LANDSCAPES AND SEASCAPES

HOW DO SUBDUCTION ZONES CONTROL SURFACE HAZARD AND LANDSCAPE EVOLUTION

SCIENTIFIC MOTIVATION

Earth surface and solid Earth processes play a central role in shaping subduction zone landscapes and seascapes and drive hazards that impact civilization. Storms and earthquake shaking mobilize rocks, sediment, and soil, which are continuously transported seaward by the ebb and flow of flooding rivers and offshore currents. Catastrophic and punctuated erosional pulses across landscapes and seascapes can initiate complicated responses and adjustments that persist for years or even decades following the events that precipitated the geomorphic cascade (e.g., Gran, 2012; Bruni et al., 2021). Slope failures resulting from volcanic sector collapse, earthquake land-level changes, and storms can all dam river channels, leading to continuous adjustments in response to changes in sediment supply or outburst floods that rapidly alter river channel morphology (e.g., Capra & Macias, 2002) - both of which can impact downstream communities. The deposition of large volumes of detritus resulting from subduction zone disturbances can modify river networks for decades to years, changing both their forms and processes in ways that may produce more frequent flooding and promote channel widening (e.g., Major et al., 2016; Korup et al., 2019). These geohazards reflect long-term solid Earth processes acting within the subduction zone (e.g., Ott et al., 2021). For example, faulting and folding of the crust between the trench and the volcanic arc modify sediment transport systems (e.g., Wells et al., 1988), build climate-altering topography, and produce ground failures (e.g., Bhattacharya et al., 2018). Volcanic and magmatic processes likewise build topography (e.g., Karlstrom et al., 2018) and influence the thermal and mechanical state of the crust (e.g., Karakas et al., 2017), which impacts short-term volcanic hazards.

Despite the substantial risks to ecosystems, communities, and infrastructure within subduction zone landscapes and seascapes posed by Earth surface disturbances and their cascading impacts, we are still unable to determine when catastrophic surface disturbances will be initiated, where the detritus produced by these events will go, and how long and how far the cascading impacts that are produced by these disturbances will extend. Likewise, it remains unclear what controls the amount of subduction zone convergence that accumulates between the trench and arc, which determines the potential for earthquakes, tsunamis, and seismically triggered mass wasting in areas often proximal to populated areas and sculpts the topography that defines subduction zone environments.

Recently developed and emerging technologies now allow us to study these Earth surface and solid Earth processes in ways never before possible. Advances have been made in the ability to observe the initiation, transport, and long-term impact of mass wasting events and to simulate the physics of the associated processes at the scale of subduction zone systems. High-resolution space-borne imaging methods now allow us to locate where and when mass wasting events are initiated, and in some cases, characterize rates of motion. Suborbital plane and drone-based platforms, coupled with computer vision developments, allow detailed characterization of downstream impacts produced by disturbances. Submarine drone and continuous monitoring technologies have very recently allowed us to capture seascape changes produced by submarine fault scarp degradation (Hughes et al., 2021) and sediment density currents that may be initiated by earthquake-generated submarine landslides. Likewise, these technologies enable us for the first time to gain both a detailed and synoptic view of the way in which areas between the trench and the volcanic arc deform in four dimensions, which allows us to begin to constrain the total subduction zone energy budget. High-precision satellite geodesy, repeat laser altimetry, drone-based and new submarine monitoring and imaging technologies, and high-resolution optical and multispectral imagery can now quantify Earth's continuous deformation and erosion in near-real time. Simultaneously, developments in computer hardware now provide petaflop-scale computation to researchers, while developments in numerical methods allow accurate simulation of multiphase physics of the flows produced by disturbances and cascading impacts. These advances allow us to use state-of-the-art numerical models that couple surface process actions and subduction-zone geodynamics to link observations to the energetics and dynamics of the processes that shape subduction zone landscapes and seascapes. This work is foundational for understanding the risks that hazardous tectonic events pose to communities occupying subduction zones. Through a decade-long effort, many of these advances will allow the community to address fundamental questions that underlie our ability to understand these hazardous events.

Research Questions

The L&S component of the SZ4D has identified two research questions and related hypotheses that leverage this suite of new observational technologies, computational capabilities, and model developments. Addressing these questions will enhance progress toward reaching the goals of the SZ4D FEC and MDE working groups, and provide a framework for interdisciplinary research that will lead to transformative advances in subduction zone science.

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 earthquakes and volcanic events? How do surface processes produce cascading and persistent impacts as material is transported across the landscape and seascape? What are the feedbacks between subduction zone earthquakes and volcanic eruptions, and sediment generation and transport across landscapes and seascapes?

What fraction of a subduction zone's energy budget goes into building and shaping subduction zone landscapes and seascapes?

For example, how much permanent deformation is absorbed in the upper plate of the subduction zone and what factors control this? How do the subduction interface, upper plate structures, and magmatic systems collectively modify sediment transport systems and respond to landscape and seascape change? How does the interplay of processes across the subduction zone contribute to the deformation energy budget that constrains the potential energy that drives landslides and the conditions that trigger earthquakes and eruptions? How do periodic changes in climate affect the crust's stress state?

From these two research questions, we have developed **testable hypotheses** in subduction zone systems. We organize these hypotheses in terms of each research question:

- Testable hypotheses for Research Question 1 | **Figure LS-1**

A broad working hypothesis addressing this question is that the frequency of events that initiate mass movements and mobilize sediment control sediment generation and transport. When sediment is generated by hillslope mass failures during storms, atmospheric rivers, and high precipitation events more frequently than solid Earth events (e.g., earthquake shaking and volcanic unrest), the former will dominate sediment generation and transport (e.g., as in LaHusen et al., 2020; Major et al., 2021). Conversely, solid Earth events may play a large role in shaping landscapes when these types of large storms, atmospheric rivers, and high precipitation events are infrequent (e.g., Bruni et al., 2021). Thus, the ratio of the recurrence time of "landscape-impacting" atmospheric events, to "landscape-impacting" solid-Earth disturbances determines the imprint that atmospheric versus solid Earth processes play in shaping various parts of a subduction zone landscape. In the case of hillslopes, when large, landslide-generating atmospheric events occur frequently, their impacts dominate landslide-related hillslope transport. When these events occur less frequently, earthquake shaking or intense volcanic rock weathering may play a significant role in the initiation of landslides. The initiation of density currents by onshore storms versus offshore seismically generated mass failures varies throughout the submarine tributary system, as the relative recurrence times of these generative events vary. In the main canyon system during sea level low stands, the main channel may be frequently occupied by onshore-generated hyperpycnal flows that ignite density currents often enough to reduce the role that large shaking events play in generating these events. In contrast, canyon tributaries within the continental slope receive few density flows initiated onshore such that seismically produced mass failures dominate density current generation. For the case of rivers, the role of atmospheric versus solid Earth events in transporting sediment depends on their relative rate of recurrence. Large magnitude injections of sediment into rivers by, for instance, volcanic eruptions, lahars, and widespread earthquake-generated landslides can locally overwhelm the transport capacity of rivers, producing large changes in aggradation and deposition within the channel. When sediment generation from hillslopes is continuous, steady transport of sediment in rivers causes few appreciable changes in river morphology.

- Testable hypotheses for Research Question 2 | **Figure LS-2**

A central working hypothesis is that the style of upper plate deformation is regulated by plate motions and coupling along the subduction megathrust, elastic and inelastic deformation processes in the upper plate, body forces generated by topography, and the rheological configuration of the upper plate (e.g., Béjar-Pizarro et al., 2013; Penserini et al., 2017; Malatesta et al., 2021). Tectonic boundary conditions, such as the plate motion vector and distribution of coupling along the subduction megathrust, which might be related to rheological changes or spatial/temporal variations in basal fluid pressures within the forearc and subduction megathrust (e.g., Barnes et al., 2019), limits the lateral stresses present in subduction zones. These tectonic stresses can conspire with tractions acting along the base of the crust, body forces generated by time-evolving topography and crustal magmatic addition, and surface loads produced by ice, extrusive volcanism, and deposition to result in the state of stress within the crust (e.g., Willett, 1999; Fuller et al., 2006; Dielforder et al., 2020; Wang, 2020).

