CROSSCUTTING SCIENCE THEMES

An Integrated Vision for Subduction Zone Hazards

Introduction

Subduction zone hazards such as earthquakes, volcanic eruptions, landslides, and tsunamis have large, expensive, and long-lived impacts on human societies. Modern examples include great earthquakes and tsunamis in Alaska (1964), Sumatra (2004), and Japan (2011); the 2014 Oso landslide in Washington State; and the 1980 eruption of Mount St Helens. All these events resulted in significant loss of life and long-lasting disruptions at local, regional, and in some cases, global scales. Although the impact to societies from major subduction zone hazard events is very high, the underlying science needed to understand such damaging phenomena remains far from settled.

The overarching goal of the SZ4D initiative is to develop an integrated understanding of how the different components of subduction zone systems interact to produce and magnify geologic hazards. Key to this understanding is unraveling the roles subduction zone physical and chemical processes play in initiating and then linking different hazards in space and time. Just as people living in subduction zones do not worry about "just" earthquakes, "just" tsunamis, "just" volcanic eruptions, or "just" landslides, SZ4D doesn't focus on "just" individual hazards. The processes at work in subduction zones often produce a cascade in which an initial hazardous event may trigger additional hazardous events that prolong and magnify the impact of the linked geohazards.

The integrative and disciplinary crosscutting nature of the SZ4D approach is deliberate and evident at all levels of the initiative.

Examples include:

- Our fundamental approach of collocating science and human resources to provide efficiency and integration throughout our activities.
- Our geographic approach, which is designed to allow integration and comparison of subduction zone processes across multiple subduction zones.
- Our organizational structure, where each working group consists of individuals who have a range of disciplinary specialties and who collaborate around common science and community goals. In addition, integrative groups, such as MCS and BECG, address identified needs that extend across all science and inclusivity goals.
- Our nurturing of a number of other integrative efforts, including designing and deploying instrument arrays that support multiple working group goals, designing a human deployment facility to address fieldwork needs across working groups, and ongoing organizing of groups around other needs—such as experimental and analytical methods—that also support multiple science goals.

SZ4D Crosscutting Science Themes

The integrative and synergistic nature of the science that motivates SZ4D is evident in the number of research themes that crosscut individual working groups (**Figure CST-1**). This chapter explores several of these themes in greater detail and highlights areas where our investigations and results provide the best opportunities to make fundamental advances across all SZ4D working groups.

Forecasting and Prediction

How do we recognize precursor signals to devastating subduction hazard events, what techniques do we need to use to monitor them, and how do we relate such precursors to the eventual magnitude and style of the hazardous event?

Subduction zones generate some of Earth's most devastating geohazards including earthquakes, landslides, volcanic eruptions, and tsunamis. Providing robust forecasts and warnings to vulnerable populations is important for mitigating the potential impacts of these disasters. The concept of forecasting is simple in principle but exceedingly difficult in execution: robust forecasts are grounded in a thorough understanding of the entire system, its uncertainties, and how it responds to changes. In this framework, the driving forces and precursory signals that lead to hazardous events (e.g., earthquake foreshocks, volcanic unrest, and slope creep) provide some information about relative hazard levels, which allow detailed monitoring to provide an ongoing evaluation of hazard potential.

While relative hazard levels can be coarsely gauged, these often inconsistent and unreliable indicators of activity cannot easily be translated into confident predictions as to when and where subduction hazards occur. This reflects gaps in our understanding of the subduction system, the nature of precursory signals, and the way the system responds to forcings. As a result, the warning signs of an impending subduction zone hazard are often difficult to determine, and catastrophes can occur with little or no warning. Thus, a focus of the SZ4D initiative is to study possible precursory signals and connect them to potential hazards through a robust understanding of the physical and chemical processes active in subduction zones and the liquid, solid, and gaseous materials that flow in and out of them.

