2. Subduction Cycles and Deformation (SCD) Initiative

This chapter describes the major accomplishments thus far of the Subduction Cycles and Deformation (SCD) initiative. The accomplishments are organized by main regions of the subduction system and by thematic approaches. Within these sections we highlight work done at the primary sites. Due to the phased funding approach, major research initiatives at the New Zealand primary site have not yet been considered for funding, so there is limited progress to report for that primary site.

2.1 Original Goals

The mission of the SCD initiative is to focus holistically on subduction margin evolution and material transfer over short to long time scales. In particular, the initiative encourages studies of 1) the properties, mechanisms, and manifestations of strain buildup and release along the subduction plate boundary, 2) the transport and release of volatiles through the megathrust zone, the fore-arc, and sub-arc and through the mantle, 3) linkages among surficial processes, fault-slip behavior, and magmatism, and 4) the many ways in which their interconnections affect the long-term growth and evolution of volcanic arcs, back-arcs, and continents. A main goal of SCD is to improve fundamental scientific understanding of some of the most destructive natural hazards on the planet.

The key questions addressed through GeoPRISMS SCD research include the following:

- What governs the size, location and frequency of great subduction zone earthquakes and how is this related to the spatial and temporal variation of slip behaviors observed along subduction faults?
- How does deformation across the subduction plate boundary evolve in space and time, through the seismic cycle and beyond?
- How do volatile release and transfer affect the rheology and dynamics of the plate interface, from the incoming plate and trench to the arc and back-arc?
- How are volatiles, fluids, and melts stored, transferred, and released through the subduction system?
- What are the geochemical products of subduction zones and how do these influence the formation of new continental crust?
- What are the physical and chemical conditions that control the initiation and development of subduction zones?
- What are the feedbacks between surface processes and subduction zone mechanics and dynamics?

The GeoPRISMS approach to these scientific questions has been highly collaborative and interdisciplinary. It builds on and expands the approach used for the SEIZE and SubFac initiatives of MARGINS. The SCD strategy drives the science in new directions in response to discoveries over the MARGINS time period and focuses on new locations: Alaska-Aleutians, Cascadia, and New Zealand. These questions span from the submarine realm of the incoming plate to the subaerial realm of the volcanic arc. Addressing them requires an amphibious portfolio of science; something that the sequestered funding of GeoPRISMS is ideally suited to support. In addition to primary site-focused research, five thematic research topics were identified as important for the SCD science plan: 1) Identifying controls on fault slip behavior and deformation history, 2) Understanding mantle wedge dynamics, 3) Fore-arc to back-arc volatile fluxes, 4) Conditions and reactions in subduction zones at depth and 5) Subduction initiation.

2.2 Major Accomplishments

We group the major accomplishments of the GeoPRISMS SCD initiative in the next five subsections. The first four are arranged by region of the subduction zone: incoming plate and shallow fore-arc, seismogenic zone (or megathrust), slab processes, and mantle wedge and arc crust. A fifth section deals with progress in thematic goals. At the end of each subsection we will list the relevant publications from research funded directly by GeoPRISMS. We also list relevant papers that have been published from MARGINS-funded research since last review (2009).

2.2.1 The incoming plate and shallow fore-arc

The nature of the incoming plate sets the stage for the dynamics and structure of subduction zones. The compositional differences between the initial rock type and volatile content of the oceanic crust and mantle are of fundamental importance to the processes that happen once a plate subducts and undergoes progressive metamorphism and volatile loss. These processes in turn have important consequences for our understanding of the nature of the seismogenic zone, the character of deep earthquakes, and arc volcanism and the formation of arc crust. The fore-arc also is a natural laboratory for geophysical observations that can determine the nature of the shallow updip limit to the seismogenic zone.

2.2.1.1 Cascadia

The temperature of the décollement is a critical parameter in identifying the potential slip area for the next large megathrust earthquake (estimated to be up to magnitude 9) in the Pacific Northwest. The objective of the GeoPRISMS project of PIs Johnson, Solomon and Harris is to determine the heat flow and fluid flux regime on the Washington State portion of the Cascadia subduction zone through a field program using the R/V Atlantis and ROV Jason II. The diverse data sets collected are being integrated and used in the development of numerical models of both fluid circulation and isotherm distribution within the sedimentary wedge (Johnson et al., 2013; Homola et al., 2015). An interesting broader impact of this study is that the data can be used to study the effects of climate change via studies of gas hydrates (Hautala et al., 2014).

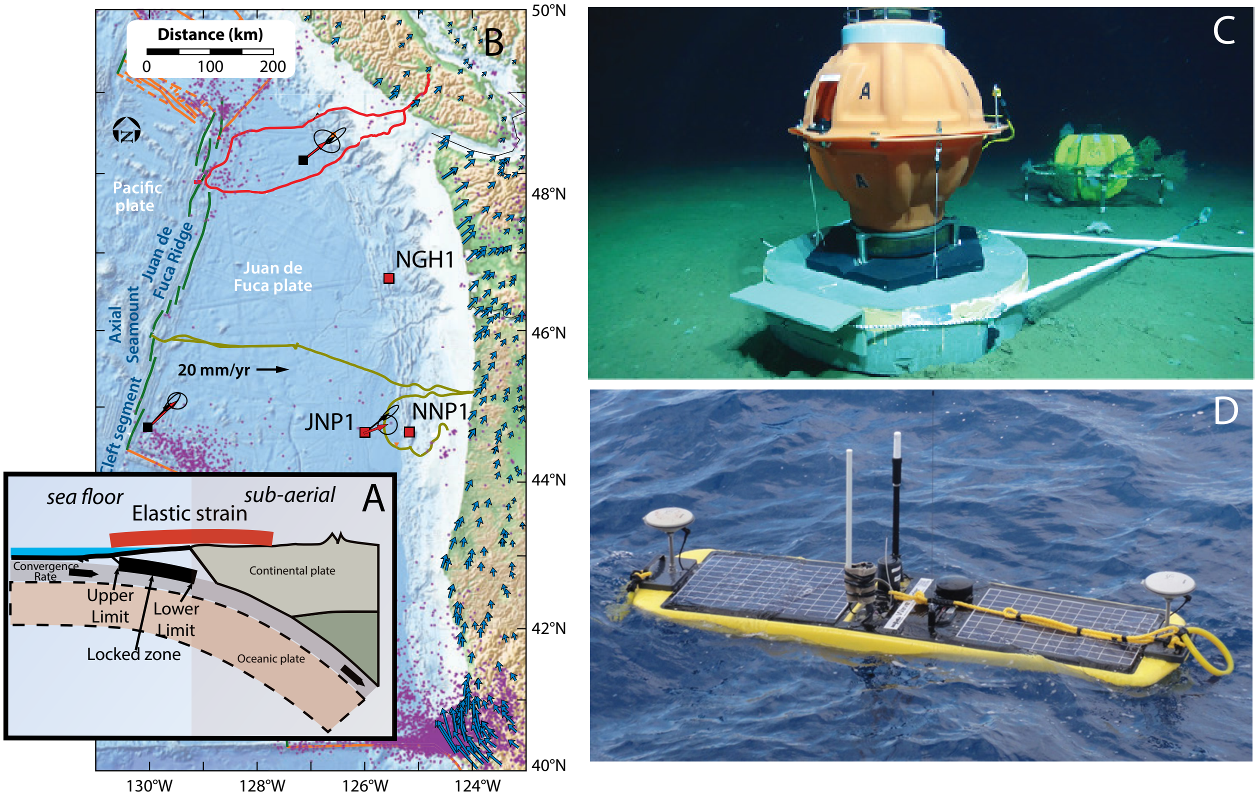


Figure 2.1. (A) Subduction cross-section showing incoming plate in contact along interface with upper plate which accumulates elastic strain as uplift and contraction. Much of the deformation occurs offshore, highlighting the significance of seafloor measurements in a space geodetic frame to bridge the subaerial and marine regions. (B) In 2014 two submarine geodetic sites, NNP1 and NGH1, were established - the first sites on the seaward slope of Cascadia subduction zone, and site JNP1 was reestablished and its position remeasured. Two earlier GPS-Acoustic sites (black squares) are also shown. Red and black arrows show the GPS-Acoustic and geomagnetically-derived plate motions relative to North America, respectively. (C) Foreground shows new seafloor benchmark with commercial transponder placed approximately 2 m from old (circa 2000) transponder at site offshore Oregon. (D) Wave Glider configured for GPS-Acoustic operations underway at sea.

Measuring strain partitioning across the megathrust requires geodetic observations of ongoing deformation, which have traditionally been made onshore for logistical purposes. However, strain buildup and release at the trench and deformation front is a key component of co-seismic tsunamigenesis. The GeoPRISMS project of PI Chadwell directly addresses this observational gap by making seafloor geodetic measurements of plate motion on the submerged oceanic portion of the Cascadia subduction zone to constrain the distribution of slip on the megathrust (Figure 2.1). Three sites have been deployed across the megathrust. An important contribution of this project to subduction zone observations is the implementation of a GPS-Acoustic Wave Glider, which can act as a replacement for high-cost ships in Cascadia and other subduction zones (e.g., offshore Alaska). The Wave Glider costs a few dollars a day to operate compared to several tens-of-thousands of dollars per day for a ship that has dynamic positioning, which is needed to hold station within 30 meters. The remeasurement of the JNP1 site (3000 m deep offshore Newport on the incoming Juan de Fuca plate) using the glider technology has allowed for a record that now spans from 2000 to 2014, making it the longest seafloor position time series anywhere. Preliminary results show that the convergence velocity is comparable to the geologically predicted rate. This supports the hypothesis that creep is occurring at the Cascadia subduction zone in central Oregon.

2.2.1.2 Hydration of the oceanic plate by outer rise normal faulting

Recent observations indicate that the mantle of the incoming oceanic plate in some subduction zones may be highly serpentinized, hypothesized to result from seawater circulation along inherited and reactivated normal faults generated at the spreading ridge (Ranero et al., 2003). Although documentation of this phenomenon remains scarce, it provides an important potential mechanism for transport of H_2O to subarc depths and possibly beyond (e.g., van Keken et al., 2011). The extent of serpentinization and its effects on the mechanics of the subduction system are poorly constrained.

