Investigating Cascadia Subduction Zone Geodynamics Through Scientific Ocean Drilling

Report of a Workshop
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Cover photo: Aerial view of the JOIDES Resolution courtesy of William Crawford and IODP.

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1. Executive Summary

The Cascadia subduction zone extends over 1000 km along the coast of the Pacific Northwest and is characterized by a warm subducting plate and the presence offshore of a structurally complex accretionary prism that has formed from extensive glacial sediments. Paleoseismic studies show that the subduction zone is the site of destructive megathrust earthquakes, which can rupture its entire length. Growing scientific interest in Cascadia over the past decade has led to extensive investments in scientific infrastructure and studies. On-land dense seismic and geodetic networks are in place to monitor the Cascadia subduction zone, and recent efforts offshore include the installation of cabled observatories, large deployments of ocean bottom seismometers, seismic and magnetotelluric imaging experiments, and nascent efforts at offshore geodesy. Cascadia and its environs has been the site of several previous drilling expeditions. Most of the drilling on the margin to date has focused on understanding shallow structure and the formation and distribution of gas hydrates while a drilling transect on the Juan de Fuca plate was designed to study the ridge-flank hydrothermal regime and the evolution of ocean crust.

Geophysical and hydrological observatories in sealed boreholes provide a powerful tool to understand the hydrology of crustal formations, a means measure the hydrologic signal from changes in volumetric strain, and a stable site for high quality seismic and geodetic instrumentation. Sealed observatories have been deployed in a number of subduction zones. The longest running deployments at Costa Rica and Nankai have captured signal from multiple shallow slow-slip events and, at Nankai, signals have been detected from the coseismic strain of distant events. At the Japan Trench the thermal anomaly associated with frictional heating was measured on the seaward-most part of the subduction fault following the 2011 Tohoku earthquake.

The Cascadia subduction zone has a number of unique characteristics that make it suitable for drilling efforts that would contribute to our understanding of the dynamics of convergent margins.

- The young age of the subducting plate and the thick sediment cover lead to a warm megathrust and a seismogenic zone at unusually shallow depths; its updip end could be within the reach of modern drilling technology.
- The subduction zone is in the late stages of interseismic deformation and thus provides a good contrast with margins that have experienced great earthquakes more recently.
- The megathrust is seismically remarkably quiet and the geodetic data on land cannot distinguish between complete locking of the fault offshore or local locking and extensive creep elsewhere. These two end member scenarios have drastically different hazards implications. Instrumented drill holes could help understand the patterns of fault locking and creep offshore.
- The high sediment supply has led to the formation of a structurally complex and atypical accretionary prism that varies along strike. Because of its high temperature, the sediments at the base of the trench are likely to have petrological traits and fluid pressures that are different from other subduction zones, thus impacting the frictional behavior of the megathrust.
- The basement of the incoming plate is quite smooth, a characteristic that is common for subduction zones that produce the largest earthquakes. Buried heterogeneities on the megathrust may be responsible for possible fault segmentation and the presence of clusters of

earthquakes off central Oregon. It is important to understand whether this region is slipping slowly during the late interseismic period and thus less likely to slip during the next great earthquake

- Cascadia is an end member in the production of episodic tremor and slip downdip of the seismogenic zone and it is logical to ask whether similar slip transients, with or without tremor, are observed updip of the locked zone. Borehole geodetic monitoring can help resolve this.

Seafloor drilling in Cascadia has the potential to address a variety of important questions related to the dynamics of the subduction zone, the characteristics of the incoming plate and structure and evolution of the accretionary prism. For the subduction zone, it is unknown if the fault is currently fully locked, over what width of the plate boundary strain accumulates and how this varies along strike. Borehole observatories will help address these issues and can provide a stable setting above the seismogenic zone for sensitive instruments to search for deformation signal of which we are currently unaware. If deeply sourced fluids can be tapped at the seafloor or in boreholes, they may provide insights into steady and episodic deformation. For the incoming Juan de Fuca plate, it is unknown if the elastic deformation and stress accumulation over the earthquake cycle influences the whole plate or is confined to a narrow region near the plate boundary. Drilling can provide constraints on the evolution of the lithosphere as it approaches the trench, along-strike variations in sedimentology, alteration and fluid compositions that might contribute to segmentation and the extent and impacts of mineral dehydration. For the accretionary prism, an improved understanding of its mechanical properties has the potential to provide insights into how it will behave when the fault ruptures which has implications for the seismic and tsunami hazards. It is important to understand how along-strike variations in the structure and properties of the wedge affect the likelihood of shallow slip or rupture arrest and what factors lead to the development of splay faults.

The workshop participants agreed on three transects for drilling. At two locations along the subduction zone, one off central Oregon and one off south-central Vancouver Island, there have been extensive site-survey operations and drilling targeting primarily shallow structure and gas hydrate accumulations. Both are excellent candidates for deeper drilling and the establishment of borehole and seafloor observatories for geodynamic studies along transects across the outer parts of the seismogenic zone. There are clear contrasts in sedimentological and structural properties between the sites that provide an opportunity to test hypotheses. At both sites, real-time cabled observatories are available to support instrument packages with high power or bandwidth requirements. A third transect crosses the Washington margin at a location where the accretionary prism has a very different structure with landward-vergent thrusts. Here the primary drilling objective is to establish a transect to constrain the nature and age of sedimentary materials so as reconstruct the timing of events that formed the unusual accretionary prism here and understand the implications for tsunamigenesis.

Funding drilling in Cascadia will be a challenge, and it will be important to seek opportunities that leverage interagency and international collaborations to support the dual scientific and hazards applications of this work. Although the drill ship will not be in the North Pacific until after 2020, it is important to submit a Preliminary Proposal for drilling soon in order to get feedback from the Science Evaluation Panel and initiate the lengthy process of planning and site selection.

2. Workshop Goals

The past few years have seen increased interest in studies of the Cascadia subduction zone. While it has long been known that Cascadia can host large megathrust earthquakes, the occurrence over the past decade of devastating earthquakes off Sumatra, Chile and Japan has heightened public awareness of the likely impacts of a similar earthquake in the Pacific Northwest. At the same time, there has been an expanded scientific focus on the Cascadia Subduction Zone. The NSF GeoPRISMS program, which studies continental margins, identified Cascadia as a Primary Site and cabled observatories have been developed off both the US and Canada. On land the 2009 ARRA (American Recovery and Reinvestment Act) funded substantial improvements to the Pacific Northwest Seismic Network and Pacific Northwest Geodetic Array. There are now ongoing efforts led by scientists to improve the resilience of the Pacific Northwest to megathrust earthquakes and to implement an earthquake early warning system for the US west coast. Offshore, ARRA funding supported the construction of ocean bottom seismometers for a 4-year community experiment to understand the seismicity and seismic structure of the Cascadia margin and Juan de Fuca Plate. Other recent activities include an amphibious magnetotelluric experiment, marine seismic imaging, a heat flow experiment on the margin and nascent efforts to obtain offshore geodetic observations that are critical for improving constraints on the seismic and tsunamigenic potential of Cascadia. Given that downhole hydrological and geophysical observations are some of the most sensitive tools for investigating subduction zone geodynamics, it is timely to consider how ocean drilling can usefully contribute to an increased understanding of the Cascadia subduction zone within the context provided by the extensive array of regional geophysical data.

With this in mind, the workshop was initially envisioned as a gathering of ~40 participants who would focus on the role instrumented ocean boreholes could play in long-term studies of the Cascadia subduction zone. However, because there was considerable interest from a broad range of scientists, the workshop goals were expanded to explore a wider range of scientific questions that could motivate ocean drilling in the Cascadia subduction zone and to discuss ideas for future drilling in Cascadia. Topics considered included: 1) determining the composition and properties of the incoming plate; 2) understanding the structure and history of the accretionary prism; 3) characterizing fault zones; 4) using boreholes for geodetic, hydrologic and seismic monitoring; and 5) integrating the full range of science into a comprehensive plan for drilling. The level of interest in ocean drilling in Cascadia was reflected in the level of attendance: a total of 80 participants, including 16 early career scientists and 15 students, attended the meeting. Despite the availability of only partial travel support, fifty participants were from out of town.

3. The Cascadia subduction zone

3.1. Geological Structure and Tectonics

The Cascadia subduction zone extends over 1000 km from Cape Mendocino, California to Vancouver Island and marks the boundary along which the small Juan de Fuca oceanic plate (including the internally deforming Gorda and Explorer plates south of the Blanco fracture zone and north of the Nootka Fault, respectively) subducts beneath North America (Figure 1). Convergence occurs in an east-northeast direction at rates ranging from 20 mm/yr or less off northern Vancouver Island and 30 mm/yr off northern California, to over 40 mm/yr off northern

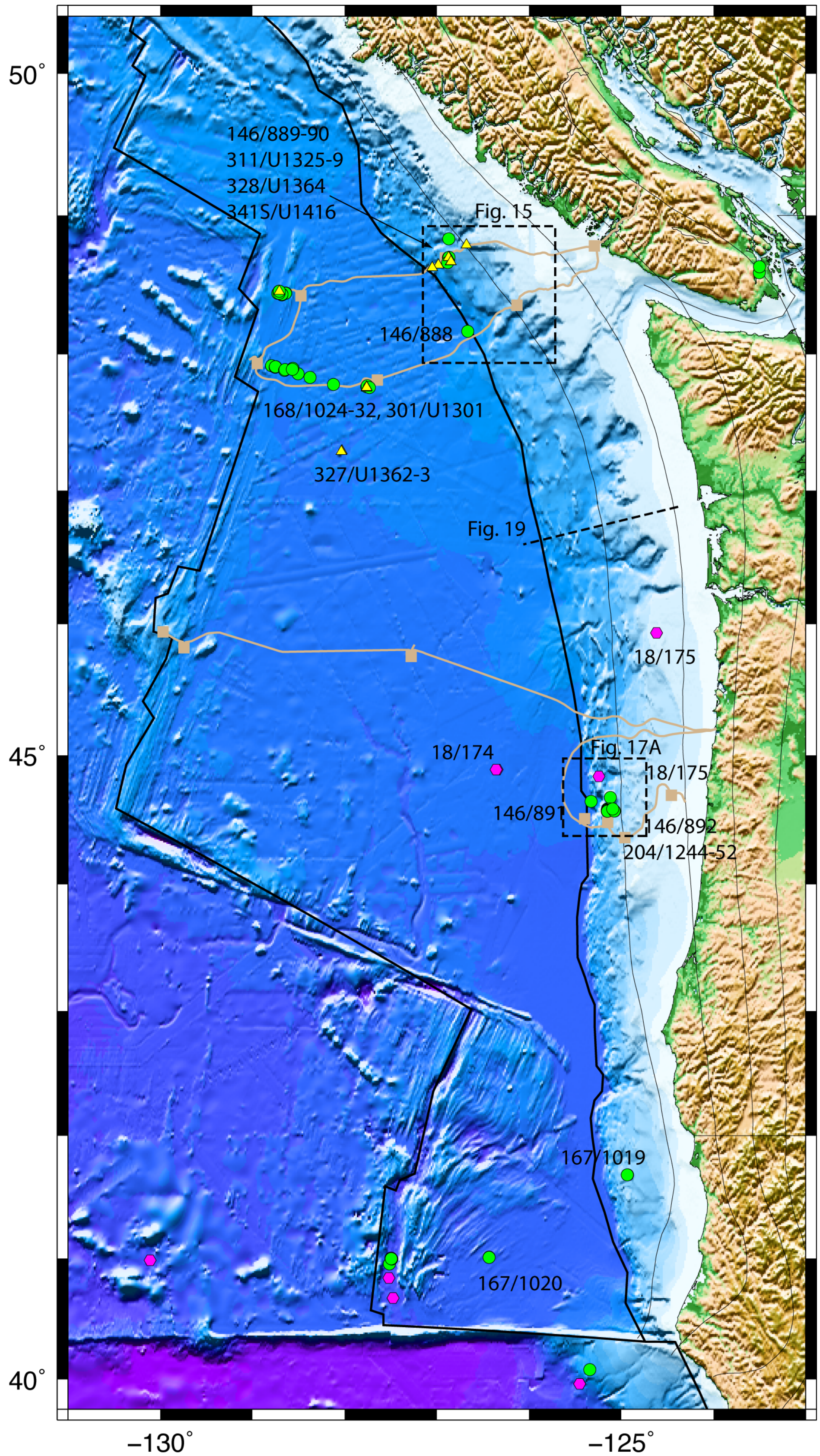

Figure 1. Map of the Cascadia subduction zone region showing drill holes from the DSDP (magenta hexagons), ODP (green circles) and IODP (yellow triangles) labelled with the leg and hole numbers; the approximate location of plate boundaries (bold black lines), contours for the slab depth spaced at 10 km (faint black lines) (from McCrory et al., 2012); the location of the NEPTUNE Canada and NSF Ocean Observatories Initiative cabled observatories (tan lines and squares showing primary cable routes and nodes) and the location of Figures 15, 17A and 19 which mark potential areas of drilling off Vancouver Island, central Oregon (Hydrate Ridge) and Grays Harbor, Washington.

Washington and central Vancouver Island (DeMets et al., 2010). Because the subducting Juan de Fuca plate is young (5-10 Ma) and thus warm, the locked zone that fails in megathrust earthquakes is relatively shallow and lies almost exclusively offshore. The Juan de Fuca plate is blanketed by up to several km of glacial sediments that bury the trench and reduce seafloor depths. Most of the sediments on the incoming plate are scraped off to form an active accretionary prism that extends shoreward from a sharp deformation front and lies outboard of older, accreted terranes that form the rock framework of the margin.

