2.3. Cascadia Margin – Primary Site

(Replaced June 20, 2012)

2.3.1. Background and Motivations: Relationships to SCD

The Cascadia subduction zone, extending from Northern California through southwestern Canada (Figure 2.13), juxtaposes a tectonically and volcanically active region with large population centers in western North America. A unique opportunity exists in the Cascadia region to gain an unprecedented view of the spectrum of active processes that influence the behavior of subduction zones, because the region is highly accessible for fieldwork and a wealth of co-located research efforts offers the rare prospect of integrating and building upon multiple community experiments and infrastructure. In the geologic record, this margin reveals a history of terrane accretion, arc evolution, large megathrust earthquakes and frequent volcanic eruptions. The structure of the Cascadia arc appears segmented in a variety of geological and geophysical parameters, including volcanic distri-bution, seismic properties of the mantle, and incoming plate structure and sedimentation. The subducting plate at Cascadia is the youngest and hottest on Earth, making this system a global end-member.

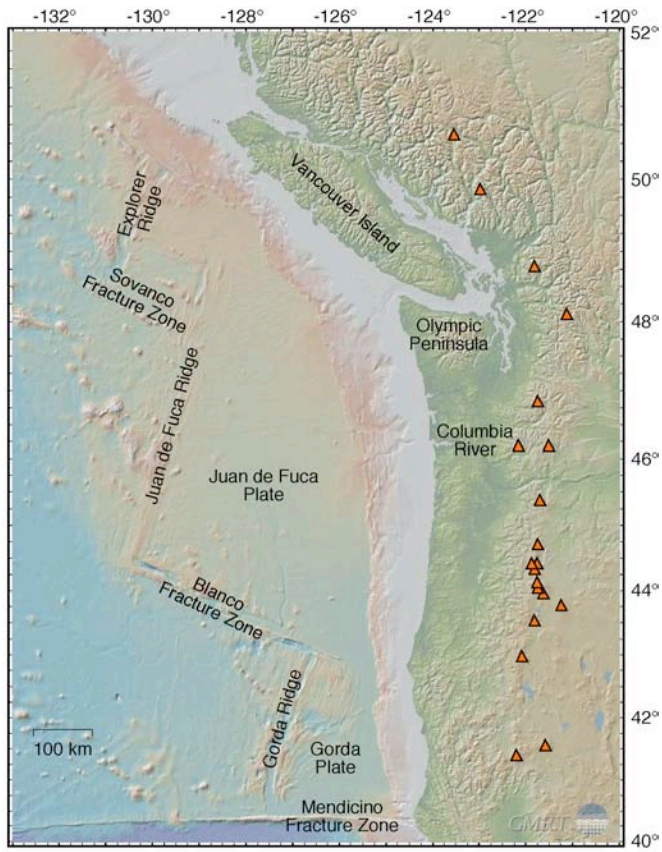

Figure 2.13. Bathymetry & topography of the Cascadia margin and associated tectonic elements. Significant arc volcanoes indicated by orange triangles. Map generated using GeoMapApp.

The GeoPRISMS community, through a series of planning workshops, designated the Cascadia subduction zone as a Primary Site at which all of the Subduction Cycles and Deformation Initiative key topics may be addressed.

• *Controls on size, frequency and slip behavior of subduction plate boundaries*

Paleoseismic evidence, gathered through both onshore and offshore studies, suggest recurrence intervals for large Cascadian earthquakes on the order of 300-500 years, with shorter recurrence intervals in the southern part of the margin. The most recent M9 earthquake occurred in 1700, and the Cascadia margin may be due for a large earthquake. Downdip of the seismogenic zone, the Cascadia plate interface also accommodates relative plate motion by slipping purely aseismically and in a transitional mode that includes transient seismic and aseismic slip. Focused geophysical studies continue to advance understanding of the temporal and spatial distribution and processes underlying these slip modes.

• *Spatial-temporal deformation patterns during the seismic cycle*

The response to the current state of stress and deformation in Cascadia exhibits a range of seismic behaviors, from relatively active beneath Puget Sound, to relatively quiet throughout western Oregon and the Olympic Peninsula. Geologic studies reveal a variety of long-term responses to plate boundary deformation throughout Cascadia. Along-strike segmentation in tremor and slow slip occurrence, the locations of offshore sedimentary basins, and other geophysical characteristics suggest linkages between processes acting from the near-surface to the plate interface. The dimensions and simplicity of Cascadia relative to other subduction zones, and its accessibility, make it ideal for thoroughly characterizing and understanding subduction zone deformation at many scales.

• *Volatiles and the rheology/dynamics of the plate boundary interface*

The release of volatiles from the subducting plate may play an important role in controlling the rheology of the plate boundary interface and the depth at which the subducting plate becomes coupled with the overlying mantle. Yet, geophysical observations suggest that the coupling depth may be universal for all arcs, at ~70-80 km. Differing devolatilization regimes for slabs with contrasting thermal states may thus not exert the primary control on this key variable. Testing hypotheses in Cascadia, where the slab is a hot global end-member, is needed to advance our understanding of the interface between the subducting and overriding plates, and mantle wedge.

• *Storage, transfer, and release of volatiles through subduction systems*

Models and observations of the metamorphic petrology of the subducted slab, key mineral phases, and devolatilization reactions at Cascadia will provide end-member constraints on the transport and distribution of volatiles throughout a region with a hot subducting plate. The identities, properties, and migration pathways of volatiles may closely relate to the slab petrology and the P-T-fO_2 conditions of the slab and mantle wedge. Relating these variables with observations of the compositions and patterns of volatile release at the surface, through volcanism and hydrothermal activity, are central to understanding the driving forces of magmatism at Cascadia and global arcs.

• *Geochemical products of subduction and creation of continental crust*

The Cascades arc is characterized by large, relatively silicic stratovolcanoes, with isolated, small mafic volcanism interspersed between the major edifices. Constraints on the net magmatic composition and magmatic flux of the Cascades arc are needed to assess the role that this arc may play in creating continental crust. The Cascades arc has migrated eastwards with time, leaving behind an exposed plutonic record in the west, ideal for accessing temporal changes in magmatic composition and distribution, and the inter-crustal magmatic systems that often are not erupted at volcanoes, and may link closely to the overall crustal evolution of the Cascades and arcs in general.

• *Subduction zone initiation and arc system formation*

Understanding the formation of the Cascadia subduction zone requires understanding the origin of the Siletz and Crescent terranes, thick accumulations of tholeiitic basalt forming the basement of the Oregon and Washington Coast Ranges. Siletz terrane basalts predate the earliest magmatic rocks of the Cascade arc by ~15 Ma and are thrust beneath the margin, suggesting an allochthonous origin. Was it an accreted oceanic plateau that collided with N. America, forcing the subduction zone to jump to the west? Or is Siletzia related to ridge-trench interactions, or perhaps the result of subduction initiation, similar to that suggested for the Izu-Bonin-Mariana arc system? Understanding the origin of the Siletzia terrane could be an important part of integrated study of the Cascadia convergent margin, clarifying how the Cascadia margin evolved and behaves today. Constraining the timing and geometry of the pre-subduction system, and the specific role of Siletzia in the initiation of subduction, is central to refining models of how subduction initiates on Earth in general.