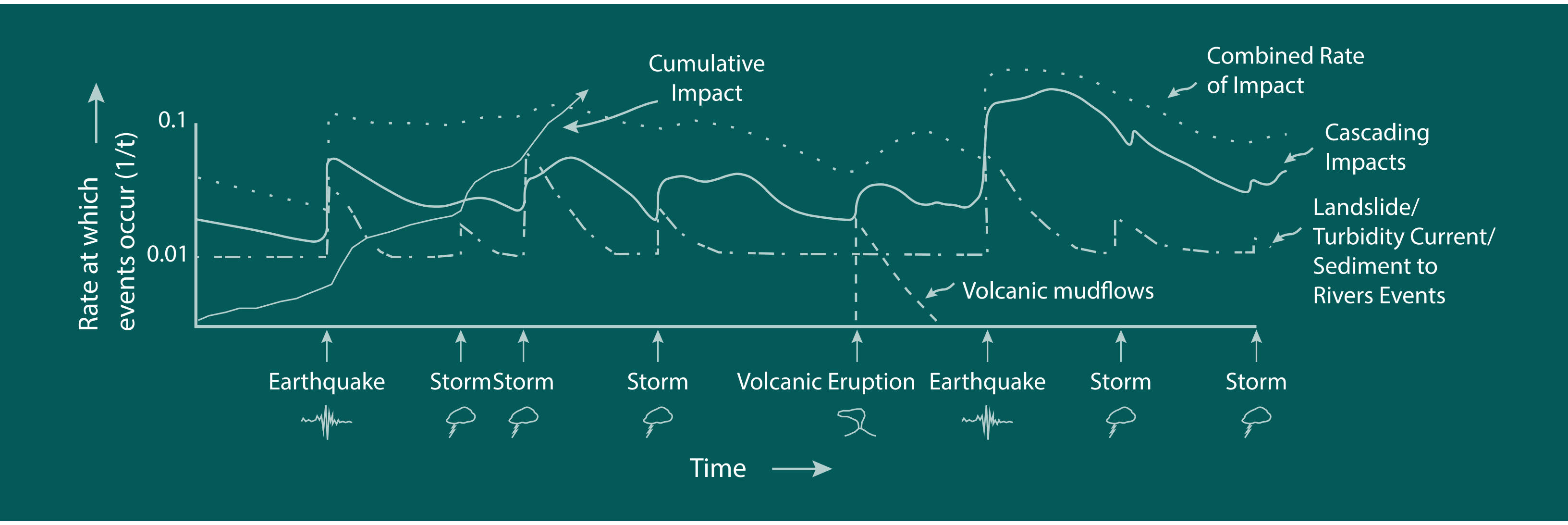


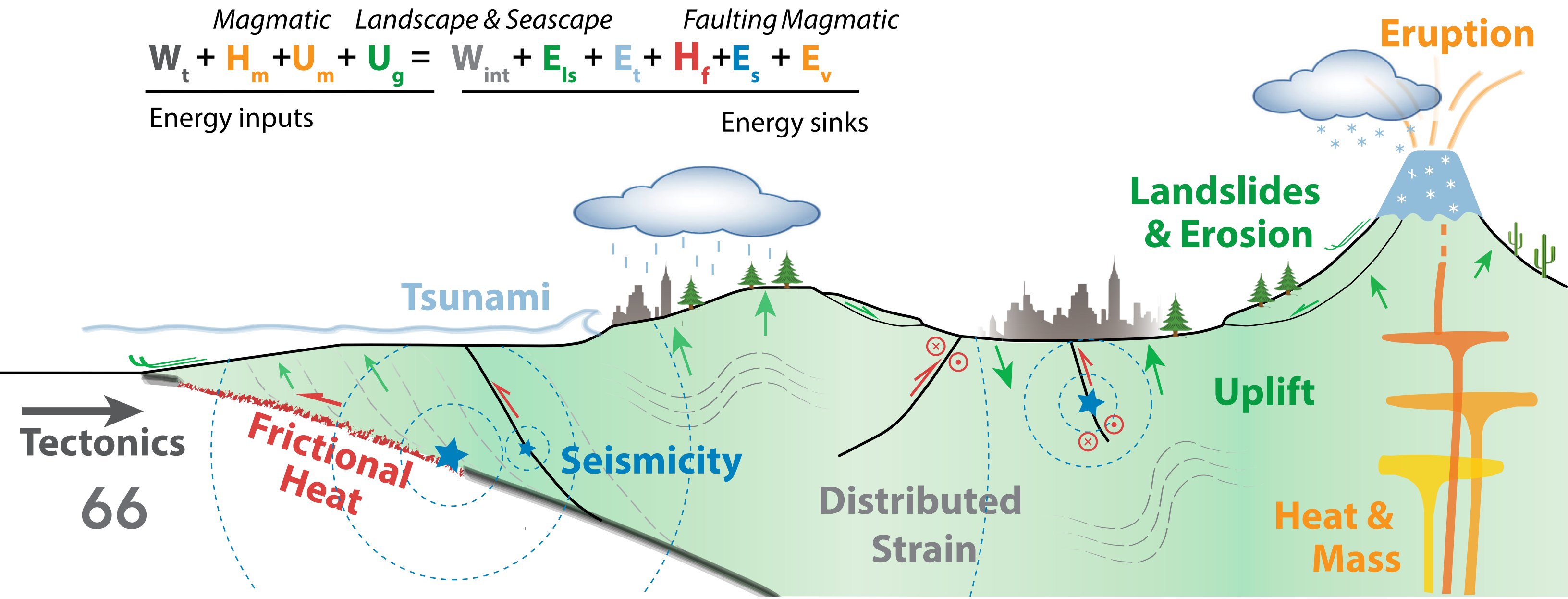
Figure LS-1. *Schematic representation of the drivers of cascading Earth surface hazards. Punctuated events, such as earthquake shaking and large storms can increase the incidence of mass failure (dash-dot line) during the event and in its wake. Likewise, volcanic eruptions can instigate mudflows (dashed line), whose impacts persist long after the eruption has occurred. These punctuated transport processes introduce large mass inputs to rivers, whose geometries may be persistently impacted in a way that generates hazards such as flooding for decades following the instigating events (solid line). This array of instantaneous and cascading impacts can produce substantial and persistent long-term repercussions that propagate throughout entire large watersheds, affecting downstream communities and infrastructure (dotted line).*

The interaction of this background stress state with the physical properties of the upper plate (such as crustal weaknesses due to preexisting terrane boundaries and thermally weakened zones) can determine the nature, degree, and distribution of elastic and inelastic strain in the forearc, and the dynamics of magmatic intrusion and eruption within subduction zone systems (e.g., Watt et al., 2013; Karlstrom et al., 2017). The state of stress informed by energy investigations provides critical constraints on the conditions that initiate earthquakes (e.g., Harris et al., 2009), landslides (e.g., Martel, 2004), and volcanic eruptions (e.g., Gudmundsson, 2012), while the energy budget itself provides constraints on the power available to drive these hazard events (e.g., Del Castello & Cooke, 2007). Such an energy budget framework provides a mechanism to connect long-term subduction zone processes to the drivers of short-term geohazards.

