FAULTING AND EARTHQUAKE CYCLES

WHEN AND WHERE DO LARGE EARTHQUAKES HAPPEN?

SCIENTIFIC MOTIVATION

When and where do large, damaging earthquakes happen? There has been remarkable progress on this central question in earthquake science in the twenty-first century. We now directly observe that faults fail sporadically at a range of rates and timescales, with slow and rapid slip interacting to produce complex temporal and spatial patterns of movement. The exceptional number of great subduction zone earthquakes in the last 15 years has enabled evaluation of their relationship to tectonic setting and prior activity. In subduction zones, networks of faults accommodate deformation, including the megathrust and faults in the overriding and subducting plates, and all of these fault systems contribute to earthquake and tsunami hazards. Evidence is accumulating that there are systematic relationships among subduction zone architecture and deformation history, fault properties, and the tendency for large earthquakes. Furthermore, tantalizing new observations of possible relationships among different types of fault slip behavior open up new avenues of exploration that will allow us to make significant strides in understanding controls on modes of deformation and earthquake hazards. Many of these observations are coming from subduction zones, where the world's largest earthquakes happen. The SZ4D Faulting and Earthquake Cycles (FEC) effort focuses around four central questions, detailed below, that define the limits of what we know about when, where, and why large earthquakes occur.

Significant overlaps exist between FEC and other components of the SZ4D initiative. Subduction zone hazards, including earthquakes, are linked through their shared dependencies on architecture, material properties, fluid migration, and the state of stress. These properties are shaped by systems-scale tectonic, magmatic, and sedimentary processes operating over millions of years. Faulting and earthquakes shape geomorphology, modulate the state of stress, and trigger mass wasting events, volcanic eruptions, tsunamis, and earthquakes in other parts of the system. As a result, a fundamental understanding of the science that drives subduction hazards requires ambitious and integrated observational, modeling, and experimental efforts to illuminate the interactions between tectonic evolution, faulting and earthquakes, landscape and seascape evolution, and magmatic processes.

This chapter describes FEC science questions, required information and activities to address those questions, a phased scientific plan, and an assessment of subduction zones most well-suited to address FEC science questions.

SCIENCE QUESTIONS

The overarching question of the Faulting and Earthquake Cycles component of SZ4D is: **When and where do large, damaging earthquakes happen?** A major goal of earthquake studies is to be able to predict relationships between geographic location and earthquake and tsunami hazards. Prediction of specific earthquakes may be impossible, but physical models of fault failure are capable of predicting important features of the earthquake cycle when developed in collaboration with observational and experimental studies. We break up this major question into four sub-questions that focus on different aspects of the subduction zone earthquake problem, each of which has societal importance. Addressing these four questions by integrating observational, laboratory, and modeling efforts will allow us to make progress on the grand challenge of earthquake predictability.

1. How do subduction zone fault systems interact in space and time? How do these fault systems and associated deformation regulate subduction zone evolution and structure?
2. What controls the speed and mode of slip in space and time?
3. Do distinctive precursory slip or distinctive foreshocks occur before earthquakes? What causes either foreshocks or precursory behavior?
4. Under what physical conditions and by what processes will slip during an earthquake displace the seafloor and increase the likelihood of generating a significant tsunami?

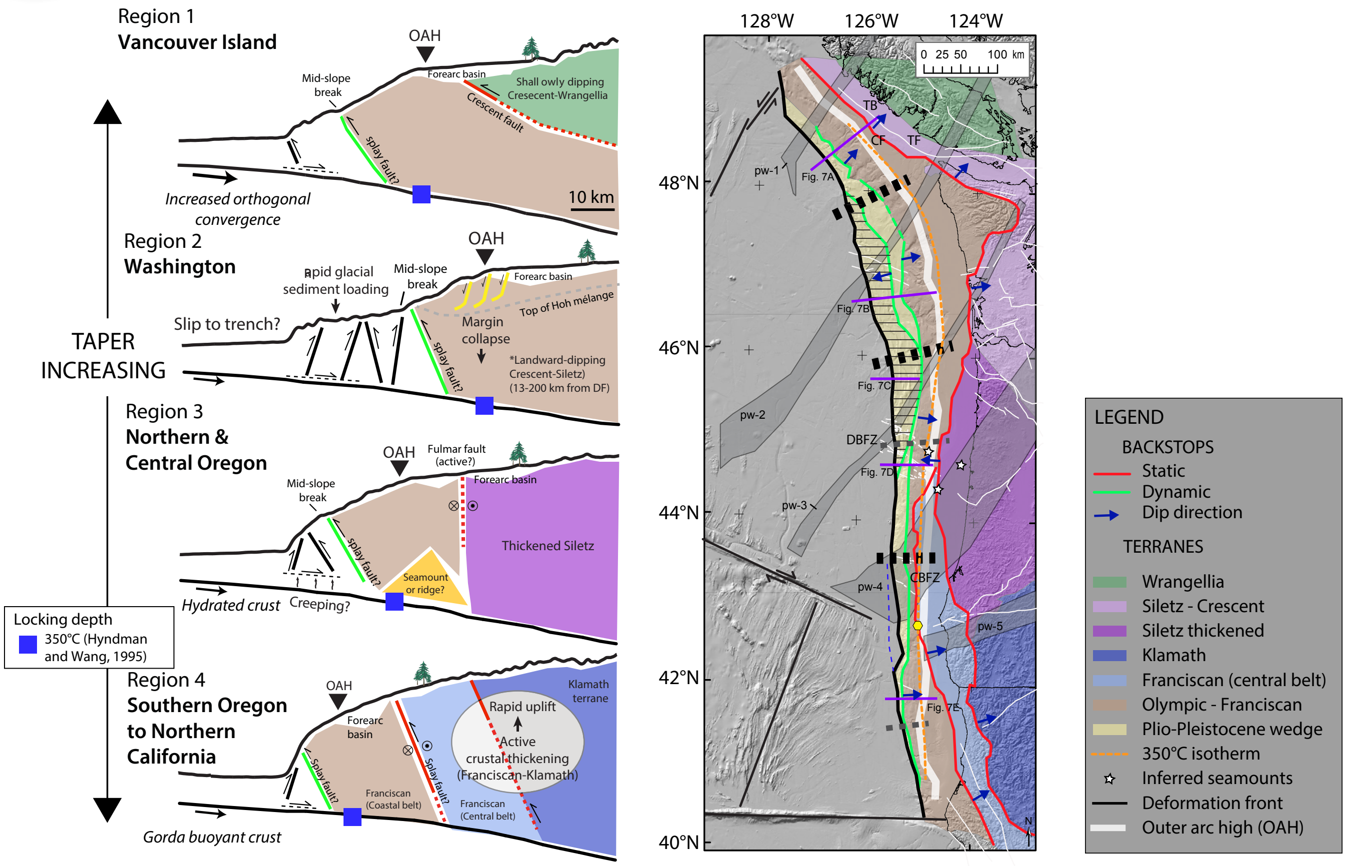


Figure FEC-1. *Synthesis of tectonic geomorphology, outer wedge taper, and structural vergence in the Cascadia subduction zone forearc. Forearc morphology is connected to megathrust behavior. From Watt & Brothers (2021).*

FEC Science Question 1

How do subduction zone fault systems interact in space and time? How do these fault systems and associated deformation regulate subduction zone evolution and structure?

Subduction zone deformation occurs through localized faulting and distributed strain within the plate interface, overriding plate, and downgoing plate at temporal scales ranging from earthquakes (seconds) to millennia. Feedbacks between faulting and distributed deformation across this system are critical to dictating where, when, and how subduction zone deformation leads to hazardous events (e.g., **Figure FEC-1**). For example, slip on the megathrust can propagate onto upper plate splay faults (Fan et al., 2017; Obana et al., 2018; Coffey et al., 2021), lead to triggered slip, or be triggered by slip on faults in the overriding and downgoing plates (e.g., Dmowska et al., 1988; Bouchon et al., 2016; Lay et al., 2011; Gomberg & Sherrod, 2014; Hollingsworth et al., 2017); load crustal faults to failure (e.g., Loveless & Meade, 2010); and trigger mass wasting and magma migration events (Linde & Sacks, 1998; Leithold et al., 2017; Roland et al., 2020). Spatial and temporal coseismic slip distribution and potential triggering of mass wasting determine tsunami generation. The location and mode of strain accumulation and release on faults (**Figure FEC-2**) is modulated by spatial variations in the physical and rheological properties of the crust and mantle in the overriding and downgoing plates (e.g., Wells et al., 2017; Sun et al., 2020, Watt & Brothers, 2021, **Figure FEC-1**), the hydraulic connectivity of fault systems (Warren-Smith et al., 2019; Bonini, 2019; Gosselin et al., 2020), and the composition, mechanics, fluid properties of subducted sediments, whose distribution and delivery are climatically, geomorphically, and tectonically controlled (e.g., Lamb & Davis, 2003; Sweet & Blum, 2016; Meridth et al., 2017).

There are several gaps in our understanding of how subduction fault systems deform and interact to generate tsunamis, ground shaking, and mass wasting events that impact coastal population centers. For example, even though faults in the overriding and downgoing plates can produce large earthquakes and tsunamis, the geometry, extent, and rupture history of these faults, and their connectivity, are less well-constrained than those of the megathrust. In situ pore fluid and stress conditions, and their spatiotemporal variations, are key properties proposed to control coupling and interactions between slip along megathrust and other faults, but measuring these parameters requires dense instrumentation and monitoring systems. Finally, integration of geological, geochemical, geophysical, and rock deformation data is essential to quantify fault interactions, but few locations have coordinated data collection and synthesis that permits system-scale analyses.