Much of onshore western Oregon and Washington and the continental shelf of Oregon is underlain by a basement of Paleocene to middle Eocene oceanic basalt with interbedded sediments known as the Crescent or Siletzia terrane. This terrane may have been emplaced via in-situ rifting and extension parallel to the margin (Wells et al., 1984), or docking of an allocthonous terrane (Globerman et al., 1982). Paleomagnetically determined clockwise rotations of coastal basalts in Oregon and Washington suggest that a process of dextral shear of the forearc has operated throughout the Tertiary. Miocene (12-15 Ma) Columbia River Basalts in western Oregon are rotated 10-30° clockwise, and Eocene Siletz River Volcanics rotated up to 90° clockwise (Wells and Heller, 1988; England and Wells, 1991). Mechanisms proposed to explain these rotations include microplate rotation during terrane accretion, basin and range extension, oblique subduction, or a combination of these (see Wells and Heller, 1988). GPS data have shown that clockwise block rotations are occurring over decadal timescales at approximately the same rate as the long-term rate (McCaffrey et al., 2000; 2007; 2013). The clockwise-rotating blocks collide with northern crystalline terranes, resulting in active north-south compression of the Puget Willamette Lowland, Olympic Peninsula, and southernmost coastal British Columbia.

Offshore, deformation of the Cascadia margin is well expressed in the fold and thrust belt of the accretionary wedge. For the most part, these structures are sub-parallel to the margin (Figure 2) and represent the response of the upper plate to the normal component of plate convergence (Silver, 1972; Kulm et al., 1973; Carson et al., 1974; Goldfinger et al., 1992; MacKay et al., 1992). The submarine forearc widens from 60 km off southern Oregon to 150 km off the northern Olympic Peninsula of Washington (Figure 2). Active accretionary thrust faults on the lower slope are characterized by seaward-vergent thrusts in a narrow part of the Oregon margin from 44° 13' N to 44° 55' N and north of 48° 07' N off Vancouver Island, and by landward-vergent thrusts between 44° 55' and 48° 07' N, on the northern Oregon and Washington margins. From 43° 17' southward to the Mendocino Triple Junction, the margin is characterized by mixed vergence (Gulick et al., 1998; Goldfinger, 1994; Goldfinger et al., 1997a; Adam et al., 2004). The broad landward-vergent province of the northern Oregon and Washington lower slope is poorly understood but has been attributed to subduction of rapidly deposited and overpressured sediment from the Nitinat and Astoria submarine fans (Seely, 1977; MacKay, 1995; Goldfinger et al., 1994, 1997a), although it may also be due to the curvature of the margin and/or to along-strike variations in sediment composition and physical properties. Growth faulting in association with mud diapiric intrusions or piercement structures is a common phenomenon on the Washington continental shelf (Snavely, 1987; Snavely and Wells, 1991).

Although subduction is oblique everywhere south of Vancouver Island, no major active arc-parallel faults equivalent to the Median Tectonic Line or Great Sumatran fault have been identified onshore in Cascadia. Snavely (1987) inferred that the Fulmar fault, a north-striking dextral strike-slip fault, offsets the continental slope and outer shelf in Oregon by about 200 km, and attributed an abrupt truncation of the basaltic Siletzia terrane to this fault. The Fulmar fault exhibits small offsets of Quaternary strata in southern Oregon and may reach the seafloor off central Oregon (Tréhu et al., 1995a), but was mainly active in the Eocene (Snavely, 1987). Some discontinuous arc-parallel faults have been identified in the Cascadia forearc, both onshore and offshore which may accommodate some northward translation of the Cascadia forearc (Weaver and Smith, 1983; Blake et al., 1985; Niem et al., 1992; Goldfinger, 1994). Goldfinger et al. (1997) identified a number of WNW-trending sinistral transverse structures deforming both the JDF plate and the Cascadia accretionary prism (Figure 2). Relatively high slip rates (5-12 mm/yr) suggest these Reidel shears may account for much of the oblique component of subduction in the outer forearc (Goldfinger et al., 1992; 1997a, McCaffrey and Goldfinger, 1995).

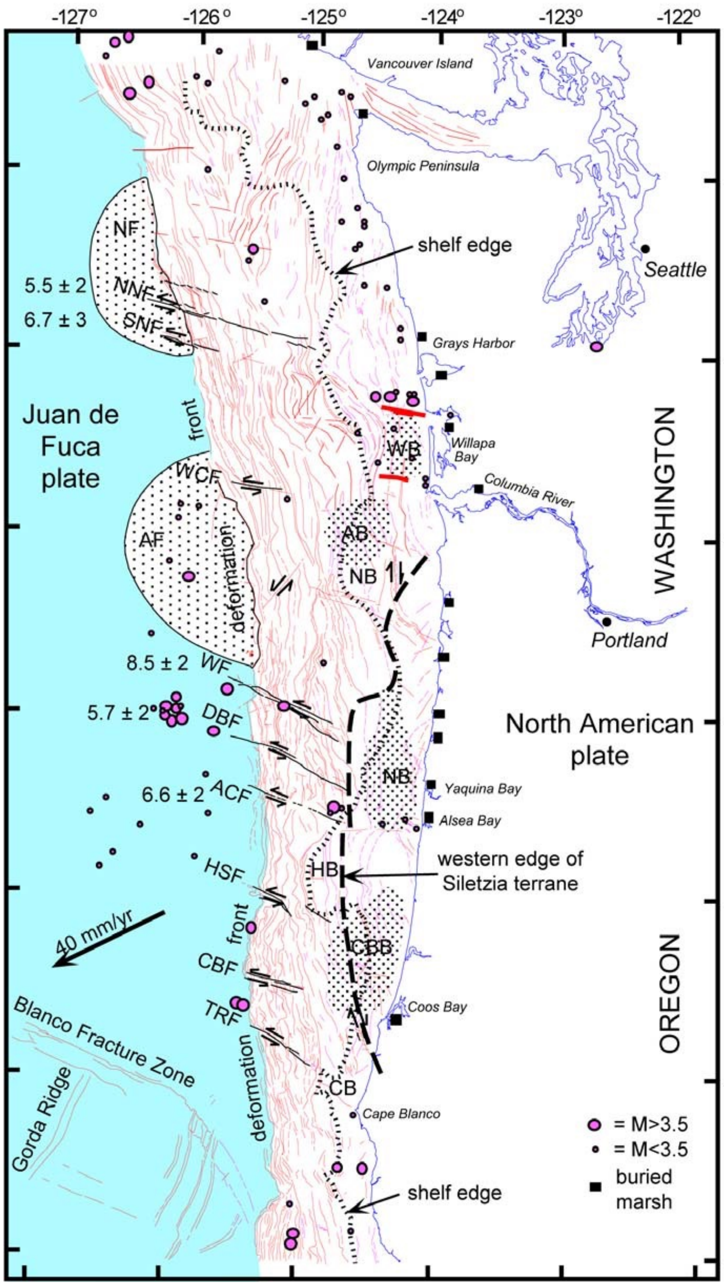

Figure 2. Active tectonic map of the Oregon and Washington continental margins. Faults and anticlines are shown with synclines deleted for clarity. Strike-slip faults, shown with slip rates in mm/yr: NNF = North Nitinat fault; SNF = South Nitinat fault; WCF = Willapa Canyon fault; WF = Wecoma fault; DBF = Daisy Bank fault; ACF = Alvin Canyon fault; HSF = Heceta South fault; CBF = Coos Basin fault; TRF = Thompson Ridge fault. NF = Nitinat Fan; AF = Astoria Fan. Major depocenters shown in stipple: WB = Willapa Basin; AB = Astoria Basin; NB = Newport Basin; CBB = Coos Bay Basin. Submarine Banks: NB = Nehalem Bank; HB = Heceta Bank; CB = Coquille Bank. Offshore seismicity is shown, with Blanco Fracture Zone and Gorda plate events removed. (Reproduced from Goldfinger et al., 1997b).

Listric and non-listric normal faults are fairly widespread on the mid to outer continental shelf and uppermost slope of the Washington and northernmost Oregon margins (Piper, 1994; McNeill et al., 1997). The most prominent normal faults are listric and deform as much as 3 km of the uppermost sedimentary section (McNeill et al., 1997). In general, listric normal faults showing activity in the Pliocene (and possibly early Pleistocene) tend to be located on the mid- and outer-shelf; more recently active Holocene and late Pleistocene faults, deforming uppermost sediments and/or the seafloor, are more commonly found near the shelf break (McNeill et al., 1997). These faults are thought to be moving on a weak surface at the top of the Hoh mélange, possibly as a result of wedge taper adjustment and westward tilt, resulting in westward extension of the underlying mélange (McNeill et al., 1997).

The southern Oregon Cascadia margin is characterized by three major submarine landslides, some of the largest in existence. The area enclosed by the three arcuate slide scarps is approximately 8,000 km^2, and involves an estimated 12,000-16,000 km^3 of the accretionary wedge (Goldfinger et al., 2000). The three arcuate slump escarpments are nearly coincident with the continental shelf edge on their landward margins, spanning the full width of the accretionary wedge. Debris from the slides is buried or partially buried beneath the abyssal plain, covering a subsurface area of at least 8,000 km^2. Reflection profiles on the adjacent abyssal plain image buried debris packages extending 20-35 km seaward of the base of the continental slope. The ages of the three major slides decrease from south to north, and are estimated to be ~ 110 ka, 450 ka, and 1,210 ka (Goldfinger et al., 2000). The massive failure of the southern Oregon slope may have been the result of the collision of a seamount province or aseismic ridge with the margin, suggested by the age progression of the slides and evidence for subducted basement highs (Fleming and Tréhu, 1999; Tréhu et al., 2012).

3.2. Paleoseismology

The Holocene history of earthquakes along the Cascadia subduction zone is constrained by indirect geologic evidence in the form of buried marsh deposits and tsunami deposits in coastal bays, estuaries and barrage lakes onshore. Buried intertidal and supratidal deposits have been reported as evidence for pre-historic coseismic subsidence using modern litho- and bio-stratigraphic analogues (Atwater, 1987; Atwater and Hemphill-Haley, 1997; Nelson et al., 2006). Sediments have been interpreted as evidence for local tsunamis triggered by slip on the Cascadia subduction zone megathrust; in some cases, these paleotsunami deposits are associated with the buried marsh deposits (Nelson et al., 1996; Atwater and Hemphill-Haley, 1997). Turbidites deposited in the deep sea offshore the northeast Pacific provide evidence for strong ground shaking from Cascadia subduction zone earthquakes (Adams, 1985; 1990; Goldfinger et al., 2003; 2012; 2013; Hamilton et al., 2015). Seismoturbidites have recently been interpreted in Inlets (Dallimore et al., 2005; Blais-Stevens et al, 2011; Enkin et al., 2013) and inland lakes (Karlin and Abella, 1992; Karlin et al., 2004, Morey et al., 2013; Goldfinger et al., 2014).

The most recent great earthquake, estimated to be magnitude 8.7-9.2, occurred on January 26, 1700 as deduced from tree ring data that constrain the year of death of cedar forests that subsided into the tidal zone, and from an orphan tsunami that caused significant damage in Japan (Satake et al., 2003). Goldfinger et al (2012) use both land and marine records to interpret a segmented record of Holocene paleoearthquakes (Figure 3) with recurrence intervals increasing from south to north. Each segment reaches the southernmost Cascadia subduction zone and segments that extend sequentially further north have recurrence intervals of 220-240, 300-380, 410-500, and 500-530 years (Goldfinger et al., 2012). These data suggest that there is a 20-40% probability of a major subduction zone earthquake (magnitude 8+) in the southern segment in the next 50 years about a 10-15% of chance of an earthquake rupturing the full subduction zone (Goldfinger et al., 2012).

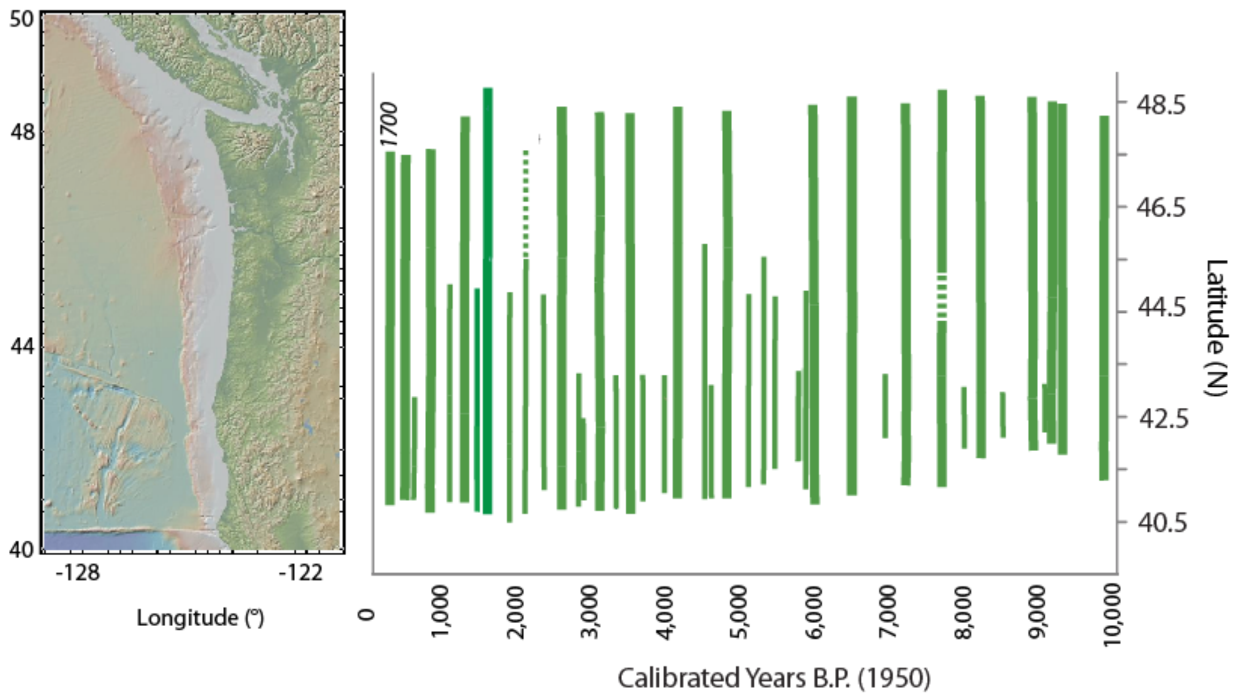

Figure 3. Holocene rupture lengths of Cascadia subduction zone earthquakes from the marine turbidite and onshore paleoseismic evidence from marsh subsidence and tsunami deposits. Green bars show the correlation along strike of deposits interpreted to result from a single event. Recurrence intervals increase from ~200 years at the south near Cape Mendocino to ~500 year off Washington and Vancouver Island. (Adapted from Goldfinger et al., 2012).

