitating Earth surface processes. Fluid processes are also highlighted in other parts of this chapter—emphasizing, for example, the role of fluids in crustal rheology, in granular flows, and in modulating climate forcings of landscape processes. The specific impacts of fluids and fluid migration on subduction zone hazards, and on resources therein (e.g., freshwater, metallic mineral deposits, geothermal energy), also means there is a close link between societal concerns and fluids processes in subduction zone systems.

4.1 Fluids in the subducting slab and deep crust. Fluids play critical roles in all parts of the subduction environment, including in the downgoing slab, where fluids and fluid migration plays important roles in many of the characteristic features of subduction zones. Hydration and alteration of the oceanic crust and fluid within accreted sediments delivers considerable fluid to the subduction zone. Variation in megathrust pore fluid pressures are thought to explain spatial and temporal variations in slip behavior observed in subduction zones (e.g., Saffer & Tobin, 2011; Audet & Schwartz, 2013; Gao & Wang, 2017; Saffer, 2017). At relatively shallow crustal levels, fluid flow derived from the oceanic crust and sediments plays important roles in megathrust deformation and seismicity on other related faults. Fluid flow throughout the subducted oceanic crust and along the subduction channel also strongly controls many of the other physical and chemical properties of the subducting lithosphere and modulates much of the complex mineralogical and chemical exchange that occurs. Deeper levels of subduction produce the metamorphic dewatering reactions that ultimately control magma production (Stern, 2002; Poli & Schmidt, 2002) and primary magma compositions (Till et al., 2019) and may also play an important role in dictating the arc volcanoes (Grove et al., 2009) and thus the localization of volcanic hazards.

4.2 Fluids in the Shallow Crust. There are numerous links and feedbacks between seismic, magmatic, and landscape processes within the shallow crust that involve fluids and fluid migration. Thus observational, experimental, and modeling constraints on the distribution and role of fluids in the shallow crust will be valuable to all SZ4D working groups. For example, shallow fault systems are strongly influenced by local fluid pressure conditions, and changes related to fluid migration can significantly impact seismicity.

Interaction between shallow crustal fluids and magmas can also produce phreatic and phreatomagmatic eruptions, such as the deadly recent eruptions at Mount Ontake, Japan, in 2014; and Whakaari/White Island, New Zealand, in 2019 (**Figure CCST-4**). These eruptions often occur with little or no clear precursory phenomena (e.g., Dempsey et al., 2020), but also involve interaction between magmatic components and shallow hydrological circulation. As a result, land surface, fluid flow, and climate will strongly influence phreatic eruptions and the resultant hazards. Crustal hydrology also influences the alteration of volcanic edifices via shallow hydrothermal circulation, and weakening associated with alteration can lead to edifices that are prone to collapse events—even when not erupting (e.g., Reid et al., 2001). Edifice collapse events can also be associated with eruptions, as happened at Mount St. Helens in 1980 and at several other Cascade volcanoes (e.g., Kent et al., 2010). Hydrothermal fluid circulation in response to magmatic heat in the shallow crust is also critical to the formation of important mineral deposits, including many critical metals and minerals (e.g., Dilles et al., 2000; Chambefort et al., 2013), and to the availability of important low-carbon geothermal energy resources.

Although the processes that may lead to external triggering of volcanic eruptions remain incompletely understood, fluid-mediated processes are also likely important in some cases (e.g., Manga & Brodsky, 2006; Seropian et al., 2021)—particularly if a volcanic system is already "primed" for eruption (e.g., Hamling & Kilgour, 2020). Hydrothermal systems associated with volcanic regions can be highly susceptible to changes and triggering via seismic activity (Seropian et al., 2021). Examples include devastating eruptions of mud volcanoes, such as that of the Sidoarjo ("Lusi") mud volcano in 2006 that took 13 lives and destroyed the homes of over 60,000 people (although there is a contentious debate about triggering via earthquake and nearby gas exploration (e.g., Tingay et al., 2008).

Figure CCST-4. *Examples of important fluid processes and fluid migration events. Clockwise from top left: The deadly 2019 phreatic eruption of Whakaari, New Zealand (CNN), lahar deposits in the Toutle River, Mount St Helens, 1980 (USGS); Sand boils associated with the 2006 Canterbury, New Zealand, earthquake (Wikipedia); A schoolhouse destroyed by the Sidoarjo ("Lusi") mud volcano, Indonesia (Wikipedia); a scaly clay melange from the Franciscan terrain (Wikipedia); cold springs feeding the Metolius River, Oregon (Travel Oregon).*

5. Impacts of Climate Variability – Preconditioning and Modulation of Subduction Zone Geohazards. This section focuses on the cross-cutting question:

- *How does climate and climate variability modulate the pace, frequency, and types of geohazards in subduction systems?*

Interactions between the atmosphere, hydrosphere, and lithosphere alter the near-surface environment, changing the material properties of the substrate exposed at and near Earth's surface, altering surface loading in space and time, transporting mass from the terrestrial environment offshore, and affecting how and where mass is accreted, underplated, and/or subducted. Regional climate and climate variability strongly affect these interactions, and, in subduction zones, they are essential to understanding the context, preconditioning, pacing, and archiving of geohazards along these dynamic plate boundaries. For example, changes in the volumetric distribution of surface masses (e.g., the ocean, glaciers, reservoirs) perturb crustal stress fields and may enhance or retard the potential for faults to rupture in earthquakes (Hetzel & Hampel, 2005; Luttrell & Sandwell, 2010). And, potentially precursory signals such as tremor and slow slip (e.g., Socquet et al., 2017) have been linked to the very small changes in pressure from tides (Houston, 2015; Tonegawa et al., 2021).

Climate and climate variability are thus an integral part of understanding subduction zone geohazards, from the impact of tsunamis generated by the megathrust, to the spatial and temporal variability of upper plate fault activity, to the pace and tempo of onshore and offshore mass wasting and volcanic eruptions. Below, we highlight how these interactions unite the SZ4D workgroups and their science objectives through the common goal of understanding subduction zone geohazards. To this end, we focus on the role of climate and climate variability on the evolution of the 4D subduction zone system and the modulation of subduction zone geohazards on three different timescales: (1) long term ($\geq 10^6$ yrs), (2) intermediate (10^6–10^4 yrs), and (3) short term ($\leq 10^4$ yrs).