• *Feedbacks between surface processes and subduction zone dynamics*

Cascadia is an exceptional natural laboratory to investigate feedbacks between surface processes and subduction zone dynamics. Recurring megathrust ruptures along the subduction zone impart immediate and long-term impacts to sediment production, dispersal, and deposition along the margin. Coseismic vertical displacements near the coast alter stream base level, which influences rates and patterns of estuary sedimentation. The impulsive coseismic shaking may also generate prodigious landslides, possibly resulting in channel aggradation and landslide-dam lakes that modulate sediment dispersal to coastal environments. Natural disturbances, such as storms and fire, have been shown to drive pulses of sediment yield along the margin, but the relative contribution of earthquake-driven fluxes remains unknown. As a result, substantial work is required to document the suite of mechanisms that drive terrestrial sediment fluxes to the continental shelf and eventually to the subducting plate. Over millenial and longer timescales, the accretionary flux into the subduction zone has been quantified for portions of the margin, although the balance of sediment accretion and erosion is poorly constrained across most of Cascadia. Sediments on the down-going slab have been implicated in slow-slip events, as well as other subduction zone processes, which emphasizes the importance of documenting sedimentary processes and records.

2.3.2. Cascadia Margin

> *The Cascadia Margin offers opportunities to address all of the SCD topics, but is particularly well-suited to exploring the nature and origin of the well-expressed episodic tremor and slip (ETS) and its relationships to great megathrust earthquakes. The young age of the subducting slab at Cascadia defines a thermal end-member for global subduction zones, enabling unique studies to understand the conditions and processes by which slabs dehydrates and arc magmas are generated. Along-strike changes in many different processes and properties enables fundamental questions about the origin of arc segmentation to be studied in a compact setting.*

The active Cascadia subduction system became established by the middle Eocene and produced voluminous magmas in the Oligocene through the Miocene; subsequently, arc igneous activity diminished. The system is notable worldwide for the youth, and therefore high temperature, of the subducting Juan de Fuca plate. The arc is also strongly segmented, and this is evident in a number of diverse data sets (geophysics, seismicity, volcano age and distribution, geochemistry, geodesy and paleogeodesy, etc.), although the ultimate causes remain unclear. In part this likely reflects the changes in tectonic setting of the arc, which varies from south to north, with impingement of the Basin and Range extensional province onto the eastern margin of the arc in northern California and southern Oregon, a weak graben along the arc axis from central Oregon to the Columbia River, and widespread basement uplift from central Washington northward into British Columbia. GPS measurements show weak cross-arc extension and right lateral displacement in the south, passing to arc-normal convergence across the strongly uplifted North Cascades. Paleomagnetic studies concur with Tertiary rocks in the southern and central parts of the arc having rotated clockwise and translated westward and northward as the Basin and Range opened to the northwest. Volcanic style correlates with neotectonic and geomorphic differences, with widespread basaltic volcanism and interspersed andesitic stratovolcanoes in northern California through central Oregon, passing to isolated andesitic and dacitic stratovolcanoes from southwest Washington into British Columbia. Diminution, isolation, and increased evolution of volcanic centers with increased basement uplift and arc-normal convergence are evidence for an important role for the crust and lithosphere in modulating magmatism.

This roughly 1000 km long region spans the subduction of the Juan de Fuca (JdF) and Gorda plates beneath North America from Vancouver Island in the north to Cape Mendocino in the south, with convergence rates of ~3-4 cm/yr (Figure 2.13). The subduction of the JdF plate has produced many great earthquakes, most recently in 1700 AD, with recurrence intervals on the order of ~500-600 years based on paleoseismic studies. Recent studies of the processes on this megathrust have focused on slow slip events and non- volcanic tremor, especially down-dip of the inferred interseismically locked region. Evidence suggests that the characteristics of these Episodic Tremor and Slip (ETS) events vary along the entire Cascadia seismogenic zone, with along-strike segmentation possibly related to changes in the upper plate geologic structure and past rupture boundaries for the great earthquakes.

The Cascadia subduction zone is the only region of the lower 48 states likely to produce a Mw 9 earthquake and has the greatest potential for volcanic eruptions. There is a significant body of work documenting great earthquakes extending back 10,000 years; the size, composition, and timing of Quaternary volcanic eruptions; and a wide range of fault slip behaviors, including slow and "normal" earthquakes, and non-volcanic tremor. A trove of new geological, geodynamic, and geophysical data has recently been collected and more will be forthcoming in the next four years thanks to NSF investments in EarthScope and the onshore/offshore ARRA-funded Cascadia Initiative. GeoPRISMS has the opportunity to facilitate the maximum scientific payoff from this investment through its interdisciplinary research community. Because of these investments, Cascadia-related GeoPRISMS research is able to begin immediately, with valuable outcomes emerging in the coming few years.

2.3.2.2. Existing Datasets and Studies in the Area and Data Gaps

NSF has enabled an ongoing community collection of onshore and offshore data by way of the EarthScope program and the ARRA-funded Cascadia Initiative. The Cascadia Initiative provides dense OBS coverage in several regions of interest to the GeoPRISMS community, as well as a real time 1 Hz GPS network and densified seismic coverage onshore expanding that provided by the Pacific Northwest Seismic Network and Berkeley Digital Seismic Network. These data are complemented by a significant investment by the Canadian government in the NEPTUNE-Canada observatory to instrument the northernmost portion of the margin both on and offshore and planned installation of an observatory offshore the central Cascadia segment as part of the NSF Ocean Observing Initiative.

There is a wealth of other existing datasets including, but not limited to:

- Well-documented ETS catalogs, delineating multiple cycles and segments.
- Continuous and campaign GPS and other land-based geodetic measurements that densely cover the entire margin to allow the study of the locking state of the megathrust and the deformation of the upper plate.
- A comprehensive paleoseismic record for subduction zone earthquakes.
- Substantial ocean drilling results, including Legs 139, 146, 169, 173 and 204, and Expedition 311, spanning from southern Vancouver Island through Oregon and northern California.
- A series of 20th century 2-dimensional multichannel seismic and 2 and 3-D active-source, large-aperture onshore/offshore surveys collected by US and international investigators, which are available to guide planning for modern 3D studies.
- Baseline onshore 3D seismic tomographic images derived using core US-Array and investigator-driven higher resolution seismic arrays combined with data from regional and teleseismic earthquake sources.
- Onland geologic mapping of forearc and backarc structure and volcanic features.
- Geochronologic and geochemical studies of Quaternary volcanic edifices. Much of these data and results from geologic mapping exist in less accessible "grey" literature (theses, field guides and other non-peer reviewed sources) and one positive outcome from GeoPRISMS will be to mine this data and move it to more accessible sources (on line databases, published papers etc.).
- High-resolution topographic/bathymetric, gravity and magnetic surveys onshore and offshore (although some gaps remain to be filled)
- Seismic data extending back to the 1970s, from over 200 seismometers operated by the Pacific Geoscience Center (Vancouver Island/British Columbia), the PNSN (Washington/Oregon) and the Northern California Seismic Network (California).
- Real-time high sample-rate GPS data with dense coverage of the active plate boundary.