SZ4D is uniquely poised to determine the conditions that trigger events and the role of upper and lower plate faults in modulating the accumulation and release of strain associated with plate convergence. To understand fault interaction on short and long timescales requires detailed information on the geometries, stress state, distribution of fluids, and material properties of subduction zone fault systems and surrounding rock. Key requirements include deformation and fluid flow from high-precision seismicity and geological studies, fault geometries and distribution of fluids from seismic reflection and controlled-source electromagnetic (CSEM) imaging, fault properties

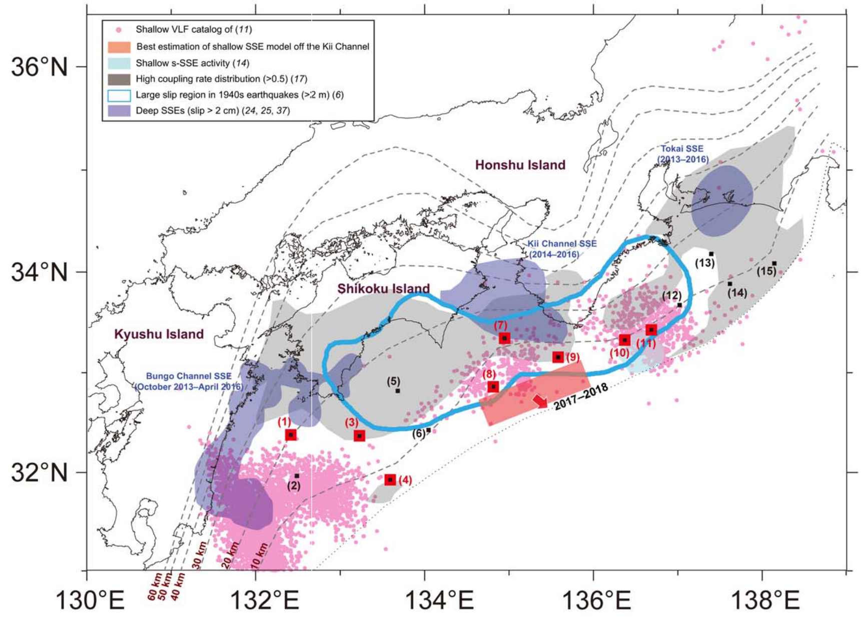


Figure FEC-2. *Spatial relationships between different modes of slip detected by seafloor instrumentation in the Nankai Subduction Zone. Gray shaded area - regions with a coupling coefficient greater than 0.5. Blue contour - regions of high slip during two M8 events in the 1940s. Red rectangle - location of the 2017–2018 shallow slow slip event. Blue regions - locations of deep, slow slip events. Pink circles - locations of very low frequency earthquakes. From Yokota & Ishikawa (2020).*

from exhumed fault systems, slip history from paleoseismic records, and material properties from experiments. Geodetic data are needed to constrain the distribution of deformation across fault systems. Numerical modeling is required to determine the roles of material properties and stress state on fault interactions, extrapolate through space and time, and guide ongoing data collection. Code development for geodynamic timescales is needed to understand feedbacks between localization and formation of faults, thermal structure, loading from mantle convection and plate tectonic forces, and the evolving landscapes and seascapes.

FEC Science Question 2

What controls the speed and mode of slip in space and time?

Slip along the subduction megathrust ranges from continuous creep to the punctuated rupture characteristic of major subduction earthquakes. In between these two extremes, there is a spectrum of slip behavior, including quasi-episodic slow slip events (SSEs) and low and very low frequency earthquakes (LFEs and VLFEs). These different styles of slip determine whether strain accumulation and release are expressed violently through damaging earthquakes or harmlessly through slow fault slip. One of the major goals of SZ4D is to understand the physical processes and conditions that control the speed and mode of fault slip and how these processes and conditions evolve in space and time.

It has long been understood that slip behavior varies spatially along the megathrust. The ability to measure deformation in some subduction zones using geodetic methods now allows us to distinguish segments that are locked and accumulating strain toward the next earthquake rupture from others inferred to be less seismically coupled or even continuously sliding, and to identify areas experiencing quasi-episodic SSEs. Furthermore, the discovery of "slow" earthquakes (e.g., tremor, VLFs) and aseismic, geodetically detected slow slip, demonstrates that slip behavior is diverse and that fault coupling also varies in time (e.g., Dragert et al., 2001; Obara, 2002; Frank, 2016). The resulting picture is complex, with substantial variations in spatiotemporal patterns of locking and strain energy release, manifested in varying styles of slip (e.g., Ito et al., 2013; Ruiz et al., 2014; Yokota & Ishikawa, 2020; **Figure FEC-2**).

Many hypotheses have been proposed to explain the distribution of slip in space and time. Some focus on physical properties of fault zone materials, including fault composition, structure, and rheology across length scales of nanometers to kilometers (e.g., den Hartog & Spiers, 2013; Hawthorne & Rubin, 2013; Ujiie et al., 2013; Saffer & Wallace, 2015; Trütner et al., 2015) and heterogeneity that leads to a mixed brittle-ductile behavior (e.g., Fagereng & Sibson, 2010; Skarbek et al., 2012; Barnes et al., 2020). Other studies suggest the distribution and composition of pore fluids and pore-fluid pressures are highly important (e.g., Liu & Rice, 2007; Kitajima & Saffer, 2012; Song et al., 2009; Warren-Smith et al., 2019; Hooker & Fischer, 2021) or focus on the roughness and topography of the downgoing plate (Wang & Bilek, 2011, 2014). A comprehensive evaluation of these and other proposed processes through a combination of observations from well-studied regions, geologic studies of analog systems, experimental studies, and numerical modeling are needed to determine fundamental controls on the speed and mode of slip. The factors above lead to our overarching hypothesis that the location and extent of hazardous earthquakes are, to some extent, predictable from measurements of coupling, strain accumulation, and past slip behavior.

Answering Question 2 and addressing the associated hypothesis that earthquake locations and sizes are foreseeable based on geodetic and historic observations requires gathering those measurements of slip events over a wide range of timescales in both onshore and offshore environments. A combination of seafloor geodetic instruments and densely distributed ocean-bottom seismometers are needed to acquire the necessary very high-resolution data offshore. The onland component of the observations can be achieved using a combination of terrestrial seismometers, the Global Navigation Satellite System (GNSS), and the new capability of the planned NASA-ISRO Synthetic Aperture Radar (NISAR) mission. Once these fundamental observations of subduction zone behavior are obtained, an integrated numerical modeling, experimental, and observational effort will be needed to understand the processes responsible for this behavior. This will include mapping structure from geophysical imaging and field mapping, collecting physical properties measurements downhole and from recovered cores, studying exhumed fault zones

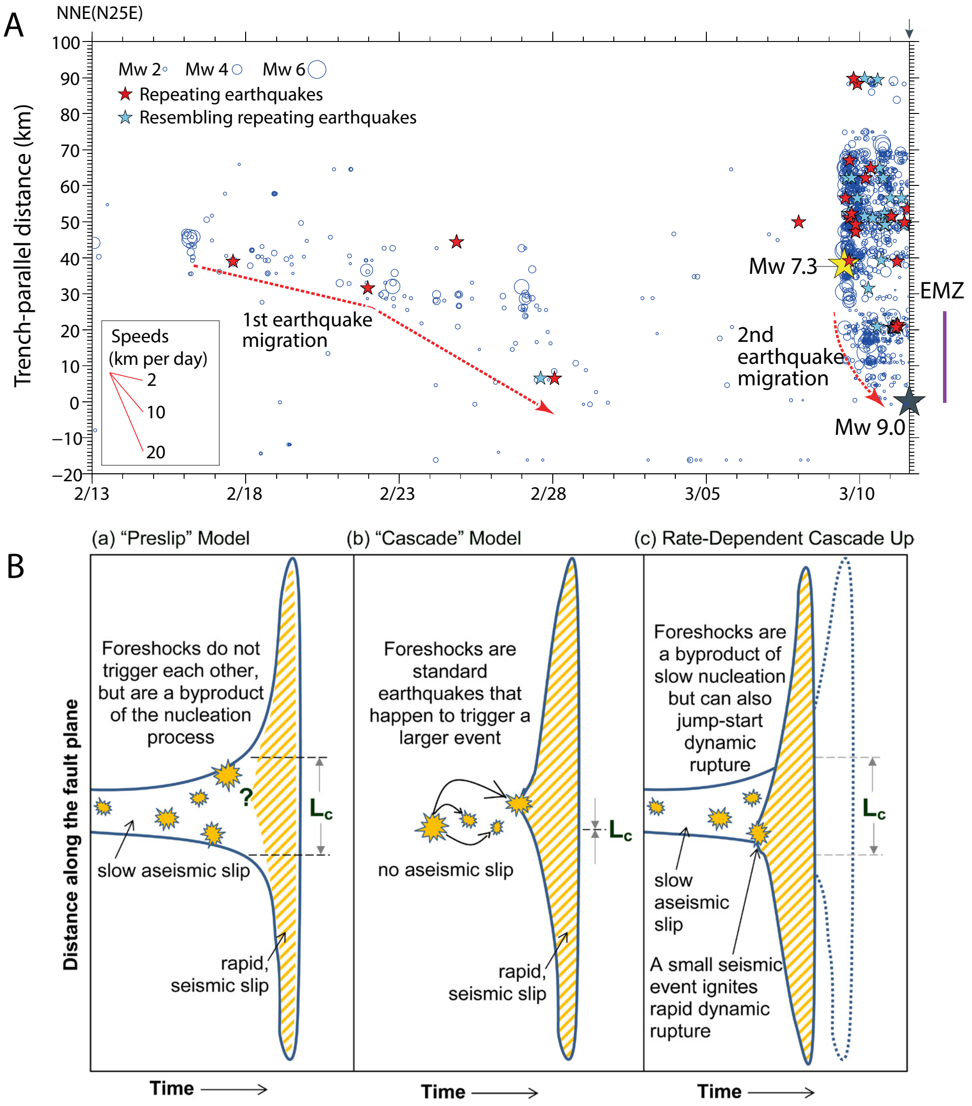


Figure FEC-3. *(A) Spatiotemporal evolution of foreshocks (blue circles) preceding the March 11, 2011, M9 Tōhoku-oki earthquake. Red dashed lines show apparent earthquake migration fronts propagating at 2 to 10 km per day. Note the clear spatio-temporal progression both during late February of 2011 and between the M7.3 foreshock and the mainshock (from Kato & Ben-Zion, 2020, modified from Kato et al., 2012). (B) Illustration of possible earthquake initiation models and associated foreshock scenarios involving substantial slow slip (preslip model), standard triggering relations (cascade model), or a combination of the two (rate-dependent cascade up model). Laboratory experiments support an accelerating earthquake nucleation process that expands to a critical nucleation length scale (Lc) preceding the dynamic mainshock rupture (from McLaskey, 2019).*

at analog sites, measuring material properties in the laboratory, and determining the history of slip events and tsunamis from paleoseismology.

Integrative modeling requires the development of 3D community codes to simulate dynamic ruptures and the earthquake cycle, in particular accounting for realistically complex geometry and material properties, viscoelasticity, inelastic yielding, and fluid transport. Augmenting these codes, and/or associated reduced order models, with data assimilation methods will enable direct integration of geophysical data.

FEC Science Question 3

Do distinctive precursory slip or distinctive foreshocks occur before earthquakes? What causes either foreshocks or precursory behavior?