Although the SZ4D disciplinary working groups agree that the ability to identify precursory signals is central to forecasting subduction zone hazards, most also agree that data collected on precursory events do not currently provide the information needed to predict the magnitude, duration, and area of impact of an eventual hazard. Important examples include the relationships between:

1. Foreshocks and earthquakes,
2. Deformation and seismic precursors,
3. Mechanisms and styles of volcanic eruptions,
4. Rapid sediment transport and flood prediction.

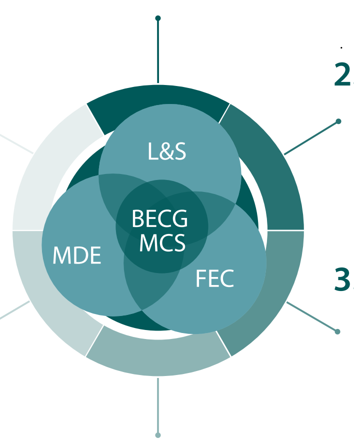
Large landslides also have precursory signals similar to some volcanic eruptions and earthquakes. However, the fundamental controls on the initiation and runout of landslides, turbidity currents, and other mass flow events remain less clear.

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

1. Forecasting and Prediction
An integrative understanding of the subduction zone system is essential for relating precursors to hazards.

2. Mass and Energy Balance
Hazards reflect the movement of mass and energy through subduction zones. Understanding the energy and mass budget requires an inherently integrative approach.

3. Rheology and Stress
The rheology of subduction zone materials influences the partitioning of stress and strain, and the nature of hazards in all parts of the subduction zone system.



4. Fluids and Fluid Migration
Fluids and fluid migration occur throughout subduction zones and influence hazards and material transport across the entire subduction system.

5. Climate Variability
Earth surface processes are strongly linked to the deeper earth in subduction zones. Climate variability, and future climate change, will strongly influence subduction zone hazards and processes.

6. Triggering & Cascading Hazards
Subduction zone hazards often occur as a cascading series of events, requiring a system wide and integrative approach to understand.

To obtain an integrated understanding of the processes and materials needed to relate precursory signals to hazards also requires us to approach subduction zone studies in novel ways and go beyond traditional disciplinary boundaries in our research. An important emphasis will be on model-data fusion. This technique is extremely useful for investigations of hazard prediction and forecasting and is also important to many other SZ4D studies. Model-data fusion requires integrating information from multiple data sources across modeling and observational domains to produce results that are more consistent, accurate, and useful than those provided by any individual data source.

The MCS integrative group is poised to fill this computational gap in the geosciences and provide physics-based and data-driven frameworks for combining the multi-scale, multi-parameter, multidisciplinary observational and laboratory datasets collected by SZ4D. The MCS will allow SZ4D scientists to apply data inversion techniques to multiple data streams to reveal the relationships between potential precursors and hazards over many different timescales. Progress in model-data fusion is specifically needed for forecasting, which uses very large volumes of diverse data from centralized and distributed sources (e.g., earthquake recordings, satellite observations, GNSS measurements). Over the past decades, significant progress has been made in statistical data assimilation in the fields of climate modeling, hydrology, and physical oceanography, and these provide important scaffolding for future MCS efforts in subduction zone hazards, where significant work to advance this field remains. Another goal of the MCS is to make it easier for SZ4D scientists to use model-data fusion methodologies in their research. The MCS will enhance and support the interoperability of data and software and enable integration and collaboration across different subduction scientific domains.

Mass and Energy Balance

How do we track the passage of mass and energy through subduction zones, and how do we relate critical transitions in mass and energy transfer to hazardous events?

Our understanding of the location, magnitude, and potential destructiveness of subduction zone hazards hinges upon our knowledge of mass and energy distribution and balance within subduction systems. Major changes in the distribution of mass and energy occur within and across Earth's surface at subduction zones in response to plate tectonic motions and atmospheric processes. Hazardous events such as earthquakes, tsunamis, landslides, and volcanic eruptions are both responses to, and manifestations of, this redistribution. As a result, recording changes in the distribution of mass and energy before, during, and after hazardous events in multiple subduction zones will provide the information necessary to significantly advance understanding of the factors that control hazards.