The apparent segmentation is reasonably consistent with paleogeodetic data (Nelson et al., 2008), secular geodetic observations (McCaffrey et al., 2013), paleo-slip models (Wang et al., 2013), variations in upper and lower plate crustal structure (Tréhu et al., 2012) and episodic tremor and slip segmentation (Schmalzle et al., 2014). The origins of segmentation is poorly understood but is presumably a result of some combination of along strike variations in the composition and structure of the overriding plate and the distribution of discontinuities such as seamounts and psuedofaults on the incoming plate that are variably masked by the thick sediment section that varies along the margin.

3.3. Geodetic and Earthquake Observations

Slip along faults accommodates most relative plate motions, and slip modes vary between the end-member behaviors of stick-slip (i.e., stuck or locked for hundreds of years punctuated by rapid seismic slip in earthquakes), and steady creep. These behaviors are best observed at subduction zones using integrated arrays of onshore and offshore seismic and geodetic instrumentation. On land, continuous seismic observations are provided by the Pacific Northwest

Seismic Network, the Northern California Seismic Network and the Canadian National Seismograph Network (Figure 4, left). There are a handful of real-time seismometers attached to the Ocean Observatory Initiative and NEPTUNE Canada seafloor cabled observatories but the majority of earthquake observations offshore come from deployments of ocean bottom seismometers, including the 4-year Cascadia Initiative that has deployed instruments along the entire US-portion of the subduction zone (Figure 5). Onshore high-sample-rate (1-Hz) GPS data is provided by ~500 stations operated by both The Pacific Northwest Geodetic Array (PANGA) and the NSF-funded Plate Boundary Observatory (PBO) (Figure 4, right). Geodetic observations on the seafloor are challenging (Bürgmann and Chadwell, 2014) and while there are nascent projects to obtain a few measurements across the Cascadia subduction zone, there are no results at present.

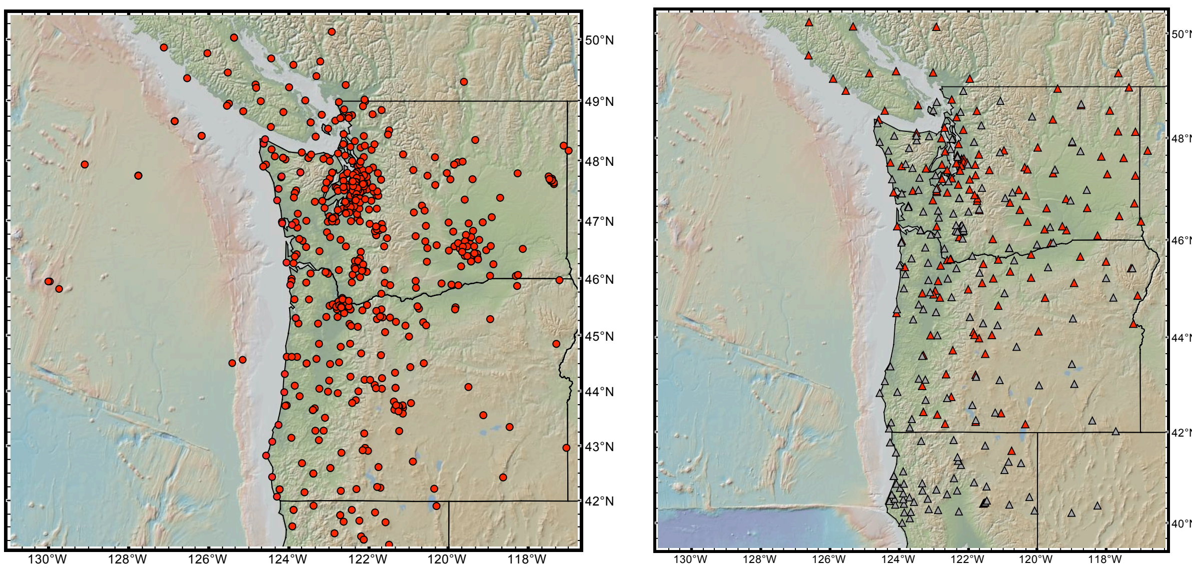

Figure 4. Permanent (a) seismic and (b) geodetic GPS networks in Cascadia.

The continuous GPS data from Cascadia, coupled with campaign GPS and longer term spirit leveling observations, resolve both the large scale rotation of the forearc discussed in section 3.1 (Wells and McCaffrey, 2013) and the contemporary rates of deformation across the plate boundary that results from strain accumulation on the megathrust and crustal faults (McCaffrey et al, 2013). Inversions of the geodetic observations are consistent with significant locking along the megathrust, with the locked zone positioned largely offshore (Wang et al., 2003). Additionally, there is distinct variability in the degree of locking along-strike. Recent studies suggest that the central section of Cascadia is only partially locked or has a very narrow zone of full locking (Figure 6c-d) and therefore exhibits appreciable aseismic creep (Burgette et al., 2009; Schmalzle et al., 2014). This contrasts with the region to the north and south, which appears strongly locked (Figure 6c-d). The major deficiency of existing geodetic observations is that the maximum strain is accumulating offshore where there are no contemporary geodetic observations. The land data are insensitive to any deformation nearest the trench and cannot determine whether the locked zone extends all the way to the trench (Figure 6c-d). Offshore geodetic observations, using the GPS-acoustic method, pressure gauges, borehole instrumentation and other techniques hold the potential to measure active deformation, both transient and long-term, on the accretionary prism and across the trench (Bürgmann and Chadwell, 2014). Such work on the Cascadia subduction zone has only just begun.

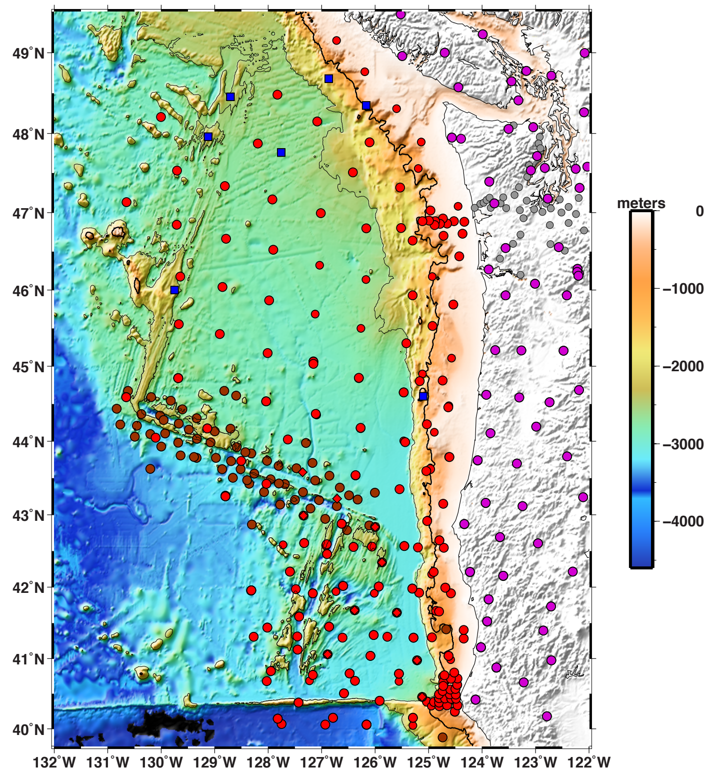

Figure 5. Cascadia Initiative and related earthquake monitoring OBS experiments offshore showing OBSs sites for the Cascadia Initiative experiment (red circles), related PI experiments (brown circles) and cabled observatories (blue squares) and broadband land stations (purple circles). (Adapted from Toomey et al., 2014).

Seismic monitoring shows that Cascadia's plate interface is anomalously deficient in earthquake activity, suggesting it may be completely locked as far east as the coast. North of Cape Blanco, M>3 interplate earthquakes are absent in catalogs dating back to 1989, with the exception of recurrent seismicity of M<5 in clusters offshore central Oregon (see below). South of Cape Blanco, there is abundant seismicity, but it is difficult to determine how much is associated with slip on the plate boundary and how much results from internal deformation of the Gorda plate.

In spite of the general lack of plate boundary seismicity, patchy seismicity of 2>M>5 has been detected on the plate boundary offshore central Oregon in the past decade at the rate of ~6 events/year (Tréhu et al., 2015) (Figure 6a-b). This activity occurs in a region where geodetic data suggest that plates are only partially locked, in contrast to the region to the north, which appears strongly locked (Figure 6 c-d) and may be related to interactions between buried subducted seamounts and the volcanic basement of the upper plate, which swings seaward in this region (Wells et al., 1998; Tréhu et al., 2012). This is also where the paleoseismic record indicates several possible segment boundaries and is the target of the central Oregon drilling transect discussed in section 7.2.

Some faults, or portions of faults, relieve stored stresses by slipping in ways intermediate between stick-slip and steady creep, sliding episodically and so slowly (over days to months) that only 'tremor' sources and low- to very low-frequency earthquakes (LFEs, VLFEs) radiate seismic energy. The small amplitude LFE signals emanate from tiny stuck spots that emit quasi-continuously, in the 1–15 Hz frequency band as slow slip fronts pass. Cascadia is the poster-child for episodic transient slow slip landward and down-dip of the locked zone, with events regularly recurring approximately every 14, 24 and 10 months in Washington, central and northern Oregon, and northern California respectively (Brudzinski and Allen, 2007). At its best, GPS data can resolve signals from a slow-slip event at their typical >35 km depth only if M_w>~6

(Aguiar et al., 2009; Chapman and Melbourne, 2009; Schmidt and Gao, 2012); sparsely distributed Plate Boundary Observatory borehole strainmeters lower this detection threshold by more than an order of magnitude (Wang et al., 2008). Because tremor may be far more easily measured than geodetically observed slow slip, it serves as an important proxy for when and where slow slip happens. While slow slip does little to relax stresses along the locked zone, and may even add to them, knowledge of its distribution and persistence provide guides as to where locked, earthquake-generating slip will likely occur. Slow slip generating VLFEs has been observed in the shallowest reaches of the plate interface offshore Japan (Yamashita et al., 2015; Davis et al., 2013a), and slip to the trench has been observed off Costa Rica and North Island, New Zealand as well (Davis et al., 2011, 2013a; Wallace and Beavan, 2010). Cascadia lacks the seafloor instrumentation required to record either the geodetic or seismic signatures of slow slip near the deformation front.