Most, but not all, large earthquakes are preceded by foreshocks close in space and time, which suggests that a preparatory process may lead to the eventual mainshock (e.g., Bouchon et al., 2013; Trugman & Ross, 2019). However, such foreshock sequences are currently only recognized in retrospect. There is a long history of investigations of such seismicity changes leading up to large earthquakes, given the clear implications for short-term earthquake forecasting (e.g., Mogi, 1969; Hardebeck et al., 2008; Brodsky and Lay, 2014; Kato & Ben-Zion, 2020; **Figure FEC-3**). In some cases, there is evidence from geodetic observations or the occurrence of repeating microearthquakes that such precursory foreshock activity is associated with slow slip (e.g., Roeloffs, 2006; Kato et al., 2012; Ruiz et al., 2014; Meng et al., 2015; Radiguet et al., 2016; Obara & Kato, 2016; Socquet et al., 2017). Earthquake cycle computer simulations and laboratory experiments also suggest that slow slip events in or near the area of final rupture may be common (e.g., Matsuzawa et al., 2013; Nakata et al., 2016; McLaskey, 2019; Barbot, 2020).

A better understanding of precursory slip behavior would potentially provide an opportunity to raise hazard alert levels when precursory slow slip and/or foreshocks occur (e.g., Mignan, 2014). Although slow slip transients spatially and temporally related to earthquake activities have been observed in many convergent plate boundaries (e.g., Liu et al., 2007; Bartlow et al., 2014; Wallace et al., 2017; Colella et al., 2017), the underlying physics remain poorly understood. For instance, migrating foreshocks prior to the M9 Tōhoku earthquake (**Figure FEC-3A**) are intriguingly similar to seismological and geodetic observations prior to the M8 2014 Iquique earthquake (Ruiz et al., 2014). However, there does not appear to be a universal pattern to the existence or spatial and temporal scales of such precursory activity (e.g., Bürgmann, 2018, and references cited therein). As a result, recognizing and understanding foreshock sequences remains a challenge (Pritchard et al., 2020).

We hypothesize that precursory signals are distinctive and correlate with certain characteristics of large earthquakes, such as magnitude and tectonic setting. If precursory signals are to be useful in hazard risk mitigation, they must not only be recognizable but also detectable. One example of a possible precursory signal is a distinctive change in SSE recurrence interval and peak slip rate of SSEs before large megathrust earthquakes.

Testing this hypothesis requires acquiring the geodetic and seismic signals that precede earthquakes in order to constrain deformation over the entire seismic cycle. Because the purported precursors can be small and thus require near-fault instruments, and the part of the megathrust where major earthquakes initiate is predominantly under water, seafloor geodetic and seismic observations will be essential and complemented by interferometric synthetic aperture radar (InSAR), GNSS, and seismometers on land. It is equally important to be strategic about site selection for this question because we cannot currently predict earthquakes based on the occurrence of foreshocks, transient creep, or other phenomena. Subduction segments that are known to be capable of seismogenic-zone-spanning earthquakes and are late in the earthquake cycle provide the best chances of capturing needed data. To maximize the overall probability of definitively delineating the extent or absence of precursory activity before large earthquakes, it is necessary to build a portfolio of instrumented subduction zones by leveraging international observational efforts through SZ4D efforts and international collaborations. In addition, we need to better understand precursory signals across space-time and disciplinary scales. Precursors have been successfully identified at the laboratory scale (Yamashita & Ohnaka, 1992; Bolton et al., 2019), in various tectonic settings, and exhibiting different faulting mechanisms (Savage et al., 2017; Cabrera et al., 2022; Simon et al., 2021; Duboeuf et al., 2017), and have been proposed from examination of paleoseismic/morphotectonics records (Hawkes et al., 2005; Cicerone et al., 2009). Informative observations may also include a lack of precursory signals before large earthquakes (e.g., Wu et al., 2014). Diverse precursory observations allow modelers to test hypotheses for the nature of asperities and the role of frictional, rheological, and geometrical controls on slip behavior across the seismogenic zone and below it while challenging the validity of proposed mechanical models and their ability to capture the range of precursory and long-term transient pre- (and post-) deformation signatures.

FEC Science Question 4

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

Tsunamis can be disastrous accompaniments to major subduction zone earthquakes. However, it is unknown what circumstances trigger large fault offsets at the seafloor that in turn can generate major tsunamis. Factors may include unusual near-trench locking of the overriding and downgoing slabs, presence of splay faults within the downgoing slab, anomalously thick or low-friction sediments in the trench, inelastic accretionary wedge deformation, and low rigidity of the shallow forearc slab (Cummins & Kaneda, 2000; Seno, 2000; Fujiwara et al., 2011; Lay et al., 2012; Sallares & Ranero, 2019; Kodaira et al., 2020; Du et al., 2021; Wilson & Ma, 2021). Also key is understanding how plate convergence is accommodated in the subduction toe. How much deformation is inelastic and distributed vs localized as slip on the decollement and splay faults? Also of interest are “tsunami earthquakes,” which generate larger tsunamis than can be readily explained by earthquake magnitudes estimated from standard seismic wave analysis (Kanamori, 1972). Because tsunami earthquakes are relatively deficient in high-frequency energy, they are particularly dangerous to local populations, who are unlikely to self-evacuate as they would for an earthquake with ground motion that is more strongly felt. Subduction zone earthquakes can trigger both submarine and subaerial landslides, which can further contribute to tsunamigenesis. Such cascading hazards constitute an important link between the FEC and L&S components of

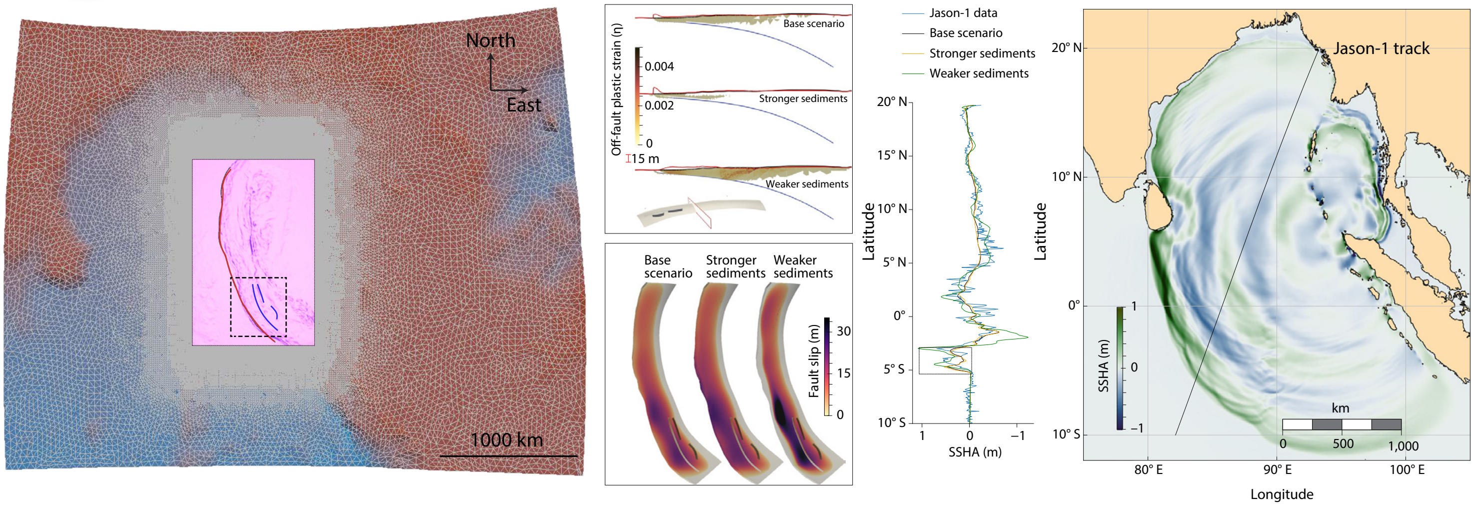


Figure FEC-4. *Observationally constrained three-dimensional dynamic rupture model and tsunami models of the 2004 Sumatra events demonstrating the importance of stress, rigidity, and sediments for earthquake tsunami dynamics. from Ulrich et al. (2022).*

SZ4D and are a feature of subduction zones in general, as described in **Chapter 2**.

The primary knowledge gap in models of tsunami inundation is often the details of near-trench rupture processes that control seafloor uplift and hence tsunami generation (Tanioka & Satake, 1996; Satake, 2015; Saito, 2019; Dunham et al., 2020). Recent work has vividly demonstrated that anticipating tsunami generation, which depends on fault rheology and system stiffness, requires accurate seismic and stress data and rock characterization (**Figure FEC-4**).

Improving our understanding of the conditions that generate tsunamis will require using historical records and/or paleotsunami studies to target regions with a known history of tsunamis and densely instrumenting the near-trench region. Linking earthquake source models to tsunami models (e.g., Lotto et al., 2019; Madden et al., 2021; Ulrich et al., 2022; **Figure FEC-4**) has the potential to revolutionize our understanding of when and where tsunamis occur. This can be accomplished by including constraints on the shallow configuration of the plate boundary acquired from high-resolution seismic imaging and constraints on frictional properties of the plate boundary fault near the trench from geological and experimental data. In particular, we aim to test the null hypothesis that tsunami generation arises from coseismic elastic deformation from fault slip, with possible rupture propagation onto splay faults predictable from the long wavelength state of stress and fluid pressure distribution, material structure, and frictional properties.

ACTIVITIES REQUIRED TO ADDRESS THE SCIENCE QUESTIONS

Recent advances in technology and increased understanding of faulting processes position the scientific community to make significant progress in answering these four questions. To assist in developing a strategy to address each question, we assembled *traceability matrices* that rigorously evaluate the required activities (**Appendix FEC-1**).