One example of how knowledge of mass and energy distribution cuts across traditional disciplines is the study of the relationship between sediment transport and subduction behavior. Sediment transport at the trench can affect slip processes and rates along the megathrust, and uplift associated with seismic activity strongly influences sediment transport. Subducting sediments also contribute to volatile species that influence the behavior of the megathrust at shallow levels in the subduction zone and impact deeper magma production rates, which ultimately contribute to volcanic activity and hazards. Mass and energy exchanges within a subduction zone also influence crustal tectonics, the rates of uplift, and the evolution of topography, where gravitational potential energy is converted into kinetic energy through sediment transport—including destructive events such as landslides and debris flows.

Accumulation of energy within the subduction system drives hazardous events and controls the scale of the event. Thus, although knowledge of the stress state might tell us how close a system is to failure, additional information on the mass and energy balance is needed to forecast the size of that failure.

Calculating the energy and mass budget of a subduction zone with sufficient detail and accuracy requires knowledge of the heat flux, strain, and stress associated with volcanism, earthquakes, and deformation, and their changes at Earth's surface (**Figure CST-2**). These measurements will be integrated into numerical models of the subduction system at a range of pressures, temperatures, and strain rates to provide a more accurate 4D picture of potential subduction zone hazards.

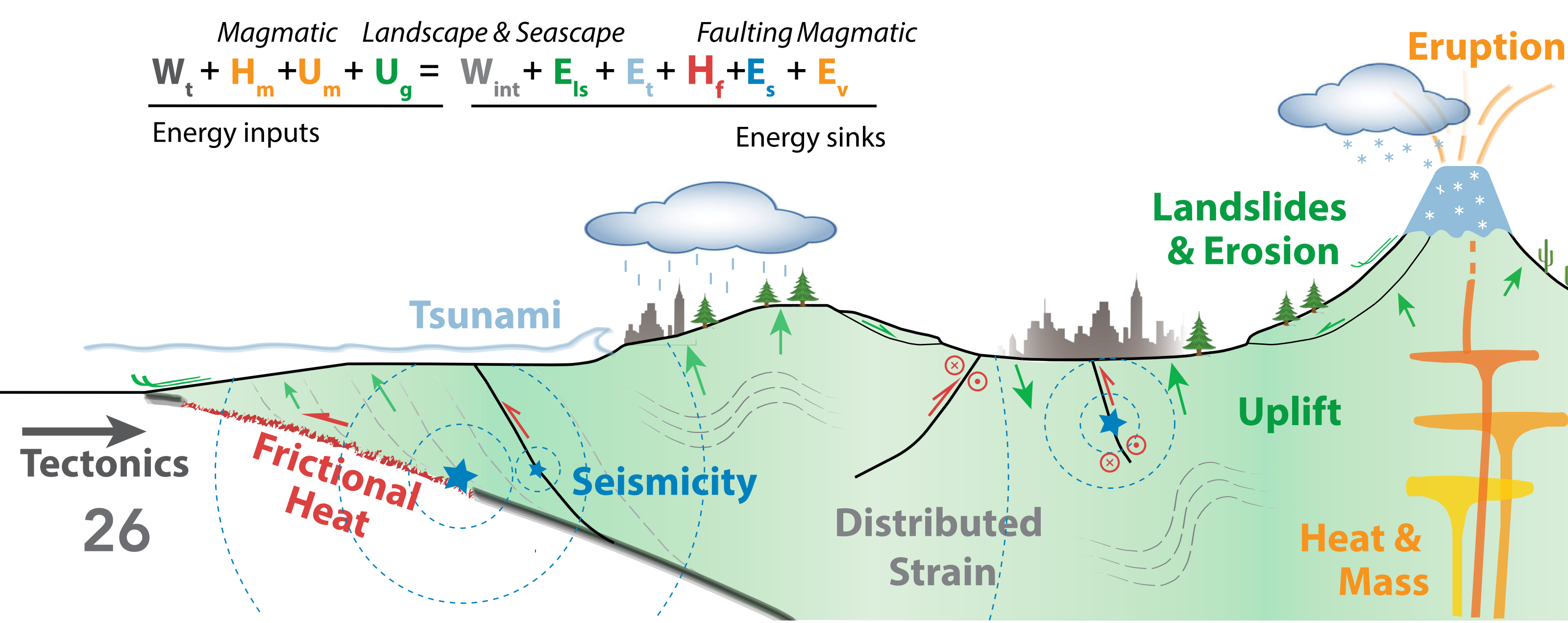
Rheology and Stress

How does the rheology of subduction zone materials influence the partitioning of stress and strain, and how does this control the nature of hazards across the subduction zone system?

When subduction zone hazards initiate, potential energy is converted into strain in the solid and fluid Earth according to the rheology of Earth materials involved in the energy release. Additionally, rheology controls the way in which continued geodynamic loads are released in time and space. Thus, understanding the rheology of subduction zone materials will enhance forecasting future earthquakes and volcanic eruptions, and the initiation and runout of mass movements such as landslides and debris flows.

Knowledge of the rheology of the Earth

Figure CST-2. *Schematic first-order energy budget of the entire subduction zone. The inset equation outlines in 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 provides information about the energy available within the system to drive damaging hazards.*