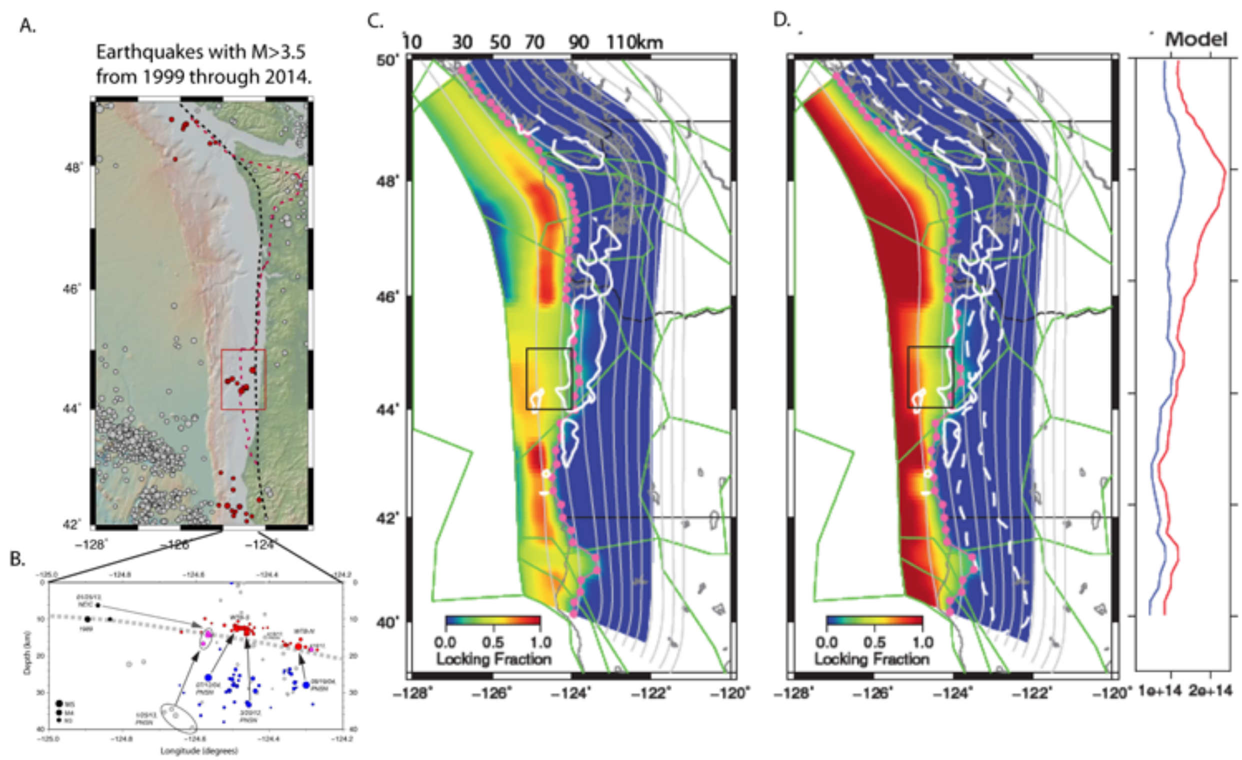

Figure 6. A. Earthquakes with M>3.5 in the ANSS bulletin. Events in red occurred within the nominally locked zone and are highlighted. The red box indicates the region shown in B. B. Events in the PNSN catalog (blue dots) that have been relocated (red dots) using a variety of approaches (Tréhu et al., 2008, 2015; Williams et al., 2011). Relocating the events using a more suitable velocity model and OBS data indicates that most of the earthquakes detected in this region, which have been occurring in persistent clusters at a rate of ~6/yr, occurred on or near the plate boundary and that PNSN locations are systematically too deep. C. One of the best-fit locking models of Schmalzle et al. (2014) based on onshore GPS data. D. An alternative locking model that fits the GPS data equally well (Schmalzle et al., 2014). E. Moment deficit for models C (blue) and D (red).

3.4. *Seismic Imaging*

Over the past two decades, there have been several natural source imaging experiments using broadband seismometers starting with the 1994-1995 TORTISS transect from the coast across the arc in central Oregon (Nabelek et al., 1996; Bostock et al., 2002) and the 2006-8 CAFE transect in western Washington (Abers et al., 2009). More recent experiments include the USArray Transportable Array from 2005-2008, with a subset of stations continuing to present, and the OBS component of Cascadia Initiative amphibious experiment from 2011-2015 (Toomey et al., 2014). These supplement coverage by the onshore Pacific Northwest seismic network and other permanent local and regional networks (Figure 5a) and provide data both for imaging of the crust and lithosphere and for location of earthquakes and other phenomena (e.g., tremor). Although currently most results image the onshore forearc, results from the offshore Cascadia Initiative OBS deployment are becoming available (Gao and Schwartz, 2015)

The locations of crustal-scale controlled source seismic studies in Cascadia are shown in Figure 7. Several multi-channel seismic (MCS) reflection and large-aperture seismic imaging surveys were conducted during the last two decades of the 20th century. These included a site survey for ODP leg 146 that provided several long transects of the northern Cascadia margin offshore Vancouver Island and a dense grid of lines across the deformation front offshore northern and central Oregon in 1989 (MacKay et al., 1995; Hyndman et al., 1993, 1994); an onshore/offshore crustal transect across the entire forearc in central Oregon in 1989/1991 (Tréhu et al., 1994, 1995a); the Mendocino Triple Junction and Blanco onshore/offshore seismic experiments in 1994 (Tréhu et al., 1995b; Beaudoin et al., 1996, 1998; Gulick et al., 1998, 2002); the ORWELL experiment off Oregon and Washington in 1996 (e.g., Flueh et al., 1998; Gerdom et al., 2000; Fisher et al., 1999) and the SHIPS experiment in the Puget basin in 1998/1999 (Brocher et al., 2001).

The crustal-scale seismic experiments of the 1980s and 1990s were followed by nearly 2 decades during which no crustal-scale active-source experiments were conducted, but high-resolution seismic data were acquired to study dynamic processes related to fluid migration and gas hydrate formation in the accretionary complex. These surveys included a 3D survey at the southern summit of Hydrate Ridge on the central Oregon margin in 2000, which was a site survey for ODP Leg 204 (e.g. Tréhu et al., 2006). A portion of the volume imaged during this 3D survey was imaged again in 2008, revealing detectible changes in the reflectivity of the primary conduit feeding the gas hydrate deposit and methane vents at south Hydrate Ridge (Bangs et al., 2011). In addition, several 2D high-resolution seismic surveys were acquired offshore Vancouver Island during this time period to support IODP Expedition 311, which sampled gas hydrates in a transect across the Vancouver margin (e.g. Riedel et al., 2006a). Comparison of results between Leg 204 and Expedition 311 revealed the importance of sediment characteristics on the dynamics of gas hydrate formation, with hydrate forming preferentially in the pore space within coarse-grained sediments where sands are present (Torres et al., 2008) and forming nodules and thin sheets with orientations controlled by the local stress field when sediments are predominantly fine-grained (Weinberger et al., 2005).

The focus returned to crustal scale imaging in 2012 with two ambitious MCS/wide angle experiments (Figure 7). The COAST experiment was an open-access MCS experiment designed as a pilot experiment for potential, eventual 3D crustal-scale data acquisition on the central Washington margin (Holbrook et al., 2012). Initial data processing was conducted by teams of student trainees, and the raw data and initial seismic sections were made available to the community soon after the cruise. These data illuminate the complexity of the central Washington margin and provide a basis for planning a drilling transect here (see section 7.3).

Perhaps the most surprising aspect of these data was the discontinuity and relatively low amplitude of the plate boundary reflection.

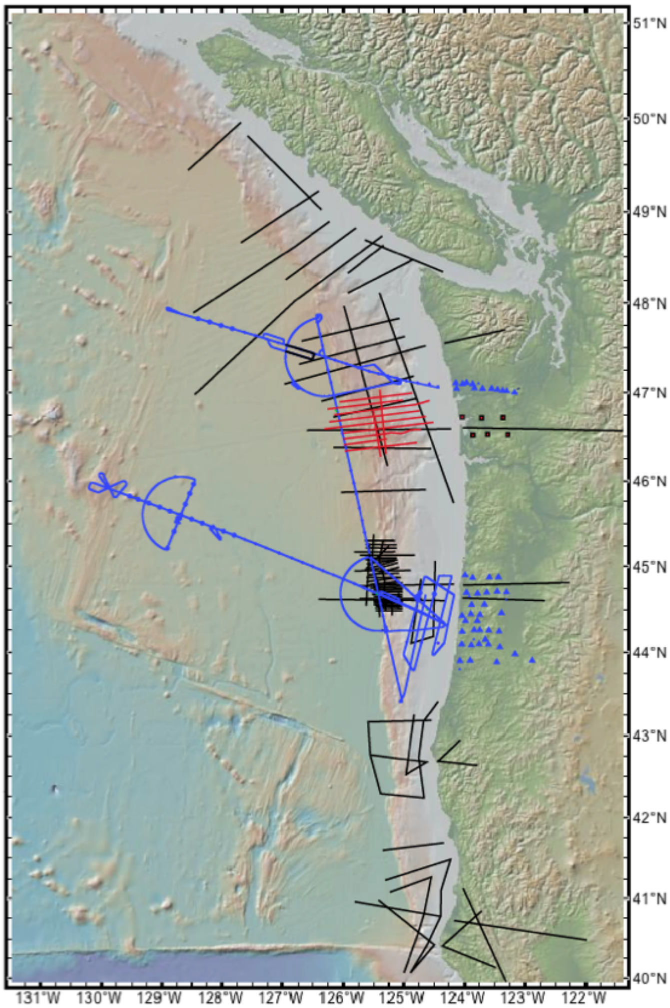

Figure 7. Locations of crustal-scale active source seismic experiments in Cascadia in the past 3 decades. Black lines show the locations of experiments prior to 2000. Red shows the 2012 COAST experiment. Blue shows the 2012 Ridge-to-Trench experiment with a piggyback onshore Earthscope flexarray project. Ocean-bottom seismometers were located at 10 km intervals along the Ridge-2-Trench profiles, providing excellent control on crustal and uppermost mantle velocity structure.

The objective of the Ridge-to-Trench experiment was to trace the evolution of Juan de Fuca plate lithosphere from its formation to subduction and included ocean-bottom seismometers at ~10 km intervals along two major 2D transects across the plate and a third line to define plate structure just before subduction. The data show distinct differences in the structure of the subducting plate between the two transects (e.g., Han et al., 2016). These data provide a basis for planning for drilling sites to constrain the nature of incoming sediments (see section 6.2). The 3D structure of the central Oregon margin was imaged through an Earthscope-funded piggyback onshore/offshore experiment in 2012, which has revealed short-wavelength, along-strike contrasts in P-wave velocity in the upper plate overlying the apparent locked zone (Kenyon et al., 2013). The geodynamic implications of such large contrasts in material properties have yet to be investigated.

As a consequence of seismic imaging, the structure of the crust and lithosphere is relatively well known compared to that of some other subduction zones. The dip of the subducting plate varies along strike and forms an arch beneath the Olympic Peninsula, probably in response to the bend in the deformation front. This bend is associated with a dramatic change in the character of the outer accretionary wedge, with the northern Oregon and Washington margin characterized by a landward-vergent frontal thrust and a broad zone of folds on the lower slope, in contrast to the narrower, steeper margins off central Oregon and Vancouver Island, which are generally characterized by a seaward-vergent frontal thrust. The dominant vergence along the southern Oregon margin is obscured by a history of large slope failures in the past 1.2 Myr. The reasons for the pronounced along-strike variation in the structure and morphology of the outer accretionary wedge and its implications for tsunamigenesis has been the subject of much debate but little consensus. Samples are needed to provide information on the physical properties and composition of the accretionary wedge sediments to establish age constraints for geologic reconstructions of wedge evolution.

3.5. Magneto-telluric imaging

Magnetotelluric surveys have been carried out extensively in Cascadia since the 1970s, with at least two thousand temporary MT stations covering the area. Most of these installations were aimed at natural resource (minerals, oil-gas, geothermal) investigations but there have also been a significant number of deployments aimed at understanding earth processes (Figure 8) including the EMSLAB experiment in 1985-6 that included a profile across central Oregon with additional stations on the incoming plate (Wannamaker et al, 1989), a profile collected across the Klamath mountains by the USGS (Box and Bedrosian, 2006; Wannamaker et al, 2014), a profile in central Washington as part of the CAFÉ experiment (McGary, 2014), two profiles across Hydrate Ridge offshore Oregon in 2004 and 2009 (Weitemeyer et al, 2011), the Earthscope MT Transportable Array (Schultz, 2009) which operated in this region from 2006-2007, the MOCHA amphibious array (Schultz et al, 2014) which was deployed from 2013-14 and which is currently being analyzed and the iMUSH MT array (Schultz et al, 2014) centered on Mount St. Helens which is being deployed from 2014-15.

The various 2-D profiles across the Cascades have contributed important constraints on the position of the resistive subducting slab, the distribution of fluids released from the slab and melt supplied to the volcanic arc and the extent of serpentinization. Of particular importance to offshore drilling is the MOCHA amphibious array which has substantially increased the number of MT stations offshore and which will when analyzed provide a three-dimensional view of the structure of the subduction zone that will complement existing seismic images and provide an improved view of fluid distributions in the mantle wedge along the margin segments.

3.6. Previous Drilling in Cascadia

There have been a number of previous scientific ocean drilling expeditions to drill into and sample subseafloor sediments and rock in the Cascadia forearc and adjacent Juan de Fuca plate (Figure 1, Table 1). Because gas hydrates play an important role in the Earth's carbon cycle, three drilling legs, ODP Leg 146 (in 1993) (Westbrook et al., 1994), ODP Leg 204 (in 2003) (Tréhu et al., 2006), and IODP Expedition 311 (in 2005) Riedel et al., 2006a) focused on understanding gas hydrates in two regions: offshore Vancouver Island and offshore Oregon. The ultimate goal of drilling was to provide constraints for models of marine gas hydrate formation in the Cascadia prism. To this end, the drilling was designed to characterize the formation, occurrence, and distribution of gas hydrates in the Cascadia prism from the deformation front landward, the migration pathways of methane and other gases from source to reservoir, and the effects of gas hydrates on the physical properties of the accretionary prism sediments.

