APPENDIX I-1

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Appendix FEC-1

FEC TRACEABILITY MATRICES

Traceability matrices show the linkages between:

1. The scientific question (Column A),
2. The broad categories of information required to address the question (Columns B–C),
3. The specific information needed to address the question (Column D), and
4. The observations, models, and experiments needed to provide specific information (Column E), which form the columns of the matrices.

The rows of each matrix list the required information and activities. Activities are color coded by category (e.g., geodesy, geology) to illustrate the breadth of interdisciplinary activities required to tackle the questions and common needs between scientific questions. The contents of this matrix are informed by discussions within the working group and feedback received from the community through surveys and town hall meetings and from other SZ4D working groups.

We describe an example from the *traceability matrix* for Question 2 to illustrate our process (**A-FEC-1**). A prerequisite for understanding controls on the speed and mode of slip in space and time is information on the speed and mode of slip itself, including in earthquakes and slow slip events. Shoreline-crossing seismic and geodetic arrays are required to provide constraints on the full range of present day slip behavior and geodetic coupling from the trench to the downdip transition to aseismic creep (e.g., **Figure FEC-5**). Paleoseismology, geology, and historical records of earthquakes are needed to explore the deeper history of where and when large earthquakes and tsunamis have occurred and for longer-term deformational processes to provide context for current behavior. Differentiating between the theories that have been proposed to explain variations in slip behavior requires constraints on materials, fluids, and structures along the plate boundary at a range of spatial scales, including the frictional properties of material along the plate boundary, heterogeneities along the plate boundary at a range of scales, and/or variations in pore-fluid pressure (e.g., Segall et al., 2010; Hawthorne and Rubin, 2013; Skarbek et al., 2012; Ando et al., 2012; Fagereng & den Hartog, 2016; Zhu et al., 2020). Differentiating between these competing explanations of what controls slip behavior thus requires constraints on materials, fluids, and structures along the plate boundary at a range of spatial scales. Seismic reflection/CSEM imaging can provide constraints on heterogeneity in plate boundary properties and indirect constraints on porosity and pore-fluid pressure at scales of tens to thousands of meters (e.g., **Figure FEC-6**), while drilling of subduction zone fault materials or studies of exhumed megathrusts onshore are required to characterize the composition and structure of fault zone materials, finer-scale heterogeneity, and fluid-rock interactions (e.g., **Figure FEC-7**). Experimental studies on subduction zone materials are needed to determine the material properties that control slip processes and will require advancements in the range of pressures, temperatures, pore pressures, and strain rates that can be accessed in the laboratory. Numerical modeling will both illuminate the parameters that need to be observed and evaluated and synthesize observations and experiments for a comprehensive understanding of controls on subduction zone behavior.

Appendix FEC-2

PHASES OF THE SZ4D FEC EXPERIMENT

Phase 0 (Preparatory Work and Refinement of Implementation Plan)

1. Infrastructure assessment and experiment planning
   a. Assessment of existing seismic and GNSS instrumentation infrastructure, including quality, accessibility, and openness of data
   b. Focused modeling effort to inform optimal design of experiments to achieve necessary resolution
2. Organization and planning
   a. Strengthen existing and establish new international and domestic connections and initial capacity building, access, data and science sharing agreements with international partners for potential target site(s)
   b. Clarify the likely synergistic relationship between SZ4D efforts with hazard estimation and warning goals in potential observatory regions

Phase 1 (Analysis and Synthesis of Existing Data and Continued Planning Activities)

1. Data assessment and compilation
   a. Synthesis and assessment of existing constraints on subduction zone history and behavior, including from seismic and tsunami catalogs, regional earthquake source parameters, slow slip locations and behavior, tide gauge and DART data, local surveys for historic events, and tsunami source area estimates
   b. Synthesis and targeted reprocessing of prior geophysical imaging results from onshore and offshore active and passive source seismic, magnetotelluric, controlled source electromagnetic data, and bathymetric data
   c. Synthesis of existing geologic, paleoseismic, and paleotsunami data from in situ and exhumed analog sites
   d. Assembly and synthesis of existing data on material properties (friction, elastic properties, hydraulic properties) and fault structure (from both in situ and exhumed systems) to inform models and identify gaps

e. Summary of region-specific modeling efforts such as simulations of regional models of stress and deformation, faulting, earthquake sequences and aseismic slip, and megathrust rupture dynamics and tsunamigenic potential and deformation
f. Begin to develop cyberinfrastructure and data processing capabilities in conjunction with partner organizations to ensure efficient use of large datasets collected in Phase 1 and Phase 2

2. Technology development
   a. Instrument developments for long-term seafloor and potentially subseafloor deployments
   b. Development of experimental apparatuses that fill critical gaps in pressure, temperature, pore pressure, and strain-rate space
   c. Modeling based assimilation, fusion, and analysis of Phase 0 "big data"
   d. Develop modeling strategies for optimal observational and experimental design to help define the highest impact observational efforts in the lab and field
   e. New modeling development capable of integrating multiple types of observables of different precision to constrain multi-scale and multi-physics modeling, in coordination with the SZ4D Modeling Collaboratory
3. Reconnaissance Work
   a. Conduct reconnaissance investigations of potential subduction analog sites coordinated between field geologists and experimentalists
   b. Conduct reconnaissance investigations of geologic and paleoseismic slip histories for upper plate crustal faults (onshore and offshore)
4. Organization and Planning
   a. Begin discussions with potential offshore fiber optic cable owners about potential use for monitoring and warning