TRACEABILITY OF THE SCIENTIFIC QUESTIONS THROUGH PRACTICAL ACTIVITIES

The L&S working group defined measurement priorities using a Science and Applications Traceability Matrix (SATM), presented in *Table A-LS1*, which relates our research questions to the geophysical observables, measurement requirements, and in some cases, technologies that may be employed to collect these measurements. The SATM has several important shortcomings, which we attempt to address in this chapter. First, the SATM framework is best suited to defining measurement requirements, but cyberinfrastructure and data management associated with data collection and analysis are also essential to the success of the L&S component of SZ4D. Furthermore, the SATM does not easily address needs such as numerical model

Figure LS-2. *Schematic first-order energy budget of the entire subduction zone. The inset equation outlines the energetic inputs (Wt - tectonic work; Hm - heat; Um - gravitational potential energy from mass in/out of the system), conservative energy terms (Ug - work of uplift against gravity; Wint - internal deformation work) and energetic sinks that are lost to the system (Els - kinetic energy of sediment transport; Et - tsunami energy; Hf - frictional heat of earthquakes; Es - seismic shaking and Ev - heat and kinetic energy of volcanic eruptions). Understanding the relationships between subduction zone processes can inform the energy available within the system that can drive damaging hazards.*



development and computational resources. For this reason, we supplement the results of our SATM process with a prioritized list of these other essential needs to ensure that the data backbone provided by the SZ4D infrastructure is complemented by the appropriate cyberinfrastructure, model development resources, and computing facilities.

Once the list of required measurements was compiled, they were assigned to one of three tiers, defined and described below, according to their importance in addressing our research questions. The highest priority measurements crosscut the largest number of key science questions and have the greatest potential to benefit the largest swath of surface and solid Earth science contained within the L&S component of the SZ4D. Measurements that might address the needs of the other SZ4D working groups and also strategically engage agencies in data-sharing partnerships were, in some cases, promoted in their relative tier to facilitate broad, multi-agency involvement in the SZ4D effort. In the following nomenclature, Tier 1 measurements reflect those of highest priority, while Tier 3 measurements are important (and in many cases necessary) measurements that did not crosscut a large number of our key science questions. Several components of the Tier 1, 2, and 3 measurements comprise detailed observation of Earth's terrestrial and submarine surface through acquisition of, for example, high-resolution bathymetric data, repeated lidar and satellite-based optical and synthetic aperture radar (SAR) imaging, GNSS monitoring, and environmental monitoring via geophysical and sensor networks. This set of surveying infrastructure, which we call SurfArray, will monitor changes in Earth's surface at unprecedented spatial and temporal detail.

Tier 1 Observational Priorities

Tier 1 priority measurements crosscut virtually all aspects of the L&S research questions and include the active imaging of the solid Earth surface, as well as changes in the surface over time. SurfArray is a critical aspect of this data collection. In particular, gathering comprehensive baseline high-spatial-resolution (<1 m postings) topography and bathymetry data will be essential for mapping past events such as landslides, mass transport via volcanic eruptions and submarine and lacustrine turbidity currents, volcanic summit inflation and collapse events, near-surface fault slip deformation rupturing (earthquake deformations, steady creep, and transient aseismic slow slip), coastal erosion and deposition, glacial loading and rebound, and anthropogenically driven geomorphic changes. We also require repeat, high-resolution imaging of the solid Earth surface in areas where events have occurred to determine the amount of mass mobilized and the surface response to these events. Importantly, these acquisition capabilities must be available for deployment immediately following atmospheric or solid Earth events to provide constraints on the surface response. Additionally, drone-based lidar and optical platforms are important complements to high-resolution subareal imagery. These generally low-cost platforms can collect the ultra-high-resolution topography that is required for change detection, albeit over small-footprint study areas, and are more rapidly deployed than larger airborne assets. Second, measurement of solid Earth surface deformation is a high priority for the L&S component of SZ4D. Satellite-based SAR acquisitions from platforms such as the NASA-ISRO SAR (NISAR) mission can be used to produce interferometric estimates of topography and surface motion, which is crucial for constraining surface deformation due to slow-moving landslides, soil creep, elastic strain accumulations around faults, and anthropogenic subsidence due to underground resource extraction. This backbone of satellite-based measurements needs to be supplemented with high temporal resolution surface motions provided by continuous and campaign GNSS monitoring. Installation of marine geodetic monuments is a key component of the L&S mission to constrain rates of deformation in the upper plate. The rates of deformation derived from these sources provide crucial constraints on the energy budget across the subduction zone and help to quantify sediment inputs that arise from motions of hillslopes whose rates are modulated over seasons and individual storms.

Tier 2 Observational Priorities

The SATM process identified four Tier 2 measurements, all of which are important for answering components of our key research questions. Several elements of Tier 2 are also central to the SurfArray, while others leverage and build on these long-term monitoring efforts. Repeated, satellite-based, high-resolution (<1 m pixels) optical imaging is a measurement that crosscuts many of our questions, but whose utility is confined to the surface. Numerous (and increasing) constellations of orbiting optical-imaging satellites provide an emerging dataset that allows observations of surface events at high spatial (meter scale) and temporal (daily) resolution. Comparison of daily images can be used to track events that generate sediment along hillslopes (e.g., landslide events) and how channel morphology adjusts as floods transport sediment downstream. Rapid satellite tasking can help target post-event landscape response.

Tracking sediment through the transport system will require networks of sensors that collect a time series of river discharge and sediment concentrations. Additionally, these ground-based sensor networks need to be able to capture the meteorological events that initiate the transport cascade, so that these spatially dense measurements can be used to downscale observations from satellites that capture broad areas at much lower spatial resolution. These sensor networks, when used in conjunction with existing satellite-based climate monitoring systems, provide the information needed to understand the triggers of storms and seasonal climate oscillations that trigger mass wasting on hillslopes.

In addition to this sensor network, a range of geochronologic capabilities will be required to contextualize real-time observations of individual sediment-generation events and constrain the subduction-zone energy budget. An enhanced ability to precisely measure samples using cosmogenic nuclides is rapidly enabling us to quantify rates of denudation at catchment to outcrop scales that span millennia to <~1 Myr. Radiocarbon remains one of the gold standards for Holocene dating. Optically stimulated luminescence and infrared stimulated luminescence methods can constrain deposit ages over tens to hundreds of thousands of years. Longer-term rates of denudation of Earth's crust (>Myr) can be established using a wide number of thermochronologic techniques. Together, these geochronologic measurements can provide insight into changes in the surface of the subduction zone, the ways in which faults accommodate long-term deformation in the upper plate, and the role that intrusions and eruptions might play in the erosion of the mountainous areas of subduction zone systems. Finally, it will be critical to track sediment transport across the subaerial and submarine transport conduits. Environmental geophysical instruments can help to quantify this transport because they can measure impulses delivered by mobilized mass during large landslide events, flood-related sediment transport, or energetic offshore density currents.

Tier 3 Observational Priorities

Finally, the L&S component of SZ4D identified a number of measurements that are essential for answering specific aspects of our research questions but do not crosscut a majority of these questions, and most of these data needs are not included in the SurfArray. Examples of these priorities include stable isotopes and clumped isotope geothermometry that can reveal past climatic conditions and paleoelevation, coring of specific areas that can reveal local earthquake histories, and trenching used to constrain earthquake history along particular faults. Their rating as Tier 3 priorities is not to be confused with their importance to the efforts of the L&S component of SZ4D. Rather, these types of measurements need to be tailored to the details of specific sites and so are not well suited to provide a "backbone" of data for many scientists studying particular subduction zone segments. Instead, these necessary measurements might be facilitated by individual PI-driven research that is supported by the larger SZ4D effort.