A first-order conclusion from the traceability matrices is that there are many commonalities in the information and activities required to answer the four FEC science questions, which fall under two overarching categories:

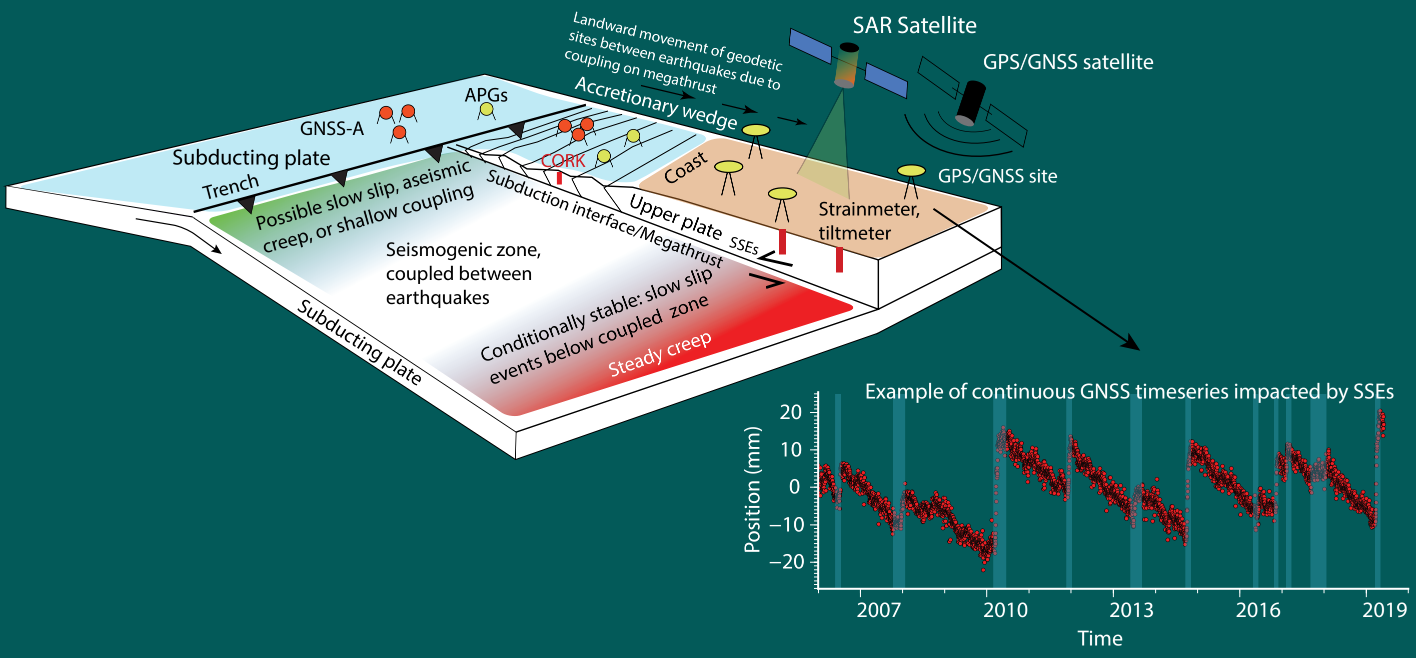
1. **New amphibious observations of subduction zone behavior, and**

2. **Innovative observational, geological, experimental, and modeling activities to understand what controls subduction zone behavior.**

An ambitious geophysical instrumentation effort is needed to acquire data that can provide a comprehensive characterization of subduction zone slip behavior over a range of temporal and spatial scales, including relationships between geodetic coupling, seismicity, tremor, and other types of slip behavior (e.g., **Figure FEC-5**). Historical, paleoseismologic, and geomorphologic data are necessary to build complete geological records of subduction zone earthquakes and deformation, estimate rates of geological processes, and provide context for present-day fault behavior.

An understanding of the processes and properties that control fault system behavior over the range of relevant scales will require tight integration of in situ and analog geological studies to integrate structure, conditions, and processes across temporal and spatial scales (e.g., **Figure FEC-6**); high-resolution geophysical imaging data to characterize subduction zone architecture and fault zone properties (e.g., **Figure FEC-7**); novel experiments that measure material properties and simulate processes at conditions currently inaccessible in the laboratory (**Figure FEC-8**); and the development of numerical models to test hypotheses across spatial and temporal scales and evaluate the interconnectedness of subduction system processes.

Figure FEC-5. *A schematic illustration of the types of slip on a subduction plate interface and the geodetic measurements that can be used to constrain these behaviors. Actual subduction zone behavior may vary significantly from this simple diagram. APG = Absolute Pressure Gauge. CORK = Subseafloor observatory. GNSS = Global Navigation Satellite System. SAR = Synthetic aperture radar. From Wallace et al. (2021).*



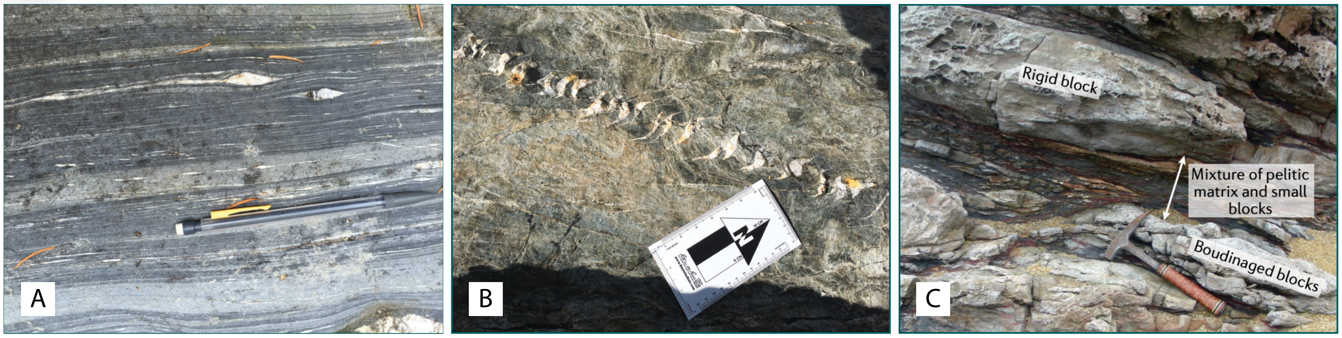


Figure FEC-6. *Field photos of exhumed subduction zone rocks: (A) mylonite from the Leech River paleo subduction thrust, Vancouver Island, BC, Canada; (B) en échelon veins from the Arosa Zone, Swiss Alps; (C) distributed deformation in an accretionary melange, Chrystalls Beach, New Zealand (from Kirkpatrick et al., 2021).*

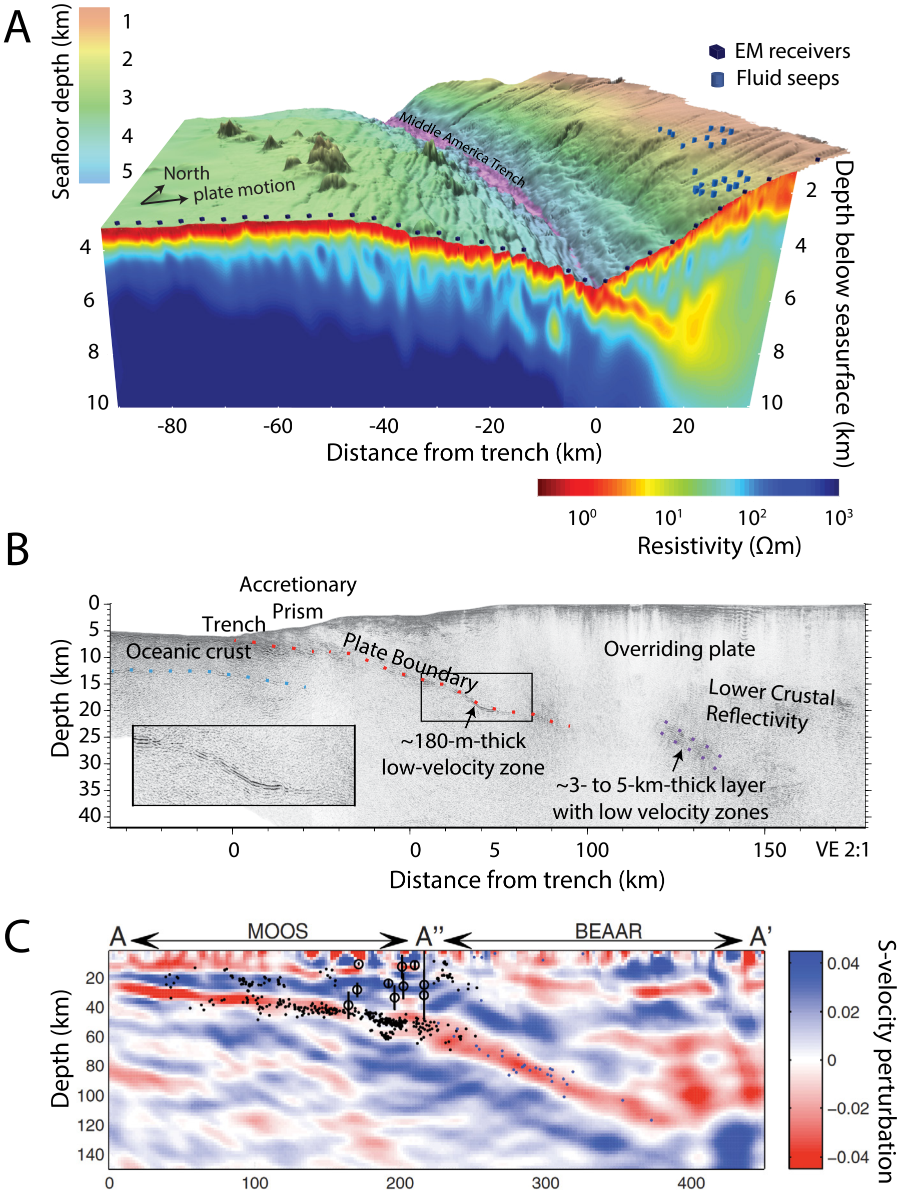


Figure FEC-7. *Complementary geophysical imaging of plate boundary geometry and properties by (A) CSEM imaging (from Naif et al., 2016), (B) seismic reflection imaging (from Li et al., 2015), and (C) Receiver function imaging (from Kim et al., 2014).*

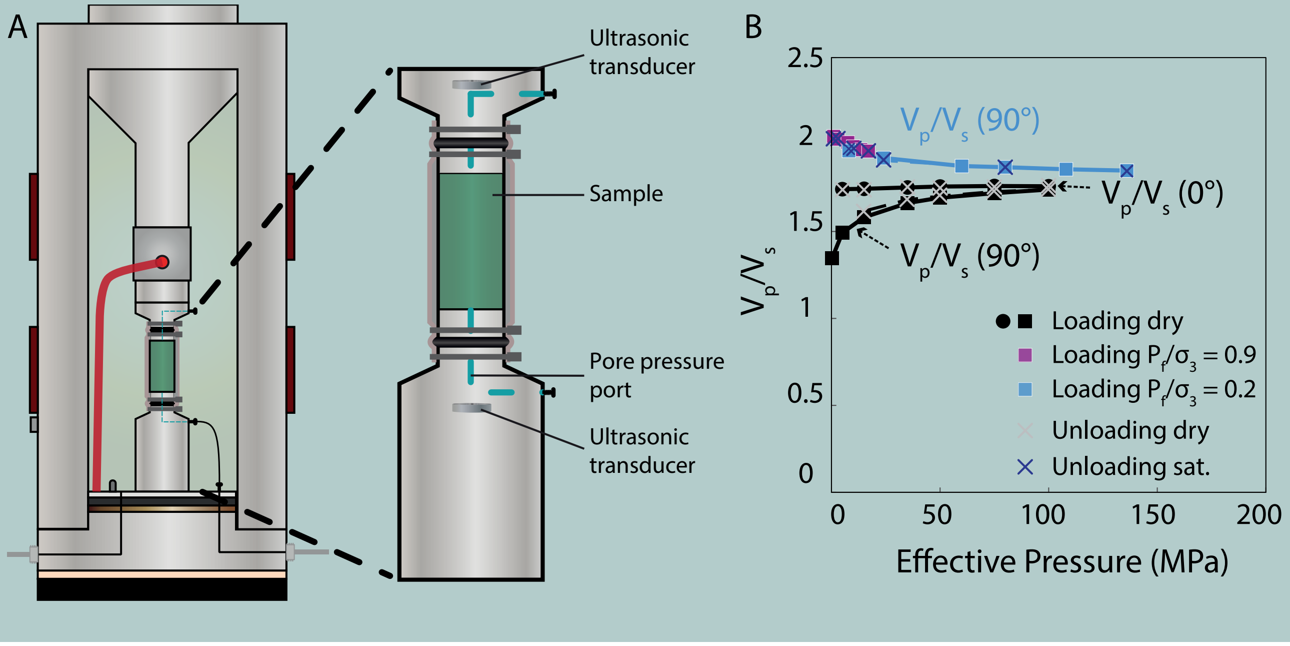


Figure FEC-8. *(A) A triaxial deformation apparatus used to measure rock properties in the laboratory, in this case elastic wave speeds in metasediments; (B) Vp/Vs determined from laboratory measurements for comparison with seismic tomography. From Fliedner & French (2021).*