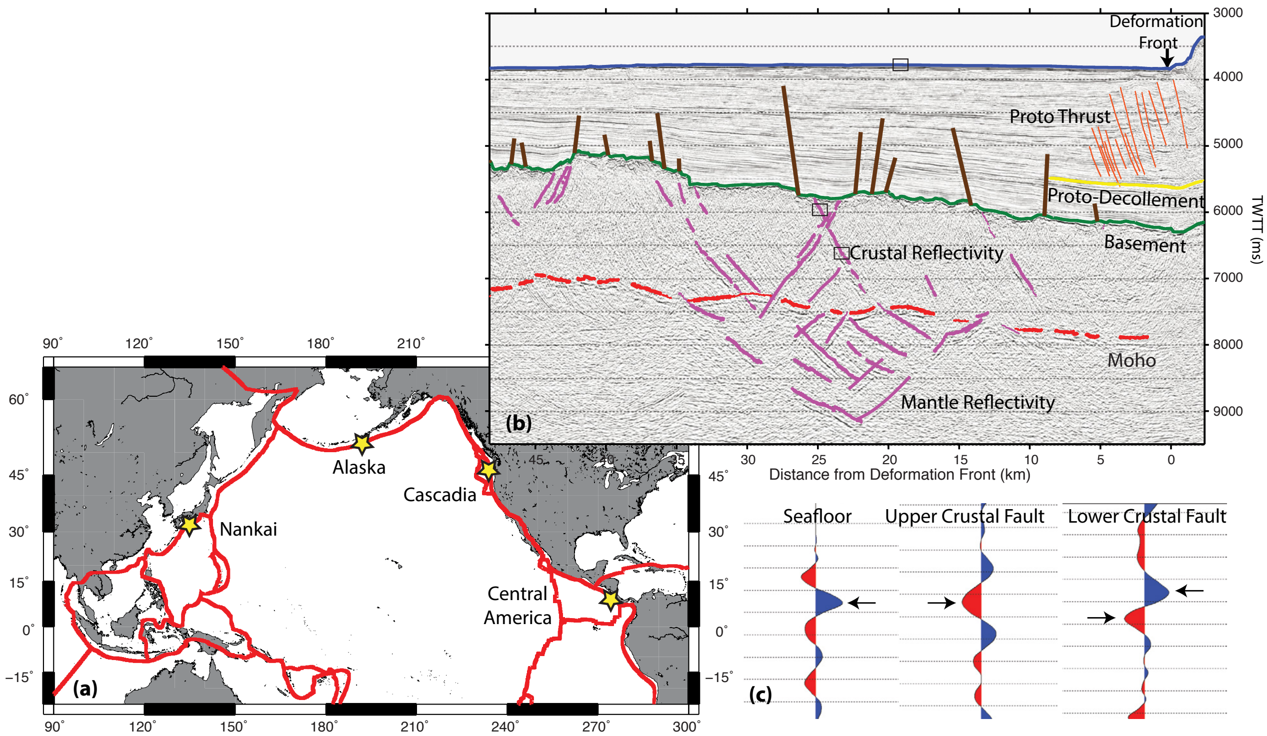


Figure 2.2. (a) Locations of the four subduction zones: Cascadia, Nankai, Central America, and Alaska (marked by yellow stars) examined in a project by Bangs and Han. (b) Prestack-time migrated MCS image of the incoming Juan de Fuca plate seaward of Cascadia subduction zone with interpretation. Seafloor, top of the oceanic crust, and Moho are shown as blue, green, and red lines; Normal faults, protothrust faults, and proto-décollement in the sediment section are shown as brown, orange, and yellow lines. Crustal and mantle reflections that are interpreted as fault plane reflections are shown in magenta lines (from Han et al., submitted.) (c) Waveform of the reflections of seafloor, upper crustal fault, and lower crustal fault in the black rectangles of (b).

The internal structure and hydraulic conductivity of the outer-rise faults and their variation over time and space have not been fully examined and quantified. In a recently funded GeoPRISMS project, PI Bangs and postdoc Han are using previously collected multichannel seismic (MCS) data to investigate the structure and fluid content in faults within representative segments of the subducting plate at four MARGINS and GeoPRISMS study sites (Figure 2.2). They will conduct amplitude preserved prestack-depth migration, 2D waveform modeling of fault plane reflections, and fluid flow modeling on 2D MCS data, and use the results to quantitatively assess the hydration state of the incoming plate at these sites.

Modelling by GeoPRISMS PI Billen and post-doc Naliboff has focused on discerning the relationship between outer-rise deformation, plate driving forces and lithospheric rheology at both short (<10,000 years) and long (>10 Myr) time scales using three-dimensional numerical modeling of the generation of outer rise faults. Analysis of time-averaged outer-rise faulting patterns indicates that downgoing plate age and velocity, downgoing-overriding plate coupling, and slab pull all significantly affect faulting patterns, while variations in brittle rheology have a significantly smaller impact (Figure 2.3; Naliboff et al., 2013).

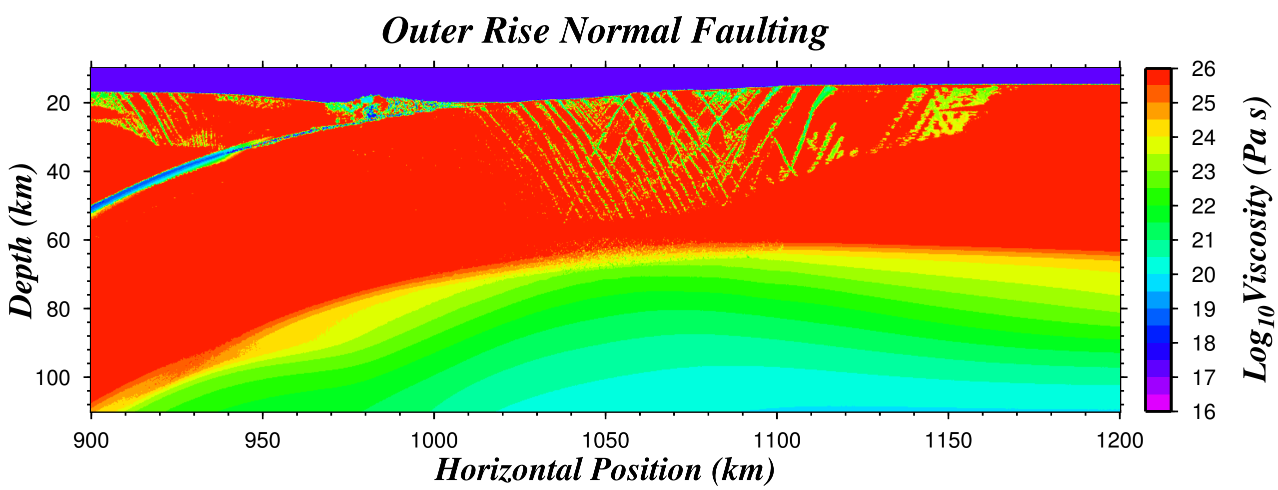


Figure 2.3. Modeling results showing viscosity structure of the overriding- (upper left) and downgoing-plate after ~ 400,000 years of deformation. Normal faults (brittle shear zones) develop seaward of the trench in the outer rise region in response to extensional bending stresses and slab pull forces.

2.2.2.3 Results from MARGINS and closely related research projects

Significant work related to the hydration state of the incoming plate has come through MT studies of Nicaragua (funded by MARGINS) and by seismic studies off Cascadia (funded by OCE-MGG).

OCE-MGG funded work by PI Carbotte employed a combined multi-channel seismic and wide-angle ocean bottom seismometer survey. The relative size of the Juan de Fuca plate allowed full seismic imaging of a plate from ridge to trench (Han, 2015). This study found that the crust becomes rapidly mature (within 1 Myr after formation) and has a structure where hydration is limited to the upper crust. No outer-rise hydration of the mantle is detected, but paleo-segment boundaries may cause enhanced hydration and locally affect subduction zone processes.

The MARGINS-funded SERPENT project used seafloor electromagnetic instruments to produce a profile of electrical resistivity along an 800 km transect spanning the outer rise and accretionary prism offshore of Nicaragua (Figure 2.4). This work provided an important corroboration of the earlier seismic work that showed extensive outer-rise faulting and mantle hydration (Ranero et al., 2003; Ivandic et al., 2008), as well as direct evidence for fluid release into the accretionary prism.

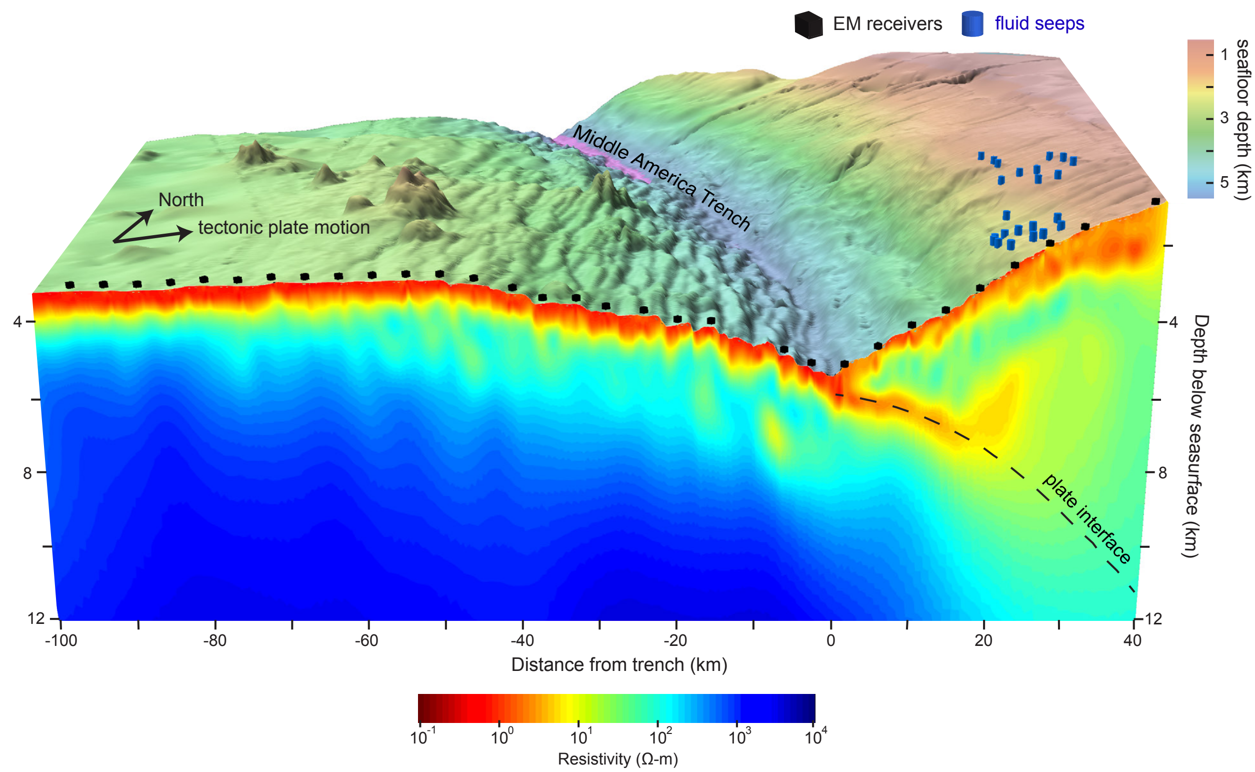


Figure 2.4. The electrical structure of the incoming Cocos plate from nonlinear inversion of deep-towed CSEM data. The vertical cross-section shows the sub-seafloor electrical resistivity structure and the stitched upper panel shows seafloor bathymetry. The black cubes show the location of EM receivers. The region of the seafloor marked by steeply dipping relief correlates with sub-vertical conductive channels, which is interpreted as evidence for the migration of seawater along bending faults. The channel of low resistivity beneath the fore-arc – congruent with the geometry of the plate interface – is caused by subducted sediments.

2.2.1.4 Related GeoPRISMS-funded publications (from appendix A3)

Rethinking turbidite paleoseismology along the Cascadia subduction zone – Atwater et al., 2014.
Faulting within the Pacific plate at the Mariana Trench: implications for plate interface coupling and subduction of hydrous minerals – Emry et al., 2014.
Incoming plate faulting in the Northern and Western Pacific and implications for subduction water budgets - Emry and Wiens – 2015.
Contemporary ocean warming dissociates Cascadia margin gas hydrates – Hautala et al., 2014.
In situ measurements of thermal diffusivity in sediments of the methane-rich zone of Cascadia Margin, NE Pacific ocean – Homola et al., 2015.
Heat flow and fluid flux in Cascadia's seismogenic zone – Johnson et al., 2013.

A geophysical and hydrogeochemical survey of the Cascadia subduction zone – Johnson et al., 2014.
Dynamics of outer-rise faulting in oceanic-continental subduction systems – Naliboff et al., 2014.
IODP workshop on using ocean drilling to unlock the secrets of slow slip events - Wallace et al., 2012.