5.1 Impacts of Long-Term ($\geq 10^6$ yrs) Climate. Over long timescales, regional climate affects water availability, dominant precipitation phase (e.g., rain vs. snow), vegetation, ice volumes, and weathering intensity and rates. These factors affect sediment generation and transport, the distribution of floods, and the dominant process shaping mountain topography (e.g., rivers vs. glaciers). The conditions imposed by long-term regional climate are relevant to understanding the context of geohazards along different subduction zone segments. For example, the geohazards associated with otherwise comparable subduction systems located in a polar region and a tropical setting are different. Glaciers will be the dominant agent of terrestrial erosion and chemical weathering rates subdued in a polar setting, while in a tropical climate, rivers are the primary process sculpting topography under the backdrop of high chemical weathering rates. The phase of precipitation and the pace and tempo of erosive floods will also be distinct. Snowfall and its seasonal melting will be predominant controls on the terrestrial hydrological cycle and flooding in a polar climate. Rainfall, perhaps mostly delivered in high-magnitude storm events, such as hurricanes, cyclones, and tropical low-pressure systems, will largely control the terrestrial hydrologic cycle and distribution of floods in a tropical setting. Collectively, these processes affect the pace, style, and type of sediment transport in the system. In polar climates, variations in onshore-to-offshore sediment flux might be seasonal, and the sediment load dominated by gravels and sands, whereas in a tropical climate sediment flux might be storm-dominated with a greater proportion of the load in the fine silt and clay size fraction.

Characterizing and quantifying differences in erosion, weathering, and sediment transport provides the requisite context to make results and insights derived from one subduction segment transferable to another. For example, the volume and characteristics of sediment delivered to the trench will be related to the long-term climate of a given subduction segment. Coarse sediment might be deposited in on and offshore forearc basins, while the finer fraction might bypass these depocenters, making it all the way to the trench. The distribution of sediments has potentially important impacts on how long-term strain is distributed across the subduction system and the rheological properties of the megathrust. Large glaciations may control the volumes of sediment on the downgoing plate, which are postulated to create end-member conditions on the mass balance of global subduction zones (accretionary versus non-accretionary). Whether a margin is losing mass (non-accretionary) or accreting mass may profoundly affect the stress state of the forearc of the upper plate, the types and rates of active forearc faults, the rheology of the entire subduction system, and the type of volcanic products produced by subduction (Clift & Vannucchi, 2004).

It has long been observed that megathrust rupture patches correlate with the location of large, deep forearc basins (e.g., Song & Simons, 2003; Wells et al., 2003). Numerical modeling studies indicate that this correlation is due to forearc basin sediment accumulation that stabilizes the upper plate such that it cannot deform as easily if the basin is underfilled (Fuller et al., 2006). Stabilization of the upper plate due to forearc sedimentation will result in more strain accumulation on the megathrust, which should increase the frequency of megathrust ruptures. Furthermore, modeling studies suggest that forearc basin sedimentation can thermally blanket the upper plate, facilitating viscous activation of the lower crust, driving upper plate crustal thickening and forearc uplift (Fernández-Blanco et al., 2020). If the forearc basins remain underfilled, the upper plate can more easily deform and accommodate more strain through the generation and activity of upper plate faults (Fuller et al., 2006). Long-term climate plays an important role, along with rock-type and tectonics, in dictating the sediment dispersal and accumulation patterns, and it is likely relevant in determining how much strain is taken up on the megathrust versus the upper plate and associated geohazards of a given subduction system.

As this sediment is delivered to and consumed by the subduction trench and enters the megathrust, it will impact the rheology and frictional properties of the plate boundary. Long-term climate will, in part, impact the volume and kinds of sedimentary products that make it to the trench and thereby plays an important role in determining the thickness, mineralogy, and porosity of sediment consumed by a subduction zone. For example, sediment starvation due to aridification of the central Andes since the Miocene likely increased plate boundary friction, causing the mountains to grow in height (Lamb & Davis, 2003). Modeling studies indicate the type and thickness of subducted sediment can impact the subduction dynamics, megathrust seismicity, and tsunamigenic potential (Brizzi et al., 2020; Ulrich et al., 2021; Du et al., 2021). The type of sediment will also play a role in determining the depth and temperature of down-dip transitions in mechanical properties of the subduction interface, and thus the transition from predominantly frictional sliding to ductile deformation (e.g., Moore & Saffer, 2001).

5.2 Impacts of Late Cenozoic Climate Variability (≥10^5 yrs). On shorter timescales, late Cenozoic climate oscillations impact terrestrial hydrology, sea level, and vegetation, and the generation, flux, and routing of sediment in a subduction zone. High-frequency variations in global temperature control the advance and retreat of continental ice sheets and alpine glaciers, which cause sea levels to rise and fall by as much as 150 m (Murray-Wallace & Woodroffe, 2014; Pico et al., 2017). Changes in regional weather patterns, temperature, and vegetation modulate variations in water and sediment discharge, resulting in unsteady rates of erosion, weathering, and sediment transport on 10^5 yr timescales. Several important aspects of climate variability impact subduction zone geohazards and represent important cross-cutting themes. Here, we emphasize the role that climate variations play in affecting surface loads and unsteadiness in the erosion and sediment transport system.

Variations in surface loading from glacial advance and retreat, sea level change, and surface erosion impact the state of stress at depth. In some volcanic and fault systems that are on the verge of failure, even small perturbations to the stress state can suppress or trigger eruptions and earthquakes. Loading and unloading arcs via changes in ice volumes for subaerial volcanoes, and sea level rise and fall for submarine and island volcanic systems, can impact the frequency and temporal clustering of volcanic unrest and quiescence (e.g., Huybers & Langmuir, 2009; Sternai et al., 2017; Satow, et al., 2021; Wallmann et al., 1988). Similarly, modeling and paleoseismic investigations suggest earthquake activity might be modulated by climate-driven variations in ice and water volumes such that seismicity and the occurrence of large earthquakes are temporally clustered (e.g., Hetzel & Hampel, 2005; Hampel & Hetzel, 2006; Hampel et al., 2007, 2010). Tectonic plate bending in response to differential eustatic loading alters lithospheric stresses near the coast and may increase or decrease fault stresses in accordance with Coulomb (i.e., resolved shear and normal stresses) stress theory (e.g., Luttrell et al., 2007). In turn, the distribution and magnitude of eustatically driven Coulomb stress changes depends upon terrestrial and submarine topography, lithospheric thickness and rheology, and the geometric attributes of faulting (i.e., orientation, dip, kinematics). While these latter studies are not focused on subduction environments, the same concepts and physical principles apply to upper plate faults in subduction zones. Mouslopoulou et al. (2016) showed coastal uplift rates in several subduction forearcs are more rapid during sea level low stands. They suggest that these pulses of rapid uplift are due to earthquake clusters. It is possible that the temporal correlation between the inferred timing of earthquake clusters and sea level fall is associated with fault unloading due to reduced water volumes. Collectively, these studies suggest late Cenozoic climate variations might cause temporal clustering of volcanic eruptions and upper plate earthquakes and thus changing hazard levels in time.