The coordinated, amphibious and interdisciplinary efforts described above require significant human and physical infrastructure. **Our highest priorities for near-future physical infrastructure are seismic and geodetic instrumentation to measure megathrust behavior; experimental deformation apparatuses capable of simulating the fluid conditions, pressures, temperatures, and strain rates that are required to study the processes that control faulting and earthquake hazards in subduction zones but are currently inaccessible with existing experimental equipment; and field infrastructure to support a coordinated and sustained effort to characterize modern and analog fault systems**. We also emphasize the urgent need for other infrastructure and activities for building comprehensive portraits of subduction zone fault geometries, properties, and histories, all of which are essential to provide context for results that will arise from SZ4D geophysical and experimental infrastructure.

Based on the *traceability matrices*, we have constructed an integrated science plan, including observational, experimental, and numerical activities, which is described in the following section.

SCIENCE PLAN OVERVIEW

The science questions and *traceability matrices* provide a framework for defining the strategy and scale of the Faulting and Earthquake Cycles component of SZ4D. Addressing the FEC science questions requires:

1. An ambitious geophysical observational effort to characterize fault behavior over the entire seismogenic zone, and
2. Modeling, geological studies, experimental work, and geophysical imaging to contextualize and understand the physical processes underlying fault behavior.

Close integration of these components requires a coordinated planning process throughout SZ4D and a phasing of activities. While specific details will depend on the regions selected for instrument deployment and field study, the general design and phasing of activities to achieve the project goals can be anticipated.

The primary component of the FEC geophysical observational effort is an amphibious geodetic and seismic network (hereafter called MegaArray). Our focus on great earthquakes requires constraining the kinematics of slip over the length and width of a seismogenic segment, including regions updip and downdip of the seismogenic zone, regions of transitional behavior, and other faults in the overriding and incoming plates (~500 x 500 km). Spatial variations in deformation over this scale are expected to control where sufficient elastic energy can accumulate to rupture in an earthquake of magnitude approximately 8 or larger. Likewise, large slow slip events, including those purported to be precursors to large subduction zone earthquakes span ~100 km (e.g., Ito et al., 2013) and thus also require a large study area. On the other hand, knowledge of the earthquake source location at high precision and detailed measurements of slow slip are also required to examine fault interaction (Question 1) and relationships between different modes of slip (Question 2). To meet both of these needs, we outline a phased effort for MegaArray involving backbone characterization over the entire study area (Phase 2a) followed by densified observations in areas of interest (Phase 2b; **Figure FEC-10**). To ensure the full three-dimensional regional context of faulting is known, additional complementary data are also required over the footprint of MegaArray, including bathymetric mapping and geophysical imaging.

Geological, modeling, and experimental efforts need be coordinated with phasing of the MegaArray, both to inform design of different phases of the array and to interpret the results that emerge from it. Geological work will follow a parallel phasing involving backbone site characterization, sampling, and testing followed by densified characterization of deformation processes, rock properties, and slip history (**Figure FEC-10**). Experimental work will follow a similar phasing and will evolve as new observations and samples are available and as equipment is developed.

The Modeling Collaboratory for Subduction has identified several critical needs to facilitate FEC-related modeling (Dunham et al., 2020). These include community earthquake cycle modeling codes that couple subduction zone fault slip with additional relevant processes (viscoelasticity, inelastic yielding, fluid transport, pore pressure, temperature evolution, and tsunami generation), which are required for physics-based seismic hazard assessment and early warning capabilities. They will also be necessary to understand linkages between subduction zone behaviors and structures, and to understand processes and quantitatively test hypotheses. Results will depend on the stress state and material structure, motivating development of codes for longer timescale geodynamics that account for feedbacks with the evolving land- and seascape, localization of deformation and formation of faults, thermal structure, and loading from mantle convection and plate tectonic forces. Regional-scale modeling must be paired with global geodynamics modeling to account for processes such as trench rollback. The development and utilization of these codes can begin immediately and are anticipated to extend across all phases of the SZ4D instrumentation effort, with focused modeling efforts at specific times to help guide array design and data interpretation as described subsequently in the phasing plan.

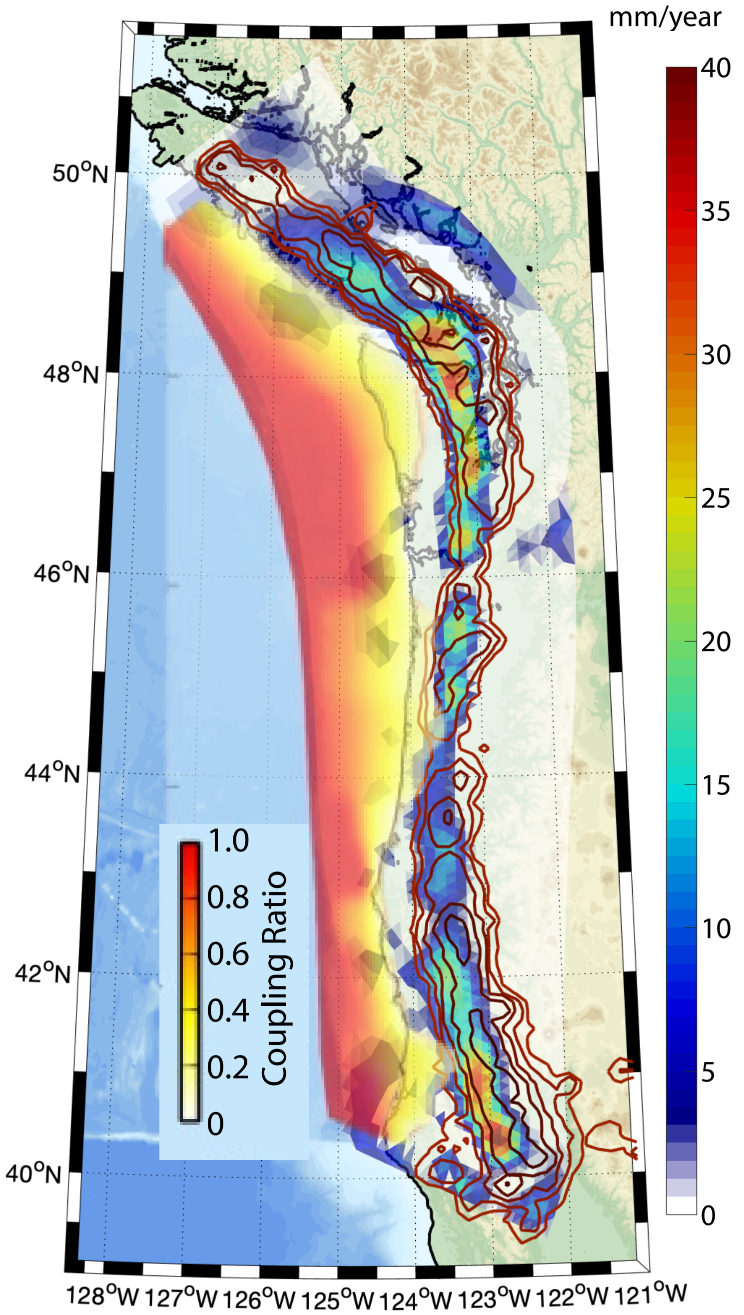


Figure FEC-9. *Comparison of geodetically detected plate coupling (red to yellow colors), geodetically detected slow slip (rainbow colors, reported as a long-term average slip rate), and seismically detected tectonic tremor (brown contours) in the Cascadia subduction zone from existing onshore seismic and geodetic data (Bartlow, 2020). Coupling model is from Schmalzle et al. (2014), and tectonic tremor is from the Pacific Northwest Seismic Network catalog (Wech, 2010).*

Overall, three primary phases of activities have been defined for project implementation, which parallel the other parts of SZ4D and are summarized below. During all three phases of the program, instrumental and field observations, laboratory experiments, and numerical modeling will inform each other (e.g., planning of new data acquisition and planning for new experiments and models). Details on activities envisaged for each phase are given in **Appendix FEC-2**. Although all components need to be closely coordinated, phasing may take place on different timescales dictated by specific needs and funding opportunities. Furthermore, analysis and integration of all components need to be ongoing throughout the SZ4D program.

PHASE 0 is a preparatory phase to develop and refine the SZ4D implementation plans. This phase includes assessing existing infrastructure in possible study areas and identifying how SZ4D can strategically build on them, and focused modeling efforts to inform the design of future observational programs. This phase will also involve building partnerships with possible domestic and international partners.

PHASE 1 includes:

1. Synthesis and analysis of existing data, modeling, and experimental work with existing capabilities aimed at addressing FEC scientific questions;
2. Technology development to ensure the availability of appropriate instrumentation, and laboratory and modeling capabilities; and,
3. Continued organizational and planning tasks to develop and strengthen partnerships. Because this phase leverages existing data, it can and should have a large geographical scope.

A wealth of existing data from many subduction zones affords us the opportunity to make progress toward SZ4D goals during Phase 1 prior to the availability of new, dedicated observations or experimental capabilities. Although the volume and quality of existing data vary greatly between subduction zones, comparative studies are necessary to generalize results from any specific subduction zone to general subduction processes. For example, studies should include:

1. Mapping plate boundary fault system architecture and determining fault zone properties,
2. Constraining the thermal state of the subduction zone from available thermal data, and
3. Evaluating subduction zone inputs, including sediment thickness and composition, porosity, heterogeneity, and roughness of the incoming plate. Compilation, selective reprocessing, and integration of existing data will help evaluate the importance of these observables and highlight critical data gaps.