materials involved in each of the major subduction zone hazards is limited, thus activities focused on rheology have broad application. For example, granular flows are mixtures of solid and fluid components and can exhibit highly complex and variable rheology and hydrodynamics where the constitutive laws are still under debate. Predicting the behavior of water-borne sediments, fault interfaces, lava and pyroclastic flows, and mass flow deposits produced by landslides all require understanding granular flow and thus concerted experimental, observational, and modeling efforts are needed here. Similarly, changes in rheology that occur during ongoing strain and deformation can produce dynamic weakening of lower crustal and mantle rocks that affect our understanding of volcanic systems, fault loading, and the support of topography.

Activities within SZ4D will sharpen our knowledge of the rheology of critical Earth materials. Leading-edge laboratory experiments will provide direct measurements of the rheology of fault-zone materials, crustal rocks, and granular flows mixtures that map how stresses are converted to strains in these materials at the relevant strains, strain rates, pressures, and temperatures. Geological data can reveal evidence of small-scale processes such as pressure solution, microcracking, crystal plasticity, and metamorphism. Geophysical measurements from the observational arrays will measure the motions of subduction zone materials at the scale of the subduction zone system in response to modeled and observed stresses, and thus provide information about in situ rheology. These rheological descriptions will be combined with geodynamic models to understand how loading interacts with the rheology of subduction zone materials to produce the motions that we observe. Rheology, studied in the laboratory and inferred at the scale of the subduction zone system, is central to understanding the dynamics that produce subduction zone hazards.

Fluids and Fluid Migration

How does fluid migration influence hazards and material transport across the entire subduction system?

A greater understanding of the distribution of fluids, the nature and consequences of fluid migration, and the physical and chemical impacts of solid-fluid interaction is integral to all parts of the SZ4D initiative. Existing work, including studies conducted by previous NSF initiatives such as MARGINS and GeoPRISMS, have provided significant insight into fluid distribution in subduction zones. The gap that remains is in our knowledge of how fluids and fluid migration mediate energy and mass exchanges at subduction zones, and how interplay of these processes produce natural hazards.

Subduction involves entry of a strongly hydrated oceanic plate into Earth's mantle. The cycling fluids into the mantle and then back into the crust drives myriad subduction zone processes. The transport of fluids deep into Earth promotes melting and magma formation and controls seismicity on the megathrust and other related faults—including those that produce the most destructive earthquakes. In addition, fluid flow throughout the subducted oceanic crust and along the subduction channel strongly controls many of the physical and chemical properties of the subducting lithosphere, and as a result modulates much of the complex mineralogical and chemical exchanges in this region.