2.2.1.5 Related MARGINS-funded papers (2009 and later; appendix A4)

Massive methane release triggered by seafloor erosion offshore southwestern Japan – Bangs et al., 2010.
Cenozoic tectonics of the Nicaraguan depression, Nicaragua, and Median Trough, Salvador, based on seismic-reflection profiling and remote-sensing data – Funk et al., 2009.
A model for the long-profile shape of submarine canyons – Gerber et al., 2009.
Rapid forearc basin uplift and megasplay fault development from 3D seismic images of Nankai Margin off Kii peninsula, Japan – Gulick et al., 2010.
Submarine landslide potential near the megasplay fault at the Nankai subduction zone – Ikari et al., 2011.
Marine electromagnetic studies of seafloor resources and tectonics – Key, 2012.
Electromagnetic detection of plate hydration due to bending faults at the Middle America Trench - Key et al., 2012.
Spatial and temporal evolution of the megasplay fault in the Nankai Trough – Kimura et al., 2011.
Fore-arc motion and Cocos Ridge collision in Central America – Lafemina et al., 2009.
The impact of splay faults on fluid flow, solute transport, and pore pressure distribution in subduction zones: a case study offshore the Nicoya Peninsula, Costa Rica – Lauer and Saffer, 2015.
Possible strain partitioning structure between the Kumano fore-arc basin and the slope of the Nankai Trough accretionary prism – Martin et al., 2010.
Integration of arrival-time datasets for consistent quality control: a case study of amphibious experiments along the middle America Trench – Moore-Driskell et al., 2013.
Analysis of normal fault populations in the Kumano forearc basin, Nankai Trough, Japan. 1. Multiple orientations and generations of faults from 3-D coherency mapping – Moore et al., 2013.
Melt-rich channel observed at the lithosphere-asthenosphere boundary – Naif et al., 2013.
Water-rich bending faults at the Middle America Trench – Naif et al., 2015.
A serpentinite-hosted ecosystem in the Southern Mariana Forearc – Ohara et al., 2012.
Analysis of normal fault populations in the Kumano forearc basin, Nankai Trough, Japan: 2. Principal axes of stress and strain from inversion of fault orientations - Sacks et al., 2013.
Evaluation of in-situ smectite dehydration as a pore water freshening mechanism in the Nankai Trough, offshore southwest Japan – Saffer et al., 2009.
Hydrostratigraphy as a control on subduction zone mechanics through its effects on drainage: an example from the Nankai Margin, SW Japan – Saffer et al., 2010.
Pore pressure development beneath the décollement at the Nankai subduction zone: implications for plate boundary fault strength and sediment dewatering – Skarbek and Saffer, 2009.
Origin and evolution of a splay fault in the Nankai accretionary wedge – Strasser et al., 2009.
Velocity-porosity relationships in smectite-rich sediments: Shikoku Basin, Japan – Tudge and Tobin, 2013.

2.2.2 The Seismogenic Zone

Recent large damaging earthquakes, such as the 2004 Sumatra, 2010 Chile, and 2011 Tohoku-oki events, demonstrate the societal importance of understanding the subduction megathrust and provide unprecedented new datasets to understand fault behavior. Discoveries in the last ten years have revealed that subduction zone faults show a wide range of previously unknown fault slip behaviors and rates, from coseismic slip to silent earthquakes, slow slip events (SSE), episodic tremor and slip (ETS), low frequency earthquakes (LFE), and very low frequency earthquakes (VLF), in addition to "normal" fast-slip earthquakes.

Although our community has made some progress in characterizing these phenomena, we do not know if these new observations represent fundamentally new types of seismic moment release or fall along a continuum ranging from normal earthquakes to creep (e.g., Ide et al., 2007). We also do not fully understand the underlying physical processes that give rise to these slip phenomena, in terms of intrinsic fault rock properties, fault architecture, and conditions (such as the pore pressure, stress state, and temperature) on the fault interface, or how these other slip processes may influence great earthquake occurrence.

A major focus of the SCD initiative is obtaining key observational and experimental constraints on faulting processes across the entire range of slip conditions and sampling these at various stages over the earthquake cycle. This effort requires a combination of: (1) new seismic, geodetic, and other geophysical field observations made at the three primary sites; (2) long-term observations of in situ mechanical, geochemical, thermal, and hydrologic conditions relevant to these slip processes; (3) theoretical and laboratory-based experimental approaches that link observations and the underlying physical mechanisms; and (4) integration of observations across multiple study sites to sample the full range of slip behaviors and/or stages in the seismic cycle.

2.2.2.1 Cascadia

Ghosh et al. (2015) performed a systematic search for VLFs in the Cascadia subduction zone under Washington during an episodic tremor and slip event as part of a postdoc project funded to PI Brodsky. They detected and located VLFs, estimated their source parameters by a moment tensor inversion method, analyzed their spatiotemporal distribution relative to tremor, and explored implications for possible source characteristics of slow earthquakes. They found VLFs in Cascadia under northern Washington during a 2011 episodic tremor and slip event (Figure 2.5). VLFs are rich in low-frequency energy (20–50 s) and depleted in higher frequencies (higher than 1 Hz) compared to local earthquakes. They found that VLFs are located near the plate interface in the zone where tremor and slow slip are observed and that they migrate along strike with tremor activity. Their moment tensor solutions show double-couple sources with shallow thrust mechanisms, consistent with shear slip at the plate interface. The seismic moment released by a single VLF is comparable to the total cumulative moment released by tremor activity during an entire episodic tremor and slip event. The VLFs contribute more seismic moment to this episodic tremor and slip event than cumulative tremor activity and indicate a higher seismic efficiency of slow earthquakes in Cascadia than previously thought. Spatiotemporal correlation of VLF and tremor activity suggests that they are the results of the same physical processes governing slow earthquakes.

2.2.2.2 Alaska-Aleutians

Variations in the in-situ conditions and physical properties of the megathrust plate interface are primary controls on great earthquake rupture, the mode of fault slip, and the manner in which slip might reach the trench to produce tsunamis. The ongoing Aleutian megathrust project by PIs Keranen, Shillington, Saffer, Abers, Becel and Nedimovic is integrating laboratory data from modern oceanic sediment and exhumed metapelites with existing, multi-resolutional geophysical data to improve the understanding of in situ conditions and processes along the plate boundary megathrust from the trench to ~30-40 km depth. Their study focuses on the Alaska-Aleutian primary site, where several existing geophysical datasets and DSDP/IODP cores can be used (Figure 2.6). They seek to develop an improved quantitative understanding of the conditions and materials along the megathrust and their relationship to seismicity, and provide a template for similar studies at other margins.

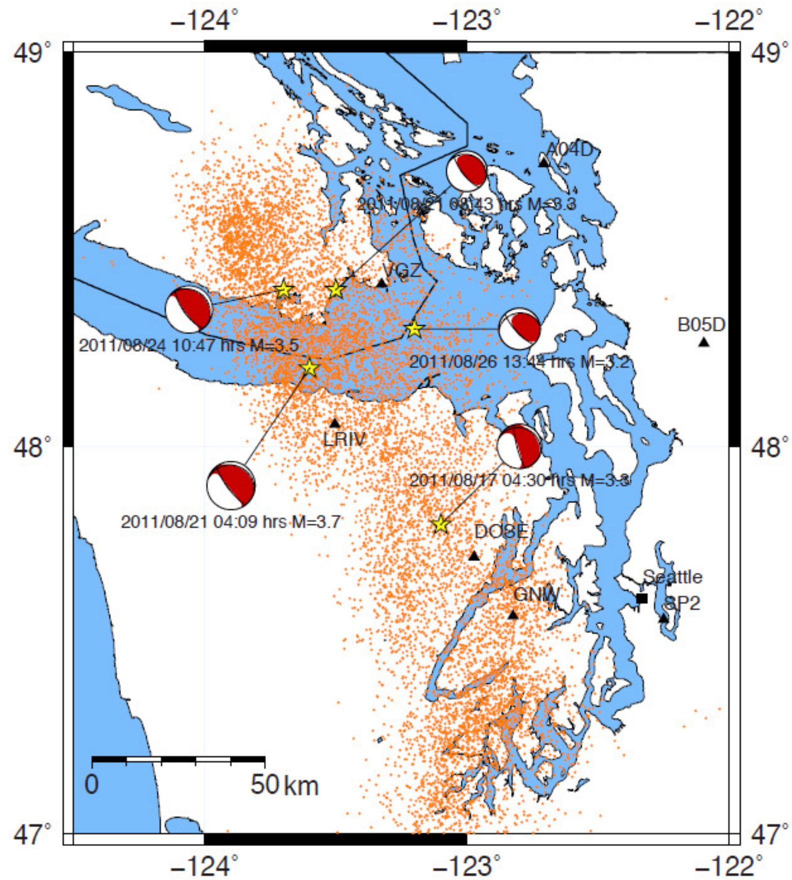
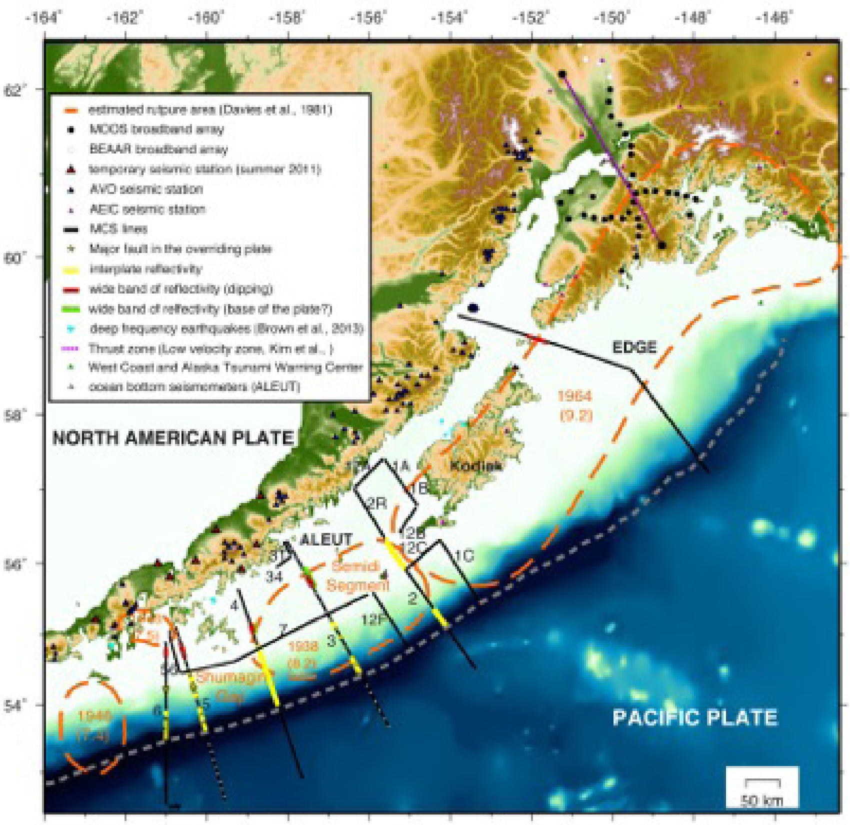


Figure 2.5. Tremor (orange dots), VLFs (yellow stars), and their focal mechanisms during August 2011. The date of occurrences and moment magnitudes (Mw) of VLFs are noted. Black triangles are the seismic stations used to obtain source parameters of the VLFs (from Ghosh et al., 2015).

The Keranen et al. project directly addresses the role of fluid production on the dynamics of the subduction interface. The downdip end of the locked zone and transition to tremor appears to be marked by a broadening of deformation based on seismic reflection data. Receiver functions indicate that the megathrust is associated with a few km wide zone with 20-30% slower Vs than its surroundings and anomalously high Vp/Vs ratios both within and downdip of the main rupture zone of the 1964 earthquake (Figure 2.7; Kim et al., 2014). Low velocity zones, high Vp/Vs and high reflectivity observed in seismic data in Alaska and in other subduction zones have been interpreted to represent very high pore-fluid pressures along different parts of the plate boundary, but could also arise from changes in sediment porosity and lithology with depth or from anisotropy in elastic properties.