Likewise, reevaluation and interpretation of existing geophysical data on subduction zone slip behavior can be used to address FEC science questions and guide planning for future data acquisition. For example, employment of new methods (e.g., machine learning techniques) can improve identification of slow slip events and slow earthquakes (e.g., **Figure FEC-9**) and can advance characterization of uncertainty in estimates of fault coupling and earthquake source parameters.

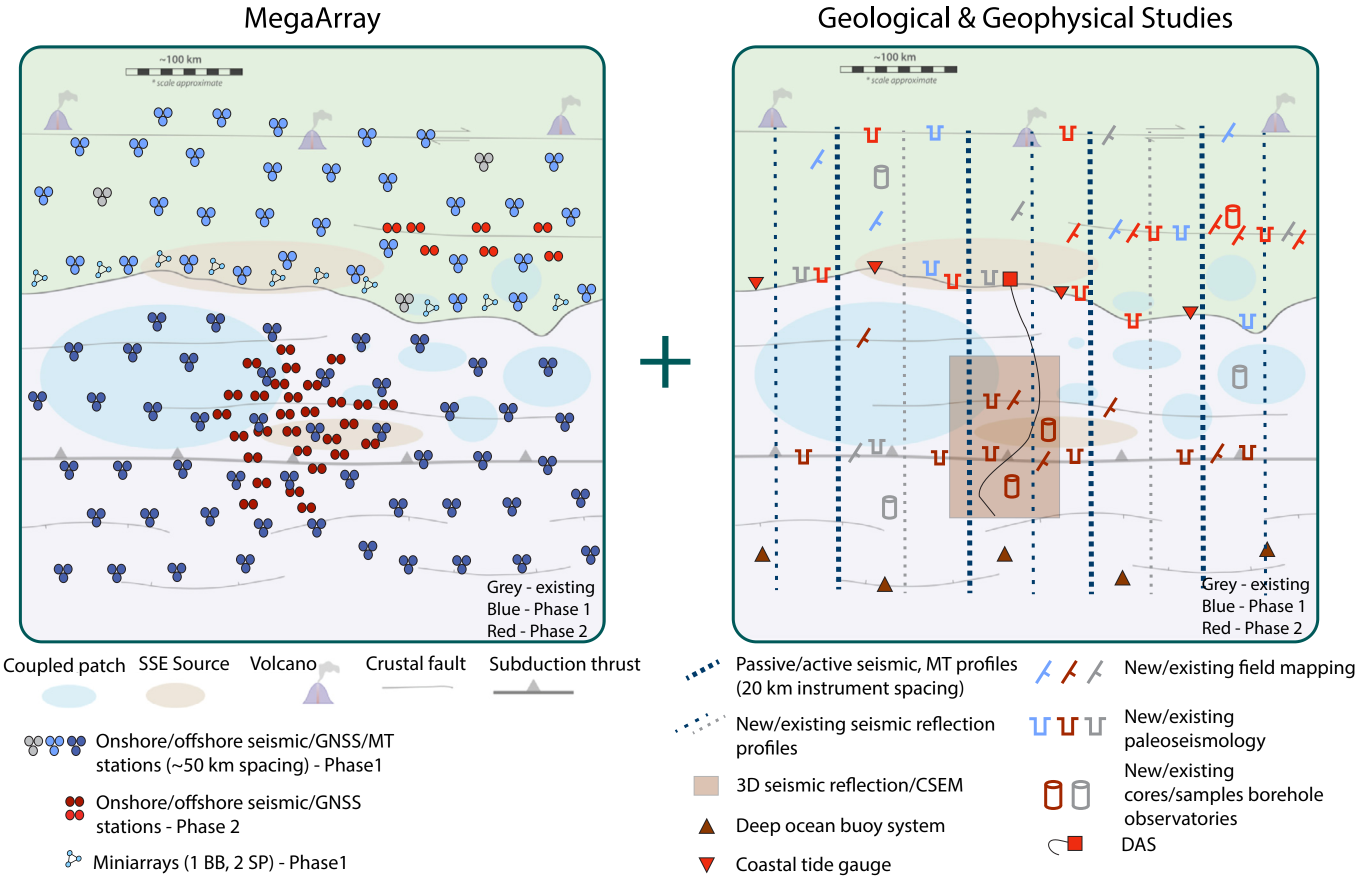
Multi-cycle numerical simulations will play a significant role in predicting which results can be generalized, as the global portfolio of subduction zones covers the entirety of the seismic cycle (inter-, pre-, co-, and post-seismic); these efforts should begin in Phase 1 and continue throughout SZ4D. Initial numerical modeling using current capabilities will be performed for the target site(s) to establish integrative, large-scale system attributes.

Geological and experimental efforts should also begin in Phase 1. To provide long-term temporal patterns of earthquakes, paleotsunami recurrence and inundation extent, spatial patterns of shaking intensity, along-strike rupture dimensions, and the vertical component of the earthquake deformation cycle, paleoseismology studies can be undertaken immediately and integrated with complementary geological and geophysical datasets (e.g., Clark et al., 2019; Walton et al., 2021). A compilation of existing studies of exhumed subduction rocks and the processes that they record is also needed to inform decisions on prioritization of new measurements and data collection (e.g., Phillips et al., 2020). This compilation would summarize deformation conditions, structure, composition, and fluid properties and the corresponding evidence of deformation processes over the full range of conditions from the seafloor to downdip of the seismogenic zone (Rowe et al., 2013; Agard et al., 2018; Behr & Burgmann, 2021; Kirkpatrick et al., 2021). Targeted reconnaissance work to constrain undocumented properties and processes of potential analog sites will be required. The experimental communities can conduct research on available samples and at the conditions of existing laboratory equipment and synthesize existing experimental data.

Phase 1 will also involve infrastructure development needed for Phase 2 observations. Examples include development of ocean bottom seismometers capable of recording for 5 to 10 years, and experimental apparatuses capable of measuring physical properties over the full range of seismogenic zone pressures and temperatures, as well as conditions relevant to slow slip and tremor. Despite rapid advances in (super-)computing and data-driven modeling, currently there exist no full-physics models that capture all planned observational and laboratory data streams. The modeling community will identify numerical methods and specific model development needed to handle the anticipated increase in data volume and diversity, unprecedented data resolution, and associated uncertainties expected from the proposed experiments. Infrastructure needs for an ambitious, coordinated onshore geological effort also need to be defined.

Organizational activities will involve strengthening partnerships. International collaborations are essential for the global scope of the SZ4D project. SZ4D efforts to understand the processes underlying geohazards complement work by US science agencies on hazard characterization and mitigation. Finally, discussions with offshore

Figure FEC-10. *Illustration of ideal notional acquisition of geophysical and active-site geological data during Phase 2a (blue symbols) and Phase 2b deployments (red symbols). The left panel shows MegaArray and the right panel shows geological and geophysical studies required to provide context for MegaArray. Note that the backbone amphibious seismic/geodetic network deployed during Phase 2a would remain in place during Phase 2b. Phase 2a would leverage existing data (gray symbols). Paleoseismology includes trenching, coastal inundation, shaking/mass slumps and terraces/crustal uplift. Additionally, bathymetry data offshore and InSAR data onshore are also needed across the study area. SSE: Slow-slip event, MT: Magnetotelluric, CSEM: Controlled-source electromagnetic, DAS: Distributed acoustic sensing, GNSS: Global Navigation Satellite System.*



cable operators and owners could potentially open up detection capabilities that would be impossible under any other circumstance.

PHASE 2 will involve new observational programs coupled with experimental and numerical studies. The observational and experimental components are divided into two parts. The first part (Phase 2a) will involve lower resolution, backbone characterization of subduction zone behavior and structure across the entire study area, while the second part (Phase 2b) will involve detailed, higher resolution characterization in areas of interest (**Figure FEC-10**).

The heart of the Phase 2 geophysical effort is the amphibious MegaArray, whose aim is to characterize geodetic locking and slip behavior (e.g., earthquakes, slow slip events). MegaArray is the centerpiece of observational effort and the highest priority component of the envisaged geophysical infrastructure. To address the FEC science questions, this array needs to span a minimum area of approximately 500 x 500 km, extending from ~100 km seaward of the trench to the backarc. Given this significant scale, the aim of MegaArray during Phase 2a is to capture the behavior at intermediate resolution (~40–50 km); MegaArray will comprise a backbone network of on-land and offshore geodetic and seismic instruments for a minimum of 5–10 years. Informed by the Phase 2a results, additional instrumentation will be deployed to densify MegaArray during Phase 2b to obtain higher-resolution constraints on slip behavior in smaller areas of interest, such as slow slip patches or places where there might be changes in fault coupling (**Figure FEC-10**). The part of MegaArray deployed in Phase 2a will remain in place during Phase 2b, and the combined MegaArray network will operate for at least another five years.

The processes underlying observed active deformation can best be understood with supporting geologic measurements; electromagnetic, active-source seismic, and heat flow profiles; swath bathymetric maps; and SAR data (**Appendix FEC-2**), and these will following a similar phasing to MegaArray, with backbone characterization during Phase 2a and more detailed efforts in Phase 2b. Some of the datasets needed for Phase 2a may already exist or can be acquired by domestic or international partners and can be leveraged by SZ4D.

Phase 2a will include active/passive geophysical imaging of subduction zone architecture across the same footprint as the MegaArray to determine the geometries and properties of the megathrust and other faults and characterize the subducting and overriding plates (e.g., **Figure FEC-7**). During Phase 2b, higher-resolution geophysical imaging will be done in areas of interest, particularly areas of densified instrumentation for MegaArray (**Figure FEC-10**). One potential opportunity is the use of seafloor seismic nodal deployments, which are currently not common in academic studies.

During Phase 2a, relevant onshore exhumed analog sites will be identified and sampled, and laboratory experiments on reference, offshore, and onshore materials can be conducted as sampling proceeds (**Figures FEC-10** and **FEC-11**). Samples collected from the regional and analog sites will be analyzed as well as additional reference materials. Paleoseismology studies will also be carried out to best constrain past megathrust and upper plate fault ruptures. During Phase 2b, studies of onshore exhumed analogs and laboratory experiments will continue but will become more targeted to address emerging observations from instrumentation and modeling efforts. Targeted and intensive geological observations will also be collected, including denser fault characterization and paleoseismology studies. Another important component of Phase 2B will be targeted drilling to obtain samples and to install offshore borehole observatories.

Throughout Phase 2, numerical, analytical, and statistical modeling that incorporates newly acquired data and results will continue and complement observations, and will further guide densification and expansion of observations for Phase 2b. Modeling of deformation processes will proceed and be updated as high-resolution data are acquired.

PHASE 3 will involve continued integration and interpretation of the observations, experiments, and numerical models from the FEC Phase 2a and 2b efforts and those of other parts of SZ4D. A significant and dedicated synthesis effort is required following the completion of most aspects of the observational program to integrate results from interdisciplinary components of SZ4D and address the science questions. This phase will also involve integration of SZ4D results into regional hazards assessments in partnership with local stakeholders.