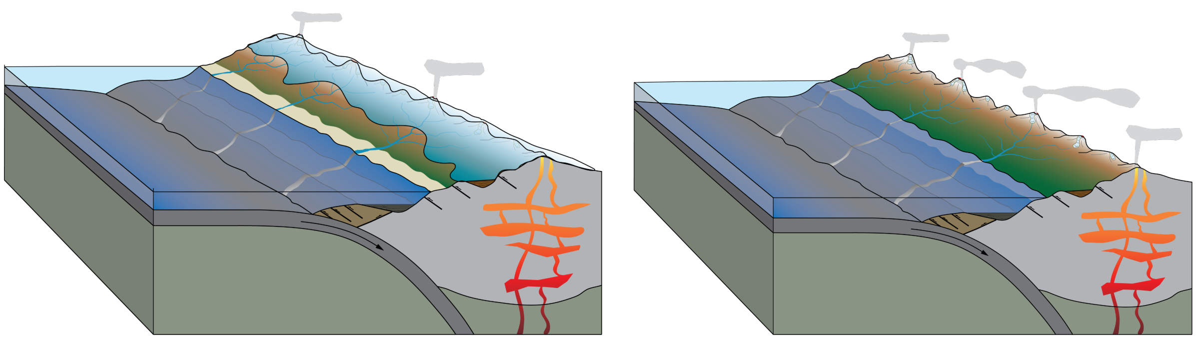

Figure CCST-5. *Schematic of a subduction zone segment during a glacial (left) and an interglacial (right) period. Ice extent is greater and sea level is lower during the glacial period. Changes in ice volume and sea level will affect the stress state in the upper and middle crust, which can modulate the frequency of volcanic eruptions and upper plate fault activity. Exposure of the coastal shelf during glacial periods at sea level lowstands will change the dynamics and connectivity of the onshore-to-offshore sediment transport system. Furthermore, these climate variations will impact vegetation, water availability, and weathering, and thus modulate sediment supply and water discharge, resulting in unsteady sediment transport through time.*

Variations in late Cenozoic climate influence the generation and transport of sediment across subduction zone landscapes and seascapes. Climate also modulates sediment supply and water discharge, such that rates of erosion and sediment transport are tightly coupled to climate. Variations in sea level over the late

Cenozoic repeatedly expose and submerge the coastal shelf environments, affecting geomorphic processes and the onshore-to-offshore sediment transport system. These variations are recorded in landforms such as marine and river terraces that are used as paleo-geodetic markers of uplift and deformation. Furthermore, climate-modulated variations in surface erosion might impact the state of stress on upper plate faults and volcanic systems in ways not yet fully understood. For example, modeling studies show that erosion can impact the seismicity of active thrust faults (Steer et al., 2014) and that erosion associated with a single typhoon in Taiwan elevated microseismicity on upper plate faults (Steer et al., 2020). It follows that sustained climate-induced changes in the spatial and temporal patterns and magnitude of erosion might influence fault activity and thus earthquake hazard in subduction systems.

5.3 Impact of Holocene to Anthropocene Climate Change (≤10^4 yrs). Climate change since the end of the last glacial maximum resulted in changes in subduction zone geohazards. The retreat of alpine glaciers can debutress over-steepened glacial valley walls, resulting in elevated rates of mass wasting in the aftermath of glacial retreat (e.g., Vilímek et al., 2005; Kos et al., 2016). The melting of alpine glaciers can result in more frequent glacial lake outburst floods that affect erosion and sediment transport and can have disastrous impacts on downstream communities (e.g., Jacquet et al., 2017; Cook et al., 2018; Huber et al., 2020). Melting of glaciers atop volcanic edifices during the Holocene can decompress upper crystal magmatic reservoirs, increasing eruption susceptibility and impacting associated volcanic hazards such as debris flows or jökulhlaups (e.g., Sigvaldason et al., 1992; Albino et al., 2010; Sigmundsson et al., 2010; Mora & Tassara, 2019). With ongoing warming trends, glacial melting is projected to continue, impacting landslide, glacial lake outburst flood, and volcanic hazards in subduction settings and elsewhere. Rising sea levels have important implications for tsunami hazards (e.g., Sepúlveda et al., 2021). Eustatic changes impart transient stress loading effects in near-coastal regions and may enhance the rupture tendency of entire subduction and upper/downgoing plate fault networks (Brothers et al., 2011; Quigley et al., 2019; Ulrich et al., 2019) These changing meteorological and environmental conditions will impact some subduction zones and alter erosional processes and sediment transport dynamics by increasing the frequency of event-triggered landsliding (e.g., Gariano & Guzzetti, 2016). We live in a time period with a unique opportunity to study how the subduction system responds to perturbations brought about by climate change, which in turn will help illuminate how the system works.

6. Triggering and Cascading Hazards. Key cascading and triggering-related cross-cutting science questions that the system-scale interdisciplinary SZ4D effort is in a unique position to address, include:

- *What environments are most likely to generate large turbidites, lahars, and landslides?*
- *How does varying susceptibility affect the preservation of the paleoseismic record in subduction zones?*
- *How do subduction zone events, such as earthquakes and volcanic eruptions, trigger other hazardous phenomena?*
- *What observations are needed to estimate the potential of cascading hazards to provide forewarning?*

To understand subduction zone hazards requires studying the interactions between tectonic evolution, faulting, and earthquakes; landscape and seascape evolution; and magmatic and volcanic processes. For example, fault slip, from slow slip to megathrust earthquakes, is interrelated and responds to external conditions (Radiguet et al., 2016; Luo & Liu, 2019). Earthquakes, volcanic flank collapses, and submerged mass slumping trigger tsunamis (Satake, 2007; Tappin, 2010; Ye et al., 2020). Landslide activity may increase due to thick tephra-coverage of hillslopes after volcanic eruptions (Korup et al., 2019). Earthquakes can trigger volcanic eruptions (Seropian et al., 2021) and fault slip in other parts of the system (Gomberg & Sherrod, 2014). Eruptions and earthquakes can initiate mass transport events both onshore and offshore (Roland et al., 2020; Mountjoy et al., 2018).

The damage from triggered events such as tsunamis, landslides, and lahars can often be greater than that from primary causes such as seismic shaking and lava flows (**Figure CCST-6**). Increasing resilience to hazards requires incorporating uncertainties and accounting for the complex dynamics of the physical subduction system as well as human and social factors across multiple spatial and temporal scales (e.g., Bostick et al. 2018). A better interdisciplinary understanding of cascading and triggering potential will in turn help to assess and formulate limits to “worst-case” hazard scenarios. For example, to recognize which geologic processes drive partial versus margin-wide ruptures in Cascadia (e.g., segmentation), a synthesis of existing observations is needed to see how differences in subduction zone structure (asperities) or frictional behavior (aseismic deformation) may ultimately provide barriers to rupture propagation (Philibosian & Meltzner, 2020; Ramos et al., 2021).

While the cascading nature of subduction zone hazards is generally accepted, the underlying mechanisms are poorly constrained. Triggering mechanisms range from direct effects, such as inertial forces from earthquake shaking, to indirect effects, such as rapid drawdown that occurs when an earthquake-generated tsunami first approaches a shoreline (Wright & Rathje, 2003). Furthermore, cascading and triggering may be set apart across spatial and temporal scales, requiring a 4D system-scale perspective. While such cascading and interacting events are a topic only emerging in operational hazard assessment (e.g., Mignan, 2014; Kumasaki et al., 2016), and present a challenge to empirical, disciplinary, data-driven approaches, they are also an opportunity to bridge multiple scales, to fuse subduction science disciplines and observations towards interoperability, and to identify opportunities to raise hazard alert levels early. Here, the MCS can provide the building blocks to test alternative physical descriptions and identify the most important processes in controlling subduction system behavior.