A primary SCD objective is to understand what controls variations in seismic activity along a margin where tectonic plates converge. The Alaska Peninsula segment of the Aleutian megathrust

Figure 2.6. Map showing existing drilling and seismic data along the Alaska subduction zone.



includes the transition from a wide, locked region on the plate interface to a dominantly creeping section. The co-location of an island chain across this segment provides an ideal setting for measuring deformation in the recently funded GeoPRISMS project of PI Freymueller. These data will be used to determine the distribution of recent slip (or lack thereof) along the plate boundary fault. This is the first time that a detailed view of how the seismogenic zone varies from a locked to a creeping section will be obtained. The findings will inform assessment of earthquake and tsunami hazards, both in relation to the Alaska Peninsula and along the US west coast due to trans-Pacific tsunamis.

In a more general sense, the availability of inexpensive, but highly precise continuous geodetic instruments on land, and improvements in similar measurements offshore, now make it possible to fully constrain the patterns of deformation that accompany the full seismic cycle within a decadal time frame by working in several subduction zones simultaneously. This is accomplished through a combination of ongoing GeoPRISMS studies (PI Chadwell in Cascadia; PI Freymueller in Alaska and related research efforts that leverage EarthScope Plate Boundary Observatory activities).

2.2.2.3 Experimental studies

The frictional behavior of natural subduction megathrust fault rocks is studied experimentally by PIs Saffer, Marone and postdoc den Hartog to evaluate the stability of megathrust rocks at in situ pressures and temperatures. A novel aspect of this project is the use of a unique suite of natural megathrust fault zone samples obtained by drilling and from well-characterized, exhumed subduction paleo-décollements. Initial results show that the behavior of these materials is similar to that of quartz-phyllosilicate mixtures and can be subdivided into three regimes: 1) low-temperature gouges with stable, velocity-strengthening behavior, 2) intermediate-temperature gouges with potentially unstable,

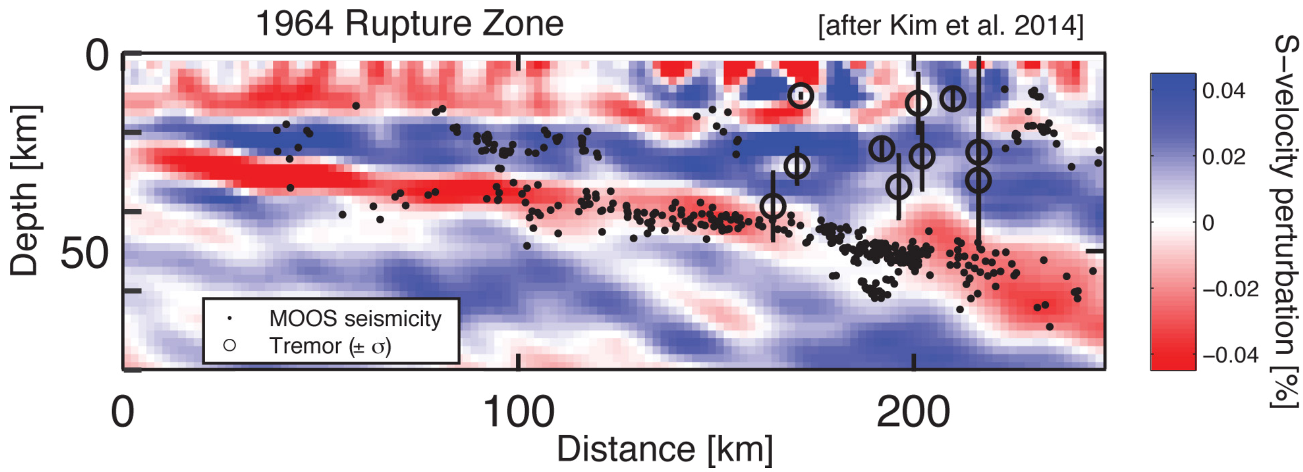


Figure 2.7. Receiver function image across Alaska subduction zone, showing low velocities along the megathrust.

velocity-weakening behavior, and 3) high-temperature gouges with velocity-strengthening behavior (den Hartog et al., 2012, 2013). The three-regime behavior is well-explained by a microphysical model in which frictional behavior is governed by a competition between rate-independent frictional slip on aligned phyllosilicates and thermally activated deformation of intervening quartz clasts by pressure solution.

In a separate GeoPRISMS-funded project PI Saffer and postdoc Kitajima study the stress conditions of both sediments coming into the trench and that of the seismogenic zone at depth. The conditions of the seismogenic zone at depth are determined by combining laboratory-derived relationships between seismic velocity, stress and pore pressure with observed velocities from geophysical surveys. Importantly they provide the first quantitative evidence that the very low frequency events down-dip from the seismogenic zone occur under conditions of low stress and high pore pressure (Kitajima and Saffer, 2012). In a separate study they determined the consolidation state of sediments retrieved from boreholes in Nankai. The determination of this initial state of the sediments is crucial in our understanding of how further consolidation and dewatering aids in the nucleation of seismicity along the megathrust (Figure 2.8; Kitajima and Saffer, 2014).

2.2.2.4 Related work from late-MARGINS funded projects

A grant to PIs Dixon and Schwartz established a GPS and seismic network on Nicoya Peninsula, Costa Rica through an international partnership. The network was fully operating when the 2012 Mw 7.6 earthquake struck. This timely observational effort allows for a much improved understanding of the earthquake cycle (see nugget by Dixon and Schwartz).

2.2.2.5 Related GeoPRISMS-funded publications (appendix A3)

Very low frequency earthquakes in Cascadia migrate with tremor – Ghosh et al., 2015.

Crustal anisotropy from tectonic tremor under Washington State in the Cascadia [sic] - Huesca-Perez and Ghosh, 2015.

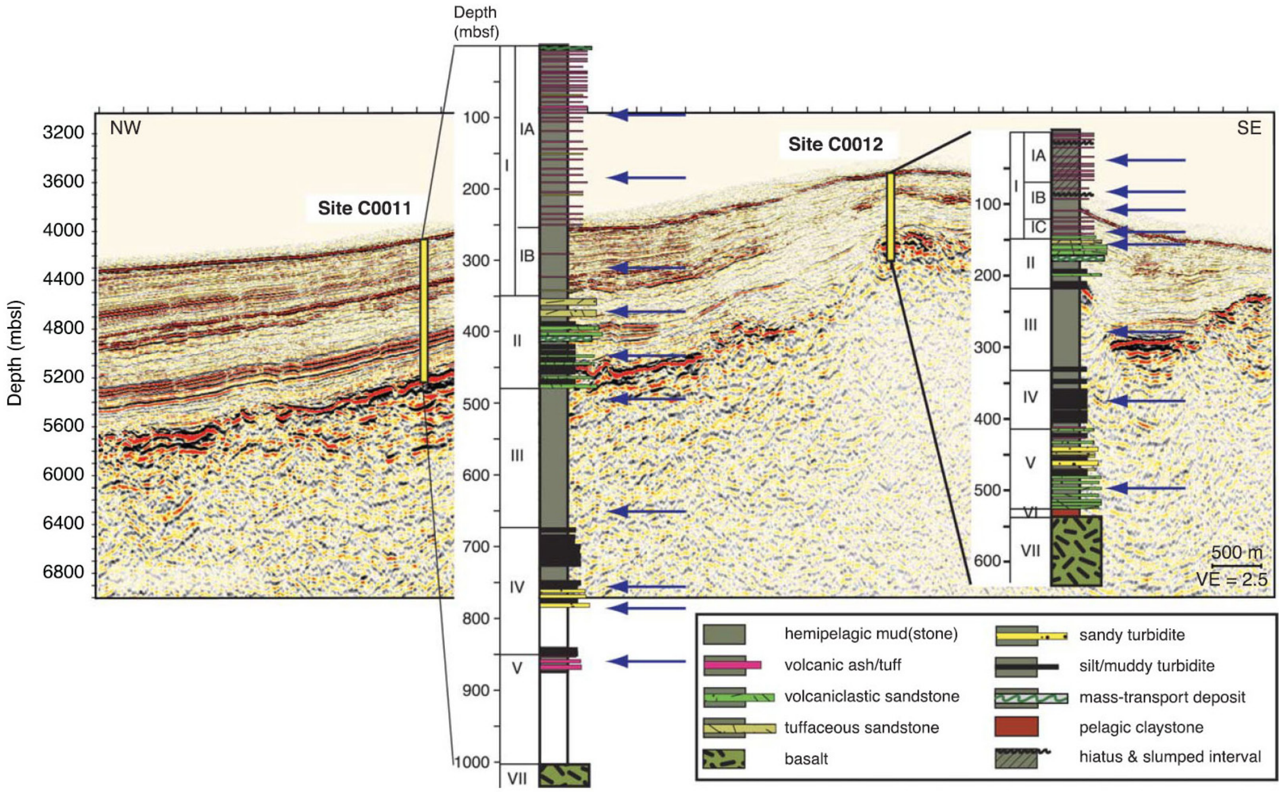


Figure 2.8. Determination of the consolidation state of sediments entering the Nankai trench is essential to determine the nature of further compaction and its role in earthquake nucleation (from Kitajima and Saffer, 2014).

Elevated pore pressure and anomalously low stress in regions of low frequency earthquakes along the Nankai Trough subduction megathrust - Kitajima and Saffer, 2012.
Consolidation state of incoming sediments to the Nankai Trough subduction zone: implications for sediment deformation and properties – Kitajima et al., 2014.
The permeability of active subduction plate boundary faults – Saffer, 2015.
Effects of smectite to illite transformation on the frictional strength and sliding stability of intact marine mudstones – Saffer et al., 2012.
Potential for geologic records of coseismic uplift and megathrust rupture along the Nicoya Peninsula – Spotila et al., 2015.

2.2.2.6 Related MARGINS-funded papers (2009 and later; appendix A4)

Hydrologic control of forearc strength and seismicity in the Costa Rican subduction zone - Audet and Schwartz, 2013
Broad, weak regions of the Nankai Megathrust and implications for shallow coseismic slip - Bangs et al. 2009
Spatial variations in earthquake source characteristics within the 2011 Mw = 9.0 Tohoku, Japan rupture zone - Bilek et al., 2012
The 25 October 2010 Sumatra tsunami earthquake: Slip in a slow patch - Bilek et al., 2011
The role of subduction erosion on seismicity – Bilek, 2010.
A geological fingerprint of low-viscosity fault fluids mobilized during an earthquake - Brodsky et al., 2009
Deep low-frequency earthquakes in tremor localize to the plate interface in multiple subduction zones – Brown et al., 2011.
Detailed data available for recent Costa Rica Earthquake – Dixon et al., 2013.