These goals did not require deep penetration, and the depth of all holes is <600 m. Offshore Vancouver Island, ODP Leg 146 site 888 was drilled to 567 mbsf in the thick (2-3 km) incoming sediments seaward of the toe and recovered clayey silts with thinly bedded to massive sands. The sediments were <0.6 Ma, indicating rapid sedimentation rates. ODP Leg 146 sites 889-890, and IODP Leg 311 U1325-1329 examined a transect from the seaward-most anticlinal ridge to 65 km

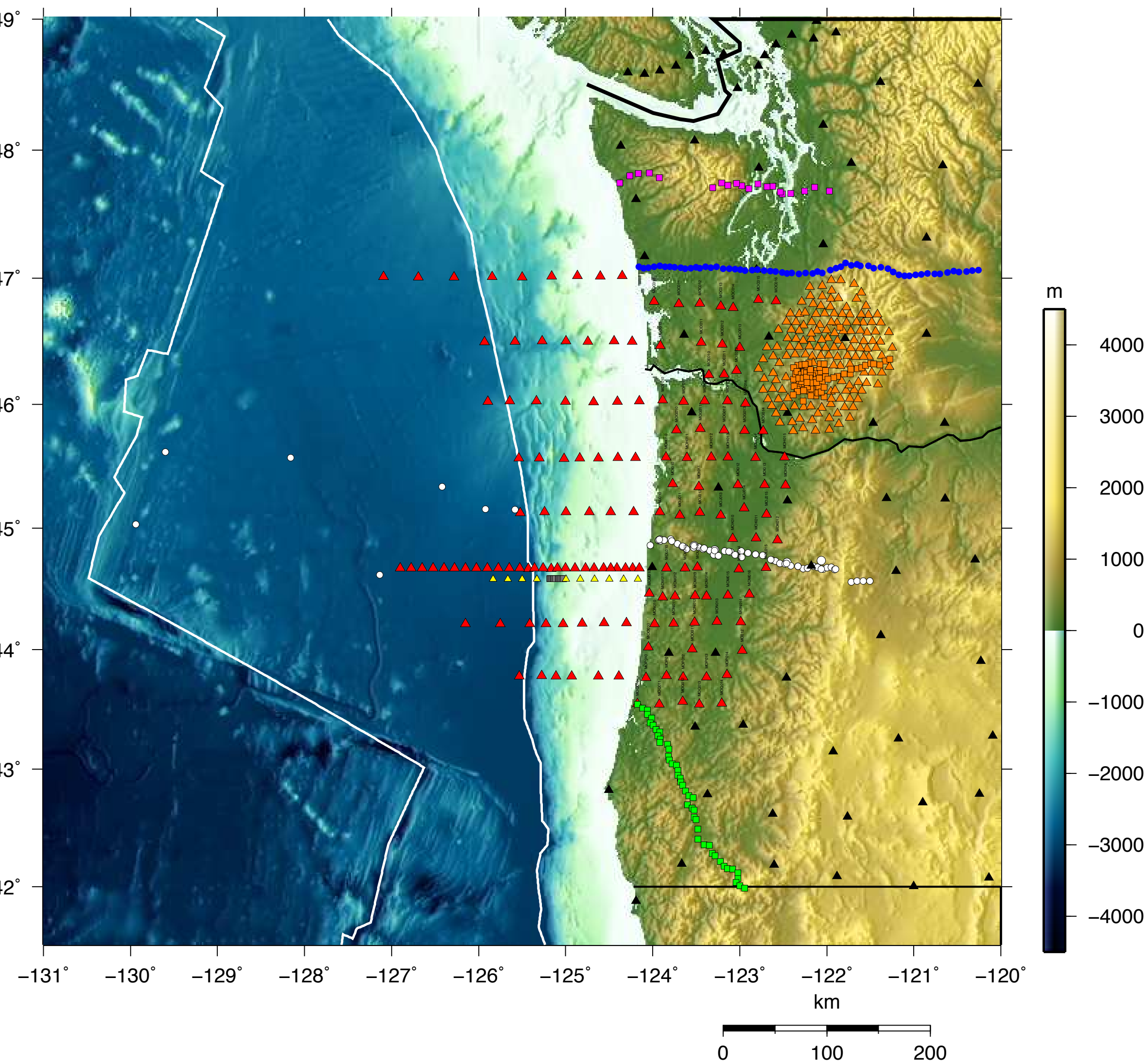

Figure 8. Cascadia non-commercial MT station coverage to-date. White circles represent a 2-D MT profile line collected during the EMSLAB experiment in 1985-1986. Green squares are a 2-D MT profile in the Kalamath margin segment collected by USGS as the SWORM array. The dark blue triangles are MT stations collected as part of the Earthscope MT Transportable Array in 2006-2007. Red triangles are the locations of the MOCHA amphibious MT array in 2013-2014, which are currently being analyzed. The yellow triangles are locations of MT stations during the Return to Hydrate Ridge project in 2009 (sparse array) and the Hydrate Ridge project in 2004 (denser cluster along same line). The orange triangles abutting the MOCHA array are stations making up the iMUSH MT array that were collected in 2014-2015, while the orange boxes are MT stations acquired by Hill et al, 2009 immediately surrounding Mount Saint Helens. The blue symbols are the locations of the 2-D CAFÉ MT profile, and the purple boxes are MT stations collected for the POM array.

from shore with hole depths ranging from 210 to 386 mbsf. Gas Hydrates are present and are actively forming in the prism mostly between about 5-10 and 30 km from the deformation front. Overall, average gas hydrate concentrations are low, less than 5% of the pore space throughout the drilled and cored gas hydrate stability zone, but locally high-concentrations, exceeding 50%

of the sediment pore space, occur mainly in the coarser-grained sandy-turbidite sediments (best documented on Expedition 311, Torres et al., 2008). The fluid advection responsible for gas hydrate formation has evolved to various extents at each of the sites leading to diverse impacts on the biogeochemical environments (e.g., Hyndman et al., 2001; Kastner 2001; Malinvero et al, 2008; Riedel et al., 2006b). Other important objectives of the drilling legs were the characterization of the composition, physical and thermal properties, and structure of the incoming plate and the prism. The results from these efforts provide an excellent background for future studies.

Offshore Oregon, ODP Leg 146 focused on the first accretionary ridge (site 891) and on the northern summit of Hydrate Ridge (site 892) (Westbrook et al., 1994). Three holes were drilled at site 891, reaching a maximum depth of 492 m and intersecting a seismically imaged, landward dipping thrust fault at 375 mbsf. Recovery was poor, but all recovered sediments were younger than 0.8 Ma. The fault zone was characterized by a sheared, clay-rich gouge. Leg 204 focused on nine sites near the summit of South Hydrate ridge and in the adjacent slope basin to the east (Tréhu et al., 2006), the deepest of which (site 1245) extended to 540 mbsf. All sites were linked structurally through a high-resolution 3D seismic site survey. This was the first drilling expedition for which logging-while-drilling data were available at all sites to guide subsequent sampling (including recovery of samples at in situ pressure) and for which all recovered core was systematically scanned immediately on recovery with a rack-mounted infra-red camera. Several holes penetrated through a very bright stratigraphic reflection that results from a gas-rich, permeable ash layer that acts as the primary conduit focusing free gas towards the summit vents. Although the concentration of gas hydrate averaged from the seafloor to the base of the hydrate stability zone is generally low (1-10%), several different zones of high concentration were identified near the base of the gas hydrate stability zone in the slope basin (15-20% of pore space), within isolated ash-rich layers on the flanks of Hydrate Ridge (4-15%), and as nodules and veins in the shallow, clay-rich sediments near the summit vents (25-40%). In the summit region, gas hydrate formation is probably very rapid, as indicated by very high pore water salinities, and gas migration through the hydrate stability zone results from a combination of high gas pressure, which generates cracks through which the gas can migrate, and high gas concentration, which outstrips the amount of water available to create gas hydrate (Tréhu et al., 2004), resulting in active venting of bubbles at the seafloor (Kannberg et al., 2013) and in massive hydrate formation in the upper tens of meters beneath the seafloor (Torres et al., 2004).

Other drilling efforts in the region include DSDP Leg 18 Sites 174 and 175 off Oregon that examined the incoming sediments and toe region of the subduction zone, respectively. Site 174 stopped at a total depth of 879 mbsf, roughly 30 m short of basement, and found 284 m of very fine to medium sands with clays overlying silty clay and silt with sand. IODP Expedition 328 (in 2010) focused on an ACORK installation for pressure monitoring near site 889 (Davis et al., 2010). IODP Leg 341 included the deployment of instrumentation to measure down temperature, pressure, and electrical resistivity, again near site 889.

Although not part of the subduction zone, ridge flank sites provide lithological information as well as insight to hydrothermal circulation and crustal alteration within the plate interior. ODP Leg 168 Sites 1023-1031 and IODP Sites 1301 examined the ridge-flank thermal regime, hydrothermal circulation, and crustal evolution along a transect of sites on the eastern Juan de Fuca Ridge Flank. The former characterized the mid-plate sediment section down to roughly

600 mbsf. Middle Valley, on the northern Juan de Fuca Ridge, was drilled at 4 sites during ODP Leg 139.

Table 1. Summary of offshore drill holes on and near the Cascadia subduction zone (see Figure 1 for locations; for details on individual sites for Leg 204, see Tréhu, 2006.)

Site(s)	**Leg / Exp.**	**Location**	**Thermal gradient**	**Sediments**	**Observatory**
174	18	Oregon: Incoming. Distal Astoria Fan	NA	0-284 mbsf: m to vf sands grading to silty clays 284-879 mbsf: silty clays and silts with rare fine sands. Basement est. @ 911 mbsf	No
175	18	Oregon: slope near toe in sediment pond.	NA	0-233 mbsf silty clay with some sand and silt turbidites. Uplifted between 0.3 and 0.45 Ma	No
888	146	Vancouver Island: 7 km seaward of toe	68°C/km	0-193 mbsf clayey silts and fine- to medium-grained sands, transitioning to massive sand 193-457 mbsf: massive sand with interbeds of clayey silt. 457.0-566.9 mbsf: clayey silt and silt Age <0.6 Ma	No
889-890	146	Vancouver Island: mid-slope	54°C/km	0-386 mbsf: clayey silts, fine sands, and diagenetic carbonates More fractured below 128 mbsf; increase in glauconite below 386 mbsf. Late Pliocene	Unsuccessful installation
891	146	Oregon: westernmost ridge	Disturbed.	0-492 mbsf: Clayey silts and fine to med sand Post-mid Pleistocene	No
892	146	Oregon: N. Hydrate Ridge	51 °C/km (with some advective anomalies)	0-178.5 mbsf: Silty clays/clayey silts with some sands. Fault zones. Early Pliocene	Yes, but no longer monitored. Hydrate clogging?
1019-1020	167	Eel River Basin and Gorda Basin	57°C/km and 189°C/km	0-278.8 mbsf: Clay with silt and diatoms and silty clay, claystone	No
1023-1032	168	Juan de Fuca Ridge flank	71 to 931 °C/km	Basement at depths up to 290 mbsf (Site 1032) Clayey silt to silty clay with silt and sand turbidites	Sites 1024, 2015,1026, and 1027

Site(s)	Leg / Exp.	Location	Thermal gradient	Sediments	Observatory
1244-1252	204	So Hydrate Ridge	52-62 °C/km	Slope accreted Astoria fan and slope basin. Deepest site 540.3 mbsf.	No
U1301A-1301B	301	Juan de Fuca Ridge Flank	230 °C/km	Basement at 262 m depth Fine- to coarse-grained turbidites, debris flows, and hemipelagic clay	Yes but CORKs now leaking
U1325	311	Vancouver Island: First slope basin	60 °C/km	0-304.3 mbsf clay and silty clay with variable frequency of silt and sand layers	No
U1326	311	Vancouver Island: First ridge	Disturbed or not long enough.	0-271.4mbsf: clay and silty clay with variable frequency of silt and sand layers	No
U1327	311	Vancouver Island: mid-slope (near 889)	Similar to 889		No
U1328	311	Vent area (~4 km SE of 889)	53.6 °C/km	Deepest hole: 300 mbsf Clay and silty clay with variable frequency of silt and sand layers	(Site U1416B) during Exp. 341S
U1329	311	Vancouver Island: 65 km from shore	72 °C/km	Deepest hole: 210.5 Clay and silty clay with coarser layers. Some conglomerates. Oldest: Miocene Hiatus 2-6.7 Ma	No
U1362A – U1362B	327	Juan de Fuca Ridge Flank	230 °C/km	Basement at 236 m	Yes but CORKs now leaking
U1364	328	Vancouver Island: Near U1327	56°C/km	Slope basin and prism to 336 mbsf	Site 1364
U1416	341S	Vancouver Island: Near 889	Similar to 889	Slope basin and prism to 240 mbsf	Site U1416

4. Borehole Observatories for Subduction Zone Studies

Boreholes have been used to access subseafloor formations for long-term monitoring for a variety of purposes. Examples include the "Ondo" temperature and pressure sensor attempted in the Nankai Trough (Shipboard Scientific Party, 1991), and seismic and strain observatories installed at several locations (e.g., Shipboard Scientific Party, 2000; Kasahara and Stephen, 2006). Proper sealing of holes is necessary for hydrologic observations and to eliminate thermal and fluid-dynamic sources of noise when making seismic and geodynamic observations. This requirement led to the development of the "CORK" (Circulation Obviation Retrofit Kit) observatory, which prevented fluid exchange between the drilled formation and the overlying ocean, and allowed the natural formation state (temperature, pressure, and fluid composition) to be observed after the effects of drilling perturbations dissipated (Davis et al., 1992). Through the 25 years since the construction and installation of the first CORK observatories, the scope of their application has expanded beyond the early efforts to document the average hydrologic state of crustal formations, and their design has been modified for a range of applications including geodynamics. The first CORKs provided a seal at the top of a solid casing string that was in turn sealed into 100 m or more of low-permeability sediment. This configuration (Figure 9, left) allowed formation fluid pressures to be measured and fluid samples to be collected either in open hole below the cased sections or through perforated sections of casing at depth. Later modifications allowed formation pressures to be measured outside the solid casing via wire-wrapped filters connected to pressure sensors at the seafloor (the "Advanced CORK", or ACORK, shown in Figure 9, center; Shipboard Scientific Party, 2002). With a plug at the bottom or top of casing, other instrument strings such as thermistors and seismometers could be installed inside the sealed casing, either at the time of drilling or later. A third configuration (dubbed "CORK II", shown in Figure 9, right; Jannasch et al., 2003) employed a different nested approach, with the large (10.75" o.d. typ.) casing used in the CORK and ACORK systems hosting a smaller casing inside, allowing instrumentation of deeper open-hole sections that remain stable below regular casing strings (e.g., Fisher et al., 2005; Saffer et al., 2009). The