Fluids and fluid migration also modulate processes within the shallow crust and at Earth's surface. Local fluid pressure strongly influences shallow fault systems, and changes related to fluid migration can significantly impact earthquake activity. Interaction between shallow crustal fluids and magmas can also produce phreatic and phreatomagmatic eruptions, such as the deadly recent eruptions at Mount Ontake, Japan, in 2014; and Whakaari/White Island, New Zealand, in 2019 (**Figure CST-3**). Alteration of volcanic edifices via shallow hydrothermal circulation can lead to edifice failure and mass wasting events. Hydrothermal fluid circulation leads to the formation of important mineral deposits, including many metals needed for "smart" technologies and for low-carbon geothermal energy components.

Climate Variability

How will climate variability, and future climate change, influence future subduction zone hazards and processes?

Subduction zones are the primary plate tectonic environments where the deep Earth directly connects to and influences materials and processes at Earth's surface, and vice versa. Interactions between the atmosphere, hydrosphere, and lithosphere alter the properties of subduction zone materials and influence surface loading and mass transport. Regional climate and climate variability strongly influence these surface processes. Thus, future climate change may have important ramifications for the types, frequency, and magnitude of subduction zone large storms, atmospheric rivers, and the mass wasting and flooding that they trigger.

Climate variability and change modulate subduction zone hazards on long ($\geq 10^6$ yrs), intermediate (10^6–10^4 yrs), and short ($\leq 10^4$ yrs) timescales. Long-term regional climate impacts water availability, the phase (e.g., rain vs. snow) and amount of precipitation, topography, and weathering intensity and rates. On intermediate timescales, climate oscillations impact terrestrial hydrology, sea level, and vegetation, which may alter the generation, flux, and routing of sediment in subduction zones (**Figure CST-4**). On shorter timescales, climate variability impacts hydrological cycling, extreme weather events, stochastic sediment transport, and vegetation coverage.

On long and intermediate timescales, climate variability affects erosion and sediment transport systems. Variations in surface loading from glacial advance and retreat, sea level change, and surface erosion also impact the state of stress at depth. Changing ice volumes increase and decrease loads on subaerial volcanoes, and rising and falling sea levels do the same to submarine and island volcanic systems, which can impact the frequency and style of volcanic unrest. Similarly, earthquake activity can be modulated by climate-driven variations in ice and water volumes. Climate oscillations also modulate sediment supply and water discharge, tightly coupling the rates of erosion and sediment transport to climate, and influencing the onshore-to-offshore sediment transport system. Climate-modulated variations in surface erosion might impact the state of stress on upper plate faults and volcanic systems in ways not yet fully understood.

Climate warming since the end of the last glacial maximum ($\leq 10^4$ yrs) has intensified some subduction zone geohazards. The retreat of alpine glaciers has resulted in elevated rates of mass wasting, more frequent glacial lake outburst floods, and glacial melting on volcanic edifices that can increase eruption frequency and impact associated volcanic hazards such as debris flows or jökulhlaups (glacial outburst floods). As seen in 2022 in Pakistan, climate-induced

Figure CST-3. *Examples of important fluid processes and fluid migration events. A: The deadly 2019 phreatic eruption of Whakaari, New Zealand (Lillani Hopkins/AP); B: Lahar deposits in the Toutle River, Mount St Helens, 1980 (USGS); C: Cold springs feeding the Metolius River, OR (Travel Oregon); D: Sand boils associated with the 2011 Christchurch, New Zealand, earthquake (Wikimedia Commons); E: Scaly clay melange from the Franciscan Terrain (Wikimedia Commons); F: A schoolhouse destroyed by the Sidoarjo ("Lusi") mud volcano, Indonesia (Wikimedia Commons).*

glacial melting and rainfall events can catastrophically influence flooding and mass wasting frequency. Rising sea levels also have important implications for tsunami hazards. Changes in weather patterns also impact the frequency and magnitude of large storms and wildfires, which also increase mass-wasting and flooding hazards.

The differences in climate regimes between contrasting geographies provide SZ4D with an unparalleled opportunity to conduct natural experiments to assess the effects of long- and medium-term climate variability and change on subduction zone processes and hazards. By characterizing and quantifying differences in erosion, weathering, sediment transport, and seismic and volcanic activity among different areas, SZ4D will be able to tease out how the subduction systems respond to perturbations brought about by climate change, and the impacts these changes have on subduction zone hazards, especially in the short term, which is of most concern to human populations.