Along-strike variability of rupture duration in subduction zone earthquakes - El Hariri et al., 2013.
Organized melt, seismic anisotropy, and plate boundary lubrication – Holtzman and Kendall, 2010.
Slip weakening as a mechanism for slow earthquakes – Ikari et al., 2013.
Non-volcanic tremor associated with the March 2010 Gisborne slow slip event at the Hikurangi subduction margin, New Zealand – Kim et al., 2011.
Imaging a steeply dipping subducting slab in southern Central America – MacKenzie et al., 2010.
No slab-derived CO_2 in Mariana trough back-arc basalts: implications for carbon subduction and for temporary storage of CO_2 beneath slow spreading ridges – Macpherson et al., 2010.
A tremor and slip event on the Cocos-Caribbean subduction zone as measured by a global positioning system (GPS) and seismic network on the Nicoya Peninsula – Outerbridge et al., 2010.
A low-velocity zone with weak reflectivity along the Nankai subduction zone – Park et al., 2010.
Nicoya earthquake rupture anticipated by geodetic measurement of the locked plate interface - Protti et al., 2014.
Collateral damage: evolution with displacement of fracture distribution and secondary fault strands in fault damage zones – Savage et al., 2011.
The role of frictional strength on plate coupling at the subduction interface - Tan et al., 2012.
Elevated fluid pressure and extreme mechanical weakness of a plate boundary thrust, Nankai Trough subduction zone - Tobin and Saffer, 2009,
Intraoceanic thrusts in the Nankai Trough off the Kii Peninsula: Implications for intraplate earthquakes - Tsuji et al., 2009.
Persistent tremor within the northern Costa Rica seismogenic zone – Walter et al., 2011.
The synchronous occurrence of shallow tremor and very low frequency earthquakes offshore of the Nicoya Peninsula, Costa Rica – Walter et al., 2013.
Interseismic megathrust coupling beneath the Nicoya Peninsula, Costa Rica, from the join inversion of InSAR and GPS data – Xue et al., 2015.
The 5 september 2012 Nicoya, Costa Rica Mw 7.6 earthquake rupture process from joint inversion of high-rate GPS, strong-motion, and teleseismic P wave data and its relationship to adjacent plate boundary interface properties – Yue et al., 2013.

2.2.3 Slab Processes

As the slab descends it undergoes dramatic changes in ambient pressure and temperature conditions. This leads to a series of progressive metamorphic reactions that release volatiles, resulting in strongly changing physical properties at depth. When the slab comes into contact with the hot mantle wedge, the dehydration of the slab accelerates (e.g., van Keken et al., 2011) and fluids are released that trigger arc melting. The nature of the processes in the slab can be deduced directly from geophysical imaging, indirectly from geochemical output in arc volcanoes, and from the field by studying exhumed terranes.

The GeoPRISMS project of PIs van Keken, Hacker and Abers continues a geodynamical-seismological-petrological collaboration to investigate whether the presence of fluids within Earth's mantle is a controlling factor determining where intermediate seismicity occurs and how fluids affect the seismological structure of the mantle wedge. There are tantalizing indications that petrological conditions play a direct role in intermediate-depth seismicity because this seismicity is located within the crust at 'cool' subduction zones, such as Alaska and Tohoku, but in the mantle at 'warm' subduction zones, such as Cascadia and Nankai (Abers et al., 2013). In Tohoku and Hokkaido, the seismicity in the crust ends when the major blueschist to eclogite transition is predicted to occur (van Keken et al., 2012) except in a narrow region at the transition from the Tohoku to Hokkaido arc (Morishige and van Keken, 2014; Morishige, in press). The correlation with very low P-wave velocities and predicted presence of free fluids from new dynamical models (Wilson et al., 2014) provide very strong evidence that, at least in the oceanic crust below NE Japan, the flow of fluids triggers intermediate-depth seismicity. The thermal-petrological models developed as part of this project are also used to predict seismic velocities that further confirm the role of fluids in the slab and in the mantle wedge. Intriguingly, an earlier prediction that the fluids that contribute to the water content of arc volcanoes in Cascadia can only be derived from the hydrated mantle portion (van Keken et al., 2011) has now been corroborated by combined geochemical and geodynamical work (Walowski et al., 2015).

Serpentinite is present in both subducting mantle and in the overlying mantle wedge. The rheology of serpentinite may play a key role in controlling seismicity and the dynamics of plate motion and movement of material within the plate interface (Hirth and Guillot, 2013). Intermediate-depth earthquakes in subduction zones have been attributed to dehydration embrittlement, in which prograde dehydration of minerals is thought to result in brittle fracturing. Deformation experiments funded by GeoPRISMS to PIs Hirth and Goldsby investigate the behavior of serpentine and suggest that serpentine deforms via semi-brittle flow, with grain-scale ductile deformation active at high pore fluid pressures (Chernak and Hirth, 2010; Proctor and Hirth, 2015). These results suggest that earthquakes in serpentinized mantle are not due to dehydration embrittlement. The experiments also demonstrate that extreme dynamic weakening occurs when rapid slip is imposed onto a fault zone rich in serpentinite (Proctor et al., 2014). The slip velocity at which dynamic weakening is observed increases in the presence of gouge. The onset of weakening for both bare surfaces and with a layer of gouge is well-explained by flash weakening at asperity contacts.

2.2.3.1 Related GeoPRISMS-funded publications (appendix A3)

Rheology and tectonic significance of serpentinite – Hirth and Guillot, 2013.
A new regime of slab-mantle coupling at the plate interface and its possible implications for the distribution of volcanoes – Morishige, 2015.
Along-arc variation in the 3D thermal structure around the junction between the Japan and Kurile arcs - Morishige and van Keken, 2014.
Role of pore fluid pressure on transient strength changes and fabric development during serpentine dehydration at mantle conditions: implications for subduction-zone seismicity – Proctor and Hirth, 2015.
Fluid flow in subduction zones: The role of solid rheology and compaction pressure - Wilson et al., 2014.

2.2.3.2 Related MARGINS-funded papers (2009 and later; appendix A4)

Thermo-petrological controls on the location of earthquakes within subducting plates – Abers et al., 2013.
The relationship of intermediate- and deep-focus seismicity to the hydration and dehydration of subducting slabs – Barcheck et al., 2012.
Three-dimensional thermal structure of subduction zones: effects of obliquity and curvature – Bengtson and van Keken, 2012.
P and S velocity tomography of the Mariana subduction system from a combined land-sea seismic deployment – Barklage et al., 2015.
Farallon slab detachment and deformation of the Magdalena Shelf, Southern Baja California – Brothers et al., 2012.
Deformation of antigorite serpentinite at high temperature and pressure – Chernak and Hirth, 2010.
Fluidity: A fully unstructured anisotropic adaptive mesh computational modeling framework for geodynamics

– Davies et al., 2011.
Along-strike translation of a fossil slab – Eichenbaum-Pikser et al., 2012.
Upper and mid-mantle anisotropy beneath the Tonga slab – Foley and Long, 2011.
Intermediate-depth earthquakes facilitated by eclogitization-related stresses – Nakajima et al., 2013.
Along-strike translation of a fossil slab - Pikser et al., 2012.
Long-term preservation of slab signatures in the mantle inferred from hydrogen isotopes - Shaw et al., 2012
Links between fluid circulation, temperature, and metamorphism in subducting slabs - Spinelli et al., 2009.
The dynamics of plate tectonics and mantle flow: from local to global scales – Stadler et al., 2010.
Systematic biases in subduction zone hypocenters - Syracuse and Abers, 2009.
The global range of subduction zone thermal models – Syracuse et al., 2010.
Structure and serpentinization of the subducting Cocos plate offshore Nicaragua and Costa Rica – van Avendonk et al., 2011.
Seismic evidence for fluids in fault zones on top of the subducting Cocos plate beneath Costa Rica – van Avendonk et al., 2010.
Subduction factory: 4. Depth-dependent flux of H_2O from subducting slabs worldwide - van Keken et al., 2011.
Thermal structure and intermediate-depth seismicity in the Tohoku-Hokkaido subduction zones - van Keken et al., 2012.
Intraslab stresses in the Cascadia subduction zone from inversion of earthquake focal mechanisms – Wada et al., 2010.
Effects of heterogeneous hydration in the incoming plate, slab rehydration, and mantle wedge hydration on slab-derived H_2O flux in subduction zones - Wada et al., 2012.
Fossil slabs attached to unsubducted fragments of the Farallon plate – Wang et al., 2012.

2.2.4 Mantle wedge and arc crust

The fluids released from the descending slab trigger melting in the mantle wedge. These melts migrate and differentiate and contribute to explosive arc volcanism and the formation of continental crust. Studies of the processes of melt generation and migration are essential for quantifying the volatile fluxes and cycling that is a primary objective of the GeoPRISMS science program. Exactly half of the SCD-funded projects (appendix A1) fall in this wedge and arc crust category; most have a strong focus on magmatic and continental crust forming processes.

2.2.4.1 Alaska-Aleutians: magma migration below volcanoes

Two recently funded projects will investigate the origin, storage and ascent of magma in different parts of the Aleutian arc with an emphasis on the role of volatiles. The first, by PIs Plank, Roman and Hauri, is an integrated geochemical and geophysical study of the Unimak-Cleveland corridor, a region of the Aleutians that encompasses six volcanoes that have erupted in the past 25 years with a wide range of magmatic water contents. The main goal is to better understand how shallow crustal processes link to and are controlled by the large-scale crustal tectonics and deep mantle melting that are ultimately responsible for arc volcanism. The results of this project will help to establish the links between two normally disconnected, big-picture problems: 1) the deep origin of magmas and volatiles, particularly the processes that control magma H_2O content, and 2) the formation and eruption of crustal magma reservoirs.

The second project, by PIs Key and Bennington, involves a seismic and magnetotelluric survey at Okmok to characterize the magmatic system beneath an active volcano in the Aleutians. The main goals are to test hypotheses regarding the role of slab fluids in arc melt generation, melt migration within the crust, and the crustal magmatic plumbing and storage system beneath an active caldera. These data will be used to study the mantle melt flux, the possible storage of melts at the base of the crust, the distribution of partial melt and magma bodies in the mid-upper crust, and the thermal and mechanical properties of the upper crust beneath the caldera.

A related project by PI/postdoc Lopez at the Katmai Volcanic Cluster in Alaska investigates the relationship of fluid movement in the subsurface of active volcanoes to elevated seismicity (see article in the Spring 2014 newsletter). Geochemical data on volcanic gases at three volcanoes in this region (Mount Mageik, Mount Martin, Trident) have been used to reveal information on the source, flux, migration and seismic signatures of fluids. He-isotope ratios at two of the volcanoes (Mount Mageik and Trident) indicate that the fluids derive in part from mantle-derived basaltic magma, whereas N and C isotopes indicate contributions from sediment and limestone, either recycled by subduction from a slab component or acquired through crustal contamination. Elevated CO_2 concentrations relative to SO_2 and HCl in the fumarolic samples from both Mount Mageik and Trident are consistent with scrubbing of magmatic gases by hydrothermal fluids. The evidence for scrubbing, combined with the strong meteoric signature of steam condensates indicates that both Mount Mageik and Trident have well-developed hydrothermal systems. Compositional gas changes can be correlated with two deep low frequency earthquakes occurring ~2 months prior.

Figure 2.9. Seismic station installation on Okmok volcano as part of the project by PIs Key and Bennington.

2.2.4.2 Alaska-Aleutians: from arcs to volcanic crust

Arc magmatism is the most important process that generates continental crust today and likely throughout Earth's history. However, average continental crust composition is andesitic and calc-alkaline, whereas average arc lava composition is basaltic and tholeiitic. One hypothesis that could help to explain this difference is that the plutonic parts of arcs, which are largely unexposed and unsampled, may be more similar to the continental crust. Therefore, understanding the genesis of plutonic rocks is a key to understanding continental crust formation and evolution via arc magmatism. The Aleutian arc is uniquely well-suited for such a study because of the extensive exposures of plutonic rocks, unmatched in any other intra-oceanic arc.