The SurfArray Environmental Sensor Network (ESN)

The importance of collecting ground measurements of climatic, hydrologic, and geomorphologic information led the L&S group to develop and design a network of instrumentation., Ttermed the SurfArray Environmental Sensor Network (ESN), itswhose purpose is to monitor and study the transport of water and sediment throughout a set of targeted watersheds. Key measurements include precipitation, soil moisture, stream water and sediment discharge, and micro-seismicity (ideally measuring three components). Fortunately, many of these variables and conditions can be easily measured with multi-component sensors. When strategically placed, these sensors become a network capable of providing the data needed to understand the environmental conditions that shape the landscape. The envisioned spatial and sensor quality of the ESN will optimize the trade-off between instrumentation costs and essential data needed to address the research questions. We envision that the ESN will operate continuously throughout the lifetime of SZ4D to capture the necessary data needed to define frequency-magnitude relationships. needed to This information will improve understanding of theunderstand dynamics of the meteorological, hydrological, and sediment transport dynamics of the system relevant to upscaling findings beyond the observational window. In addition to this long-lived and stationary network, L&S requires a more nimble, rapid response component to array design and deployment, where instrumentation and expertise can be developed rapidly. This flexible, rapid-response, small-scale array could acquire data from a given region of interest in the immediate aftermath of a landscape-altering event (e.g., large rainstorm or earthquake).

The SurfArray ESN is designed to collect data at a range of spatial scales. At the largest scale, sensors will be deployed to measure precipitation, soil moisture, and micro-seismicity at roughly uniform ~100 km grid-based spacing at the scale of a subduction zone segment (**Figure LS-3A**). The primary intent of this large, evenly spaced sensor deployment is to enable calibration of remotely sensed data products related to precipitation and soil moisture, such as NASA's Global Precipitation Measurement

Mission (GPM) data product. This coarsely spaced sensor array will allow regional calibration of satellite-derived measurements, thereby enabling even broader spatial coverage overto other subduction zone segments that may not contain dense, in situ environmental data.

Within this coarsely spaced sensor suite of sensors, we will also establish a series of sensor arrays that span the coastline to the volcanic arc (**Figure LS-3B**). Using a nested approach, in which relatively coarse estimates of information gathered over large areas will be used to inform more detailed information to sub-domains that are instrumented more densely. Specifically, we will comprehensively characterize several large drainage basins whose mainstems drain roughly parallel to the convergence velocity vector. If two large drainage basins are instrumented, each basin can take advantage of other SZ4D -PI- led comparative experiments, such as the impact of arc volcanism on geomorphic processes and geohazards (**Figure LS-3B**). At the scale of the largest drainage basin, we will deploy an array of the sensor arrays that will capture smaller-scale variability in precipitation, soil moisture, and micro-seismicity across the study area. We anticipate instrument spacing at ~5–50 km, depending on access, permissions, power, and roads. We also plan to install stream water discharge and suspended sediment gauges in the mainstem of the drainage basin. The instrument spacing will be in log-distance or log-drainage area increments to capture more rapidly changing conditions in the headwaters. Within the large watershed-scale array, instruments will be more densely spaced in third to first order drainages that are roughly perpendicular to the flow direction of the mainstem. This spacing will ideally capture much of the tectonic, lithologic, and weather variability from the coast to the arc that results in the observed signals in the mainstem river system. We anticipate instrumenting three to seven smaller-scale basins depending on basin heterogeneity and logistical considerations. Within these small basins, we will have one stream water discharge and suspended sediment sensor at the outlet and four to ten precipitation, soil moisture, and micro-seismicity sensors distributed throughout each basin (**Figure LS-3B**).

We envision using a range of sensors of varying types, quality, and costs. L&S needs high-quality sensors that require a connection to the power grid to operate. At these sites, the highest quality sensors will contain multiple (possibly up to twelve) components. As a baseline for hillslope sites, low-cost precipitation gauges, soil moisture sensors, soil temperature sensors, and micro-seismic instruments will suffice (e.g., Raspberry Shake), but three-component seismometers are preferred. These sites will likely be co-located with MDE and FEC instrumentation to minimize cost and ease logistics associated with instrument maintenance. For river sites, we will need to acquire instruments that measure stream discharge, suspended sediment, precipitation, and microseismsmicro-seisms. These sites might also be outfitted to measure freshwater chemistry and bedload transport via impact plates or higher-quality seismometers. We anticipate that these high-end sites are equipped to transmit data in real time or first process data on-site and then transmit the processed data intermittently. This capability is critical for monitoring station health and data quality and capturing extreme events.

Mid-tier sites do not need to be connected to the power grid and could be powered through high-efficiency batteries charged using solar panels. Mid-tier stations will have fewer sensors than the high-end sites, but we will require

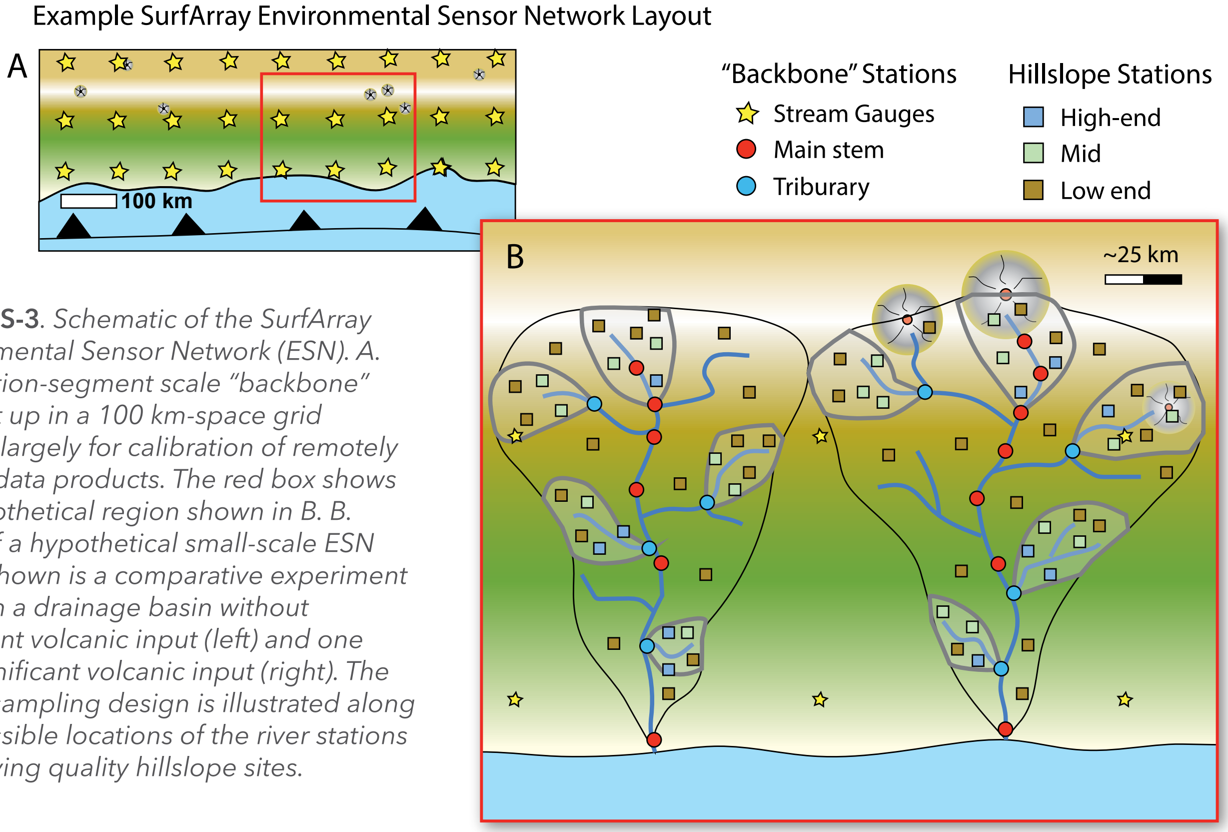


Figure LS-3. *Schematic of the SurfArray Environmental Sensor Network (ESN). A. Subduction-segment scale "backbone" array set up in a 100 km-space grid pattern, largely for calibration of remotely sensed data products. The red box shows the hypothetical region shown in B. B. Zoom of a hypothetical small-scale ESN setup. Shown is a comparative experiment between a drainage basin without significant volcanic input (left) and one with significant volcanic input (right). The nested sampling design is illustrated along with possible locations of the river stations and varying quality hillslope sites.*

precipitation, soil moisture, and micro-seismic measurements at hillslope sites. At river sites, we will need sensors for collecting precipitation, stream discharge, turbidity, and micro-seismic measurements. Similar to the above, mid-tier sites would ideally be capable of transferring data in real time in some form; however, recognizing potential challenges, data loggers will work if no other options are available.