Outstanding gaps in available data include detailed seismic imaging of critical regions of the plate boundary megathrust, the subducting slab, mantle wedge, and overlying volcanic arc. This gap will be diminished in the near future as new projects come on-line, including offshore 2D multichannel seismic surveys, onshore volcanic imaging studies, and analysis of new OBS and geodetic data, although holes will still remain, in particular, offshore geodesy. Expanded catalogs of seismicity, tremor and GPS displacements are needed to clarify the temporal and spatial distribution of deformation processes along the margin, and their relationships to megathrust properties. New high-precision geochemical analyses of arc rocks are needed to assess magmatic processes and sources, and volatile fluxes. A comprehensive knowledge of sediment flux through time, both onshore and off, is needed to assess the interplay of sedimentary processes and tectonics along the margin.

2.3.3. Potential Topics for GeoPRISMS Studies

Community discussions identified a set of future research directions for Cascadia, guided by new observations, growing infrastructure and data sets, and the ability to carry out integrated studies of the Cascadia subduction system. Key targets and topics include, but are not limited to:

2.3.3.1. Great earthquakes, interseismic locking, and ETS.

Cascadia is thought to be at a late stage of its great megathrust earthquake cycle and is exceedingly rich in ETS (Figure 2.14). Such slow-slip phenomena likely tell us something about the seismogenic potential of the Cascadia plate interface. Strain release associated with slow aseismic slip events may be nearly equal to that accumulated between major earthquakes, and if verified, it implies little if any strain exists to sustain seismic rupture into the slow slip zone. However, an unexplained gap of several 10s of km appears to exist between source locations for tremor and slow slip and areas of inferred significant plate locking. Does the extremely low interplate seismicity at present indicate a fully locked megathrust? The inference of the locking state at Cascadia is limited by the poor offshore resolution of land-based geodetic measurements and depends on how much of the observed geodetic deformation is attributed to permanent upper plate deformation. A clear definition requires near-source observations such as seafloor geodesy. What is the physical mechanism of ETS? What is the relationship between the seismogenic zone and the ETS zone? Is there really a gap between them? Answering these questions requires improved observations at Cascadia, as well as comparative studies with subduction zones at different stages of their earthquake cycles, including in other settings with ETS-type phenomena. In particular, little information exists about slow slip phenomena above the plate interface offshore, although based on studies elsewhere (mostly Japan), they are likely to occur there. GeoPRISMS promises to provide needed offshore observations, in such a way that a complete picture, extending from the trench to the back-arc, of Cascadia plate-interface slip may be developed.

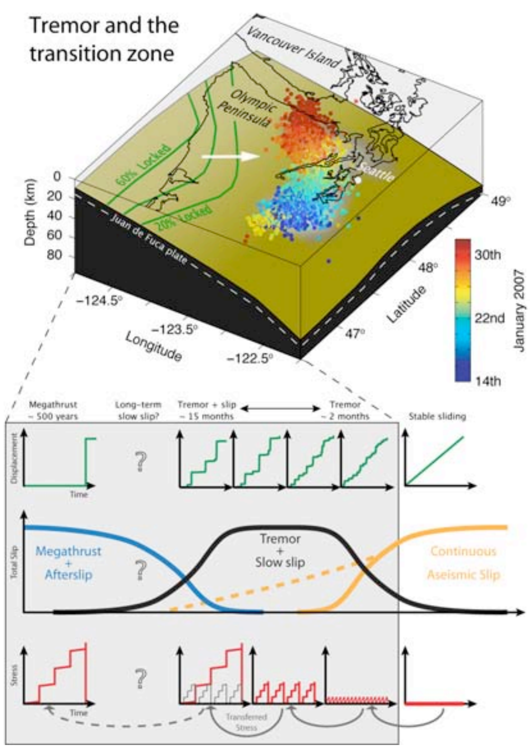

Figure 2.14. Top (from Forsyth et al., 2009): The Juan de Fuca plate subducts beneath the North America plate with convergence direction shown by the white arrow. The plates are locked along part of their interface (khaki-colored surface) by varying degrees; the locking model here shows the fraction of relative plate motion that isn't occurring, increasing downdip from 60% to 20% (green contours) (from McCaffrey et al., 2007). Inland of the locked zone, tremor epicenters projected onto the plate interface (circles) overlie the area that experienced slow slip (gray area on plate interface) during January 2007. Color shading of tremor epicenters shows its temporal migration. Bottom (from Wech et al., 2011): Top panel shows a profile of displacement timelines from the locked zone to stable sliding. Middle panel shows a schematic profile of how the different regions accommodate plate convergence. Lower panels shows a schematic profile of stress timelines, illustrating a stress transfer model in which stable sliding loads the downdip weakly coupled tremor region, which slips easily and transfers stress updip to stronger portions of the fault.

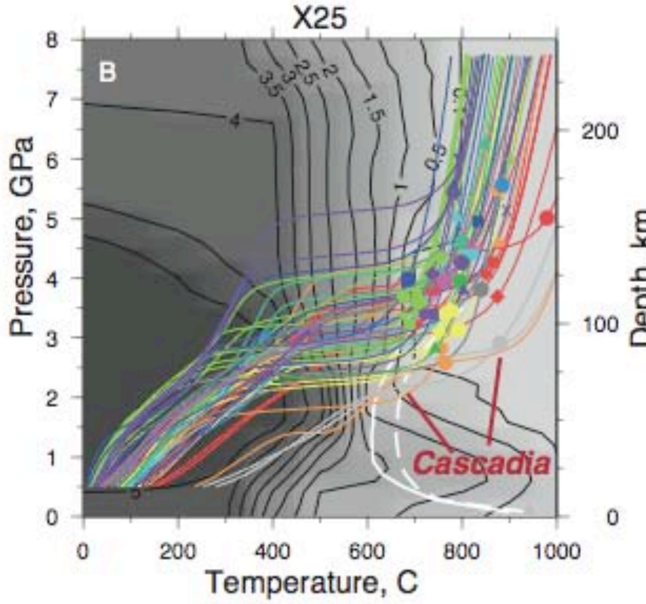

Figure 2.15. Calculated slab surface temperature-pressure paths (colored) for worldwide subduction zones, superimposed on plot of structurally bound H_2O retained in metabasalt (grayscale). Note that Cascadia slab models define the high-T at low-P endmember of subduction systems, and that the basaltic slab would be expected to be nearly anhydrous by ~3 GPa, typical of slab depths beneath active arcs (modified from Syracuse et al., 2010).

2.3.3.2. The hot and dry slab paradox

The young subducting slab at Cascadia is calculated to be one of the hottest worldwide (Figure 2.15). Such high slab temperatures predict early devolatilization, i.e., beneath the forearc rather than the arc. Furthermore, geodynamic modeling predicts only modest hydration of the subducting lithosphere prior to entering the trench, limiting the overall availability of H_2O beneath the Cascade arc. These characteristics suggest that fluid-flux melting processes beneath the Cascades should be minimal, requiring alternative mechanisms and/or sources for creating arc magmas. Paradoxically, however, Cascades magma compositions are broadly similar to those of other arcs, and existing measurements of pre-eruptive water contents in Cascadia basalts also seem within the range of other arcs. These pieces of evidence suggest a disconnect between geophysical and geodynamic predictions and the magmatic record. To resolve this, geochemical and petrological estimates of volatile fluxes in Cascadia need to be reconciled with thermal models that predict a hot and dry subduction system. Questions to address include: What are the relative contributions of fluid-flux and decompression melting to Cascadian magmas? How hydrated is the young oceanic plate prior to subduction? What are the pathways and processes by which volatiles are transported by the downgoing slab and released into the mantle wedge beneath the magma generation zone? The relationship between timing and extent of slab dehydration, and the role of volatile fluxes in magmatism remains unclear. Integrated geochemical and geophysical studies of the Cascade arc, combined with experiments and modeling, are needed to resolve this enigma.