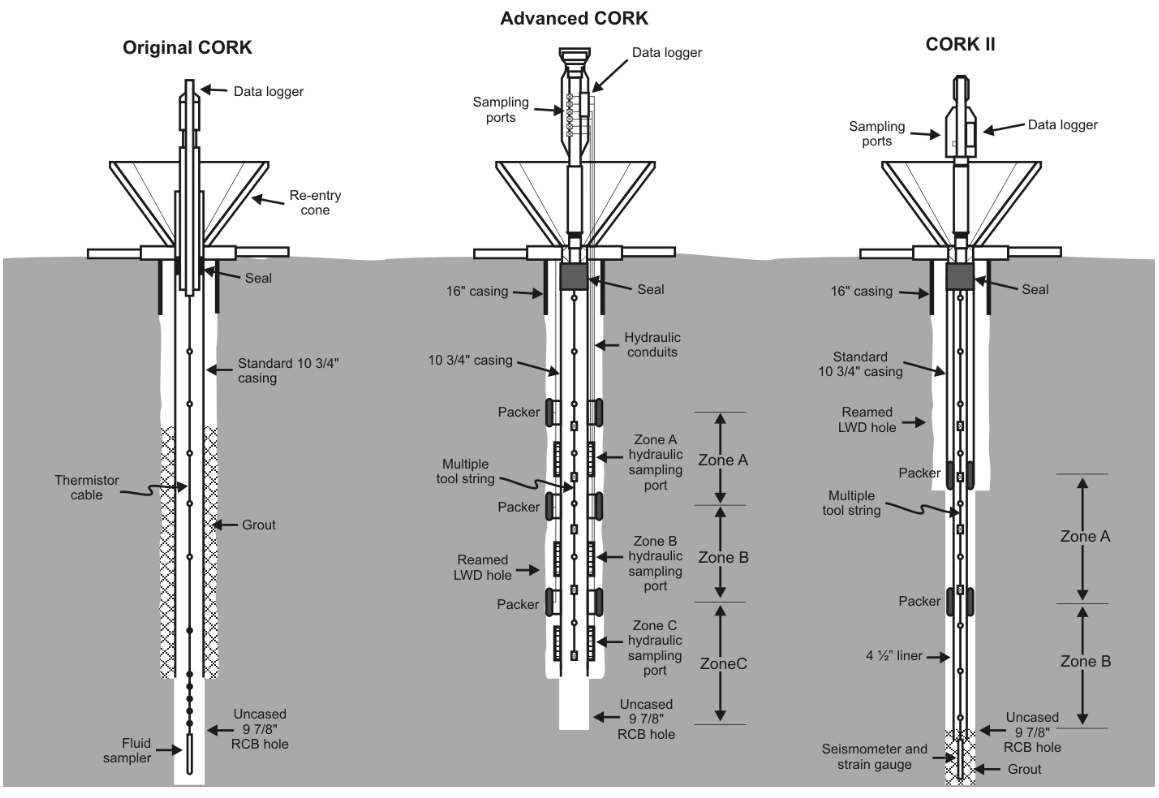

Figure 9. Schematic of CORK, ACORK, and CORK II observatories (adapted from summary by Becker and Davis, 2005). Installations have ranged in depth from 150 m to roughly 1 km beneath the seafloor, have included up to six pressure monitoring levels, and have hosted thermistor strings, fluid samplers and flow meters, seismometers, strain gauges, and tilt sensors within and below the primary casing strings.

efficacies of all types of installations depend on the quality of seals established between the instruments, casings, and the surrounding low-permeability sediment formation. Natural leakage to the seafloor should also be insignificant so that the formation pressures measured can be used as a sensitive and reliable proxy for tracking volumetric strain over long periods of time.

CORK observatories have been installed in a number of subduction zone settings, including Cascadia, Barbados, Mariana, Nankai, Middle America, and the Japan Trench. Among these, experiments at Costa Rica and Nankai are the longest running, and both have captured several episodes of slip. The installation in the Japan Trench targeted the time immediately following the Tohoku-Oki earthquake in 2011 and captured the thermal anomaly associated with the slip along the seaward-most part of the subduction fault. These thus serve as good examples of how CORKs can be used for seismic and geodynamic studies.

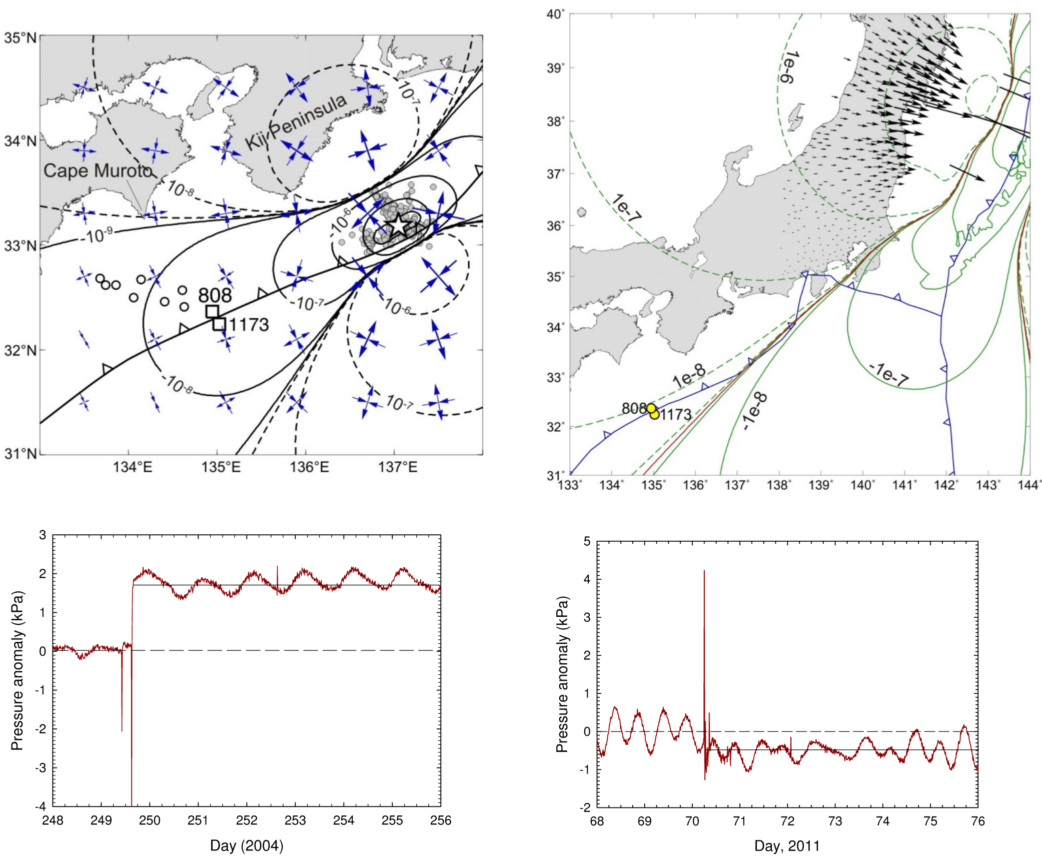

Figure 10. Pressure records from ODP Nankai site 1173 at the time of distant large earthquakes (220 km range from Mw 7.5 Off Kii, left, 940 km range from Mw 9.0 Tohoku-Oki, right), showing the effects of regional co-seismic strain (adapted from Davis et al., 2013a). Volumetric strain is contoured in the map-view panels. Sensitivity of pressure to strain is expected to be approximately 5 kPa μstrain^{-1}.

Pressure records at Nankai have captured signals caused by regional co-seismic strain (up to 940 km away from the Tohoku-Oki earthquake; Figure 10), and records from both Nankai and Costa Rica have captured numerous slow-slip episodes at the outermost subduction prisms. At Costa Rica, strain-induced pressure transients occurred several days after the initiation of low-

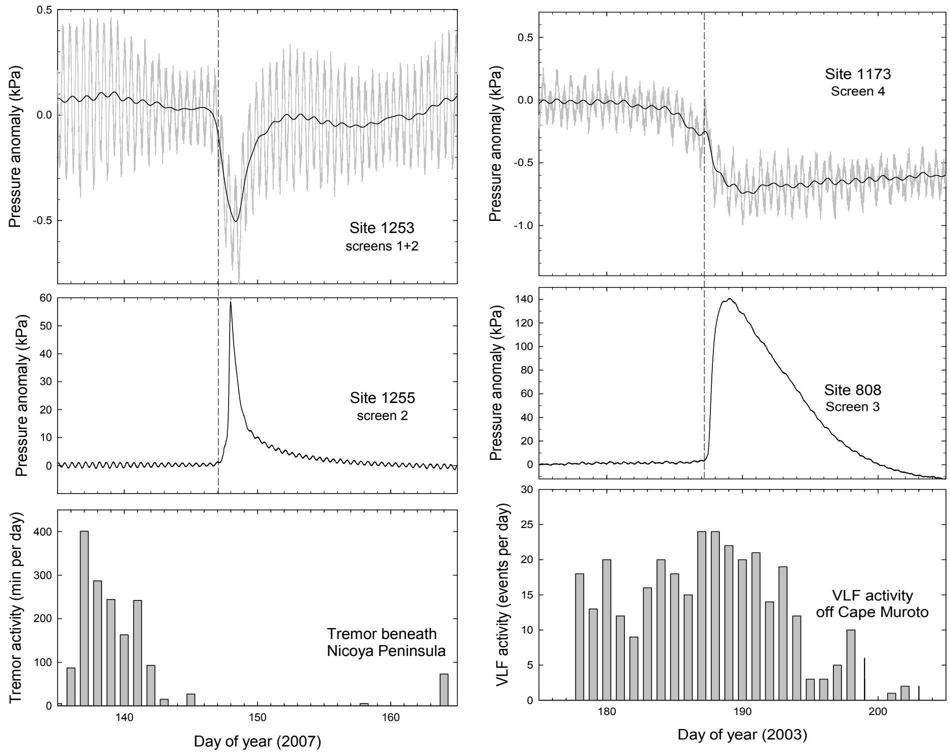

Figure 11. Pressure records at times of slow slip events at the outer Costa Rica and Nankai subduction zone prisms. The delay between the initiation of very low frequency earthquake (VLFE) and tremor activity, and the transients observed at the prism toe sites suggests very slow up-dip slip propagation (adapted from Davis et al., 2015). A roughly coeval fluid compositional anomaly was observed at Costa Rica (Solomon et al., 2009).

frequency earthquake swarms and tremor-and-slip events many tens of km down-dip (Figure 11), confirming that very slow slip can extend all the way to the trench between major subduction thrust earthquakes. The records from the Costa Rica sites also showed that slip at the prism toe at the time of the 2012 Nicoya earthquake was slow, neither seismogenic or tsunamigenic. The first indication of slip at the toe took place roughly 1.5 days after the earthquake, then was followed by a series of slow slip events (Figure 12) and quasi-continuous deformation until the end of the current recording epoch 16 months later.

It is clear from all these records that signals associated with both distant and local slip can be resolved by properly located CORK observatories. It is unknown what styles of local deformation will occur offshore Cascadia (long-term results from Hole 1364A drilled and instrumented in 2010 are not yet available), but something as simple as pressure and temperature monitoring over decadal time frames will unquestionably be valuable. Other downhole observations (e.g., strain, tilt, and displacement) will be highly complementary, and observations made that do not require boreholes will expand the geographic scope of what is learned at the borehole sites themselves.