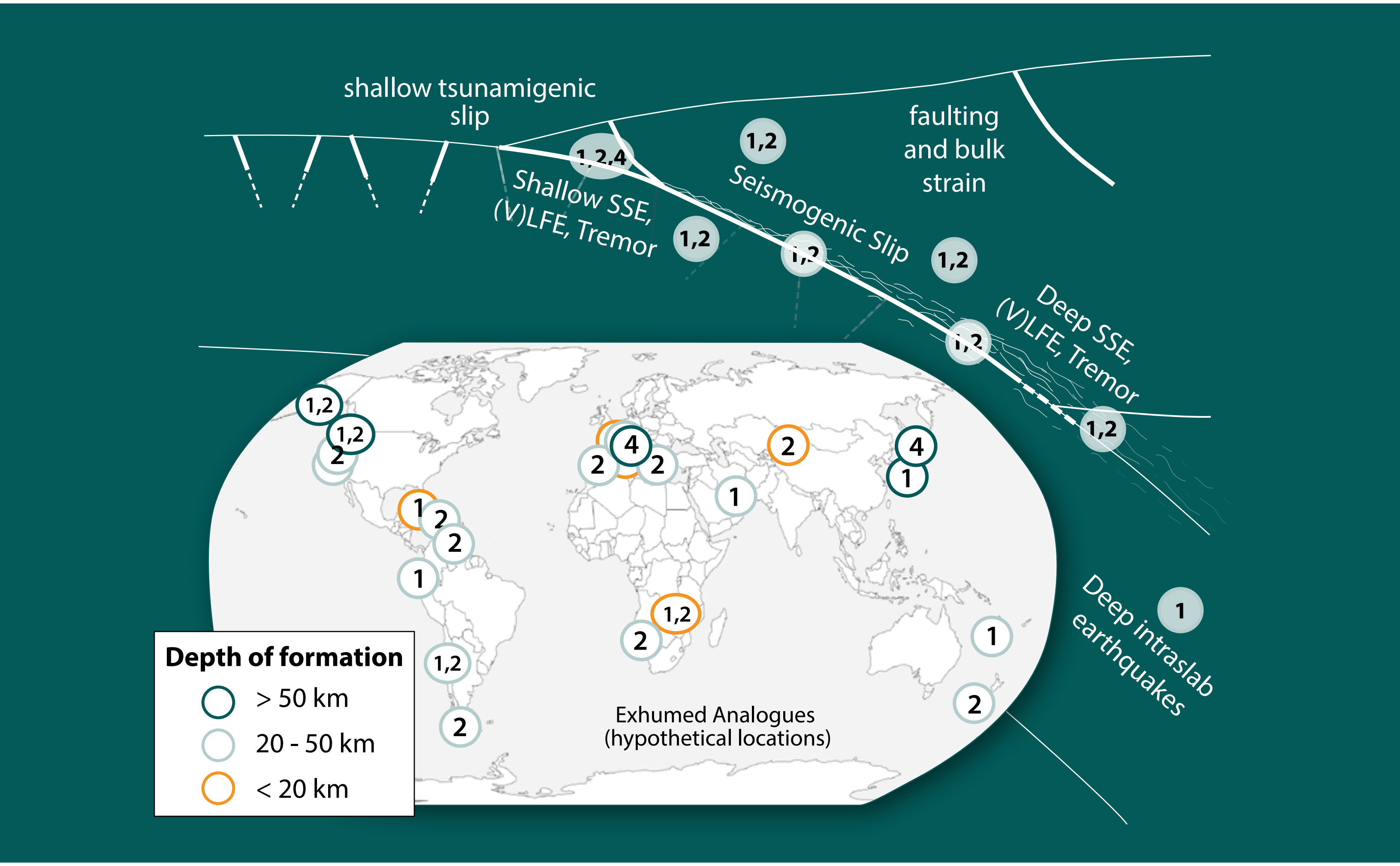


Figure FEC-11. *Illustration of strategy for sampling and analysis of exhumed samples. Circled numbers indicate FEC science questions for which exhumed samples from a given part of the subduction system would be most relevant.*

PORTFOLIO STRATEGY AND SITE SELECTION

To address all of the FEC science questions, new observations of active subduction zone systems are critical, and a strategy is necessary to define the suite of sites. Our strategy is to build a portfolio of sites capable of producing large subduction zone earthquakes and tsunamis and that have locked fault zones. The sites should also exhibit variability in the mode and speed of slip within and between them. The data gathered from this portfolio of sites will be used to understand controls on slip behavior on the megathrust and on other subduction zone faults. Knowledge of seismic coupling is important for addressing all four science questions; the degree to which the plates are locked affects all aspects of the seismic cycle as well as the related landscape and volcanic processes. Question 3 on earthquake precursors demands studying a suite of sites in order to maximize success. For this particular question, the stage in the seismic cycle is an important factor in site selection for focused SZ4D observational programs. We expect to rely heavily on leveraging international partners to ensure that the collective global portfolio of instrumented subduction zones will capture key information.

Guided by the science questions and the Traceability Matrix (**Appendix FEC-1**), which specify the detailed measurements needed to address the science questions, a list of required scientific attributes was developed (**Figure FEC-12**). Note that all the high-priority attributes can be traced to the scientific questions (**Figure FEC-12**). A subset of these criteria is relevant to the hazard associated with a particular subduction zone, which is relevant to the overarching mission of SZ4D and to potential domestic and international partners. An Inventory of Subduction Zones was assembled that tabulates these high-priority attributes for Earth's major subduction zones (**Appendix FEC-3**) and thus can be used to inform decision-making about site selection. Based on our compilation, we score each subduction zone on how well it satisfies a given scientific criteria, weighting each criterion based on the number of science questions for which it is relevant (**Figure FEC-12**) and on the relevance of that criteria to the hazard of the subduction zone. See **Appendix FEC-3** for details. The thresholds in this scoring are arbitrary, and the total scores given to a particular subduction zone would vary if different thresholds were chosen; consequently, the specific score given to any particular subduction zone is not meaningful. Other important factors for identifying possible study sites include consideration of overlaps with other components of SZ4D, the priorities of potential domestic and international partners and local stakeholders, the availability of existing data and infrastructure, and logistical considerations.

The screening of sites in **Appendix FEC-3** highlights some regions that would be particularly favorable for addressing the FEC science questions. Several subduction zone segments along South, Central, and North America possess many of the high-priority scientific attributes, including parts of the Chilean subduction zone, Ecuador, Mexico, Cascadia, and parts of the Alaska/Aleutian subduction zone. Other sites that score highly in this screening are parts of the Japan and Sumatran subduction zones. Considering this screening, logistical considerations, and the needs of other parts of SZ4D, we propose that the ideal portfolio includes **Chile, Cascadia, and Alaska**. All sites are capable of producing large earthquakes and exhibit regions of strong coupling. These sites

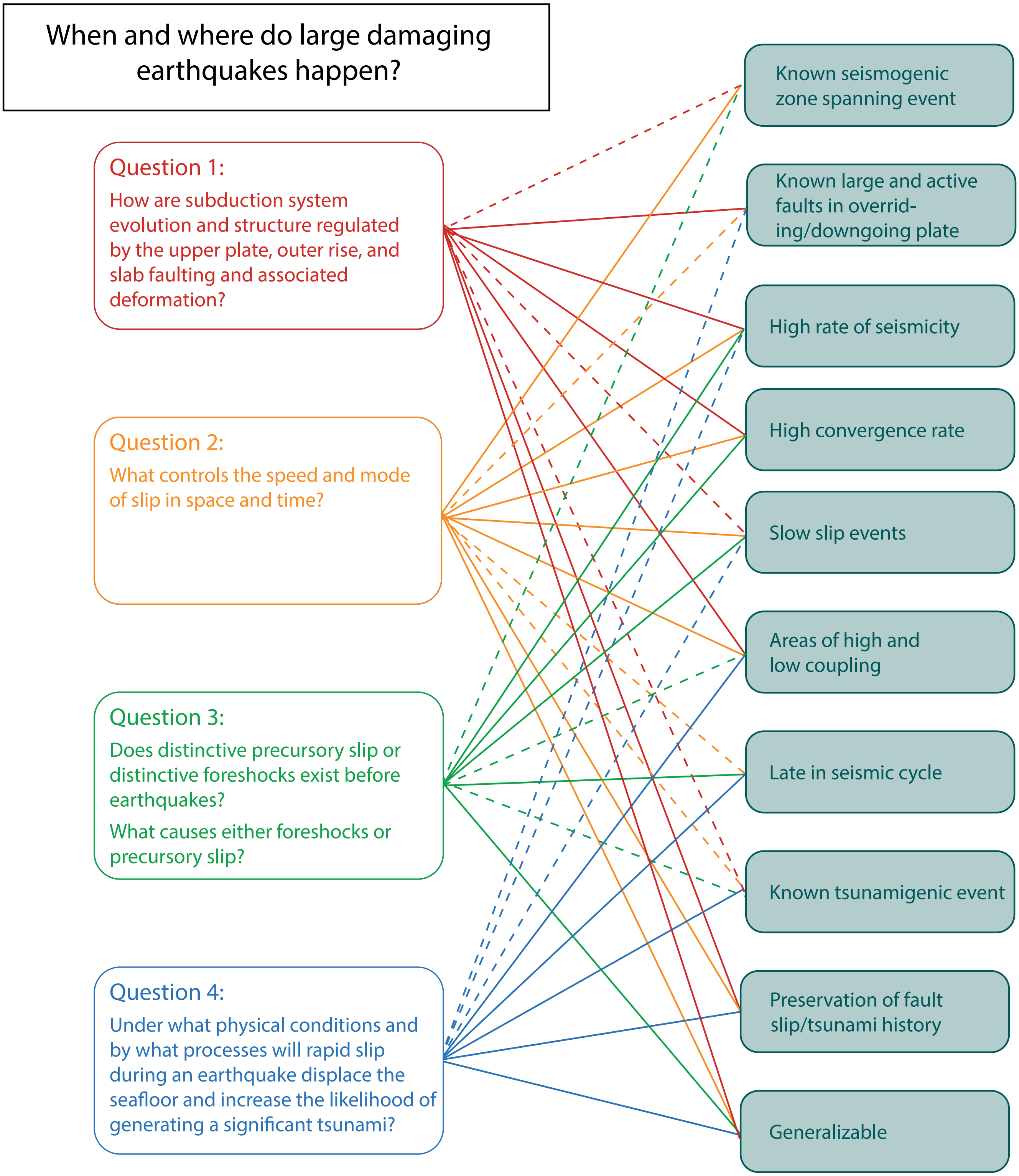


Figure FEC-12. *Wiring diagram showing relevance of subduction zone criteria to each scientific question. Thick, solid lines indicate that the criterion is required to address the question. Thin dashed lines indicate that the criterion is desirable but not required to address the question.*

display differences and similarities in behavior and hypothesized controlling parameters (e.g., thermal structure, subduction inputs) and stage in the seismic cycle, enabling comparisons that are important to address the science questions and that will advance our understanding of hazards in all sites. Foundational observations and knowledge exist in all sites that can be leveraged by SZ4D. Finally, this combination of sites enables excellent national and international partnerships.