2.3.3.3. Role of volatiles in megathrust coupling / decoupling

Substantial aqueous fluids are thought to be carried into the Cascadia megathrust fault zone with the subducting plate, in the pore space of the thick sediment pile, fractures in oceanic crust, or hydrous minerals. The very young and hot subducting slab should cause most of the hydrous minerals to dehydrate at shallower depths, where high pore-pressures can most affect the strength of the plate interface, the slip behavior of the megathrust, and the long-term coupling of the slab with the overlying mantle wedge. The slip behavior of the megathrust, including seismic rupture and locking, aseismic creep, sub-convergence creep ("partial locking"), and episodic slip and tremor, is thought to be linked to fluid processes, and in particular, high pore fluid pressures in the fault zone. Corresponding evidence for a weak interface is given by low margin-normal compression inferred from earthquake focal mechanisms and other stress indicators, and minimal frictional heating on the megathrust inferred from heat flow measurements. A range of questions arise in efforts to explain the interplay of fluids and fault processes: How can high fluid pressures be maintained in this environment? What is the balance between fluid production and permeability? Under what conditions does elevated pore fluid pressure make the fault more seismic or aseismic? Laboratory experiments are needed to simulate in situ conditions to constrain how various hydrous minerals in the fault zone affect fault slip.

2.3.3.4. Imaging physical properties deep within the crust and upper mantle.

Certain phenomena, including the transition from stick-slip to stable sliding along the megathrust and the migration of magma through the crust, are difficult to image geophysically, but provide critical insights into processes occurring deep within the subduction system. For example, preliminary geophysical imaging of the subducting slab and overlying crust and mantle wedge reveal strong correlations between locked zones, tremor regions, and zones of seismic reflectivity and anomalous Vp/Vs ratios, suggesting a petrologic or metamorphic control on these transitions in slip behavior. These observations potentially relate to dehydration reactions and fluid release along or below the plate boundary, capable of producing near lithostatic pore fluid pressures. The association of ETS with very high pore fluid pressure is consistent with preliminary theoretical modeling demonstrating that slow slip events can arise spontaneously under extremely low effective normal stress. However, the geophysical conditions for, and physical mechanisms of, ETS occurrence are largely unknown. A key contribution from GeoPRISMS studies could be the improvement of traditional techniques for imaging subsurface seismic velocity and electrical conductivity to better image these processes, and the integration of these images with other geophysical and geochemical observations.

2.3.3.5. Along-strike compositional diversity of lavas and tephras and distribution of volcanism

The Cascades represents a key location to investigate the causes of variation in the style, distribution and composition of volcanic output along the arc, and for study of the interplay between lithospheric and crustal conditions, heterogeneity within the downgoing slab, and fluxes of magma produced within the mantle wedge. Although stratovolcanoes occur along the arc, there are significant variations in both the range of compositions and in the rates of volcanic output. There are also differences in the style of volcanism, with the isolated stratovolcanoes occurring in northern Washington and British Columbia contrasting with a relative abundance of dispersed mafic magmatism occurring in Oregon and California. Compositional and productivity variations are not systematic along strike (Figure 2.16), as might be expected if the gradual decrease in age of the Juan de Fuca plate exerted overriding control. Instead these variations appear to reflect more localized interactions within the crust, lithosphere or downgoing plate. Thus, the ultimate controls on the distribution of volcanism in Cascadia remain uncertain. Specifically, what parameters influence the formation of large central volcanoes that occur along the arc versus more dispersed monogenetic volcanism that characterizes the regions between the larger volcanoes? Is this distribution linked to properties or geometry of the slab, structures in the mantle wedge, or structures in the upper plate? How do the relatively localized back-arc volcanic complexes (Simcoe, Newberry, Medicine Lake) relate to the arc system? What are the roles of mantle fluxes, solid/fluid flow vectors, and crustal magma processing? A combination of geochemical, petrological, geophysical, and modeling studies are needed to place constraints on the production of various types of magma and how they interact with their surroundings, from the point of generation in the mantle wedge to their ultimate emplacement in the crust or at the surface.

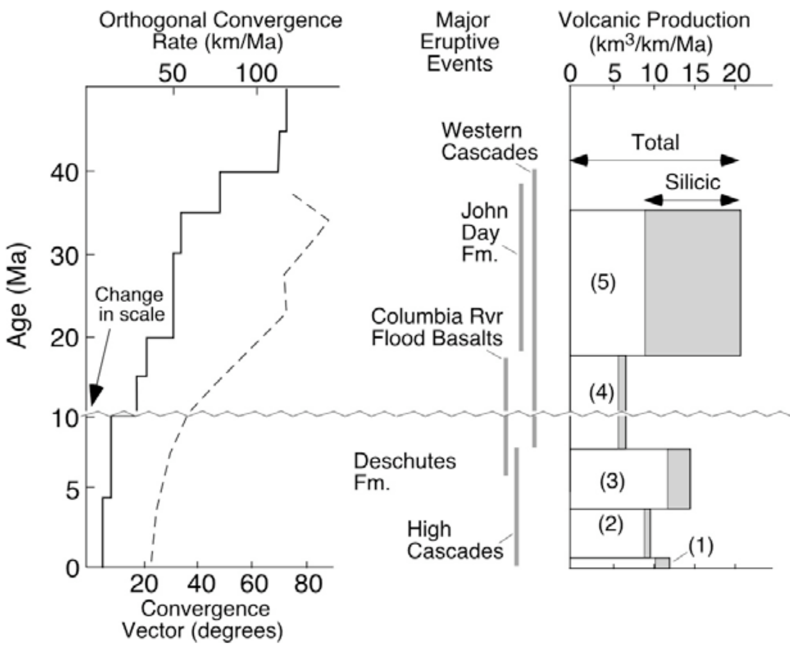

Figure 2.16. Comparison of orthogonal convergence rate and convergence vector with magma production rates for the Central Oregon Cascades over the previous 40 million years. Figure modified from Priest (1990), convergence rates (solid line) and vector (dashed line) are from Verplank and Duncan (1987). The intervals representing major eruptive episodes on the arc and nearby are shown. Numbers 1-5 show the eruptive episodes defined by Priest (1990) and represent: (1) 0.730-0 Ma; (2) 0.731-3.9 Ma; (3) 4.0 - 7.4 Ma; (4) 7.5-16.9 Ma and (5) 17.5-43.2 Ma.

2.3.3.6. The nature of segmentation along the subduction zone.

A number of diverse data sets (geophysics, seismicity and paleo-seismicity, volcano age and distribution, geochemistry, geodesy and paleo-geodesy, etc.) reveal that the Cascadia subduction zone is segmented along strike. Key uncertainties remain. Are the scales of segmentation the same for different data sets? What are the ultimate controls of segmentation evident in different data? What is the influence of the incoming plate on segmentation? What is the influence of the inherited crustal structure and composition of the upper plate? Do the same factors control segmentation along the plate boundary at depths of 30-50 km (the ETS domain) and at depths of a few to ~20 km (the nominally locked zone)?