Low-end sites will be on hillslopes only and consist of rain gauges, soil moisture sensors, and low-cost micro-seismometers. These sites can either be run entirely on high-efficiency batteries with software designed to maintain battery life for 6 to 12 months on a single charge. Alternatively, these sites can be connected to solar panels to maintain longer battery life. If positioned in areas with cellular service, these devices can stream data via the internet of things (IoT) at a relatively low cost. In more remote areas without cellular reception, it is likely that these low-end sites will capture and store data on data loggers. Furthermore, the low-cost sites could be distributed throughout the larger drainage basins to provide additional spatial coverage.

Other Infrastructural Needs

While our SATM process was valuable for identifying the key L&S measurement priorities, there are several infrastructural needs that do not cleanly fall within its rubric. The three general categories discussed by our working group included the need for a robust cyberinfrastructure for organizing, distributing, and archiving data from the SurfArray; integrated field-based experiments and observatories to systematically manipulate/observe transport events and coordinate measurements; and the development of high-throughput geochronologic facilities capable of meeting the demands of the SZ4D project in a way that maintains uniform quality standards. Organizations such as OpenTopography, NASA's Earthdata, and UNAVCO/IRIS may serve as a backbone for cyberinfrastructure, but the heterogeneous data sources will require support to implement. (These needs share affinity with the MDE group.) Field experiments, both onshore and offshore, could be imagined to observe, and perhaps even initiate, mass transport events - coordinated measurements within field observatories would most effectively utilize resources for this type of effort. Additionally, methodologies such as detrital Ar-Ar would be revolutionary for tracking provenance, but new high-throughput geochronology facilities might need to be developed to enable this capability.

Finally, numerical modeling must be a central tool for addressing the hypotheses arising from our key research questions. Five different core modeling needs were identified by the L&S group to investigate the research questions enumerated above. First, investigation of the drivers of geohazards such as landslides requires models of landslide initiation that can approximate self-organization and spontaneous-order for failure plane coalescence and slope instability that are physics-based and can reproduce area-magnitude, area-depth, area-volume, and scaling relationships. These models must be three-dimensional and capable of handling complex surface geometry (i.e., realistic topography) and internal heterogeneity (e.g., fractures and variable material properties such as soils, regolith, and bedrock). Second, simulation of water and mixtures over Earth's surface requires a performant, shallow-water equation solver that simulates flows over arbitrarily complex topography that span clear water to slurries and two-component Coulomb mixtures that allows kinetic sieving of solid phase, water, and sediment exchanges from a potentially erodible bed. Third, simulation of the downstream impacts of mass failures resulting from solid Earth or atmospheric events requires an open-source, performant alluvial transport and bed evolution solver that couples the dynamics of water flow in rivers to sediment transport. These codes must be capable of handling transitions between wetted surface and dry perimeter and must explicitly couple sediment transport mechanics to the evolution of the flows' containers. Fourth, these two sets of codes must be coupled to one another to simulate the cascading hazards studied by the SZ4D. And finally, to analyze the work-energy budget of subduction-zone systems requires coupled surface process and tectonic, geodynamic, magmatic models. Existing efforts (e.g., Computational Infrastructure for Geodynamics [CIG] and Community Surface Dynamics and Modeling System [CSDMS]) and models (e.g., Landlab) provide logical paths forward. But, these models must be run at the resolution required to capture the hillslope-channel transition and must span transport across the entire subduction zone - a requirement that could be met by increased model efficiency and ease of model integration.

Given the diverse L&S modeling requirements, we need a funding structure that enables sustained development of methodologies that simulate landscape-forming processes over the vast range of timescales of their operation and that link these surface processes to solid Earth geodynamics. For example, numerical models of forearc deformation must include elastic and inelastic deformation at short and long timescales, surface processes, localized slip along discontinuities, thermal structure of magmatic systems, and fluid flow architecture of the forearc. Currently, no single modeling framework handles all of these processes well. In addition to the human resources that are required to develop these coupled models, large-scale computational infrastructure is necessary to run models at the scale of a subduction zone. These essential needs may be met by collaboration with, and commitment from, those with the numerical expertise and access to large-scale computational resources, specifically the SZ4D-MCS, CSDMS, and CIG.

NOTIONAL EXPERIMENTS

The L&S working group developed a set of notional experiments to test the hypotheses derived from our research questions. The design of our notional experiments follows the philosophy that strict tests of conceptual models require some sort of experimental manipulation in which relevant conditions are held constant while a single factor is systematically varied. In natural systems of the scale and complexity of entire subduction zones, this type of experimental manipulation is not possible, and so our approach relies on comparing subduction zone segments where many of the relevant factors are known and the cross-comparison yields insights on the effects of variations in a single factor. The paired experimental design may be used to falsify quantitative models of geomorphic transport and forearc deformation within subduction zones, in a similar way as a strictly controlled experiment might. Finally, such a paired subduction zone segment design is useful for identifying the ideal geographies of our natural experiments, where controlled variations in the particular factors of interest may be present.

Notional Experiment 1

This experiment explores the role of recurrence time of landscape-impacting solid Earth, magmatic, and atmospheric events on the events that generate sediment and transport it to offshore sinks (Research Question 1; **Figure LS-1**). For these experiments, we would ideally use a paired set of subduction zone segments that have either similar solid Earth or atmospheric conditions, while the other set of factors varied between the subduction zone segments. For example, to explore the impact of atmospheric events on sediment generation, we would ideally seek areas with consistent convergence rate, subduction angle, and frequency-magnitude relationships for large earthquakes and magmatic events, while climatic parameters (e.g., precipitation, storminess, and temperature) would vary. The differences in climate would presumably alter the distribution of the frequency, magnitude, and spatial extent of storms impacting the subduction zone landscapes and seascapes. In this case, a successful experiment would require field measurements and data to capture the impact of a single event and the integrated effect of multiple events, as well as longer timescale data that would elucidate how these events cumulated to produce the long-term transport of mass across the subduction zone system. For example, satellite and ground-based measurements of precipitation would allow determination of the associations between storms and mass wasting events. The location and rates of mass wasting could be constrained using seismologic, ground, or remote sensing observations. The magnitude of sediment generation could then be determined by reoccupying portions of the baseline high-resolution dataset, and sediment load measurements and drone resurveys could be used to track how this sediment is filtered downstream and changes valley morphology.

It is also important to acknowledge that many of the factors that we would like to hold constant in such a paired study may covary with one another because of the processes in operation. For instance, climate-driven sediment delivery to the trench has been hypothesized to impact coupling along the plate interface of subduction zones, and so at least over long timescales, it may be difficult to isolate these factors. Because natural experiments may not allow perfect isolation of controlling factors, parametric studies using numerical models might augment the study of the natural systems by serving as thought experiments to better interpret covariations seen in natural systems. Necessarily, such models should couple solid Earth deformation (earthquakes and magmatic) with surface processes. This will allow comparison with field data that characterize processes occurring at a similarly wide range of timescales.