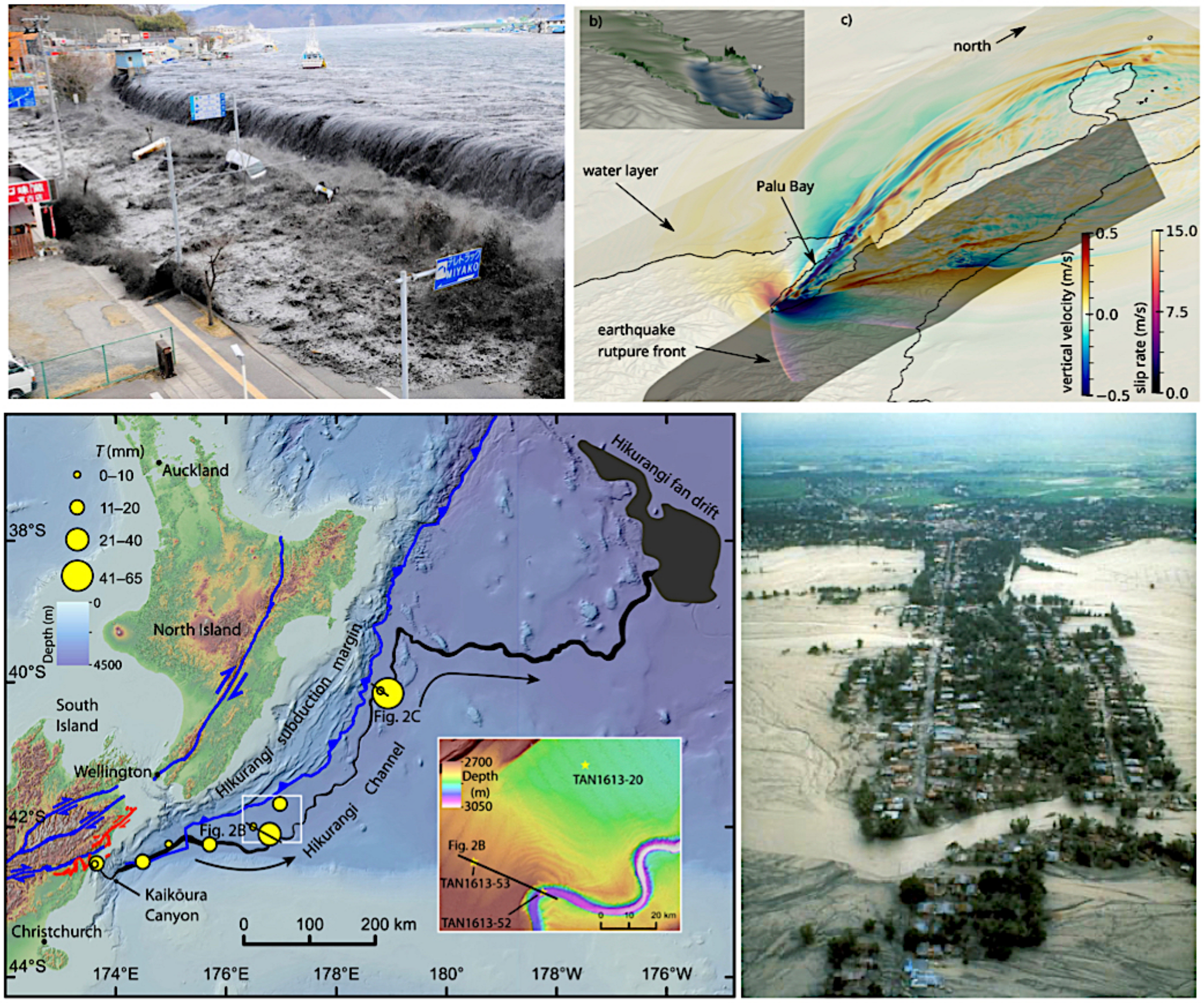

Figure CCST-6. *Examples of triggering and cascading subduction zone hazards. From left to right: The 2011 Tōhoku-Oki tsunami (Reuters) caused more fatalities than the shaking of the Mw9.0–Mw9.1 earthquake. High-performance computing (HPC) model of the multi-physics of earthquake rupture and seismic, acoustic, and tsunami wave interaction during the 2018 Palu, Sulawesi, Indonesia, earthquake and tsunami (Krenz et al., 2021). Turbidity current over 680 km triggered by the 2016 multi-fault Kaikoura, New Zealand, earthquake (Mountjoy et al., 2018). Mt. Pinatubo Lahar in 1991 (Reuters).*

4.1.2 Data and Technical Synergies

The interrelated subduction zone seismic, volcanic, and mass-movement geohazards share commonalities beyond the scientific ones that can benefit from a joint research strategy. Leveraging common partnerships, instrumentation and facilities, cyberinfrastructure and data management, and capacity building activities can result in significantly more scientific advances. In particular, a common regional focus allows development of deep partnerships, strategic deployment of physical infrastructure, and accumulation of contextual information that enables multidisciplinary interpretation. Co-located and coordinated instrumentation, cyberinfrastructure, and human resources can be brought to bear on the study of these geohazards together and separately. Technical convergence stems from shared mechanical processes, shared geography, and shared modes of interacting with societies to promote hazard mitigation. These practical considerations create an opportunity to gain significantly more scientific understanding from a joint effort than from dispersed, uncoordinated ventures.

COMMON PARTNERSHIPS

The geographic focus of SZ4D allows for leveraging of partnerships. International collaborations are complex and require significant investment to establish diplomatic, cultural, and physical connections. This is particularly true when a capacity building effort is involved, as described in Chapter 3.1 of this report and summarized below.

COMMON INSTRUMENTATION AND FACILITIES

Physical infrastructure needs share many commonalities across the individual working groups, including needs for a network of in situ observational technologies, a capability to support focused field experiments and/or campaigns, access to and support for laboratory facilities for geochemical and geochronological analyses as well as mechanical experiments, along with a modeling collaboratory to lead integration of data with cross-scale, process models for improved understanding of the entire system dynamics (as described in Chapter 3.2).

During the first part of the twenty-first century, rapid technological advances have enabled us to observe subduction zone phenomena in four dimensions with unprecedented temporal and spatial resolution. From trenches to volcanoes, a suite of field-deployed, quasi-permanent sensing systems will be needed to collect time-series data on active processes. The suite may include seafloor geodetic (acoustic-GPS and pressure) and seismometry elements in a network, ideally with real-time (or at least minima-latency) data transmission capability and potentially including borehole-based observatories, to be used to detect elastic strain accumulation and its release on a wide range of spatial and temporal scales (e.g., locking, slow slip, and tremor events). Onshore, existing geodetic and seismic networks aimed at capturing deformation related to the earthquake cycle (e.g., EarthScope Plate Boundary Observatory) could be enhanced and expanded to other countries, similar to the efforts already taking place in Chile. At the volcano scale, new synthetic aperture radar (SAR) missions such as the NASA-ISRO SAR (NISAR) mission with weekly coverage will greatly enhance deformation measurements and should be supplemented with a suite of multidisciplinary ground-based instrumentation.