A recently funded project led by PIs Kelemen, Goldstein, and Cai will map and sample plutonic rocks exposed on the central Aleutians and their coeval volcanic host rocks to understand the extent and origin of the compositional differences between lavas and plutons through time and space. In a pilot study using samples of plutons from the Aleutians collected by the US Geological Survey from 1950 to 1980, they found that Eocene-Miocene plutonic rocks and Holocene volcanic rocks show distinctly different elemental and isotopic signatures, which indicate that they were derived from distinct parental magmas. This difference could reflect temporal variation of the mantle under the region or fundamentally different mechanisms that form plutons and lavas.

The timing of Aleutian Arc inception and subsequent compositional evolution through the initial stages of arc growth are poorly known. PIs Jicha and Kay are funded to better determine the age and early stages of this inception (see their Spring 2015 newsletter article). $^{40}Ar/^{39}Ar$ incremental heating experiments and geochemical analyses revealed that most of the subaerial samples of the older portions of the central and western Aleutians are <40 Ma and thus provide little information on subduction initiation. As a result, the project was refocused to constrain the along- and across-arc chemical evolution of the central and western Aleutians over the last 40 Myr of arc history. A key finding from the new data is that a subduction-recycled sediment melt component was not involved during the early development of the western Aleutian Arc, but has become more pronounced during the Quaternary. One $^{40}Ar/^{39}Ar$ age of a mafic xenolith from Kanaga Island (interpreted as a lower crustal cumulate related to arc magmatism, e.g., Kay et al., 2014) has yielded the oldest ages yet reported in the Aleutian arc (47.8±4.3 Ma). They interpret this age as a time of metamorphism and recrystallization of mafic arc cumulates by younger arc magmas intruding the existing arc crust. Chemical and $^{40}Ar/^{39}Ar$ analyses of lavas and gabbros indicate a change in the strike of magmatic centers on Attu, which combined with paleomagnetic data suggests a significant clockwise rotation of the western Aleutians along with uplift between 16 and 8 Ma.

Among the key characteristics shared by bulk continental crust and some subduction zone magmas is calc-alkaline affinity, a rapid draw-down in Fe concentration early in a magma's cooling and differentiation history. Resolving the key roles that H_2O, oxygen fugacity (fO_2), and magma bulk composition play in controlling calc-alkaline trends is important for understanding how continents initially formed and have grown through time. GeoPRISMS research by PIs Jackson, Cottrell and Kelley examines the role of fO_2 in calc-alkaline differentiation and the creation of continental crust in the Aleutian arc. This work builds on MARGINS-funded research (Cottrell et al., 2009; Kelley and Cottrell, 2009, 2012; Brounce et al., 2014) which had the important conclusion that slab fluids may be very oxidized. The main goals of the new project are to examine how fO_2 of magmas varies during differentiation and degassing at individual volcanoes and how it varies along strike of the Aleutian arc as a function of material derived from the subducted slab. The work will also include an experimental study quantifying the effects of H_2O and fO_2 on calc-alkaline differentiation trends during crystallization of magmas at crustal pressures. In Fall 2015, they will collect new samples of the most strongly calc-alkaline Aleutian magmas as part of the NSF-sponsored shared platform for Aleutians research.

2.2.4.3 Cascadia

Recent studies at Cascadia can be used to correlate the metamorphic state of the slab (Rondenay et al., 2008; van Keken et al., 2011; Cozzens and Spinelli, 2012) and the volatile concentrations of primitive basaltic magmas (Ruscitto et al., 2010, 2011, 2012; Walowski et al., 2015) providing important evidence for the pathways of fluids rising from slab to the arc. Two GeoPRISMS research programs in the Cascades are focused on the processes of mantle upwelling and magma generation beneath the arc and back-arc and the movement and storage of magma within the crust.

Full wave ambient noise tomography has revealed three separate, low shear-wave velocity anomalies along the back arc in the upper mantle ~200 km east of the Cascade arc (Gao and Shen, 2014). The back-arc low velocity anomalies are spatially correlated with the three main arc-volcano clusters in northern California, Oregon, and Washington (Figure 2.10). The geometry of the low-velocity regions suggests they are caused by subduction-driven upwelling and decompression melting beneath the back-arc. Gao and Shen (2014) interpret the along strike variation as an indication that large-scale, plate-motion-induced flow in the back-arc mantle wedge is modulated by small-scale convection, resulting in a highly 3D process that defines the segmentation of volcanism along the Cascade arc.

The goal of the ongoing iMUSH project is to image the architecture of the greater Mount St. Helens (MSH) magmatic system from the subducted plate to the surface, including the extent and characteristics of highly crystalline magma bodies, and to resolve major tectonic controls on volcanism along the Cascade arc. MSH was chosen as the target because it is currently the most active volcano of the Cascades arc in the northwestern US. This four year collaborative effort involves 12 PIs at 7 institutions in the US and Europe and is supported by both GeoPRISMS and EarthScope. The project involves a variety of geophysical techniques (active and passive seismic experiments, extensive magnetotelluric sounding) integrated with geochemical and petrological data to image and interpret the crust and upper mantle in the greater MSH area. The iMUSH geochemical work focuses on crystal mush inclusions/xenoliths sampled from dacitic volcanic rocks from MSH. Dating of zircons in these inclusions shows that they are part of the young MSH magmatic system and thus provide information on crystallization, differentiation and storage of magma feeding the volcano.

An important aspect of understanding the temporal evolution of crust produced in arcs is to determine how changes in large-scale crustal tectonics affect the composition of arc magmatism and productivity of melting in the underlying mantle. To investigate these questions, PIs Kent, Duncan and Grunder are conducting geochemical and geochronological studies of the Deschutes Formation (~7.4- 4.0 Ma) in the Central Oregon Cascades (see nugget by Pitcher et al.). Located just east of the active High Cascades, the Deschutes Formation preserves a remarkable stratigraphy that records the initial stages of the High Cascade arc following a major eastward shift in volcanism ~7.5 Ma. Over 120 (uncorrelated) airfall tuffs and 130 ignimbrite units are contained within the formation, suggesting that the arc may have been much more magmatically productive and explosive during this phase than at any other time within the last 17 Ma. An important new result is that glass compositions from the Deschutes Formation ignimbrites have much higher FeO* at a given CaO or SiO_2 concentration when compared to other Quaternary Cascade lavas. In this regard, they are more similar to volcanics

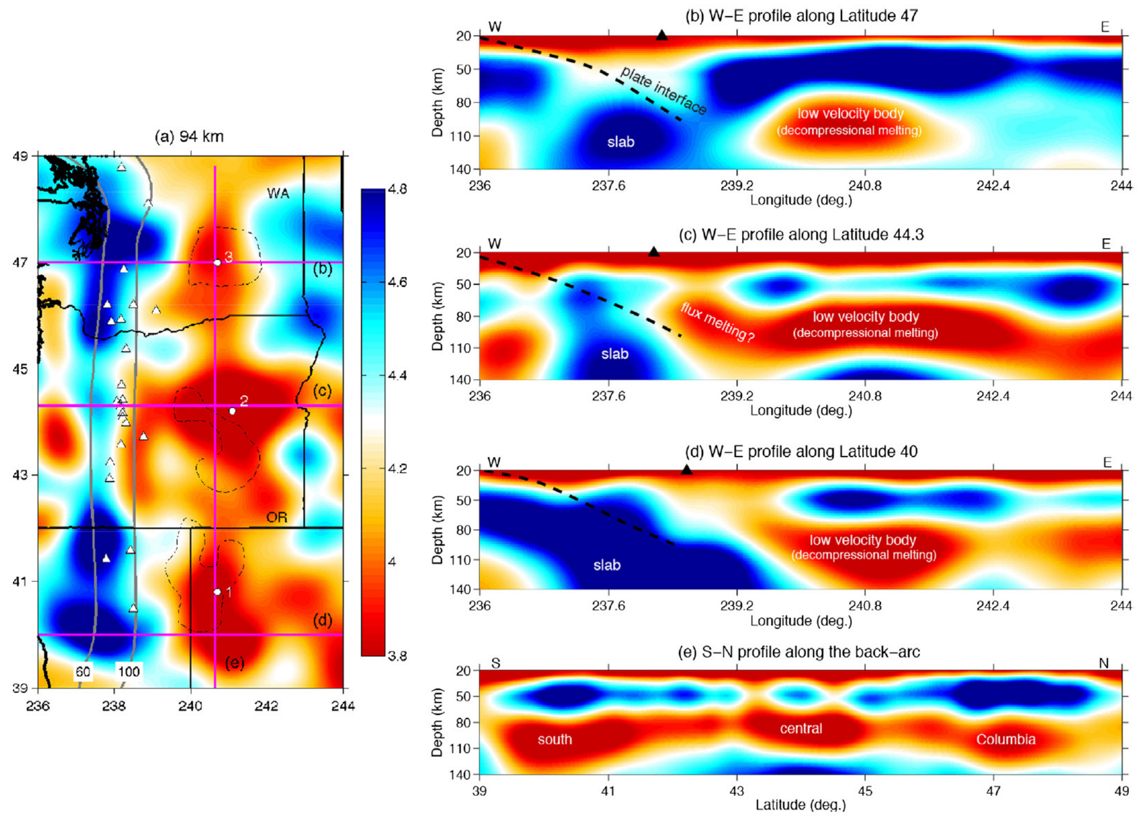


Figure 2.10. Segmented low-velocity anomalies along the Cascade back-arc. (a) Horizontal slice at depth of 94 km (Vs in km/s). The black dashed lines outline the amplitude of largest negative Sp phase from receiver functions. The magenta lines mark profile locations in (b)-(e), respectively. All the panels share the same color bar. (b-d) W-E profiles across the back-arc anomalies. The triangles mark the volcano centers. The Juan de Fuca plate interface at depths of 20-100 km is projected. (e) S-N profile along the back-arc low-velocity anomalies, which spatially correlate with the three volcano clusters as in (a). Gao and Shen (EPSL, 2014).

from the High Lava Plains. This could be an indication of hotter and drier melting conditions during rift-related mantle upwelling and partial melting of mafic crust.

2.2.4.4 Other studies

The Rosario segment of the Alisitos oceanic arc (Baja California, Mexico) is under investigation by PIs DeBari and Busby as a field analog for the Izu-Bonin Arc. Their study focuses on a tilted but undeformed and unmetamorphosed upper to middle crustal section mapped in detail by Busby et al. (2006). They are determining the detailed relationships between plutonic, hypabyssal, and volcanic rocks using field, geochemical, and geochronological data to investigate the relationship and proportion between volcanic and plutonic rocks in juvenile arc crust and whether arc crust composition changes with time. The primary goal is to construct an island arc crust "Virtual Field Model" as a reference model for Izu-Bonin-Mariana drilling outcomes from the IODP Expeditions in 2014.

MARGINS and GeoPRISMS-funded research by Hacker and others (Rioux et al., 2010; Hacker et al., 2011a, b; Behn et al., 2011; Hacker et al., 2012; Worthington et al., 2013) addresses important questions about the generation of continental crust. Their research demonstrates that buoyancy differences between mafic and felsic rocks during subduction can potentially result in overall addition of more felsic rocks to the lower crust. Processes that contribute to this differentiation include sediment subduction, subduction erosion, arc subduction, and continent subduction (see nugget by Hacker). An important suggestion is that bulk continental crust may be more silica rich than generally considered.

2.2.4.5 Related GeoPRISMS-funded publications (appendix A3)

Upper mantle structure of the Cascades from full-wave ambient noise tomography: evidence for 3D mantle upwelling in the back arc – Gao and Shen, 2014.

Validation of recent shear wave velocity models in the United States with full-wave simulation – Gao and Shen, 2015.

Continental lower crust – Hacker et al., 2015.

Sharing resources for Aleutian arc research – Jicha et al., 2014.

$^{40}Ar/^{39}Ar$ geochronology of subaerial Ascension island and a re-evaluation of the temporal progression of basaltic to rhyolitic volcanism – Jicha et al., 2013.