2.3.3.7. Subduction initiation beneath Cascadia and the origin of the Siletzia terrane

Arc volcanism began in Cascadia by 35-45 Ma, indicating that the Cascadia subduction zone formed sometime before this. Why and how did it form, well to the west of the pre-existing Andean-type margin in Idaho (Challis Arc; Idaho Batholith)? The formation of the Cascadia subduction zone is linked to emplacement of the Siletzia terrane, a mafic LIP (~2.6 million km^3) that is exposed in the Cascadia forearc, the Coast Ranges of Oregon and Washington. Siletzia lavas mostly erupted underwater, comprising basal tholeiites overlain by alkalic lavas. Volcanism began in the south (56-53 Ma) and migrated north (54-50 Ma). There have been many explanations for voluminous Siletzia volcanism, including 1) an accreted oceanic plateau, 2) beginning of the Yellowstone mantle plume, 3) a tear in the subducted plate, and 4) continental-margin rifting due to interaction with a trench-ridge-trench triple junction. Based on studies of the Izu-Bonin-Mariana arc system and ophiolites, it is increasingly clear that many forearcs form as a result of voluminous yet ephemeral igneous activity accompanying subduction initiation, suggesting the alternate possibility that Siletzia formed in response to formation of the new Cascadia subduction zone.

Because it is so accessible and so controversial, Siletzia provides a remarkable opportunity for testing and refining models of subduction initiation. It is exposed above sea level for ~200 km width, and because Cascadia is a young, accretionary margin, negligible crust has been removed by tectonic erosion. The complete record is preserved, allowing igneous forearc crust to be studied in greater detail than anywhere else in the world, allowing an unparalleled opportunity to test and refine subduction initiation models. This understanding is central to the success of the larger GeoPRISMS effort to understand the Cascadia convergent margin. The composition of Siletzian lavas reveal ambient mantle compositions, unaffected by subduction-related metasomatism, critical information needed for solving how modern Cascade arc magmas form. It is also important to understand Siletzia forearc lithosphere because its mode of formation is manifested compositionally, exerting important controls on upper plate rheology and thus upper plate deformation and seismogenesis, which can be studied in unparalleled detail because the subducted slab interface is as little as 15 km below land. It is thus clear that understanding the role of Siletzia in the initiation of the Cascadia convergent margin is central to understanding the modern Cascadia geosystem as well as for refining models of how subduction initiates on Earth.

2.3.3.8. Short-term and long-term effects of sediment genesis, transport on accretion and erosion

The transport of sediment from the subaerial forearc to offshore is both a response to tectonic processes and also a generator of sediment records of past tectonic events. In addition, these sediments play a significant role in defining the forearc structure, the mechanics of earthquake rupture, and partitioning of sediments through accretion and subduction. The Coast Ranges, the Salish/Puget/Willmette forearc basin and the Cascade Range to the east, collectively form an active orogenic belt, most of the mass of which is ultimately redistributed by erosion. In the time frame of megathrust earthquakes (hundreds of years) and for the spatial scale of the Coast Ranges, subduction zone earthquakes affect the genesis, transport and storage of sediment through the Coast Ranges to the estuaries and offshore. In the longer term (millions of years) and over the whole upper plate from the arc to offshore, the accretionary flux from mass accreted or erupted onto the upper plate must be balanced by the erosional flux. Is such a balance in steady state, as proposed for the Olympic Mountains (the only subsystem studied to date)? What is the role of subduction zone earthquakes in initiating landslides, in creating readily mobilized sediment sources and in modulating estuaries as sediment storage compartments or as conduits for sediment delivery to the offshore? Can records from lakes, especially landslide-dammed lakes, be valuable archives of erosion history in the Coast Ranges? How effective are carbon and other biomarkers in tracing sediment through watersheds to the offshore and can these methods, along with sediment transport data, be applied to determine sediment mass balances for Coast Range watersheds located at different latitudes along the Cascadia margin? How are these sediments distributed in the offshore environment and reworked during deformation? Improved inventories of sediment yield data, sediment accretion rates, uplift rates, and a modeling framework specifically adapted to different portions of the margin will help address these questions. Offshore studies will be advanced by state-of-the-art 3-D active source seismic imaging techniques integrated with sediment transport and geodynamic modeling.

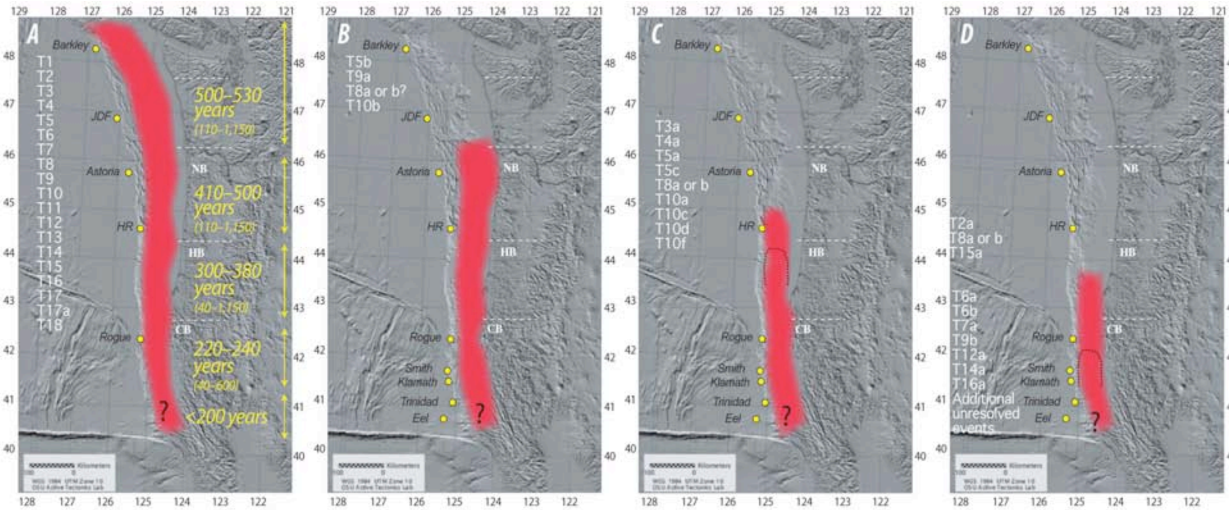

Figure 2.17. Holocene rupture lengths of Cascadia great earthquakes based on marine and onshore paleoseismology. Four images showing rupture modes inferred from turbidite stratigraphic/14C correlation, supported by onshore radiocarbon data. Marine core sites controlling rupture-length estimates are shown as yellow dots. A, Full or nearly full rupture, represented at most sites by 19 events. B, Mid-southern rupture, represented by 3–4 events. C, Southern rupture from central Oregon southward represented by 10–12 events. D, Southern Oregon/northern California events, represented by a minimum of 7–8 events. Recurrence intervals for each segment are shown in A. Rupture terminations are located approximately between three forearc structural uplifts, Nehalem Bank (NB), Heceta Bank (HB) and Coquille Bank (CB). Paleoseismic segmentation shown also is compatible with latitudinal boundaries of episodic tremor and slip (ETS) events proposed for the downdip subduction interface (Brudzinski and Allen, 2007) and shown by white dashed lines. A northern segment proposed from ETS data at approximately lat 48° N. does not show a paleoseismic equivalent. (Figure from Goldfinger et al., 2012; see for details).