Access to certain facilities, even if not necessarily dedicated solely to SZ4D, will be critical to enable these envisioned observational efforts. In the marine setting, the program will need to have access to surface vessels for instrument deployment, retrieval, and seafloor observation, including deep submergence, autonomous underwater vehicle (AUV), and/or remotely operated vehicle (ROV) access. A pool of modern broadband ocean bottom seismometer/ocean bottom pressure (OBS/OBP) instruments will need to be available to the program, along with other emerging seismic and geodetic technologies. Equally critical is a capability for high-resolution seabed (bathymetry and backscatter) and subsurface (seismic reflection and refraction, and electromagnetic) imaging. We also need continued access to a seafloor deep drilling capability as well as vessels and tools that can flexibly and/or autonomously download data from seafloor instruments, likely including AUVs/ROVs and autonomous gliders. Finally, all of the working groups have outlined work that will result in the collection of geologic samples. These physical samples will need to be stored and distributed to the community for analyses. Community reference materials and standards will also require storage and distribution upon request. Shared facilities will ensure uniformity in how samples and their metadata are stored and handled.

Allied with the field campaigns, a similar concerted laboratory effort will be required to address many of the essential processes that drive subduction phenomena. For example, drilling projects, including the Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE), JFAST, and San Andreas Fault Observatory at Depth (SAFOD) have provided samples and a framework for laboratory mechanical friction experiments (along with many other physical properties) that have led to breakthroughs in understanding the physics of locking, seismic slip, transients, and conditional behavior. At deeper levels on the plate interface, laboratory experiments are needed to elucidate the pressure and temperature of dehydration reactions, and relationships between deformation, pore fluids, and chemical reactions. A gap in experimental capabilities exists across much of the seismogenic zone including the very region where slip transitions from seismic to aseismic, requiring new equipment and approaches to access these critical conditions. An outstanding challenge in experimental petrology is the development of accurate geobarometers, sorely lacking for volcanic/plutonic systems, that would constrain the depths of magma stalling and storage.

As a program that focuses on 4D observations, time series, and temporal evolution, SZ4D requires geochronology. A rich variety of approaches are needed to access the 4D evolution of the subduction system, from the minutes to years of magma ascent recorded in the chemical zonation of volcanic crystals, to multidecadal geodetic signals across earthquake cycles from coral stratigraphy, to thousands of years of tectonic denudation recorded in cosmogenic isotopes from the land surface, to arc crust construction over millions of years from radiogenic isotopes in crystals. Real-time observations must be integrated with long time series to fully capture the dynamics of tectonic and volcanic systems. Geochronological labs are distributed widely and require coordinated partnerships with SZ4D observationalists, modelers, and theorists.

COMMON CYBERINFRASTRUCTURE AND DATA MANAGEMENT

Data management and data discovery tools are crucial parts of a community infrastructure. Interdisciplinary science can only thrive when the entire geoscience community can access and utilize data from all disciplines, which in turn requires suitably packaged data streams and a data infrastructure to ensure the availability, accessibility, and open distribution of the products of the entire effort. This level of interoperability requires dedicated, professional data managers along with carefully designed and maintained software. Searchable datasets need to be created that include fully descriptive metadata about uncertainties and limitations. Linkages between existing data archive capabilities such as those at the IRIS Data Management Center (DMC), the Seismic Data Center, and the International Ocean Discovery Program (IODP) should be seamless with SZ4D data management systems. Communication about the datasets needs to be built into the organizational structure so that potential users are aware of, understand, and can access data from multiple disciplines. For some disciplines, these data tools are mature (e.g., the IRIS DMC for seismic data), while for other disciplines, these tools require further development.

CAPACITY BUILDING ACTIVITIES

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

A successful SZ4D program will lead to scientific discoveries and applications otherwise not possible. The combined physical and intellectual infrastructure will enable observations in 4D that would otherwise not get made. To realize the SZ4D vision of a new understanding of subduction zone processes and hazards requires a sufficient level of science funding to analyze, integrate, and synthesize these new observations. A key to succeeding in this balance over a 10 year or more timeframe is to build in mechanisms that preserve scientific agility. The long-term goals of the SZ4D Initiative will require international partners and a framework that will outlast its construction, benefiting the science community after 10 years.

4.2 Geography

The main goal of the SZ4D initiative is to improve understanding of the world's subduction zone hazards. An integral piece of this effort is to obtain new observational data on earthquakes, tsunamis, volcanoes, and mass movement. It has become clear that dense, consistent, long-term instrumentation along with high-level data management is key to making major advances in this area.

Our geographic needs require a hybrid approach. The Faulting and Earthquake Cycles (FEC) and Landscapes and Seascapes (L&S) working groups identified technical requirements that include focused arrays, while the Magmatic Drivers of Eruption (MDE) working group identified the need for a more distributed approach to data collection of volcanoes. As discussed in Chapter 4.1, for both scientific and practical reasons, focusing a majority of resources on one or two regions will likely maximize scientific gain. We plan to supplement this geographical focus by creating a coalition of countries for collaborative subduction zone studies that will leverage existing efforts at subduction zones around the world and enable comparisons among subduction zones and generalization of the results of focused study.

SUMMARY OF REGIONAL FOCUS NEEDS

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

The modeling, geological analog, and experimental efforts also benefit from placing these observations in context, where boundary conditions from a specific region can be determined from known geometries and histories. All of these components can be tied together by concrete observations gathered in a geographic context.

As described in the Introduction to this document, the Research Coordination Network (RCN) working groups have used traceability matrices to develop science questions through identifying common science needs. An inventory of subduction zone segments was also collated so that individual regions could be systematically assessed for their relevance to the scientific priorities. Each group individually weighed the relative value of the segments and then met together to balance needs. Reconciling the visions that were presented in Chapter 2 led to the logic presented in this chapter.

COOPERATION WITH INTERNATIONAL PARTNERS

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

THE VALUE OF COMPLEMENTARY SITES

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

For certain observables, the global portfolio of sites includes major international efforts. The SZ4D 2020–2021 International Webinar Series highlighted some of these efforts. For instance, Japan, Taiwan, and Cascadia already have existing seafloor cables that are providing rich datasets that should be thoughtfully complemented with any new instrumentation.

KEY GEOGRAPHY REQUIREMENTS

Scientific Requirements

Each working group worked through key scientific requirements. First, the paired experimental design advocated by the L&S group requires comparison subduction-zone systems in which particular factors could be regarded as fixed, while a limited number of other factors varied. The ***four essential site characteristics*** required to carry out L&S's notional experiments and hypothesis testing included: (1) at least some proportion of the site must include subaerial forearc exposure (free of ice); (2) observational constraints must exist *or be acquirable* at suitable sites; (3) at least some portion of the sites must include rocks with minerals amenable to geochronology and thermochronology such as quartz, apatite, and zircon; and (4) safe access to the study area is at least possible, and that particularities of data release within individual countries do not preclude open export and publishing of data and research results. Once subduction-zone segments meeting these conditions were identified, a pairing of segments in which independent variation in specific factors of interest (e.g., plate convergence rate) were mapped onto the L&S notional experiments to determine the optimal pairing of subduction-zone segments.