Borehole observatories can also contribute significantly to drilling in response to megathrust earthquakes. The Japan Trench Fast Drilling Project drilled through the plate boundary near the

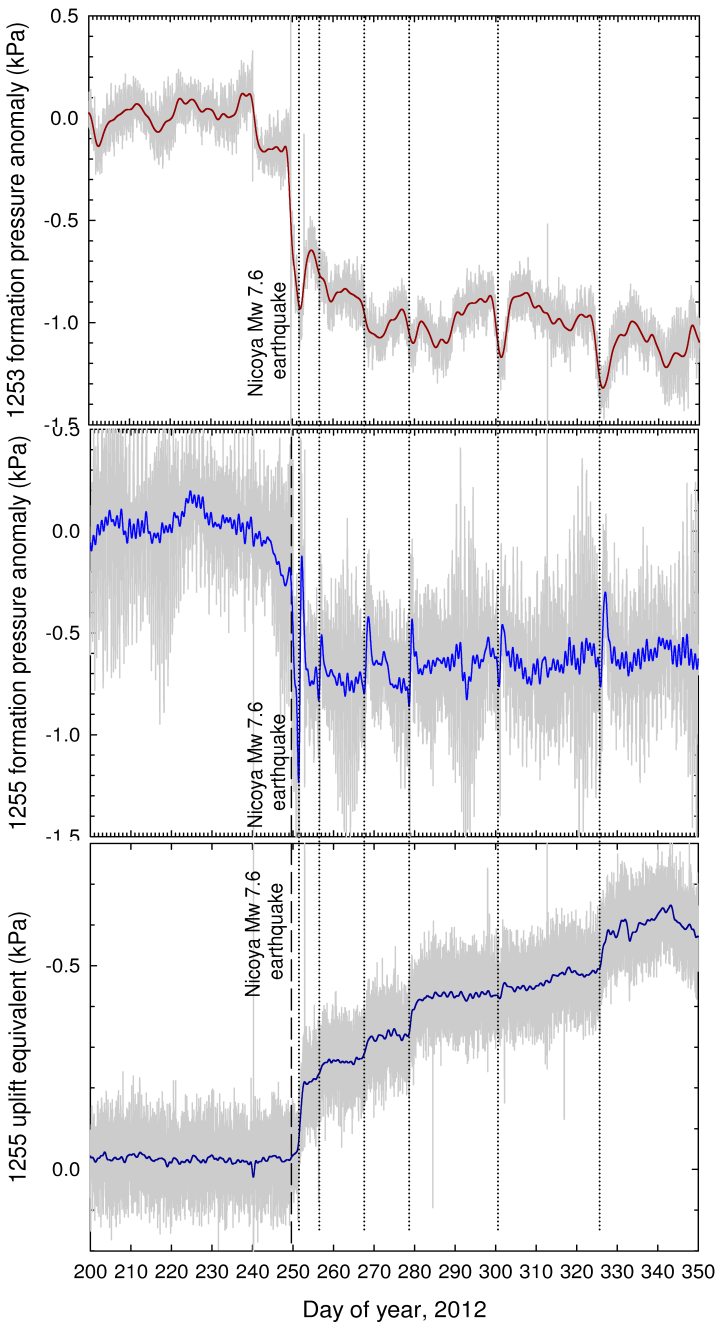

Figure 12. Formation and seafloor pressure records from CORKs at the toe of the Costa Rica subduction prism at the time of the 2012 Mw 7.6 earthquake beneath the coast of Nicoya Peninsula, Costa Rica. Following the co-seismic pressure drop indicating dilatation at both sites, a series of transients very similar to those seen in Figure 11 occurred, the first 1.5 days after the earthquake itself. At the time of each, a step-wise decrease in seafloor pressure at the prism site relative to the incoming plate site was observed, indicating uplift (adapted from Davis et al., 2015).

toe of the subduction zone 16 months after the Tohoku-Oki magnitude 9 earthquake (Chester et al., 2013) and installed a temperature monitoring string extending upwards from the plate interface (Fulton et al., 2013). The residual temperature anomalies near the plate interface (Figure 13) were used to estimate frictional heating during the earthquake and a low dynamic coefficient of friction of 0.08. The decay times of the temperature anomaly induced by drilling can also be used to infer vertical variations in permeability (Figure 13) and temperature anomalies following a local earthquake with a magnitude of 7.4, show that it changed fluid flow paths. Similar rapid response drilling would be invaluable in Cascadia when a large subduction zone earthquake occurs.

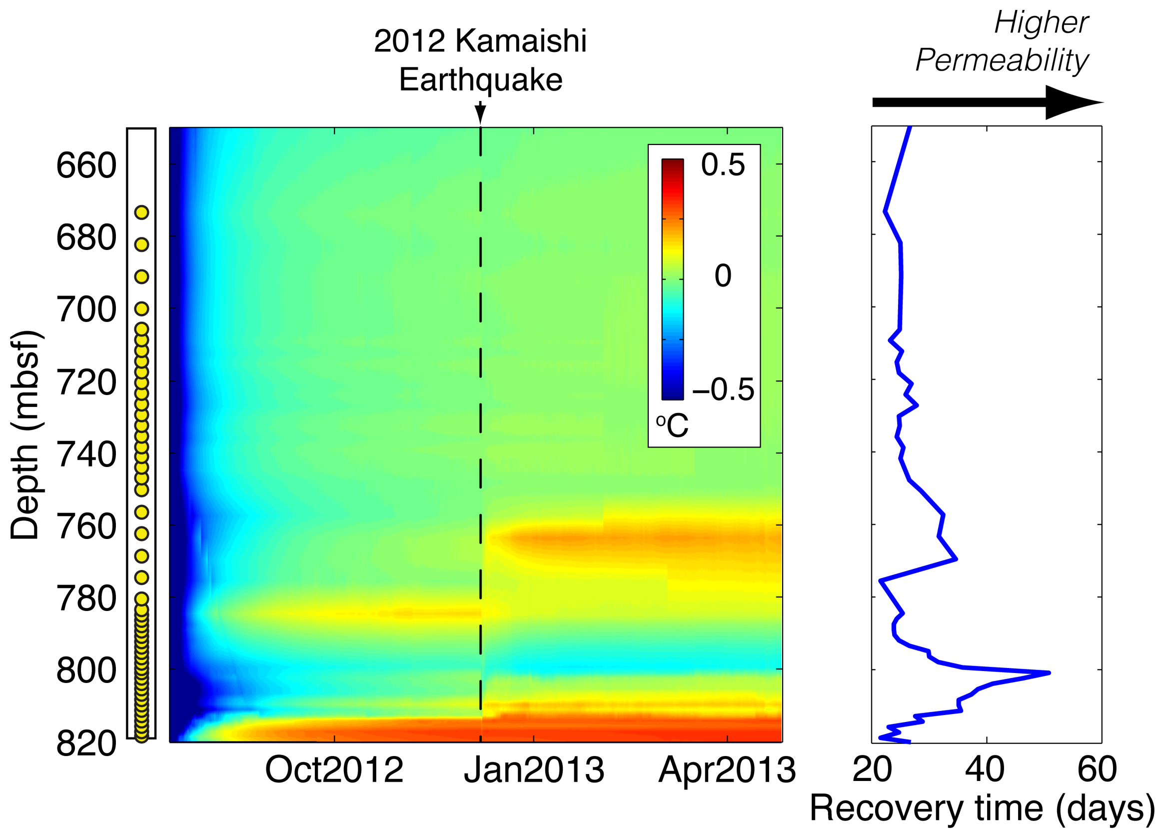

Figure 13. Results from the Japan Trench Fast Drilling Project that installed a temperature observatory on the outermost subduction fault (IODP Japan Trench Site C0019) 16 months after the Tohoku-Oki magnitude 9.0 earthquake (Fulton et al., 2013) (Left) Residual temperatures as a function of depth below the seafloor and time measured by a vertical array of temperature sensors (yellow dots on the left). The plate interface is at ~818 m depth. (right) The recovery time for temperatures following drilling as a function of depth; larger times are indicative of higher permeability.

5. Why drill in Cascadia?

Studies of the Cascadia subduction megathrust can contribute to understanding fundamental geodynamic processes in convergent margins as well as to mitigating seismic/tsunami risk along the west coast of North America. To understand how to apply knowledge learned from other subduction zones to the specific setting of Cascadia and how studies of Cascadia can be optimally configured to add to the scientific understanding of subduction zones, it is important to recognize Cascadia's special or unique characteristics. Appreciating these characteristics highlights why Cascadia serves as an end-member representative for some margins and a contrasting example for others. It also helps us identify priorities in designing future field experiments to test competing scientific hypotheses. The following six characteristics are particularly relevant to the study of the Cascadia megathrust through scientific drilling and monitoring.

1. Cascadia has a very warm megathrust because of the very young age of the subducting plate, a thick insulating sediment cover on the incoming plate, and a moderate subduction rate. For this reason, the megathrust seismogenic zone is considered to be located at shallower depths than in most other subduction zones (Hyndman and Wang, 1995). Its updip end could be within reach of modern drilling technology.

2. Cascadia is currently at a very late stage of interseismic deformation. With more than three centuries since the last great earthquake, Cascadia's forearc crust exhibits wholesale landward motion and a low rate of elastic margin-normal shortening, in contrast to other margins that have experienced great earthquakes more recently (Wang et al., 2012). Cascadia's position in the evolution of interseismic deformation is thus unique, and observations here will add valuable insight into subduction zone geodynamics.

3. The Cascadia megathrust is eerily quiet today in terms of producing small thrust earthquakes, which is different from almost any other subduction zone. The quietness indicates either complete locking of the megathrust or aseismic creep, with the latter being an intriguing scenario hardly seen elsewhere. A model with full locking extending from just offshore to toe of the prism along most of the subduction zone and a model of a mostly creeping megathrust with just local locking fits the observations equally well (e.g., Schmalzle et al., 2014) (Figure 6c-d) as do a variety models intermediate between these end members. Thus, these two scenarios cannot be distinguished by existing geodetic observations, all of which are land based, but they have drastically different hazard implications.

4. Cascadia has ample sediment that deeply buries the trench. The high supply of sediment also leads to a large accretionary prism of complex and often atypical structural characteristics that vary dramatically along strike. Any creeping motion of the megathrust that breaches the buried trench should perturb the sediment cover, giving rise to geodetic signals that can be captured by near-field geodetic monitoring. Because of the elevated temperature, the bottom section of the "trench" sediment is expected to have petrological and fluid pressure traits very different from, for example, the Japan Trench and Nankai Trough, affecting the frictional behavior of the Cascadia megathrust.

5. The incoming igneous crust at the Cascadia subduction zone is very smooth compared to many other subduction zones, with relatively low relief inherited from the Juan de Fuca Ridge spreading center, relatively few seamounts, and little outer rise faulting associated with bending of the down going plate. Low relief of subducting igneous crust is a globally general characteristic of subduction zones that are known to have produced giant ($M \geq 9$) earthquakes and is thought to promote long-range megathrust rupture along strike (Wang and Bilek, 2014; Scholl et al., 2015). However, buried heterogeneities on the megathrust may be present, as inferred from the patchiness of the slip distribution in the great Cascadia earthquake of AD 1700 interpreted on the basis of microfossil paleoseismic evidence (Wang et al., 2013), long-term segmentation derived from the turbidite studies (Goldfinger et al., 2012) and the presence of clusters of plate boundary seismicity off central Oregon (Tréhu et al., 2015) (Figure 6a-b). It is important to confirm that in this region, which extends from ~43-46°N, the plate boundary is slipping slowly during the late interseismic period, to determine whether such patches are persistent features controlled by local geology, and to evaluate whether they should slip less during the anticipated next great earthquake.

6. Cascadia is a global end member in the production of episodic tremor and slip (ETS) downdip of the seismogenic zone. The reasons for the extraordinary vigor of ETS here, and for along-strike variations in the periodicity of ETS, are not understood. It is logical to ask whether similar creep transients, with or without accompanying tremor, also occur near the "trench", presumably updip of the locked seismogenic zone (e.g., Davis et al., 2015). Some rate-state friction models predict no creep updip of a spatially continuous locked zone (e.g., Liu, 2013), but some predict creep including episodes of accelerated creep (e.g., Shimamoto and Noda, 2014). Episodic slip activity downdip and updip of the seismogenic zone may also vary through a megathrust earthquake cycle. Borehole geodetic monitoring will help to test these competing models.

5.1. Infrastructural Synergies with Drilling

Cabled Seafloor Observatories

Both the Canadians and the US have developed cabled observatories that extend across the subduction zone and Juan de Fuca plate to the Juan de Fuca Ridge. The Ocean Networks Canada NEPTUNE cabled observatory includes two sites on the margin, Barkley Canyon at 400-985 m depth and Clayoquot Slope (formerly named ODP 889) at 1200 m depth while NSFs Ocean Observatories Initiative cabled array and cabled portions of the Endurance array occupies a profile off central Oregon with nodes at the slope base, southern hydrate ridge and in 600 m and 80 m of water. Cabled observatories can support monitoring objectives that require real time data, enable malfunctioning instruments to be identified and fixed as soon as possible, and allow experiments in which scientists can remotely control the response to events. Equally importantly they facilitate the operation of instruments whose power and bandwidth requirements exceed those that can be supported by standalone packages. These capabilities are useful for instrumented boreholes.

Since the installation of the NEPTUNE Canada cabled observatory in 2009, the mid-plate CORK in ODP Hole 1026 has been connected to the cabled observatory, enabling pressure sampling rates much higher than typical for standalone CORKs. In 2016, downhole instruments for monitoring tilt, seismic motions and temperature will be installed inside the cased IODP hole 1364A at the Clayoquot Slope site and these sensors along with the pressure monitoring already underway will be connected to cabled observatory. The power and timing requirements of this sensor suite would be difficult to sustain in an autonomous configuration and real time data will facilitate the use of the seismic data by the Canadian Seismic Network and will enable scientists to observe transient geodetic signals as they occur. Similar installations could potentially be installed at drill holes located near other nodes on the US and Canadian cabled observatories.

Earthquake Early Warning

The USGS along with a coalition of university partners is in the early stages of developing an earthquake early warning system for the US west coast. The ShakeAlert system will integrate real-time seismic and geodetic observations to provide the public with seconds to minutes of warning of shaking at sites that are sufficiently far from an earthquake's epicenter. At present only a very limited amount of offshore seismic and bottom pressure data is potentially available to this system from the offshore NEPTUNE Canada and OOI cabled array observatories.

Expanded offshore data could improve warning times for megathrust earthquakes. Although the highest priority for new offshore infrastructure for early warning would be an expansion of the footprint of cabled seafloor sensors, there are synergies with drilling. For example, borehole sensors could enhance the sensitivity of offshore geodetic observations both for use in early warning and complementary scientific studies to identify signals that are potentially precursory to large earthquakes. Expanded cabled observatories would provide more options to co-site instrumented boreholes.