2.3.3.9. Earthquakes and the turbidite record.

Inferences have been drawn from turbidite records that earthquakes rupturing only part of the plate boundary (M>~8 events) have regularly occurred in southern Cascadia, whereas the northern portion ruptures only in entire-boundary, M9 earthquakes (Figure 2.17). The boundaries between rupture regions may also correlate with observed geophysical segmentation noted above. These suggestions warrant further study as they have important impacts on hazard estimates and our basic understanding of the earthquake cycle along the plate boundary. A promising 'amphibious' approach (working in both marine and onshore environments) to test these inferences involves correlating offshore turbidite records with those from onshore studies in lakes, also presumed to record seismogenic ground-shaking. Studies of the overall linkages between earthquakes and turbidite generation and distribution are also warranted, to confirm that the latter can be used as a proxy for paleo-earthquakes.

2.3.3.10. Paleogeodesy applied to Cascadia

Paleogeodetic information provides critical data on relief generation in the past at different temporal and spatial scales. Generation of relief ultimately drives wedge mechanics in the long term and can be used to model crustal strain build up and release in the short term. Investigations into the generation and evolution of topography at the Cascadia convergent margin is a nascent field. On short-term time scales, co-seismic and interseismic land level changes at coasts are potentially recorded in microfossil assemblages that are preserved as relative sea level change in response to plate convergence. Over longer time scales, the ability to determine uplift rates in rocks within the Cascade Range through techniques such as (U-Th)/He and fission track age dating has potential to provide constraints for wedge dynamic modeling within the Cascadia forearc wedge.

2.3.3.11. Role of surrounding regions

Cascadia did not develop in isolation, and important questions remain regarding the evolution of Cascadia in relation to surrounding geologic provinces. These include the Yakima fold and thrust belt, the Basin and Range, The High Lava Plains, Klamath/Sierra block, the Mendocino triple junction, the Yellowstone hot spot trail and the Juan de Fuca ridge. How have the interactions between the subduction zone and these geologic provinces changed through time to influence the formation and evolution of the North American continent?

2.3.4. Potential GeoPRISMS Studies

Future GeoPRISMS studies in Cascadia can leverage many significant existing and newly acquired datasets. Some additional studies, however, will also be useful.

<u>Geophysical studies:</u> A necessary complement for the available and planned datasets will be imaging from active source seismology to better characterize the structure and composition of the onshore and offshore regions in targeted areas. Example studies fundamental to GeoPRISMS objectives include 3-D marine seismic surveys to better resolve the megathrust interface, structural architecture of the subducting and overriding plates, and seismic properties of the margin. High-resolution active source seismology experiments onshore, embedded in a dense passive seismic network, coupled with Magneto-telluric (MT) data, could elucidate melt pathways and zones of magma storage within target arc volcanoes, providing independent constraints to better interpret existing geochemical and petrological models of volcanic processes. Such studies could test existing models for magma transfer, and improve our understanding of magma differentiation, crustal evolution, and volcanic hazards. Marine MT studies are needed to extend the onshore grid of MT stations, included as part of the EarthScope USArray program. Marine data would provide constraints on the incoming plate structure, and provide connections between the downgoing slab and the conductive mantle wedge. Long-period seafloor MT instruments deployed with the Cascadia amphibious array would provide the opportunity to jointly interpret velocity and conductivity of the plate boundary. Additional heat flow measurements are needed across the entire margin: the incoming plate, across the accretionary complex, and within the volcanic arc. Creative new approaches are needed to correct conventional measurements for the effects of ocean water temperature changes offshore and shallow meteoric water onshore.

<u>Seafloor Geodesy:</u> A potentially transformative new observation that GeoPRISMS could enable is quantification of seafloor motion throughout the earthquake cycle (a.k.a., seafloor geodesy). NSF's Cascadia Initiative will provide a seamless onshore-offshore seismic network that spans a subduction zone thrust interface. The onshore geodetic (GPS) component of the initiative, however, stops at the shoreline, severely limiting our ability to fully constrain the likely slip distribution in the next great Cascadia earthquake. The duration of the GeoPRISMS Program (5-10 years) and its shore-line crossing approach, could enable a suite of offshore geodetic

benchmarks, optimally, deep-moored GPS buoys linked to submarine cabled observatories (e.g, NEPTUNE), to obtain periodic or continuous measurements over a long time span. This would be a unique and revolutionary dataset for understanding a great M9 earthquake before it happens.

High-precision isotopic, petrologic, and experimental studies of Cascade magmas: As the worldwide hot-slab end-member, the Cascades provide opportunities to evaluate how the transport and supply of volatiles, and potentially slab melts, influence the compositions, productivity, and spatial configuration of arc magmatic systems. Due to long-term geologic mapping, sampling, and dating studies by the USGS, the magma types, proportions, and ages of Cascade volcanic products are as well or better characterized than in other arcs, but comprehensive petrogenetic studies utilizing modern high-precision isotopic measurements of Sr, Nd, Pb, Hf, Os, and O, measurements of trace element and dissolved volatile concentrations, constraints on magmatic redox states, and experimental studies, have not kept pace. High-precision analytical approaches are required for understanding the origins of Cascade magmas because much of the pre-arc crust is unevolved, so crustal interactions need not produce large isotopic and chemical effects, and can be difficult to distinguish from signals produced at slab and mantle-wedge depths. With notable exceptions (Medicine Lake, Shasta), experimental studies on Cascade magmas have focused on upper crustal magma storage and syn-eruptive ascent (Mt. St. Helens), as opposed to deep crustal, mantle, and slab depths that might be sites of magma generation and differentiation.

Field studies of subduction-related metamorphic and igneous processes: A variety of exposed terranes in the Cascadia region provide unique windows into the deeper slab, crustal, and temporal processes that have converged to assemble the modern Cascadia subduction zone. The Juan de Fuca plate, currently subducting under North America, is a remnant of the larger Farallon plate that started subducting in the Mesozoic. Exhumed remnants of the Farallon plate and the interface between the subducting and overlying plates are exposed in the Cascadia region in the form of high-pressure/low-temperature metamorphic rocks, including the Shuksan Metamorphic Suite in the Northern Cascades, as well as the Catalina Schist and the Franciscan Complex to the south and west of the Cascadia primary site. Investigations of these exposed high-pressure terrains provide direct links to the subducting plate presently beneath the active Cascadia arc, and may provide representative analogs for the metamorphic reactions associated with warm-slab subduction. Field, laboratory, and geodynamic modeling studies of the Siletzia terrane and its relationship to the Cascadia forearc can provide important temporal constraints on the initiation and construction of the early Cascadia arc. In particular, studies will determine whether Siletzia is an exotic terrane that collided with N. America or if it formed in place. Specific mapping studies should focus on constraining the timing of collision and the sequence of events leading to the formation of a new subduction zone to the west, and the relationship between Siletzia and onset of subduction-related magmatism. Additionally, the crystalline core of the North Cascades provides unique opportunities to study the architecture of arc mid- and lower crust. The Skagit Gneiss, Swakane Gneiss and Chiwaukum Schist, for example, may be metasedimentary rocks. The processes by which these sediments were emplaced remains largely unknown, but these felsic materials may play a key role in arc crustal growth and continental crust genesis. Petrological, geochemical, and geochronological studies of these various exposed crustal rocks will provide essential input to the interpretation of isotopic and chemical signals in modern arc volcanic rocks in Cascadia, and to the interpretation of geophysical mapping of the plate interface, mantle wedge, and crustal structure at this primary site.