Triggering and Cascading Hazards

How do cascading sequences of events impact subduction zone hazards?

One example of the importance of taking an integrated approach to understanding subduction zone processes is the role triggering and cascading processes play in subduction zone hazards. Cascading hazards refers to how individual events, such as individual earthquakes or volcanic eruptions, can trigger other events that can be as, or more, hazardous than the original sequence. Examples of this process abound. Earthquakes, volcanic flank collapses, and submerged mass slumping trigger tsunamis. Landslide activity may increase due to thick tephra-coverage of hillslopes after volcanic eruptions. Earthquakes can trigger volcanic eruptions as well as fault slip in other parts of a system. Eruptions and earthquakes can initiate mass transport events both onshore and offshore.

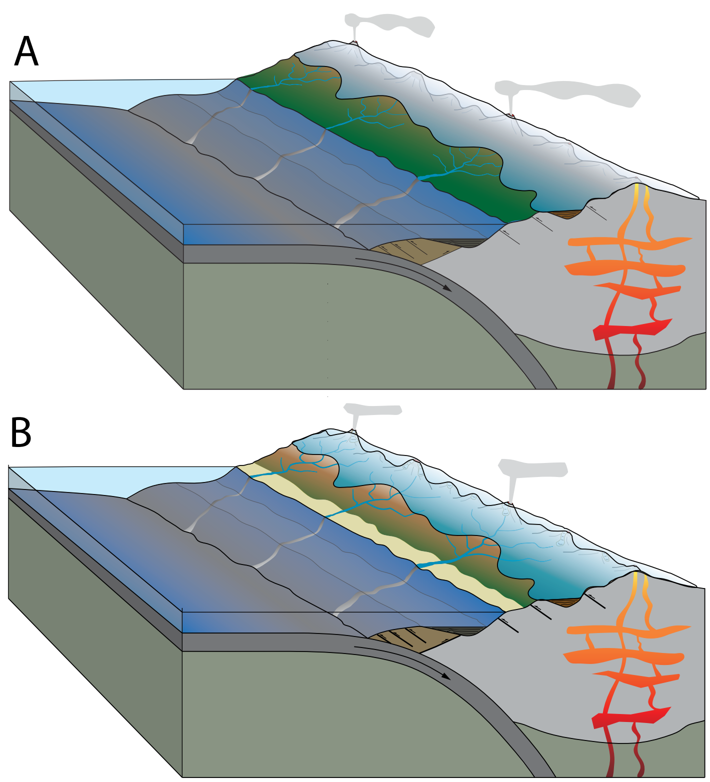
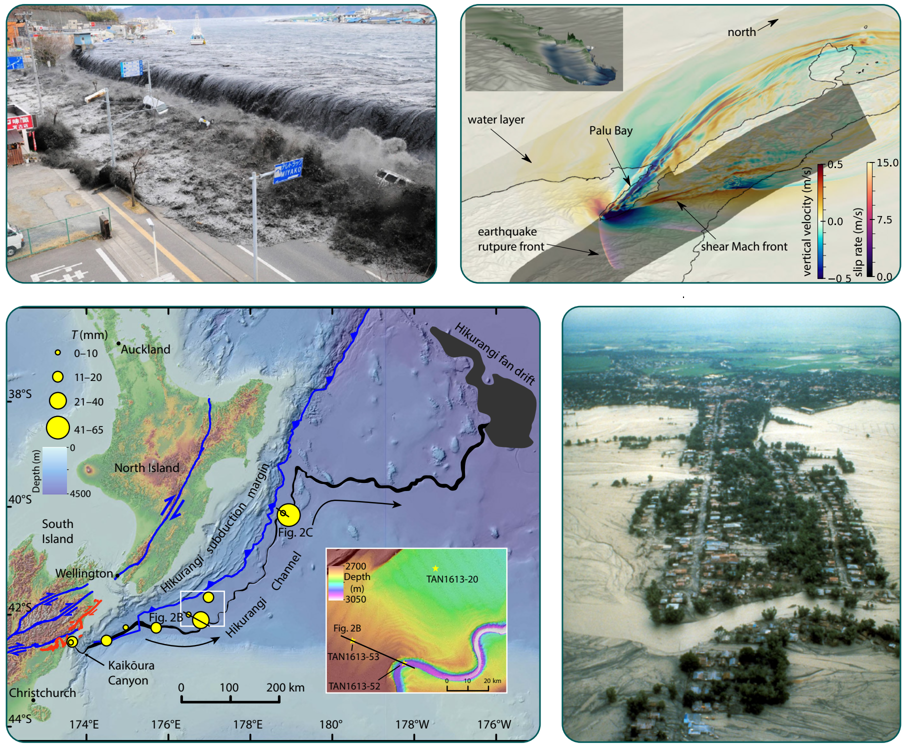