Reaction-driven cracking during retrograde metamorphism: olivine hydration and carbonation – Kelemen and Hirth, 2012.

Acoustic characterization of explosion complexity at Sakurajima, Karymsky, and Tungurahua volcanoes – Matoza et al., 2014.

2.2.4.6 MARGINS-funded papers (2009 and later; appendix A4)

Shear wave anisotropy beneath Nicaragua and Costa Rica: implications for flow in the mantle – Abt et al., 2009.

Constraints on upper mantle anisotropy surrounding the Cocos slab from SK(K)S splitting – Abt et al., 2010.

Chlorine isotope variations along the Central American volcanic front and back arc – Barnes et al., 2009.

Malaguana-Gadao Ridge: identification and implications of a magma chamber reflector in the southern Mariana Trough – Becker et al., 2010.

Implications of grain size variation on the seismic structure of the oceanic upper mantle – Behn et al., 2009.

Fluid circulation in a complex volcano-tectonic setting, inferred from self-potential and soil CO_2 flux surveys: The Santa Maria-Cerro Quernado-Zunil volcanoes and Xela caldera (Northwestern Guatemala) – Bennati et al., 2011.

Correlating geochemistry, tectonics, and volcanic volume along the Central American volcanic front – Bolge et al., 2009.

An inversion-based self-calibration for SIMS measurements: Application to H, F, and Cl in apatite, Boyce et al., 2012.

Lunar apatite with terrestrial volatile abundances – Boyce, 2010.

Variations in $Fe^{3+}/\Sigma Fe$ of Mariana Arc Basalts and Mantle Wedge fO_2 - Brounce et al., 2014.

Temporal evolution of mantle wedge oxygen fugacity during subduction initiation – Brounce et al., 2015.

RU_CAGeochem v.3, a database and sample repository for Central American volcanic rocks at Rutgers University – Carr et al., 2013.

High-precision determination of iron oxidation state in silicate glasses using XANES - Cottrell et al., 2009.

The oxidation state of Fe in MORB glasses and the oxygen fugacity of the upper mantle - Cottrell et al., 2011.

Redox heterogeneity in mid-ocean ridge basalts as a function of mantle source – Cottrell et al., 2013.

Ingassing, storage, and outgassing of terrestrial carbon through geologic time - Dasgupta, 2013

The deep carbon cycle and melting in Earth's interior - Dasgupta and Hirschmann, 2010.

Sulfur isotope fractionation during the May 2003 eruption of Anatahan volcano, Mariana islands: implications for sulfur sources and plume processes – de Moor et al., 2010.

Directions of seismic anisotropy in laboratory models of mantle plumes – Druken et al., 2013.
CO_2 solubility and speciation in rhyolitic sediment partial melts at 1.5–3.0 GPa – Implications for carbon flux in subduction zones - Duncan and Dasgupta, 2014.
Eruption of South Sarigan Seamount, Northern Mariana Islands: insights into hazards from submarine volcanic eruptions – Embley et al., 2011.
Constraints on upper plate deformation in the Nicaraguan subduction zone from earthquake relocation and directivity analysis – French et al., 2010.
Hydration of mantle olivine under variable water and oxygen fugacity conditions - Gaetani et al., 2014.
Galapagos-OIB signature in southern Central America: mantle refertilization by arc-hot spot interaction – Gazel et al., 2009.
Plume-subduction initiation in southern Central America: mantle upwelling and slab melting – Gazel et al., 2011.
Continental crust generated in oceanic arcs - Gazel et al., 2015.
Crustal and mantle shear velocity structure of Costa Rica and Nicaragua from ambient noise and teleseismic Rayleigh wave tomography – Harmon et al., 2013.
Crustal structure across the Costa Rican volcanic arc – Hayes et al., 2013.
Emergence of a low-viscosity channel in subduction zones through the coupling of mantle flow and thermodynamics - Hebert et al., 2009.
Izu-Bonin-Mariana Forearc crust as a modern ophiolite analogue – Ishizuka et al., 2014.
Centam & IBM Geochem database version 1.02 – Jordan et al., 2012.
Mantle melting as a function of water content beneath the Mariana arc – Kelley et al., 2010.
Water and the oxidation state of subduction zone magmas – Kelley and Cottrell, 2012.
The influence of magma differentiation on the oxidation state of Fe in a basaltic arc magma – Kelley and Cottrell, 2012.
Origin of cross-chain geochemical variation in Quaternary lavas from the northern Izu arc: using a quantitative mass balance approach to identify mantle sources and mantle wedge processes – Kimura et al., 2010.
Arc Basalt Simulator version 2, a simulation for slab dehydration and fluid-fluxed mantle melting for arc basalts: modeling scheme and application – Kimura et al., 2009.
The influence of magmatic differentiation on the oxidation state of Fe in a basaltic arc magma - Kelley and Cottrell, 2012.
Shearing melt out of the Earth: an experimentalist's perspective on the influence of deformation on melt extraction – Kohlstedt et al., 2009.
Nature of crustal terranes and the Moho in northern Costa Rica from receiver function analysis – Linkimer et al., 2010.
The impact of slab dip variations, gaps and rollback on mantle wedge flow: insights from fluids experiments – MacDougall et al., 2014.
Electromagnetic constraints on a melt region beneath the central Mariana back-arc spreading ridge – Matsuno et al., 2012.
Upper mantle electrical resistivity structure beneath the central Mariana subduction system – Matsuno et al., 2012.
Nitrogen sources and recycling at subduction zones: insights from the Izu-Bonin-Mariana arc – Mitchell et al., 2010.
The effect of tetrahedral Al^{3+} on the partitioning of water between clinopyroxene and silicate melt - O'Leary et al., 2010.
Along-arc variations in the pre-eruptive H_2O contents of Mariana arc magmas inferred from fractionation paths - Parman et al. 2011
Why do mafic arc magmas contain ~4wt% water on average? – Plank et al., 2013.
Seismic attenuation tomography of the Mariana subduction system: Implications for thermal structure, volatile distribution, and slow spreading dynamics – Pozgay et al., 2009.
Shear velocity structure of the Mariana mantle wedge from Rayleigh wave phase velocities – Pyle et al., 2014.

New Pliocene-Pleistocene $^{40}Ar/^{39}Ar$ ages fill in temporal gaps in the Nicaraguan volcanic record – Saginor et al., 2011.
Evaluation of geochemical variations along the Central American volcanic front – Saginor et al., 2013.
The seismic mid-lithosphere discontinuity – Selway et al., 2015.
Deep pooling of low degree melts and volatile fluxes at the 85E segment of Gakkel Ridge: evidence from olivine-hosted melt inclusions and glasses – Shaw et al., 2010.
Constraints on the composition of the Aleutian arc lower crust from Vp/Vs – Shillington et al., 2013.
Mid-ocean-ridge basalt of Indian type in the northwest Pacific Ocean basin – Straub et al., 2009.
Slab and mantle controls on the Sr-Nd-Pb-Hf isotope evolution of the 42 Ma Izu-Bonin volcanic arc – Straub et al., 2010.
Temporal Evolution of the Mariana Arc: Mantle Wedge and Subducted Slab Controls Revealed with a Tephra Perspective - Straub et al., 2015.
Viscous constitutive relations of solid-liquid composites in terms of grain boundary contiguity: 1. Grain boundary diffusion control model – Takai et al., 2009a.
Viscous constitutive relations of solid-liquid composites in terms of grain boundary contiguity: 2. Compositional model for small melt fractions – Takai et al., 2009b.
Viscous constitutive relations of solid-liquid composites in terms of grain boundary contiguity: 3. Causes and consequences of viscous anisotropy – Takai et al., 2009c.
Silicic magmas in the Izu-Bonin Oceanic Arc and implications for crustal evolution – Tamura et al., 2009.
Two primary basalt magma types from Northwest Rota-1 Volcano, Mariana Arc and its mantle diapir or mantle wedge plume – Tamura et al., 2011.
Sources of constructional cross-chain volcanism in the southern Havre Trough: New insights from HFSE and REE concentration and isotope systematics - Todd et al., 2010.
Hf isotopic evidence for small-scale heterogeneity in the mode of mantle wedge enrichment: Southern Havre Trough and South Fiji Basin back arcs - Todd et al., 2011.
Across-arc geochemical trends in the Izu-Bonin arc: Contributions from the subducting slab, revisited - Tollstrup et al., 2010.
Melting phase relation of nominally anhydrous, carbonated pelitic-eclogite at 2.5-3.0 GPa and deep cycling of sedimentary carbon - Tsuno et al., 2011.
The effect of carbonates on near-solidus melting of pelite at 3 GPa: Relative efficiency of H_2O and CO_2 subduction - Tsuno et al., 2012a.
Flux of carbonate melt from deeply subducted pelitic sediments: Geophysical and geochemical implications for the source of Central American volcanic arc - Tsuno et al., 2012b.
Recent contribution of sediments and fluids to the mantle's volatile budget – Turner et al., 2011.
Grain-size distribution in the mantle wedge of subduction zones - Wada et al., 2011a.
Sharp thermal transition in the forearc mantle wedge as a consequence of nonlinear mantle wedge flow – Wada et al., 2011b.
Monogenetic, behind-the-front volcanism in southeastern Guatemala and western El Salvador: $^{40}Ar/^{39}Ar$ ages and tectonic implications – Walker et al., 2011.
Light elements and Li isotopes across the northern portion of the Central American subduction zone – Walker et al., 2009.
The role of water in generating the calc-alkaline trend: new volatile data for Aleutian magmas and a new tholeittic index – Zimmer et al., 2009.

2.3 Thematic studies

2.3.1 Subduction initiation

Subduction initiation is a major event in plate tectonics and the initial stages of subduction zone development are different from established, mature subduction zones. Initiation of new subduction zones may be associated with major rearrangement of the forces that drive and resist plate tectonics. Unique magmas may be produced that are limited in time to the earliest stages of subduction. As subduction zones mature through time, they may also evolve structurally and manufacture continental crust.

New Zealand was chosen as the primary study site for investigating processes of subduction initiation because it has two of only a few well-preserved examples of subduction initiation worldwide – the newly initiating Puysegur Trench to the south of New Zealand and an outstanding record of Eocene subduction initiation at the Tonga-Kermadec-Hikurangi Trench in the north. However, because of the phased funding approach, this topic has yet to be addressed in New Zealand in the GeoPRISMS program. Interaction with New Zealand scientists through a series of well-attended workshops has been key for developing science plans for proposals to be submitted to NSF for the 2015 and 2016 GeoPRISMS deadlines. Related work in the Aleutians is underway as described above.

2.3.2. Feedback between subduction dynamics and surface processes

A primary distinction of the GeoPRISMS program compared to MARGINS is the explicit inclusion of surface processes and their feedbacks in the evolution of continental margins. Earth surface processes impact lithospheric evolution and continental margin structure remarkably. Surface processes convey materials and alter them as they are transported. Important questions remain about the relative roles of biological processes, climate, and erosion rate in modulating material flux and weathering rate and processes. Other surface processes including erosion and glaciation/deglaciation on central volcanoes may also have significant influence on volcanic outputs owing to decompression or compression of underlying mantle and/or of magma chambers, and these in turn may influence arc volatile fluxes and therefore climate. On a longer time scale, the formation, transport, storage, and ultimately the delivery of sediments from the upper reaches of volcanic terranes to fore-arcs to trenches have a direct influence on the subducting volatile fluxes. The resulting distributions of different sediment types also influence the distributions, geometries, and mechanisms of deformation and fault slip across the boundary, which in turn influence rates of uplift and exhumation. Clarifying the interplay between surficial and deep-seated processes at subducting margins is fundamental to understanding the long-term evolution of plate boundaries and interpreting ancient analogs.