Notional Experiment 2

This notional experiment seeks to understand the interplay between evolving topography, deformation, and magmatic processes within the upper plate of the subduction zone. (Research Question 2; **Figure LS-2**). While many variations are possible for the notional experiment, two variants outlined here offer key insights into the feedbacks between subduction zone and Earth surface processes. In one variant, we would compare subduction zone segments with similar degrees of accretion rate, coupling, magmatic flux, and forearc lithotectonic complexity, but different mean forearc slopes, to isolate the interplay between topographic loading and upper plate deformation and magmatism. In another variant, we would compare subduction zones with similar viscous coupling depth, mean slope, contraction rate, mantle melt influx rates, and heat flow, but different lithotectonic complexity and duration of subduction, to illuminate the role that crustal structure and subduction history produced by the geologic assembly of the forearc and arc plays in partitioning deformation and magmatism in the upper plate. In both of these cases, high-resolution topography allows identification of active structures in the forearc, provides a base map for field observations, and details the configuration of watersheds throughout the volcanic arc and forearc. Geologic, geochronologic, and thermochronologic observations constrain the long-term rates of exhumation due to the action of forearc structures and magmatic processes. Finally, numerical models that are framed as either parametric studies or simulations can be used to construct predictions that can be ruled in or out using the field observations.

These notional experiments represent abstract aspirational studies that could ideally be performed if subduction zone segments with all of the targeted variations existed. However, natural circumstances do not present all combinations of factors of interest in the notional experiments. Thus, the possible sets of experiments, and the specific forms they will take, depend on the characteristics associated with paired sets of particular subduction zone segments. In this way, it is not possible to divorce the discussion of our notional experiments from the natural conditions available in specific subduction zone systems. The section on **Site Evaluation** lends some specific form to the notional experiments through a review of the properties of different subduction zone segments and a comparison of segment pairs. That chapter seeks to identify obvious sets of subduction zone segments whose comparison might lead to reasonably well-constrained natural experiments. However, the general form of our notional experiments is intended to allow space for individual PI-driven research that might compare particular aspects of subduction zone segments that are not specifically called out in the **Site Evaluation** section as being most amenable to addressing our research questions through a decade-long, community-wide initiative.

IMMEDIATE SCIENCE ACTIVITIES

While the majority of our proposed hypotheses require new and cutting-edge datasets, significant progress can be made through the analysis of existing data and ideas. Below we describe examples of how existing datasets and numerical models may advance our understanding of how mass is mobilized and transported across landscapes and seascapes, and constrain the energy budget of subduction zone systems. Additionally, we describe the ways in which these analyses could be coordinated with the primary SZ4D experiments.

Recent advances in airborne and terrestrial lidar techniques, as well as autonomous underwater vehicle bathymetric surveys, have provided high-resolution digital elevation models that allow us to explore short- and long-term surface deformation and disturbances across landscapes and seascapes (e.g., Booth et al., 2018; LaHusen et al., 2020; Hilley et al., 2020). For example, in Cascadia, where a significant portion of the landscape has been imaged at high resolution (e.g., Oregon Department of Geology and Mineral Industries, Puget Sound Lidar Consortium), recent work to correlate landslide surface roughness with event age (e.g., LaHusen et al., 2016) enabled researchers to develop landslide inventories based on geomorphic criteria and to test the extent to which climatic changes (e.g., Booth et al., 2018) or ground shaking (e.g., LaHusen et al., 2020) have contributed to changes in landslide abundance. These long-term archives of landslide age and distribution are essential to understanding how solid Earth and atmospheric events mobilize mass across Earth's surface. Yet, only small segments of subduction zone landscapes, where variations in forcing factors may be subtle, have been characterized to date. Newly collected bathymetry and sediment cores may make analogous techniques applicable offshore (e.g., Hill et al., 2020), helping to elucidate the extent of slip on recent megathrust ruptures and to discriminate marine turbidites created during shaking from other triggering mechanisms. Similarly, new analyses of drainage basin morphology shed light on linkages between the subduction zone earthquake cycle and the development of forearc topography (Penserini et al., 2017; Gallen & Wegmann, 2017; Gallen & Fernández-Blanco, 2021), which is directly applicable to testing the subduction zone energy budget. Likewise, new approaches that link surface deformations, coastal and offshore geometry, and interseismic coupling (e.g., Saillard et al., 2017) would leverage existing data to provide an expanded and holistic view of the subduction zone energy budget.

Additionally, modern geodetic techniques such as InSAR can reveal centimeter-scale surface deformation that can provide further insight into crustal deformation during different phases of earthquake cycles, volcanic unrest, landslides, and anthropogenic disturbance (e.g., Bürgmann et al., 2000; Avouac, 2015; Shirzaei et al., 2016; Murray & Lohman, 2017; Handwerger et al., 2019). A holistic view of high-resolution surface change across a subduction zone landscape remains elusive, but the data exist to create a community dataset for monitoring regional surface change (e.g., *InSAR Norway*). Geochronology can provide insight into longer-term rates and patterns of deformation and erosion within subduction systems. For example, cooling-driven exhumation recorded by thermochronology has been used to identify the timing of subduction initiation (e.g., Thomson et al., 1998; Sutherland et al., 2009; Schoettle-Greene et al., 2020) and geodynamically significant events such as subduction of seamounts, spreading ridges, or extrusion and oceanward migration of a slab (e.g., Villagómez and Spikings, 2013; Stevens Goddard & Fosdick, 2019). Luminescence and 10Be surface exposure dating of differentially uplifted marine terraces and shorelines places limits on the timing and rates of subduction zone uplift and active tectonics within the upper plate (e.g., Saillard et al., 2011; Gallen et al., 2014; Binnie et al., 2016; Ott et al., 2019a), while catchment-wide erosion rates from detrital cosmogenic radionuclides allow an estimation of landscape evolution and erosional response to such subduction-driven uplift (e.g., Olivetti et al., 2012; Ott et al., 2019b). Geochronology data such as these are essential for understanding aspects of all proposed hypotheses for SZ4D landscapes and seascapes, from direct observations of surface disturbance and sediment flux to time-evolving boundary conditions for magmatic and tectonic deformation models. Yet, at present, these data are generally limited to individual studies and specialized researchers.

In the context of achieving SZ4D's immediate science goals, modeling studies serve two important purposes. First, models can link various subduction zone processes to one another, elucidating key feedbacks that crosscut the three working groups. For example, in the case of studies situated in extensional systems, models have been used to directly quantify the changes in energy that accompany the creation and destruction of topography. Redistribution of sediment through erosional and depositional processes diminishes body forces in some regions (surface uplift) while increasing loads in others (surface lowering) (e.g., Fuller et al., 2006). Moreover, arc magmatic processes build topography and impact climate while creating impulsive loads on existing topography (e.g., Lee et al., 2015). Simultaneously, magmatism modifies the chemical reactivity of surface rocks, sediment distribution pathways, and underlying crustal rheology. These numerical models have been used to link seemingly disparate observables to one another, such as erosional efficiency to the localization of deformation. For example, models have shown that more erosive conditions localize deformation onto fewer, longer-lived normal faults, while inefficient erosion tends to distribute the strain across many faults with little offset (e.g., Olive et al., 2014). Further, models have associated the location of eruptions in rifts with the creation of rift valley topography (e.g., Maccaferri et al., 2014). Similar models can be readily developed for subduction systems to gain insight into links between solid Earth processes, climate, rock lithology, lithospheric rheology, and magmatism - all of which are central components of the subduction zone energy budget.