2.3.5. Research Strategies, Resources and Partnerships

GeoPRISMS can play an important role in facilitating community use of existing infrastructure and new community activities already underway to enable multidisciplinary science along the Cascadia margin. This is possible within a 3 to 5 year timescale. Clear opportunities exist to leverage EarthScope facilities and intellectual resources, along with new OOI and Neptune-Canada offshore deployments. Strong cooperation already exists, and will be enhanced, with USGS researchers at Cascades Volcano Observatory and elsewhere, who maintain and monitor seismic and volcanic activity. Additional collaborations exist with many international researchers, in particular in Canada (Geological Survey of Canada) as well as in Japan and Europe. GeoPRISMS research in Cascadia will engage a broad range of US, Canadian, and international scientists, and leverage a rich trove of geologic and geophysical data accumulated both onshore and offshore over recent decades.

Cooperation within the GeoPRISMS community will be guided by topical working groups to plan and coordinate Cascadia research focusing on, for example, (1) integration of multiple datasets to develop the best constrained model of the plate interface (location and physical characteristics); (2) synthesis of observations of surface deformation to create an onshore-offshore lithospheric map of deformation; (3) design and implementation of a multidisci-plinary experiment to illuminate the structures of magma pathways and reservoirs beneath active volcanoes that cannot be resolved with existing datasets.

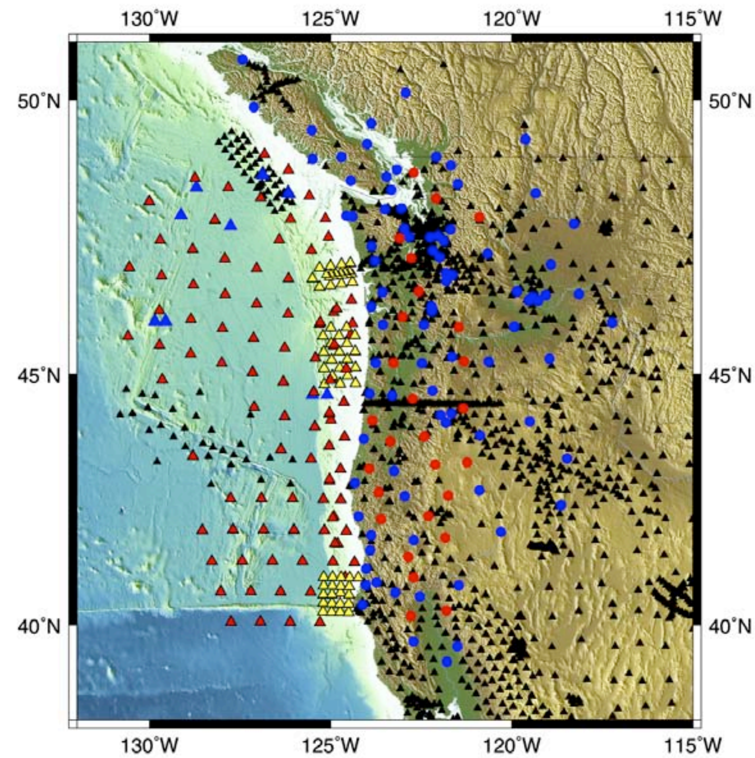

Figure 2.18. Stations that will have publicly available seismic data as of 2015. Offshore triangles show data to be collected over the 4 years of the Cascadia initiative. Circles on land show locations of USArray stations that will be deployed until 2013 as part of the Cascadia Initative. Black triangles on land show data from past PASSCAL and Earthscope Flexible Array deployments. More than 200 high-rate GPS stations that are part of the Cascadia initiative (not shown) will be available through 2018.

2.3.5.1. Cascadia Initiative

The Cascadia Initiative (Figure 2.18) was funded by the ARRA. It includes reoccupation of selected EarthScope US-Array sites and upgrading of PBO GPS sites to high-sample rate, real-time recording as well as construction of 60 broadband ocean bottom seismometers (managed as the Amphibious Array Facility) that are being deployed for 4 consecutive year-long deployments starting in summer 2011 (see http://cascadia.uoregon.edu/CIET for maps of the current and planned deployments). This facility is being operated as a Community Experiment (see 2.3.5.2).

2.3.5.2. Community Experiments

In addition to the Cascadia Initiative, an open-data access experiment to acquire a series of 2D multichannel seismic reflection lines across the Cascadia accretionary complex offshore Washington is planned for July 2012 on the R/V Langseth, an example of a "community experiment," in which projects are planned and vetted by and for the community. The data acquisition phase is being run as a "teaching cruise," with ~16 young investigators and graduate students participating in the cruise. These were selected from an applicant pool of 55 and were chosen in part based on their potential for writing future proposals to use the R/V Langseth. Initial data processing will be performed rapidly by a commercial company and will be available to the community very soon after the cruise. Funding for further data processing and interpretation for this and other Community Experiments will be through PI-initiated proposals to the NSF Marine Geology and Geophysics program.

2.3.5.3. EarthScope Program

EarthScope aims to explore the structure and evolution of the North American continent mainly through its three major observatories: the USArray seismological and magnetotelluric facility, the Plate Boundary geodetic Observatory, and the San Andreas Fault Observatory at Depth. Cascadia figures prominently in the research targets for EarthScope and is highlighted in the EarthScope Science plan (http://www.earthscope.org/ESSP). The GeoPRISMS and EarthScope science questions/targets are complementary and have been discussed at joint planning workshops. The onshore component of the Cascadia Initiative is managed by EarthScope Facilities (IRIS for seismology and UNAVCO for geodesy; 2.3.5.1). In addition, sustained and synoptic onshore observations from EarthScope (Figure 2.18), as well as an active science community (with a dedicated NSF program and portable instrumentation for investigator-driven proposals), and a vigorous broader impacts apparatus provide an important implementation partnership for GeoPRISMS. The EarthScope and GeoPRISMS science programs at NSF are well coordinated for joint proposal review and leveraged support.

2.3.5.4. Cooperation with US Government Agencies

In addition to the aforementioned NSF-sponsored programs that complement GeoPRISMS, other NSF programs may offer collaborative opportunities for Cascadia studies (e.g., the Network for Earthquake Engineering Simulation with facilities for doing active seismic source studies). US Geological Survey programs focused on earthquake, volcano, and landslide hazard reduction increasingly rely on partnerships. Not only does the USGS partner directly with GeoPRISMS community members, but it may serve as a link between GeoPRISMS and state and local institutions with whom USGS regularly partners and who can provide valuable data, knowledge, and field access. Opportunities to collaborate exist with other US agencies, such as the National Oceanic and Atmospheric Administration that oversees tsunami research, and the US Office of Naval Research.