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

The ideal sites for the FEC component would possess the following characteristics: known large and active faults in overriding and downgoing plates; high convergence rates; known slow slip events; high seismicity rates; known strong gradients in coupling along strike; a known tsunamigenic event; a preservation of the history of fault slip, earthquakes, and tsunamis; and evidence of a large earthquake in the past that ruptured the entire seismogenic zone. There is a preference to be late in the seismic cycle, if possible. The FEC sites that meet these criteria are generally segments that extend ~500 km along strike.

Logistical Requirements

The goal of the initiative is to enable large-scale, multidisciplinary interaction with deep knowledge of the field context. This ambition requires a high degree of safety for a large number of scientists who may visit the region either directly as part of the SZ4D initiative or in complementary projects. Therefore, any region that has serious, ongoing, well-documented security concerns should not be a focus of SZ4D field efforts. The U.S. State Department Travel Advisory list provides a useful compilation of security information. Any region that is at level 3 or 4 on this list for non-COVID reasons at the time of a proposal submission cannot be a field site (We have an understanding that COVID-related travel concerns will be reduced by the time of the project.) Scientists from those regions will hopefully still be able to contribute through to our international efforts. The establishment of a practical limit based on the federal guidelines is simply a matter of establishing a common, objective standard for work that involves a substantial number of participants traveling to the region utilizing federal funding.

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

THE GLOBAL PORTFOLIO

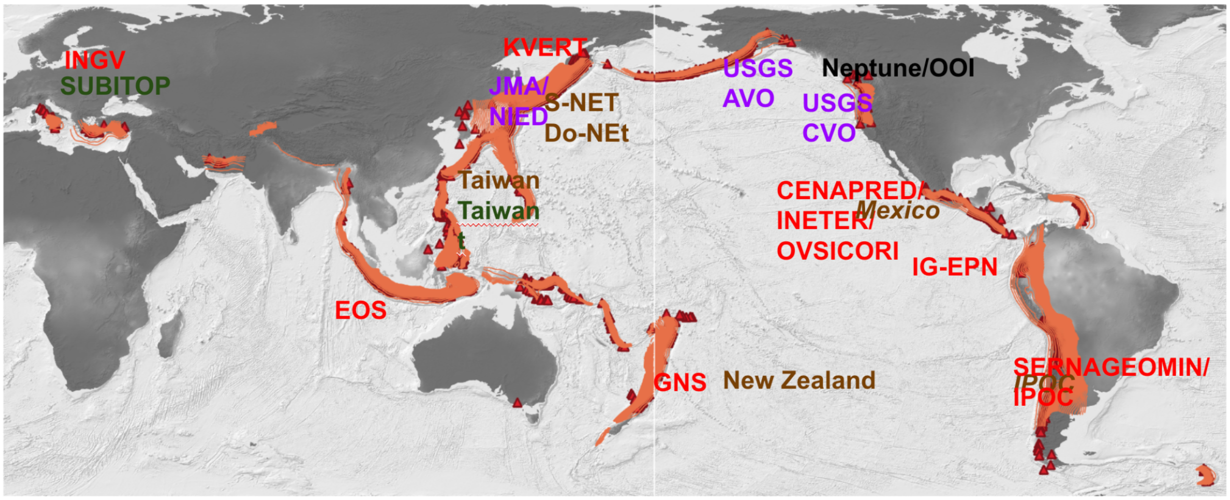

Figure G-1. *A partial view of major infrastructure initiatives with the color code corresponding to SZ4D focus areas.*

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

A major goal of SZ4D is to help build the global portfolio of instrumentation and activities so that in sum the scientific community has a stronger base of observations to draw upon. This strategy requires first developing a coordinated global network of subduction zone observatories to share technologies, data, and insights. Informal interactions between scientists and observatories exist, but the global portfolio would benefit from more regular and formal structures for technology, data, and human exchange.

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

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

REGIONS OF SPECIAL INTEREST

The requirement for complementary subduction zones combined with the need to complement existing efforts leads to a natural strategy of nterpol on one domestic and one international region. Certain regions have emerged from the working groups' efforts as areas of most natural overlap that meet the above requirements. The SZ4D RCN recommends putting further effort into developing potential collaborations and exploring possibilities in these regions of special interest.

Chile

Chile is arguably the most exciting subduction zone in the world from the point of view of geohazards. The 4500 km of continental subduction zone encompassed in a single country make it globally unique. Factors such as slab dip, convergence rate, and climate vary systematically along the subduction zone, which allows many natural experiments to be carried out along a single subduction zone system. Rapid convergence leads to abundant seismic, volcanic, and landslide activity. This significant exposure is constantly being assessed and characterized by in-country governmental organizations, and so scientific discoveries made by the SZ4D have a clear pathway to implementation in applied sciences through partnerships with these organizations. The opportunities presented by the Chilean subduction zone have produced efforts that have been ongoing in the region for decades with onshore and temporary offshore instrumentation. Importantly, there is a robust community of geohazards scientists working in Chile in both academic and national observatory settings. This community has developed internal networks and also built international collaborations with German, French, American, and other partners to develop instrumentation that was well situated to capture some of the most significant earthquakes in the early twenty-first century. Chile has 96 volcanoes with eruptions in the Holocene and 33 discrete eruptions have been recorded in the twenty-first century. International collaborations have also produced a backbone of moderate-resolution bathymetry for much of the margin, allowing collection of high-resolution bathymetry in targeted areas. Significant onshore and offshore passive and active seismic imaging has been done over the last two decades, which can be strategically complemented by SZ4D efforts. Chilean and Argentine networks span the entirety of the subduction zone system and have enabled a substantial amount of on-the-ground domestic and international data collection to take place over the last 40 years. Opportunities may be present in Chile both on and offshore to complement the existing efforts.

Cascadia

The Washington, Oregon, and northern California margin has the largest associated risk of any domestic subduction zone and thus deserves special attention. The societal implications associated with a major volcanic eruption or the tsunami associated with the eventual magnitude 9 earthquake weigh heavily on the region.