SITE EVALUATION

The L&S working group conducted an evaluation of site characteristics to identify those subduction zones that offer conditions to carry out the notional experiments. We evaluated subduction zone segments in steps. First, we performed a comprehensive review of different subduction zone segments, which were defined to achieve roughly equivalent along-strike dimensions (~200–400 km) where tectonic, geologic, and climatic parameters might be viewed as approximately constant (**Table A-LS2**). We then used an "advocacy" approach, in which working- and interest-group members familiar with these areas summarized the properties of these different subduction zone segments. Importantly, we reviewed both scientific and logistical aspects when considering site appropriateness. In a second step, the working group identified segments that would be problematic for study by the L&S community, either because of a lack of essential attributes or logistical factors that would prevent safe access to those areas. In a third step, we mapped our notional experiments onto sets of these subduction zone segments to determine those groupings that might be used to perform "quasi-controlled" experiments in which many properties were regarded as approximately equivalent, while a limited number of others varied. This process helped to identify a number of combinations of subduction zone segments that appeared to meet the design of the notional experiments.

The group determined **four essential site characteristics** required to carry out our notional experiments and hypothesis testing.

- **First**, at least some proportion of the site must include subaerial forearc exposure (free of ice).
- **Second**, observational constraints must exist or be acquirable at suitable sites. (These observations are described and ranked in the section on **Traceability of the Scientific Questions Through Practical Activities**).
- **Third**, we require at least some portion of the site to include rocks with minerals amenable to geochronology and thermochronology such as quartz, apatite, and zircon.
- **Fourth**, we require that 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.

In our final step, we discussed the remaining subduction zone segments to identify pairs that might make favorable comparisons and that would allow us to conduct some form of the notional experiments. Although not included among the currently discussed SZ4D focus regions of Chile, Cascadia, and Alaska, we note some of these below either as pairings to segments of these focus regions or independently, as they may be viable for smaller-scale PI-driven notional experiments (e.g., the Hikurangi subduction zone; **Table A-LS2**).

We identified several interesting pairings of the Cascadia subduction zone with other subduction zone segments, particularly Chile. Cascadia is an accretionary margin that experiences large, megathrust ruptures and is situated in a temperate climate. The topography of the subduction zone system lends itself to producing significant orography - an attribute that was of interest to many in the working group. **An ideal first comparison to Cascadia might be the Central Hellenic subduction zone**, which exhibits similar rates of convergence, but whose megathrust largely creeps aseismically and whose forearc is actively extending. The hot summer Mediterranean climate and widespread exposure of carbonates contrast with the climate of, and rock types exposed within, Cascadia. Thus, while their convergence rates are similar, rupture behavior, forearc stresses, climate, and exposed lithology are not. While it was acknowledged that the lack of control on many factors may confound simple application of the notional experimental framework, there was a sentiment that such a comparison might provide insight into our key research questions. **An ideal second comparison with Cascadia might be made with the Maule-Valdivia segment of the Andean subduction zone**. Here, the two segments share many similar characteristics, including climate, physiography of the arc, the generation of large subduction zone earthquakes, the degree of coupling of the subduction megathrust, and in some areas, the presence of a young downgoing oceanic slab. Yet, the rate of convergence along the Maule-Valdivia segment is far higher than the Cascadia subduction zone, which allows us to systematically vary the time of impacting solid Earth versus atmospheric processes (Research Question 1) by comparing these two segments. Additionally, the rate of energy added to the upper plate due to frictional coupling along the megathrust is likely higher in the Maule-Valdivia segment, which provides a systematic manipulation of the energy inputs into the subduction zone system between these two cases (Research Question 2). **The Central Hellenic subduction zone** exhibits similar rates of convergence to Cascadia but differs in its rupture behavior (its megathrust largely creeps aseismically), forearc stresses (it's actively extending), climate (hot Mediterranean), and exposed lithology (carbonate). While these differences may confound simple application of the notional experimental framework, there was a sentiment that such a comparison might provide insight into aspects of our key research questions.

Another pair of subduction-zone segments that might be compared include the Alaskan (mainland) subduction zone and the Austral Andes. Both of these segments are located in high-latitude areas, where glacial erosion is a central landscape feature. Both have a component of trench-parallel motion, which partitions upper plate strain. However, convergence rates along the Alaska subduction zone segment are far greater than the Austral Andes, allowing a systematic variation of convergence rate, which impacts landscape processes (Research Question 1) and the energy budget of the subduction zone system (Research Question 2). There may be additional utility in the Alaska subduction zone system in this comparison, as systematic, along-strike differences in the nature of the subducted material vary along strike, which could alter the normal tractions acting along the base of the upper plate due to differences in the buoyancy of the subducting material. Logistical challenges in both these segments include poor infrastructure and limited field seasons, which would increase costs and require more time and human resources.

Segments along the Andean margin provide a unique opportunity to control for and vary many factors related to both our research questions. The climates along the Andean forearc are controlled by macroscale atmospheric and ocean circulation, which sets up large climate differences along the subduction zone segments. The scale of the subduction zone segments is large enough to discriminate the effects of individual rupture segments and boundaries of climate systems from one another. For example, comparisons between the Ecuadorian, Arica, and Maule-Valdivia segments control for tectonic geometries, but allow variations in climate to be explored, which affects delivery of sediment to the subduction trench. Comparisons between the Arica and Pampean segments allow climate to be held fixed, while tectonic geometry could be studied. Comparisons between some parts of the Peruvian and Pampean segments might allow climate to vary in flat-slab subduction areas.

In general, the group noted that there are "gradients upon gradients" within the larger Andean subduction system, which provide a rich opportunity to build a substantial number of notional experiments.

A smaller-scale PI-driven experiment outside these regions, but that pairs with the Pampean segment in Chile, would compare it with the Peruvian segment of the Andean margin, both of which involve flat-slab subduction but have different climates. Other paired systems considered potentially fruitful include the Nankai and Cocos-Panama subduction (in the area of northern Costa Rica), where convergence rates are broadly similar, but the thickness of sediment entering the trench varies systematically between the two systems. In Nankai, the thick sedimentary section is associated with active accretion of the margin, whereas the sediment-starved Cocos Plate is not and appears to have fundamentally different upper-plate deformation kinematics. These two contrasting situations likely alter the energy budget between these subduction zones as the transfer of mass from the downgoing slab to the upper plate likewise transfers energy to the subduction zone system (Research Question 2).

The L&S working group members noted particular opportunities to draw on the investments of other countries and organizations interested in subduction zone research. For example, there is already a wealth of information from the Nankai, Mediterranean, and Hikurangi subduction zones - setting up cooperative and data-sharing agreements with Japan, the EU, and GNS New Zealand. Thus, while it is clear that the SZ4D will not be active in all of the subduction zone systems our group discussed, partnerships with international organizations have the potential to greatly expand the breadth of scientific discoveries by increasing the number of experiments we might execute.

OUTLINE OF INITIAL PLAN FOR COMMUNITY COORDINATION

The SZ4D initiative provides an exciting opportunity for the Earth surface process community to study subduction zone landscapes and seascapes. Community coordination will be especially important for the success of the L&S component of SZ4D. We regard the community as spanning engaged scientists, institutions, and domestic and international partners collectively invested in SZ4D.

To build this community, we propose a range of SZ4D L&S-level programs to promote community engagement, network building, idea exchange, and ultimately synthesis of results. An international exchange of researchers would be one such program to build capacity and collaboration among host countries. SZ4D-sponsored graduate student and faculty exchanges with international hosting countries would build lasting relationships among the global subduction-zone science community. Additionally, a wealth of information collected by the potential host country of Chile exists - and more exchanges involving international students and senior scientists would help to integrate this prior knowledge-base into SZ4D efforts. A successful international community would require partners to be co-equal investigators with access to educational opportunities for themselves and their students. Similarly, a domestic graduate student exchange program among SZ4D-supported PIs would foster the exchange of ideas and integration of research needed for a successful L&S program. The international and domestic graduate trainee exchange programs would help to coordinate PI and student-level research, but more importantly, promises to broaden the knowledge base of student participants, expand their professional networks, and jump-start a community of next-generation leaders in subduction zone surface process science. In addition, a structured and coordinated training and exchange program would be able to acknowledge outstanding contributions to subduction zone surface process research. We envision partnering with existing public and private scientific capacity-building programs, such as those sponsored by the USAID Bureau for Humanitarian Assistance, GeoHazards International, and others.