To address the role of surface processes on tectonic, subduction zone and volcanic arc processes, PI Koons and Hallet have instituted a numerical modeling approach to examine late Pleistocene climate-tectonic processes in southern Alaska. This location is ideal for addressing many of the questions related to surface processes and sediment production and delivery to subduction zones because of the large sediment flux signal created by Pleistocene glacial erosion coupled with extensive seismic reflection mapping and scientific drilling to constrain the mass flux through time and to provide physical samples for inclusion in integrative studies.

Accretion, uplift, and erosion of sedimentary rock on the continents bring previously buried organic carbon (OC) to the surface (Figure 2.11). If mass wasting is sufficiently rapid, as is the norm on convergent margins, the exposed fossil C is recycled into the sedimentary system, thereby avoiding oxidation in subaerial outcrops. The recycled fossil C is blended with younger material as sediments move across the surface. The primary objective of the GeoPRISMS project by PI Blair is to assess the presence of multicycle organic C (fossil plus younger terrestrial material) on subduction margins beyond the mid-continental slope. They analyzed samples from the three GeoPRISMS primary SCD focus sites to determine if terrestrial OC and kerogen (from eroding bedrock on land) are delivered to the respective trenches. In a cross-margin transect, North Island NZ, the %OC is relatively constant (0.4-0.6%), but the reactive (terrigenous and biogenic) OC decreases dramatically offshore, suggesting that the bulk of OC delivered to the Hikurangi Trough is primarily kerogen. In Alaska, at site U1417 of IODP Expedition 341, observations of discrete coal and plant fragments, coupled with initial shipboard measurements, imply good preservation of a traceable, terrestrial organic carbon signal at this input site to the Aleutian Trench (Jaeger et al., 2014). Variations in the volume or nature of kerogen delivered to this location may indicate an altered terrestrial erosion pattern, which is likely driven by a combination of tectonics/uplift and glacial incision of bedrock in the Southern Alaska Margin.

2.3.3 ExTerra: the study of exhumed terranes

The SCD science plan recognized that addressing the key research questions also requires research that cannot be accomplished solely at primary sites. In particular, processes taking place at depth within subduction zones, processes not presently taking place in modern subduction zones, or processes that can only be resolved through comparative study, cannot be directly sampled or observed within the primary sites or over the decadal time scale of GeoPRISMS. Yet these processes are fundamental to constraining and contextualizing observations made at the primary sites. Thus five thematic research areas were identified in the SCD science plan. One of these research areas (Conditions and Reactions in Subduction Zones at Depth) has captured the interest of a group of self-organized researchers, called ExTerra (for Exhumed Terranes), working under the umbrella of GeoPRISMS, investigating rocks exhumed from fossil subduction zones. This community has worked to define research questions specific to the study of exhumed rocks through workshops supported by GeoPRISMS (AGU mini-workshop, 2011; website and communication support) and NSF Petrology and Geochemistry (Goldschmidt workshop, 2013). The community has identified Field Institutes as a way to approach the study of exhumed rocks. The ExTerra Field Institute concept develops a new paradigm for collaborative geological research: collaborative fieldwork to collect materials held communally, broad interactions through workshops, and student exchanges among research laboratories. Each researcher contributes a different analytical expertise in a collaborative effort towards a transformative understanding of dynamic subduction-zone processes. This community is actively working to find venues and resources with which to explore this new paradigm of collaborative research.

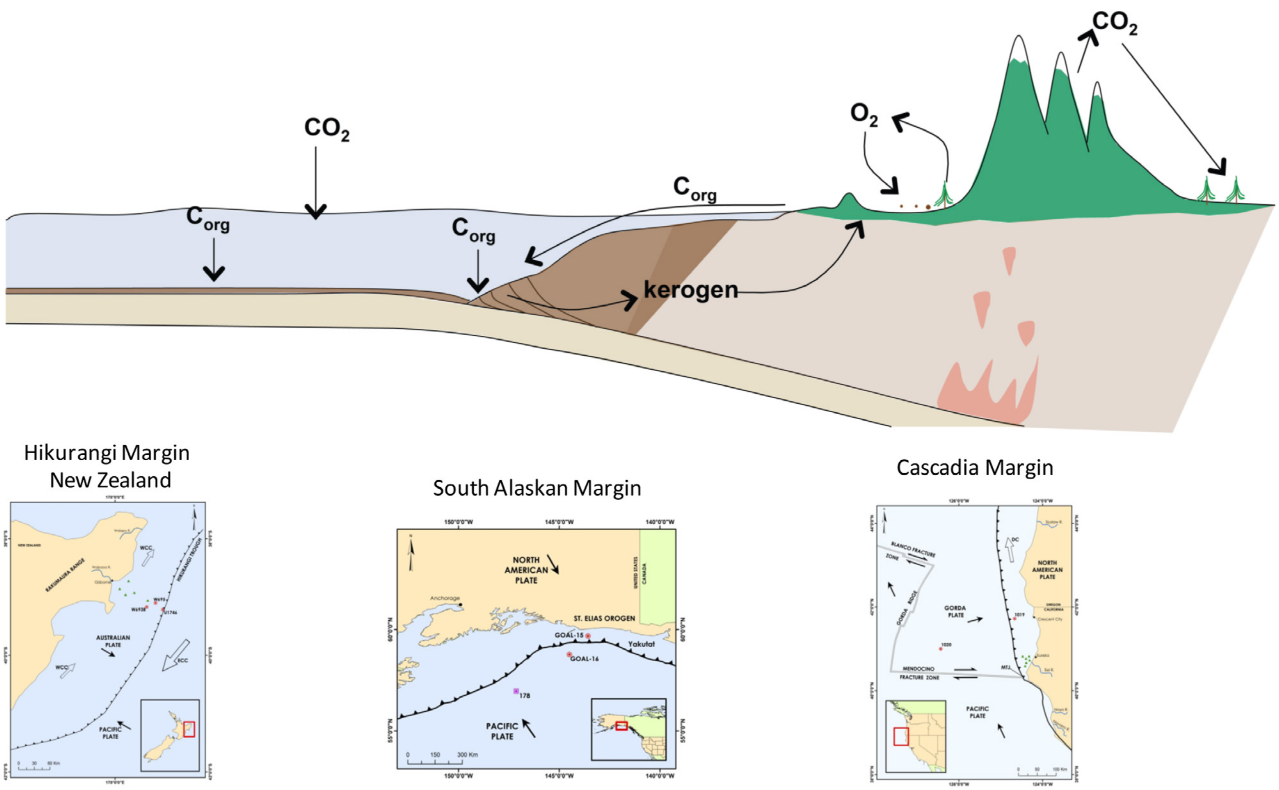


Figure 2.11. The subduction margin carbon cycle and the three SCD study areas.

2.3.4 MARGINS-funded work (2009 and beyond)

Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere - Aufdenkampe et al., 2011.
Terrestrial sources and export of particulate organic carbon in the Waipaoa sedimentary system: Problems, progress and processes, Blair et al., 2010.
Silica gel in a fault slip surface: field evidence for palaeo-earthquakes? - Faber et al., 2014.
The timescales of subduction initiation and subsequent evolution of an oceanic island arc - Ishizuka et al., 2014
Migrating Shoshonitic magmatism tracks Izu-Bonin-Mariana intra-oceanic arc rift propagation - Ishizuka et al., 2010.
Signals of watershed change preserved in organic carbon buried on the continental margin seaward of the Waipaoa River, New Zealand - Leithold et al., 2013.
Record of mega-earthquakes in subduction thrusts: the black fault rocks of Pasagshak Point (Kodiak Island, Alaska) - Meneghini et al., 2010.
The processes of underthrusting and underplating in the geologic record: structural diversity between the Franciscan Complex (California) and the Kodiak Complex (Alaska) and the Internal Ligurian Units (Italy) – Meneghini et al., 2009.
Fore-arc basalts and subduction initiation in the Izu-Bonin-Mariana system - Reagan et al., 2010.
The geology of the southern Mariana fore-arc crust: Implications for the scale of Eocene volcanism in the western Pacific - Reagan et al. 2013.
The influence of crustal strength fields on the patterns and rates of fluvial incision – Roy et al., 2015.
Structural geology of Robben Island: implications for the tectonic environment of Saldanian deformation – Rowe et al., 2010.

Signature of coseismic decarbonation in dolomitic fault rocks of the Naukluft Thrust, Namibia – Rowe et al., 2012a.
Fault rock injections record paleo earthquakes – Rowe et al., 2012b.
Fluid-rich damage zone of an ancient out-of-sequence-thrust, Kodiak Islands, Alaska – Rowe et al., 2009.
Emplacement and dewatering of the world's largest exposed sand injectite complex – Sherry et al., 2012.
To understand subduction initiation, study forearc crust: To understand forearc crust, study ophiolites - Stern et al., 2012
A variably enriched mantle wedge and contrasting melt types during arc stages following subduction initiation in Fiji and Tonga, southwest Pacific - Todd et al., 2012
Heading down early on? Start of subduction on Earth - Turner et al., 2014.
Fluid-rock interaction recorded in black fault rocks in the Kodiak accretionary complex - Yamaguchi et al., 2014.
The 'subduction initiation rule': a key for linking ophiolites, intra-oceanic forearcs, and subduction initiation - Whattam et al., 2011

2.4 Summary of Progress to Date, and Future Directions

The SCD Science Plan is ambitious in scope, reflecting the vital scientific and societal interest in subduction zone processes. The wide community input at the SCD planning workshop identified the outstanding questions that should be studied in the upcoming decade, and it prioritized approaches that could address these questions. Subsequent guidance provided by GSOC to the NSF on further prioritization of projects has settled on a phased primary site approach, but within the Science Plan itself, the consensus has been to encourage competitive proposal submissions that address any of the seven primary SCD questions within this phased primary site approach (Section 2.1). At this midpoint review of SCD, it is apparent that this approach has proven successful, given the wide range of GeoPRISMS studies funded to address these seven research areas. Substantial progress has been made on these seven topical areas because of these GeoPRISMS features: workshops and AGU special sessions that brought investigators together repeatedly; strong leveraging of resources with other NSF and federal and state programs; the establishment of primary sites where existing resources/data were present; and the encouragement of a thematic approach to address questions or topics that could not be completely addressed at just the primary sites.

Because subduction zones are such complex systems, the phased approach for deployment of field experiments at the primary sites has been the optimal method to maximize limited resources. Existing resources in Cascadia (Cascadia Initiative/EarthScope; USGS Volcano Observatory) made this a logical choice for initial focus. SCD field programs here are wrapping up or are ongoing. Of the seven primary SCD questions, all but subduction initiation have been initially addressed in Cascadia. The logistical challenges of working in Alaska-Aleutians (AA) have resulted in many of the campaign-scale geophysical and sampling projects just coming on line. However, the wealth of existing samples collected over decades in the Aleutians has allowed for several geochemical and geochronological questions to be addressed and are guiding future sampling programs. Another key aspect of SCD work in AA that has fostered results on the key questions in the first five years is the leveraging of existing field data in marine geophysics and scientific ocean drilling. Because of the phased approach, the seven SCD questions have yet to be addressed in New Zealand in the GeoPRISMS program. Interaction with New Zealand scientists through a series of well-attended workshops has been key to moving science planning along at this primary site and a proposed International Ocean Discovery Program drilling expedition to the Hikurangi Subduction Margin in FY18 holds promise for addressing several SCD questions. The eventual phasing in of support for work in New Zealand and data collection at the two other primary sites will further the ability to conduct the synthesis studies that require a comparative, synoptic approach.