Scientifically, the Cascadia subduction zone possesses some attributes that are favorable for addressing scientific questions of L&S and MDE. Cascadia exhibits significant along-strike variability in volcanism, including erupted volumes differing by a factor of two between the southern and northern portions of the arc, and major changes in the partitioning of volcanism between intermediate and silicic-dominated central volcanic edifices and fields of more mafic and dispersed monogenetic centers. However, the slow convergence rate and low seismicity rates make Cascadia a suboptimal region to address many of the FEC science questions, particularly those concerning the relationships between earthquakes and other slip behavior and precursory behavior. Consequently, this region lends itself best to a subset of approaches, such as paleoseismology, geophysical imaging, deep-time study of onshore fault systems and relatively quiescent but diverse volcanoes, and slow slip and tremor. There is a wealth of existing data that can be leveraged for studies of Cascadia and comparisons to other subduction zones, including seismic data from the Cascadia Initiative, onshore/offshore active and passive seismic imaging (including the recent acquisition on a synoptic 2D deep penetration seismic reflection/refraction dataset along the margin), magnetotelluric profiling, bathymetric mapping, extensive subareal high-resolution topographic mapping, lava geochemistry, and onshore/offshore geological studies. There are also abundant opportunities for collaborations with other US organizations, including the USGS, the latter of which is targeting Cascadia for its subduction initiative. The ideal study strategy is thus to combine a study of Cascadia with a faster subducting analog that can provide the information on human timescales that will ultimately be important to interpreting and predicting the future behavior of the United States' most prominent subduction zone.

Aleutians/Alaska

The Alaska/Aleutian subduction zone has frequent and diverse eruptions and frequent earthquakes, and thus some sections of this ~2000 km long subduction zone were considered favorable study areas by the FEC and MDE. For the FEC, the variations in coupling, rupture history, and seismicity off the Alaska Peninsula make this region an attractive possible target for study; one segment was thought to be relatively late in the seismic cycle. The occurrence of a series of large interplate earthquakes here in 2020–2021 has released some of the stored energy, diminishing one of the appeals of this location. The region has a rich diversity in arc structure and tectonics, sediment and volatile influx feeding primary magma generation, and crustal magma differentiation processes, with the resulting outcome the production of a complete range in eruption styles from its diverse volcanic centers. However, this region is problematic for the L&S group due to the recent glacial history, which makes many aspects of required geochronology problematic, and the lack of an extensive subareal forearc with which to study important geohazards such as landslides and flooding. The focus of their work requires substantial exposed land surface.

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

4.3 Program Structure and Governance

Given the ambitious vision for an SZ4D program, a management structure and governance will be necessary that enables:

I. Management of significant **infrastructure,** including instruments deployed in the field and in laboratories, open access to near-real-time data, a Modeling Collaboratory and other new SZ4D consortia, and deployment of scientists to make critical, systematic measurements
II. **Innovative research** supported by proposal-driven funding, including seed funding
III. **Coordination** across the SZ4D disciplines, focus sites, and cross-cutting themes; coordination with funding agencies; implementation of a collective impacts model across all communities to ensure maximum societal impact; evolution of the SZ4D program as needs change and unforeseen discoveries and circumstances arise; two-way communication with international, operational, and stakeholder partners; and community governance

Figure SG-1 shows a proposed model for implementing this governance and management structure. The three major components of the program include a **Center** that manages and coordinates the different components of SZ4D, **Facilities** (both developed as part of SZ4D, as well as existing Facilities) that provide support for instrument development, acquisition, and deployment, as well as data management, and a **Science Program** at NSF whose mandate is to identify the most promising SZ4D-centered research projects through a merit review process. The organizational structure shown in **Figure SG-1** is designed to provide independent oversight of each of the components of the SZ4D effort, as well as management and coordination structures to ensure successful project execution.

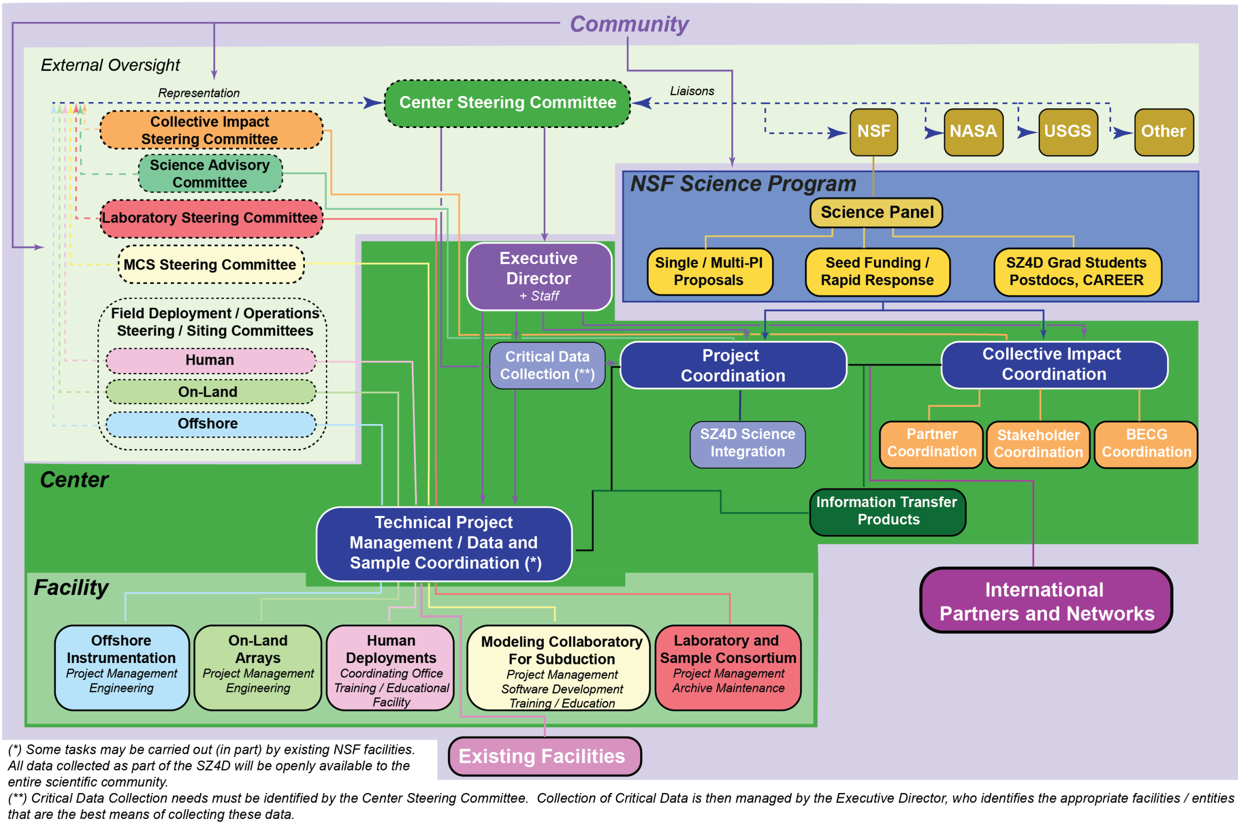

Figure SG-1. *Organizational diagram showing the independent oversight entities (ovals surrounded by dashed lines), management structures, and particular management objectives (ovals surrounded by solid lines).*

I. SZ4D CENTER AND GOVERNANCE

A successful SZ4D Program will include a governance structure that guides evolution, evaluates progress, coordinates all involved communities, ensures information transfer, and fosters partnerships for SZ4D. Coordination at all levels is necessary to build the intellectual infrastructure of SZ4D; this is what enables broader scientific problems and greater outcomes than the sum of constituent parts. This coordination will be achieved through both the oversight bodies as well as the envisioned management structure. Oversight of the Center will be provided by a Center Steering Committee, whose membership will include representatives from the associated facility oversight committees (see below), as well as additional members selected by a self-nomination process. Specifically, a representative from each of the facility oversight committees will sit on the Center Steering Committee to ensure clear lines of communication and coordination of the Center and Facility efforts. Additionally, a slate of potential additional members of the Center Steering Committee will be created by a self-nomination process open to the entire SZ4D community. The Center Steering Committee will then select new members from this slate to continually populate and rotate the committee membership. Importantly, all members of the Center Steering Committee will have fixed (but staggered) terms to ensure the broadest possible access of the Committee to potential members of the community. Included in this representative oversight will be participants from partner countries to ensure that their priorities are represented throughout the SZ4D initiative.