Meetings offer another means of SZ4D L&S community building. We plan to hold annual SZ4D L&S-sponsored international and domestic workshops, webinars, conferences, and field trips to further community development. These events will have topical and planning themes with defined goals. For example, events can serve the purpose of coordinating new, ongoing, and past PI experiments and datasets, identifying new research and infrastructure needs, showcasing new studies and findings, and synthesizing results across disciplinary, organizational, and political boundaries. These events would also provide a platform to organize logistics and assess progress toward the overarching L&S science objectives. The L&S working group sees benefit in a centralized means of facilitating exchange opportunities, developing professional networks, and fostering a new scientific community.

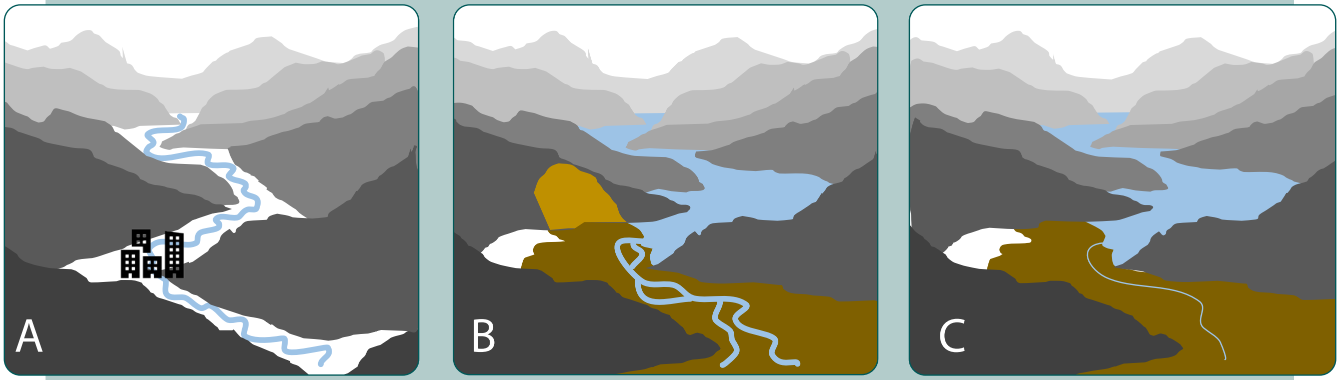
A structure for coordination of community science is necessary to build an engaged network of participating scientists, institutes, and facilities necessary for the execution of scientific priorities, research activities, and data management. We present two end-member potential organizational structures that facilitate the SZ4D L&S notional experiments through PI-driven studies. Both organizational structures aim to maximize transparency, build community consensus on essential scientific targets, and organize PI-driven research and data streams to enable community-wide efforts to allow a successful, comprehensive synthesis of results. One coordination plan involves the identification of overarching scientific priorities needed to achieve the goals of the bigger-picture experiments. Program solicitations would be carefully tailored to stimulate PI-driven research proposals targeting the identified scientific goals. Proposals would be assessed on quality and alignment with the mission forwarded within the specific solicitation and SZ4D more broadly. The goal would be to foster a PI-driven ecosystem of science and data generation and sharing that produces the building blocks needed to realize the broader notational experiments. An alternative organizational structure focuses on building a scientific advisory group with the task of finding a consensus of scientific targets that drive decision-making and study design to ensure that each essential component of the experiment is completed. This model differs from the last in that program targets are more specific, and a broader community is engaged in building consensus on incremental science targets. In this case, the science would still be PI-driven, but program directives would be more tightly tethered to objectives defined by the community. Such a community-driven advisory structure might allow adaptation to emerging SZ4D questions and continual alignment of the investigations around community-driven science priorities.

To be able to simulate subduction systems, community coordination is needed for the development, implementation, and maintenance of large-scale technological, data acquisition, and modeling infrastructure and for analytical facility support and access. Many Tier 1 L&S SATM measurements involve terrestrial and submarine remote-sensing surveys (drones, airplanes, and satellites) with large spatial footprints. Additionally, the SurfArray ESN will require substantial facilities support to deploy, maintain, and manage data from this instrument network. These data streams require partnerships with and support for existing facilities that maintain the available expertise, equipment, and infrastructural capabilities. In some cases, these capabilities and data already exist or will soon be available (e.g., NASA-ISRO NISAR, ESA Copernicus Sentinel missions, commercial high-resolution imagery), and SZ4D partnerships could serve to facilitate and streamline data access. In other cases, data and infrastructure exist that assist in maintaining data streams, but additional SZ4D support will help expand the existing capabilities to handle the needs of L&S (e.g., USGS, OpenTopography, NASA Earthdata, IRIS, UNAVCO, CUAHSI). Finally, new technological developments and associated infrastructure are needed to integrate generated datasets across the subduction zone landscapes and seascapes (e.g., seamless merging of new and existing topographic and bathymetric data) that can be developed and maintained by partnering with existing facilities and/or by forming new organizational units within SZ4D.

Analytical data (e.g., geochronology), must be acquired and synthesized to test L&S hypotheses. Unlike many of the large, centralized data facilities that can be used to process and archive remote-sensing data, geochronologic facilities are numerous and somewhat heterogeneous in their instrumentation and protocols. Thus, SZ4D will need a vehicle to allow individual PIs engaged in SZ4D investigations to access these heterogeneous facilities in a way that maintains consistent data quality through the adoption of common protocols and standardization. We suggest drawing and expanding on existing NSF investments in EarthCube to ensure that results are comparable across labs and subduction zone segments. Through SZ4D coordination between modelers, field scientists, and geochronologists, key modeling needs will be identified and new capabilities generated for hypothesis testing using coupled subduction system models. Central to this effort is coordination and collaboration with SZ4D-MCS to help identify key science targets and modeling needs to meet L&S research objectives. Furthermore, this process can benefit from the existing groundwork for coupled surface process-geodynamic numerical model development and infrastructure provided by NSF-sponsored organizations such as the CSDMS and the CIG. Collaborations between these organizations have already led to the development of new infrastructure that is capable of more easily coupling geodynamic and Earth surface process models. L&S would ideally collaborate and integrate with these existing efforts and help inspire new modeling efforts and capabilities.

SIDEBAR 4

Landslides and cascading downstream impacts



Large seismically, climatically, or volcanically triggered landslides in mountainous watersheds commonly set off a cascade of downstream hazards (e.g., Pierson and Major, 2014; Fan et al., 2018). Long runout debris flows and avalanches destroy infrastructure far from the slope failure (**Figure S4-1A, B**)(e.g., Voight, 1990; Wartman et al., 2016), and where they encounter lakes or reservoirs produce catastrophic tsunamis (e.g., Genevois and Ghirotti, 2005; Wiles and Calkin, 1992). Landslides frequently produce dams that impound water for days to months after a landslide (**Figure S4-1B**), unleashing massive floods upon gravitational failure (**Figure S4-1C**)(e.g., Costa and Schuster, 1988). Landslides can also reroute rivers through forcing avulsions (**Figure S4-1B**) and inhibit coarse sediment transport, resulting in aggradation of 10's of meters of gravel for kilometers upstream of landslides (e.g., Finnegan et al., 2019), wreaking havoc on infrastructure and ecosystems along the river corridor (e.g., Korup, 2014). Finally, large changes in river elevation through first aggradation and then incision due to the downstream transport of debris can occur for centuries following large landslides (**Figure S4-1A,B,C**)(e.g., Stolle et al., 2019) and can impact communities >100 km away (Sarker et al., 2014).

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