Figure CST-4. *Schematic of a subduction zone segment during a glacial (A) and an interglacial (B) period. Ice extent is greater and sea level is lower during the glacial period. Changes in ice volume and sea level will affect the stress state in the upper and middle crust, which can modulate the frequency of volcanic eruptions and upper plate fault activity. Exposure of the coastal shelf during glacial periods at sea level lowstands will change the dynamics and connectivity of the onshore-to-offshore sediment transport system. Furthermore, these climate variations will impact vegetation, water availability, and weathering, and thus modulate sediment supply and water discharge, resulting in unsteady sediment transport through time.*

Figure CST-5. *Examples of triggering and cascading subduction zone hazards. From left to right: The 2011 Tōhoku-Oki tsunami (Reuters) caused more fatalities than the shaking of the Mw9.0–Mw9.1 earthquake. High-performance computing (HPC) model of the multi-physics of earthquake rupture and seismic, acoustic, and tsunami wave interaction during the 2018 Palu, Sulawesi, Indonesia, earthquake and tsunami (Krenz et al., 2021). Turbidity current over 680 km triggered by the 2016 multi-fault Kaikoura, New Zealand, earthquake (Mountjoy et al., 2018). Mt. Pinatubo Lahar in 1991 (Reuters).*



The risks to human populations from triggered events such as tsunamis, landslides, and lahars can often be greater than that from primary causes such as seismic shaking and eruptions that initiated them (**Figure CST-5**). Thus, mitigating the risk of hazards requires accounting for the complex dynamics of the subduction system across multiple spatial and temporal scales. Such an accounting can only be achieved with an integrative, system-wide approach to studying subduction zone hazards, such as that proposed by SZ4D.

While the cascading nature of subduction zone hazards is generally accepted, the underlying mechanisms are often poorly constrained. Triggering mechanisms can range from direct effects, such as earthquake shaking, to more indirect impacts, such as the rapid drawdown that occurs when an earthquake-generated tsunami first approaches a shoreline. Such cascading and interacting events are a topic only now emerging in operational hazard assessments, and they present a challenge to existing empirical, disciplinary, data-driven approaches. However, they are also an opportunity to fuse subduction science disciplines and observations toward interoperability, and to identify opportunities to raise hazard alert levels early.

REFERENCES

Krenz, L., Uphoff, C., Ulrich, T., Gabriel, A.-A., Abrahams, L. S., & Dunham, E. M. (2021). 3D acoustic-elastic coupling with gravity: The dynamics of the 2018 Palu, Sulawesi earthquake and tsunami. In SC '21: *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis*, 63, 1–14. https://doi.org/10.1145/3458817.3476173

Mountjoy, J. J., Howarth, J. D., Orpin, A. R., Barnes, P. M., Bowden, D. A., Rowden, A. A., Schimel, A. C. G., et al. (2018). Earthquakes drive large-scale submarine canyon development and sediment supply to deep-ocean basins. *Science Advances* 4, 3. https://doi.org/10.1126/sciadv.aar3748