The Center Steering Committee is responsible for providing the scientific direction and oversight of the SZ4D Center Executive Director and staff, whose responsibilities would include:

A. Coordination across SZ4D facilities, working groups, field experiments, allied projects, scientific community models, cross-cutting themes
B. Coordination with funding agencies and international partners
C. Implementation of a Collective Impact framework to achieve long-term broader impacts (see Chapter 3.1)
D. Coordination with host countries from the outset, including academic-agency advisory committees (e.g., for each target volcano), community outreach during inter-event times, host country student, and scientist training to promote collaborations.
E. Coordination with facility operators and community stakeholders
F. Hosting of workshops focused on tough thematic problems or regional integration
G. Support for needed Phase 0 scoping activities that can happen right away
H. Development and implementation of information transfer products and activities

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

We also anticipate that data needs may emerge that are not defined at the outset of the new SZ4D facilities that are described below. Additionally, a nimble, event-based rapid response capability may be required to capture the phenomena we wish to understand as part of SZ4D. Because there are many potential responses and data types, we have designed a Critical Data Collection mechanism to direct resources to the appropriate facilities and entities in the event that novel data must be collected rapidly, or activities must be performed to guarantee that all of the pieces of the SZ4D project fit together properly. This Critical Data Collection mechanism will be overseen directly by the Center Steering Committee, in consultation with the Science Advisory Committee. These scientific needs will be communicated to the Center Executive Director, who will then determine the appropriate facilities and entities to task with Critical Data Collection. This mechanism is intended to enable the identification and collection of emergent data needs that require flexible allocation of resources to combinations of facilities and entities, while guarding against a Center-based ad hoc science funding program.

Finally, Collective Impact and scientific coordination activities must be overseen by committees that are dedicated to identifying high-impact collective impact activities and science synergies, and to making sure these tasks are managed competently. As with the Facilities steering committees (described below), coordination of these activities with the Center Steering Committee will take place through representation on the Center Steering Committee, which will allow a two-way flow of information between these more specific committees and the Center Steering committee. The membership of these committees will be determined by the Center Steering Committee (in consultation with these specific committee's members) based on a slate of candidates created from an open self-nomination process. Members of these committees will serve fixed, staggered terms of 3-5 years to ensure the broadest possible participation, while providing continuity to the direction of these SZ4D activities.

II. INFRASTRUCTURE AND FACILITIES

SZ4D will require both new infrastructure as well as new partnerships with existing facilities. New infrastructure includes instrument development (e.g., seafloor), establishment of instrument networks (e.g., volcano sensor arrays), support of field deployments of instruments on land and at sea, and data collection efforts that require people as the primary observational instruments (e.g., paleoseismology and volcano chronology). New consortia are envisioned, such as the Modeling Collaboratory and a consortium for laboratory experiments, in order to meet objectives of SZ4D that are beyond the scope of current consortia. The specific facilities components that we view as essential for supporting SZ4D research include:

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

The new facilities would ultimately fall under the larger management of the SZ4D Center to ensure coherent data collection and coordination throughout the duration of the SZ4D. However, each of these facilities needs ready access to scientific expertise and a granular level of oversight of each's activities. Thus, each facility component would be associated with its own scientific steering committee, whose membership would be determined by an open nomination process, and whose members would serve for fixed terms. As with the Center Steering Committee, a slate of potential members of each Facility's Steering Committee would be derived from an open self-nomination process. Members would then be selected by the Center Steering Committee, in consultation with the members of the Facility Steering Committee. The rotating composition of the Facilities' Steering Committee would allow broad participation in the scientific oversight process, while providing continuity to the direction of the facilities. Paramount is the inclusion of members from partner countries to ensure that their priorities are represented in all of the facility data collection efforts. As described above, the scientific activities of the facilities would be coordinated through representative membership on the Center Steering Committee, to ensure that the direction of the facilities was coordinated to maximize scientific impact and efficiency throughout the lifetime of the SZ4D project.

In addition to these new facilities, it may be beneficial to expand the capabilities of existing facilities and consortia, leveraging their expertise to support the collection and distribution of new and novel instrument networks and datasets. For many objectives, SZ4D is anticipated to partner with existing or forthcoming facilities or organizations, such as managing seismic and geodetic data with SAGE/GAGE, acquiring high resolution elevation data from Open Topography, or collecting geochronologic data with the National Consortium for Geochronology. Additionally, many organizations successfully manage field deployment of on-land seismic and geodetic instruments, including the EarthScope Consortium (ESCO, successor to IRIS/UNAVCO) and the USGS Earthquake Hazards Program. Organizations specializing in geophysical data archiving and real-time access to data are NASA-JPL, IRIS/UNAVCO, and the USGS Earthquake Data Centers and Volcano Observatories. For experimental petrology, geochemistry and structural data archiving and access, LEPR, ENKI, GEOROC, IEDA, PetDB, and Strabospot are excellent examples of existing database efforts. The National Consortium for Geochronology is a natural partner for the acquisition and archiving of geochronology data. High-resolution topography and bathymetry data are acquired, archived, and shared through NCALM, 3DEP, OpenTopography, Marine Geoscience Data System, and IEDA. The OBSIC group will be essential in coordinating the design and implementation of ocean bottom seismometer components, as will other marine operators such as UNOLS and IODP. It will be imperative to partner with international organizations for major field deployments (e.g., within Chile, as an example, OVDAS, SERNAGEOMIN, and many universities). Curation of physical samples and experiments will be necessary for coordinated efforts, and CONVERSE, the Smithsonian Institution, and IEDA are already developing new models. Existing centers such as CIG and SCEC are valuable partners for code development, training and hosting thematic workshops. To maximize the impact of SZ4D in hazard mitigation, partnerships with the World Volcano Observatories (WOVO), the USGS Hazards program, VDAP (Volcano Disaster Assistance Program), GEMS (Global Earthquake Model), and NOAA tsunami early warning centers will be vital.

While it would be desirable to have a central data management system that is tailored to the SZ4D effort, this may be difficult to implement in practice due to the myriad NSF-supported facilities and data management systems that currently exist. For this reason, we envision that, from a practical standpoint, data management may be coordinated by the Center, who would offer a portal to a Center-based data management system (where possible) as well as other data management systems that exist (or are based on existing data management systems).

III. SZ4D SCIENCE PANEL

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