The largest risk in the United States from subduction earthquakes is Cascadia; however, that subduction zone poses fundamental challenges to geophysical observation. The slow convergence and low earthquake rate limit the opportunities to learn from events prior to a catastrophic occurrence. A focused effort on Cascadia would be likely to either fail to capture any major earthquake or, perhaps worse, capture the anticipated devastating earthquake without having a chance to utilize any new information from SZ4D beforehand. A faster, but otherwise analogous subduction zone, provides a much higher probability of learning and developing our knowledge base so that we can usefully address the Cascadia problem.

Both Chile and Alaska are useful analogs for Cascadia, however, the logistical challenges of the limited land, rough seas, and extreme weather of Alaska also impact the infrastructure that would be required for MegaArray. Thus, we recommend focusing MegaArray in Chile. Targeted geophysical observations should be collected along the Cascadia and Alaska subduction zones to fill knowledge gaps and enable comparisons; one possible example is seafloor geodesy in Cascadia and Alaska. Analyses of existing data, field studies of active deformation, and numerical modeling are expected to be spread more evenly across these three sites. Analog studies will require a larger geographic spread.

To understand the processes that control subduction zone fault slip behavior, we also require geologic and experimental studies. Thus, the geological component of FEC also requires portfolios of multiple active and analog geology sites. Geologic studies of active subduction zones are necessary to constrain deformation over geologic timescales and modern deformation on upper plate faults and will be coordinated with the sites of instrument deployment for FEC and L&S. Study of onshore exhumed analog sites will be required to define the structures, rock compositions, and physical conditions at depth that control variations in coupling and slip behavior in space and time (e.g., **Figure FEC-11**). A preliminary **inventory of potential analog field sites and their characteristics** provides a useful starting place for assessing the geological possibilities. Phase 1 will build on this work to develop a short list of potential analog sites.

The final selection of study areas and balance of activities and infrastructure between them will take into account overlapping needs of the other SZ4D working groups, logistical considerations, and the priorities of domestic and international partners and local stakeholders as discussed in the Geography section of this plan (**Chapter 5.1**).

SUMMARY AND OUTLOOK

A long-standing grand challenge in Earth science is understanding when and where large earthquakes occur. We have identified four sub questions where the scientific community is poised to make major new advances due to recent progress in understanding, the availability of new instrumentation and advancements in computational capabilities. Addressing these questions and the broader grand challenge of controls on large earthquakes necessitates collection of high-resolution data. These data will provide new constraints on subduction zone fault behavior. Detailed geological, experimental, and geophysical studies will enable characterization of fault zone properties and architecture. The measurement and modeling of fault zone properties and processes will lead to a better understanding of fault zone behavior and contextualize it, as detailed in FEC traceability matrices. A concerted and focused community effort involving ambitious and coordinated observational, experimental, and modeling components is needed, both within the FEC part of SZ4D and with other parts of SZ4D. To be successful, this deep and long-term collaborative effort necessitates that activities are interleaved and phased, as described in the FEC notional science plan. The FEC component of SZ4D also has significant facility needs; the technically complex physical infrastructure of the geophysical and laboratory components requires professional support. The need for both tight integration and significant observational infrastructure supports a geographical focus on a small number of active subduction zones. We are optimistic that the strategy described here will yield fundamental new insights into subduction zone deformational processes and on the resulting hazards.

Achieving the goals set forth by the FEC component of SZ4D will not only provide new understandings of the fundamental processes that control when and where large, damaging earthquakes happen, but will also result in tangible improvements in our ability to mitigate risks posed by earthquake and tsunami hazards. Answering the four driving science questions will provide improved physics-based models for earthquake and tsunami hazards in all parts of the subduction fault system that will both allow for regional assessment of and planning for hazards, as well as result in an improved ability to monitor, interpret, and respond to the precursors to large earthquakes in real-time. While the scope of SZ4D necessitates geographic focus, through integrative and comprehensive study, FEC will provide a fundamental understanding and the development of new conceptual and physical models of earthquake hazards that can be employed in other regions to improve hazard mitigation.

SIDEBAR 2

A modern view of subduction-zone earthquakes

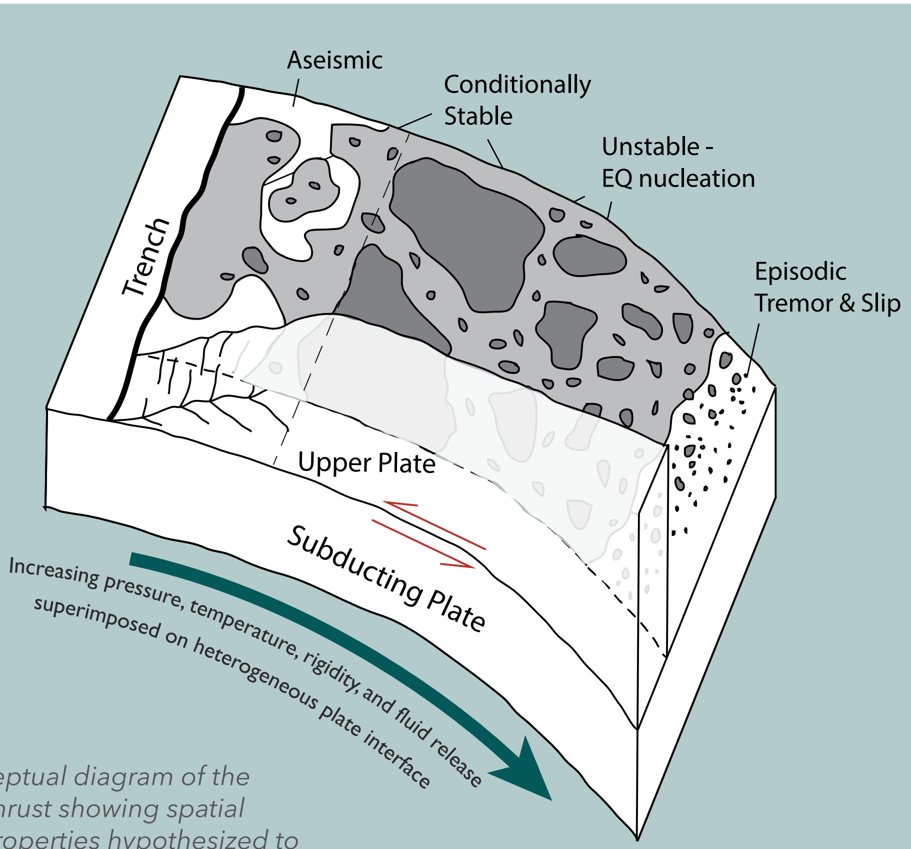


Figure S2-1. *Conceptual diagram of the subduction megathrust showing spatial heterogeneity in properties hypothesized to underpin the diverse spectrum of observed slip modes. After Li et al. (2015) and Lay et al., (2012).*

Over the past 2.5 decades, the advent and deployment of modern instrument networks has sparked a revolution in our view of subduction zone earthquakes. This view has evolved away from simplified models in which a "seismogenic zone" that locks interseismically and hosts great earthquakes is restricted to a specific depth band, and is bounded by regions where the megathrust slips via continuous creep. Instead, we see a much more complicated and heterogeneous picture (**Figure S2-1**). A rapidly growing body of observations has revealed a spectrum of slip behavior on subduction megathrusts globally, spanning timescales from seconds to years. These modes of slip include regular (fast) earthquakes; tsunami earthquakes and low frequency and very low- frequency earthquakes characterized by a higher abundance of low-frequency energy in radiated seismic waves than for typical earthquakes; slow slip events, in which transient fault motion occurs over weeks to months; and continuous aseismic creep. These diverse slip behaviors are in some cases patchy, overlapping in their spatial extent, and are not restricted to specific depth, temperature, or pressure conditions.

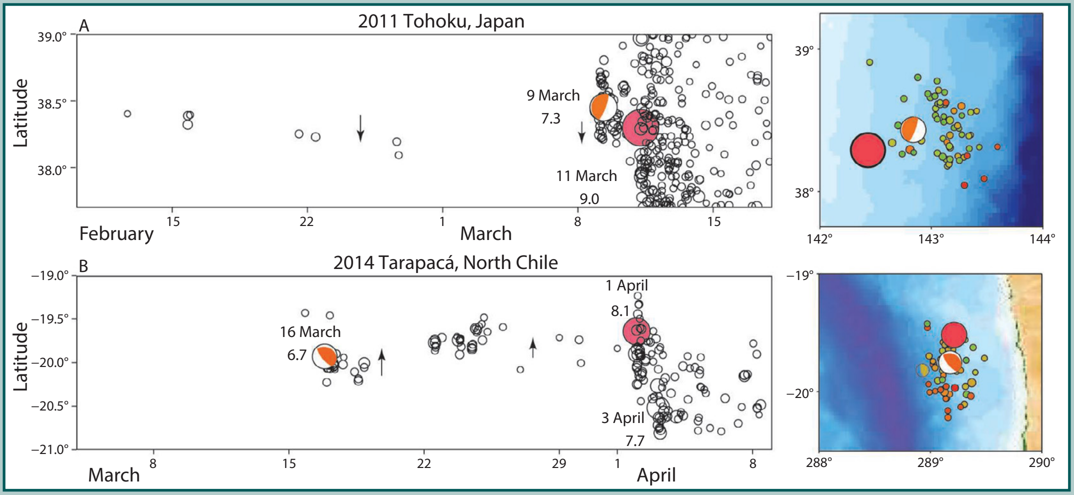


Figure S2-2. *Spatiotemporal evolution of seismicity leading up to the 2011 M 9.0 Tohoku (top) and 2014 M 8.1 Tarapaća (bottom) earthquakes (reproduced from Brodsky & Lay, 2014), showing the migration and coalescence of foreshocks leading up to the mainshocks of these great earthquakes.*

The recognition of these diverse slip behaviors has sparked a revolution in seismology, geodesy, and laboratory rock/fault mechanics – opening new windows to understand the properties [rheology?] of the subduction interface; the interplay of fluids, geology, and metamorphism; and the physics and scaling of earthquakes. Additionally, modern observations of foreshock migration and coalescence show that for at least some large events, a preparatory phase may occur and be detectable with a sufficiently dense network (**Figure S2-2**). These emerging observations also highlight potentially important interactions of fault patches, including triggering and precursory phenomena.

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