Phase 2a (Backbone Constraints)

1. Data acquisition
   a. Slip Constraints
      i. Establish a backbone geodetic network for characterizing deformation and locking at a nominal resolution of 100 km x 50 km along-strike and downdip, which requires a similarly spaced, staggered network of GNSS-A stations. In the near-trench region, where deformation can be much more localized, transitions between coupled and slipping zones may be missed due to spatial aliasing
      ii. Deploy a broadly distributed (~50 km spacing), amphibious network of seismic and electromagnetic stations, and use passive source imaging, to enable initial characterization of earthquake and slow slip behavior offshore
      iii. Densify onshore geodetic and seismic stations. GNSS sites should have a nominal

spacing no less than the depth to interface at that location (>~40 km near coast of most environments). Near-coast GNSS should be designed for real-time tsunami monitoring. Densification of onshore seismic networks should include arrays for improving offshore earthquake detection and location

  - **iv.** Determine and acquire available viable L- and C-band SAR data for time-series interferometry, identifying large-scale deformation, with localizations associated with surficial processes and upper-plate dislocations. Establish continued collection of SAR data from available satellites
  - **v.** Conduct reconnaissance investigations of onshore paleoseismic sites for subduction megathrust slip histories

- **b.** Process Constraints
  - **i.** Take measurements of materials recovered from previous drilling and sample collection, or those that serve as priority representative materials for fault and wall rock
  - **ii.** Collect linear MT/broadband seismic profiles with ~20 km instrument spacing for imaging large-scale subduction zone architecture and broad-scale seismicity patterns, collocated with active source seismic lines.
  - **iii.** Collect multibeam swath bathymetry and acquire deep-penetration 2D active source seismic reflection and refraction data (at maximum of 50 km spacing) as well as heat flow probe data
  - **iv.** Collect high-resolution bathymetry along coastal areas

2. Synthesis and modeling

  - **i.** Integrate geodetic, seismic, and paleoseismic data to map locking and slip behavior
  - **ii.** Integrate geophysical imaging, heat flow,, and geology to determine subduction zone architecture and properties
  - **iii.** Combine architecture, physical property, and slip information to constrain processes controlling locking and slip
  - **iv.** Include new information on subduction zone structure and processes in probabilistic scenario modeling to estimate expected future slip behavior. Use numerical models to explore data sensitivities and provide uncertainties based on the intermediate-resolution data to guide installation of new sites in Phase 2

3. Technical Development

- **a.** Continue to develop cyberinfrastructure and data processing capabilities in conjunction with partner organizations to ensure efficient use of large datasets collected in Phase 1 and Phase 2
- **b.** Continue to develop and refine seismic and geodetic instrumentation based on the results of the backbone deployment, in preparation for Phase 2

4. Organization and Planning
    a. Develop and coordinate the physical infrastructure needed to share, analyze, and archive geologic and experimental samples
    b. Upgraded/reinforced on-land GNSS stations (where available) for longevity, communications, and site stability. Create a plan for long-term maintenance and data collection, archiving, and reduction
    c. Design the dense amphibious seismic/geodetic deployment for Phase 2

Phase 2b (Targeted, High-Resolution Constraints)

1. Observational
    a. Slip Constraints
        i. Informed by early results and modeling, densify the GNSS-A and ocean-bottom seismic/pressure network to capture high-fidelity features of coupling, seismicity, and slow slip. This may include deployment of fiber optic cable for distributed acoustic sensing (DAS) analysis
        ii. Continue updates to land-based GNSS and seismic networks as needed (e.g., to enable high-rate (10 Hz) GNSS, augment land-based GNSS/seismic stations with strong motion for capture of earthquake rupture signals)
        iii. Install onshore borehole observatories to capture transients in slip, hydrogeology, or strain
        iv. Instrument faults in the overriding plate with geodetic, seismic, and strainmeter sensors, as needed
        v. Continue collection of all available SAR data
        vi. Conduct paleoseismic investigations of long-term megathrust and crustal fault slip histories
    b. Process Constraints
        i. Use repeat-track multibeam bathymetry surveying in cases of shallow fault slip
        ii. Collect high-resolution geophysical images in regions of interesting slip behavior. Deploy a dense array of seismic nodes and combined OBS/OBEM instruments for active and passive source seismic and passive MT imaging. Conduct a 3D seismic reflection survey, and s dense controlled-source electromagnetic survey
        iii. Conduct geologic and experimental investigations of subduction zone analogs and inputs, including both onshore and offshore samples
2. Interpretation
    a. Analyze all new and existing observations on subduction zone behavior and structure
    b. Experiments will continue to inform modeling and geologic characterization to ensure that

necessary measurements are being made and correctly understood/applied. Experimental plans will evolve in response to emerging observations

c. Validate and calibrate data-centric modeling tools against larger community models. Modeling tools will be built to assimilate emerging high-resolution observations (e.g., rapid on-demand analysis). Models will be built to explore which theoretical developments and constraints are necessary to interpret sensor network data streams

Phase 3 (Synthesis)

1. Interpretation
   a. Integrate results from all components to address science questions
   b. Conduct targeted data analysis, modeling, and experiments to address key questions that arise during synthesis
   c. Integrate new results from SZ4D work into regional hazards frameworks in collaboration with local stakeholders
2. Organization and planning
   a. Develop plans for adoption and continued operation of SZ4D networks as appropriate