2.3.5.5. International Collaborations (Canada, Japan)

The Geological Survey of Canada (GSC), with GPS and seismic networks covering much of the northern Cascadia margin, has a strong Cascadia research program and has developed collaborative relationships with many U.S. Earth Science institutions. NEPTUNE Canada, a cabled seafloor monitoring system, is already contributing to the OBS operations of the Cascadia Initiative and the design of seafloor monitoring networks in the U.S. The Japanese subduction zone research community has a sustained, keen interest in studying the Cascadia subduction zone, because Cascadia and Nankai (SW Japan) are both end-member warm-slab subduction zones and share many striking similarities and because Cascadia and the Japan Trench (NE Japan) are opposite end-member warm-slab and cold-slab subduction zones. The GSC, JAMSTEC (Japan Marine-Earth Science and Technology Center) of Japan, University of Victoria, and Woods Hole Oceanographic Institution have an ongoing joint project, SeaJade, to monitor seismic activity in northern Canada, in coordination with the CI. The first SeaJade deployment of OBSs was made in 2010. The second deployment will take place in 2013.

2.3.5.6. International Ocean Discovery Program and Ocean Observing Initiative Opportunities

GeoPRISMS has a number of Cascadia-related science objectives in common with the International Ocean Discovery Program (IODP) and the Regional Cabled Observatory (RCO) of the Ocean Observing Initiative (OOI). IODP and OOI are currently collaborating on installing borehole instrumentation on the Canadian Neptune cabled observatory on the accretionary prism offshore Vancouver Island (see http://www.neptunecanada.ca/about-neptune-canada/neptune-canada-101/ and section 2.3.5.5), and proposals are in the development and evaluation stage for borehole observatories on Hydrate Ridge on the continental margin off Oregon (http://www.interactiveoceans.washington.edu/story/OOI+Regional+Cabled+Network%3A+The+Cabled+Component+of+the+NSF+Ocean+Observatories+Initiative).

The IODP and its predecessors have carried out several drilling legs off the west coast of North America. Their margin projects have focused on gas hydrate and fluid processes, and their mid-plate and ridge-flank projects have focused mainly on hydrothermal processes in the young oceanic crust. The IODP and its predecessors have supported a series of cruises to the flank of the Juan de Fuca ridge to study the hydrology of oceanic crust (ODP Legs 139 and 168; IODP Expeditions 301 and 327). These expeditions, and continuing work at this site, provide important background constraints on the temperature and water content of the lithosphere subducted in Cascadia. IODP focus sites at other subduction zones around the world, including the ongoing SEIZE initiative in the Nankai trough, the J-FAST project in the Japan trench, Project IBM in the Izu-Bonin arc, and the CRISP project off Costa Rica are also very relevant. Many U.S. scientists are participating in deep drilling projects to sample and monitor the updip portions of the seismogenic faults at Nankai, Costa Rica, and Japan Trench, to recover in situ sections of arc crust at different evolutionary stages in the Izu-Bonin arc, and are involved in developing IODP proposals to study slow slip at the Hikurangi margin, New Zealand, and other IODP subduction zone studies. There is potential to explore further IODP drilling and monitoring along the Cascadia margin.

The NEPTUNE cabled observatory and the OOI-RCO also include broadband seismometers and other seafloor sensors on the accretionary complex that provide data to address GeoPRISMS Cascadia science objectives. NEPTUNE has been recording seismic data since 2011. The RCO includes plans for several arrays in which a broadband seismometer is embedded in focused arrays of short period seismometers; these arrays will be installed in 2013.

2.3.5.7. Rapid Response.

Earthquakes, tsunamis, volcanic events, landslides and other geologic events provide learning opportunities that should not be missed. Most of these events come with little or no warning. GeoPRISMS must be poised to capitalize on these opportunities when they arise. This may require developing official response plans and/or collaborating with agencies (e.g., USGS, FEMA) that already have plans and facilities ready. At a minimum, flexibility should be built into GeoPRISMS plans such that facilities may be reconfigured and redeployed nearly immediately. Researchers seeking to conduct scientific research as part of a rapid-response effort to a geologic event are directed to the NSF guidelines for submitting RAPID proposals (http://www.nsf.gov/pubs/policydocs/pappguide/nsf10_1/gpg_2.jsp#IID1), and are encouraged to contact NSF program officers directly for guidance on the submission of such proposals.

2.3.6. Broader Impacts

2.3.6.1. Geohazards

Fundamental contributions to understanding processes that underlie the hazards posed by earthquakes, volcanoes, tsunamis and landslides will be made through GeoPRISMS and EarthScope. The offshore component of GeoPRISMS permits observation of seismic and aseismic deformation in areas where presently few exist, and the amphibious nature of the Cascadia Initiative promises a more complete view of the subduction zone processes that drive the geologic hazards. Products of GeoPRISMS and EarthScope research will have direct impact on the certainty and resolution of monitoring and long-term hazard assessments, particularly hazard maps. For example, higher resolution images of plate interface coupling should lead to better forecasts of the rupture limits of future great earthquakes, as well as their potential to generate tsunamis. New understanding of accretionary wedge deformation and splay faulting also will improve models of Cascadia tsunami potential and impacts, needed for new probabilistic tsunami hazard maps. Volcano hazard assessments rely heavily on models of the magmatic systems that govern the unique behaviors of each of Cascadia's volcanoes, and thus will benefit from focused volcanic GeoPRISMS and EarthScope studies. The enhancements to infrastructure and technologies for measurement of geologic phenomena, data analysis methodologies, and deeper understanding of geologic processes made through GeoPRISMS and EarthScope directly impact time-dependent and even real-time hazard assessments and response. In addition to expanding and improving continuous geodetic and seismic monitoring networks, the development of earthquake early warning system for Cascadia would not be possible without GeoPRISMS and EarthScope.

2.3.6.2. Student and Teacher Involvement

Both the GeoPRISMS and EarthScope programs have well established outreach pathways that can provide support to students and teachers from the K-12 classroom through and beyond the postdoctoral level. The GeoPRISMS program, in cooperation with the Science Education Resource Center (SERC), has put together a collection of mini-lessons that capture many of the key scientific advances of the last decade. Though primarily aimed at an undergraduate audience, this resource can be adapted to younger or informal science audiences. The GeoPRISMS Distinguished Lectureship Program (and the EarthScope Speakers series) provides a pool of experts that can offer talks aimed at both specialized and more general audiences. Additional efforts to encourage a new generation of undergraduates to take part in Cascadia science include an ongoing effort to develop a formal or informal GeoPRISMS REU program that would be based on the very successful model pioneered by IRIS. The EarthScope program has a mature outreach program, many parts of which are based around the USArray program that is so important to the Cascadia region. In addition to the numerous resources provided for students and teachers on the EarthScope web page and in the Active Earth Monitor, the Teachers on the Leading Edge program provides a source of professional development for Pacific Northwest teachers of Earth Science. Further opportunities for students in the Cascadia region include participation in the OBS deployment and retrieval cruises and the Cascadia open-access 2D seismic reflection cruise.

2.3.6.3. Engaging Local Communities

Residents throughout the Cascadia region are routinely exposed to the hazards associated with subduction zone seismicity and the many active volcanoes that are proximal to major population centers. In many cases, outreach by the USGS, universities, and other organizations has familiarized a significant segment of the population with the inherent hazards of living in the area, as well as the role of geologic processes in the development of the spectacular natural resources of the region. GeoPRISMS and EarthScope activities in the Cascadia region offer an excellent opportunity to connect with people who live along this active plate tectonic boundary. Scientists can take the opportunity to visit schools and give community presentations while working in the area. The deployment of instruments near schools is a means to engage young people and educate them on their surroundings. Education and outreach efforts should also involve follow-up with local communities on the results of scientific investigations in the area (not just visits during field campaigns).