6. Cascadia Drilling Objectives

Seafloor drilling in Cascadia is important for addressing a variety of scientific questions related to the dynamics of the subduction zone, the characteristics of the incoming plate, and the structure and evolution of the accretionary prism. In the following sections, each of these topics is addressed in turn.

6.1. Seismologic and geodynamic monitoring

There is a broad knowledge gap between the kinematic rigid motion of tectonic plates and the dynamic nature of episodic slip and earthquakes along plate boundaries. At some scale, plates are not rigid; distributed elastic strain must be accumulated and released before, during, and after slip events, with spatial and temporal scales of plate deformation set by the viscoelastic structure and properties of the lithosphere and asthenosphere involved. Conceptually, this is easy to describe, but observational constraints on just how plate boundary and plate interior motion and deformation are distributed are difficult to acquire in offshore regions. The importance of filling this gap in knowledge is unquestionably high for the simple reason that slip along convergent plate boundaries produces the world's largest earthquakes. The greatest recent advances have been made as a result of the increasing geographic coverage and local density of Global Positioning System (GPS) continuous monitoring sites and the expansion of the global and local low-frequency seismic networks. There are inherent inabilities of data from these sites - which are located almost exclusively on land - to provide accurate constraints on the nature of interseismic strain accumulation or slip along subduction faults that lie almost entirely offshore. Notable exceptions include Sumatra, where islands allow terrestrial observations much further offshore than elsewhere, and Japan, where offshore networks of seismic and GPS instruments have been installed. Their value is highlighted particularly well in the case of the Japan Trench, where seafloor pressure and GPS instruments added invaluable constraints on the distribution and magnitude of slip at the time of the 2011 Tohoku earthquake, and in the case of the Nankai Trough, where an expanding network of seafloor and borehole seismic, pressure, and strain sensors is beginning to document interseismic deformation events. Early observations from sites like these provide excellent guidelines for designing a monitoring capability at Cascadia that will provide a "baseline" of observations relatively late in the interseismic earthquake cycle, a means to observe episodic or steady interseismic strain, and a capability to observe the details of seismogenesis and tsunamigenesis should a large earthquake occur.

Scientific questions that are currently without answers at Cascadia include:

1. *Is the seismogenic zone currently fully locked? That is, is the entirety of inter-plate convergence accumulating elastic stress in advance of a future earthquake?*

2. *Over what width across the subduction zone does strain accumulation take place?* Episodic slip with associated tremor is known to occur down-dip of the seismogenic part of the fault, and the Juan de Fuca plate appears to retain most of its velocity close to its first point of contact with the subduction plate boundary. In some locations where down-dip episodic slip occurs, slip is also observed along the outermost part of the subduction thrust. At Costa Rica, this slip occurs in approximate synchrony with down-dip episodic slip (see section 3). Does any of the slip associated with down-dip episodic slip at Cascadia propagate through the seismogenic zone, or is it arrested at a fully locked fault?

3. *What is the state of stress in the incoming plate and over what breadth across the incoming Juan de Fuca plate do stress and strain accumulate through an earthquake cycle?* Borehole pressure observations in the plate interior have revealed rapid reactions to seismogenic slip on the Blanco transform, Nootka transform, and Juan de Fuca Ridge plate boundaries up to 500 km away. Secular strain accumulation cannot be documented because of the relatively short hydrologic drainage time constant that is characteristic of the existing sites, but long-term strain could be observed with hole completions that address this particular question. Is it possible that the distance over which stress is transmitted over the period of an earthquake cycle is sufficiently great to influence the full dimension of the plate? Or does elastic deformation and accumulation of stress occur only in the immediate vicinity of the locked subduction plate boundary?

4. *What are the mechanical properties of the outer Cascadia accretionary prism?* With appropriate observations, might it be possible to estimate where and how rapidly fault rupture will occur during a subduction earthquake, thus providing insight into the seismic and tsunami hazards faced at Cascadia? Surprises at Tohoku may reduce our hopes of trustworthy answers, yet addressing this question is certainly justified.

5. *Are there any indicators of deformation of which we are currently unaware?* With lower detection thresholds provided by sensors located directly above the seismogenic zone and the outermost prism, and by improved sensor technology, will activity analogous to the very-low-frequency earthquakes and associated slip at the Nankai prism be discovered? And with long-term observations, might temporal variations be seen in activity, or possibly in the mechanical properties inferred from offshore observatory data?

6. *Do deeply sourced fluids with diagnostic compositions travel up faults and reach to levels that can be accessed, either at the seafloor or in boreholes, and can these lead to insights into steady or episodic deformation?* Observations at Costa Rica demonstrate that strain-induced signals can be observed.

Addressing these questions will require observations made over both a broad scale and yet with some detail. Boreholes and certain other elements of a geodynamics observatory array will be costly and time consuming to establish, and thus can only address broad-scale issues. Objectives requiring more detailed observations, for example to provide accurate determination of small earthquake locations, will need to be approached with coordinated seafloor observations. The DONET observatory provides a useful working model as a starting point for discussion, and of course the observations made to date in CORK monitoring observatories provide valuable guidelines for the placement, depth, and design of boreholes.

Some obvious observations that can address the questions articulated above include:

1. Low-frequency ground motion, including tilt, velocity, and acceleration (from which displacements can be determined). Such observations can be made at the seafloor and in boreholes. The latter provide a quieter environment somewhat buffered from oceanographic noise, but seafloor installations will be necessary to provide the detail of coverage necessary to observe lateral gradients (e.g., to discriminate local and regional signals), and to locate small events.

2. Pressure, measured at the seafloor and in boreholes, the former to augment observations of seismic ground motion and to identify geodetic signals such as those observed at Costa Rica (see section 3), the latter to observe secular or transient volumetric strain.

3. Position, measured with seafloor instruments coupled acoustically to the sea-surface and to the GPS reference frame. This would address questions about the distribution of current interplate coupling, and prepare for the observation of large displacements associated with a large earthquake.

4. Fluid samplers, both at the seafloor at locations of seeps above deep-seated faults, and in boreholes.

5. New sensors being under development include self-calibrating pressure and gravity sensors and optical fibers for horizontal strain.

Workshop attendees agreed that any plan for siting observatory instruments needs to remain flexible as new information from any studies becomes available (e.g., following the analysis of data from the Cascadia Initiative OBS deployments, the EM transect, SeaJade OBS deployments, and from OOI and NEPTUNE Canada instruments), and that future plans should include expansion of seismic and geodynamic monitoring along the length of the subduction zone. At the same time, they agreed that an experiment should begin with a realistic distribution of drilling sites that includes three transects, two devoted to the establishment of long-term monitoring observatories, and positioned along existing observatory cable routes to facilitate long-term borehole and seafloor observations. The three transects are discussed in section 7; here we will summarize the general strategy for hole siting at the two transects devoted to observatory monitoring. Each of the holes would be completed in a manner similar to the original ACORK configuration used at Nankai Trough (Holes 808I and 1173B) and Cascadia (Hole U1364A), with multiple monitoring screens mounted outside solid casing for pressure monitoring and in some instances for through-casing fluid sampling. Holes would be sealed at the bottom of the casing, leaving the holes open for ground-motion, strain, and temperature sensors, with coupling provided by clamps or backfill.

An ideal distribution of observatory boreholes would include the following. Each of the sites would be surrounded on some appropriate scale (geophysically suitable, yet technically feasible, e.g., up to 10 km) by autonomous or cabled seafloor instruments.

1. A mid-plate site, several tens of km seaward of the accretionary prism toe, to document strain associated with all of the incoming plate's boundaries, and to provide a balanced view of events within and beneath the subduction prism from the seaward side.

2. A hole pair on either side of the frontal prism thrust structure to document any deformation activity there, analogous to hole pairs at Costa Rica and Nankai which have been extremely useful in revealing episodic deformation and discriminating local slip and far-field elastic strain (see section 3). Further considerations may lead to the conclusion that the "mid-plate" site and the seaward hole of this pair can be one and the same.

3. One or more holes further landward to document the changing mechanical properties of the prism, and possible interseismic deformation above or along the seismogenic zone itself.

Specific instances are considered below for a tentative working plan. Actual locations are bound to change as new site survey observations are made and as more detailed discussions take place. We note, however, that it will be important to have this planning mature quickly so that preparations can be done in parallel to pave the way to cable infrastructure access.

6.2. The Incoming Plate

Changes in physical and mineralogical properties of the subducting sediments and igneous crust with depth in the subduction zone are intimately linked to fluid production, pore fluid pressure, fault mechanics, and fluid flow. The return flow of fluids transfers heat, solutes, and gases from deep within the forearc to the ocean contributing hydrocarbons to the gas hydrate reservoir and metabolites to the deep biosphere. It is essential to document the in situ physical conditions, material properties, and composition of the subduction inputs, as well as the frontal thrust system. Thorough characterization of the incoming stratigraphy and upper oceanic basement rocks that comprise the protolith provides the initial conditions of the fault rocks at depth, essential for experiments and models of the evolution of the forearc and plate boundary.

The incoming plate at Cascadia is very warm because of its young age, thick sediment cover that inhibits the advective transfer of heat between the crust and ocean, and moderate convergence rate. As such, it is rather unique compared to other margins, but also provides the opportunity to sample changes in material and chemical properties that typically occur much deeper and out of the reach of riserless drilling at other subduction zones. For example, the temperature at the sediment-basement interface just seaward of the deformation front in central Washington is ~225°C, and smectite dehydration is well underway in the incoming crust prior to subduction. Direct sampling of the incoming plate and the frontal thrust system would further our understanding of the impact of higher-temperature diagenetic reactions on material properties and the evolution of fluids not just at Cascadia but other subduction zones as well.

Sediment supply is unusually large throughout the Cascadia basin because of highly active submarine canyons and voluminous watersheds (e.g. Carson et al., 1986; Davis and Hyndman, 1989). This delivery network drives total sediment thickness to a maximum of >3000 m (Underwood, 2007). The basin floor contains several individual channel-levee complexes and two submarine fans, the Nitinat Fan offshore WA and the Astoria Fan largely offshore OR. Offshore Oregon, The basal decollement of the accretionary prism propagates into the abyssal-plain facies, well beneath the lowermost submarine fan deposits (e.g. Goldfinger, 1996). Sediment delivery and composition vary along strike of the Cascadia subduction zone and through time – incoming sediment thicknesses roughly doubled from 1.6 Ma to present. There appears to be a correlation between percent smectite in the incoming sediments and segmentation of thrust vergence. In general, the landward verging segment appears to have higher smectite concentrations and the seaward verging segments have higher proportions of chlorite and illite (Underwood, 2002). The combination of high trench sedimentation rates and smectite dehydration seaward of the deformation front suggest higher fluid production and pore fluid pressures at the frontal thrust compared to other margins. These along-strike variations in sedimentation rate and composition likely play an important role in segmentation of thrust vergence along the margin.

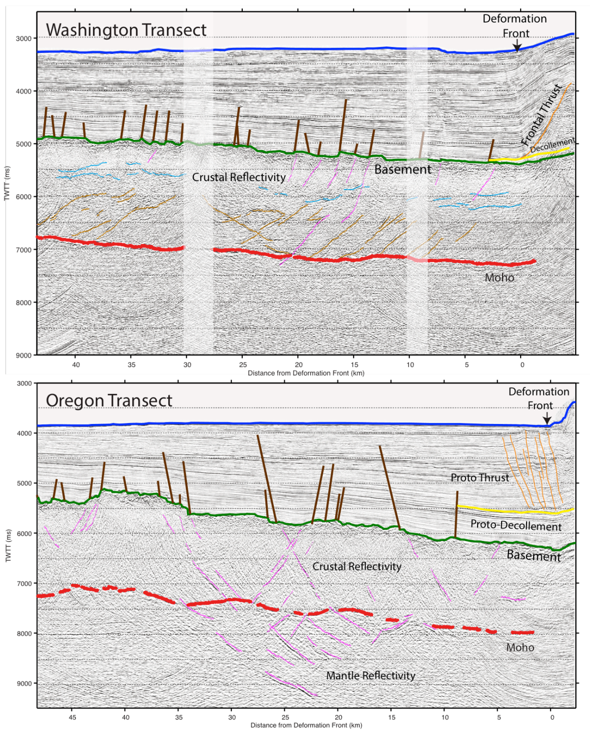

Figure 14 MCS reflection images from the Ridge-to-Trench study showing faults attributed to subduction bending within the sediments, crust and extending into the upper mantle near the deformation front. (Reproduced from Han et al., 2016).

Faulting within the outer trench rise due to plate bending into the subduction zone is believed to play an important role in the hydration of the incoming plate and is well documented at many subduction zones globally. At Cascadia, seismic reflection transects from the Ridge-to-Trench study reveal faults attributed to outer rise bending within ~ 70 km of the deformation front (Han et al, in revision, Figure 14). The extent of subduction bend faulting varies along the margin and is greater offshore central Oregon than Washington with crustal scale faults extending 6-10 km into the upper mantle and offsetting the sediment section to near the seafloor along the Oregon transect but limited to the upper-mid crust and deep sediments along the Washington transect (Figure 14). These differences in the extent of outer rise faulting are likely associated with differences in the hydration state of the crust and may play a role in pore fluid pressures within the sediment section and properties of the decollement, that in turn contribute to regional variations in subduction zone properties.

In summary, the documentation of the incoming plate mineral assemblages, hydration state, lithology and composition-dependent frictional properties should be an integral part of all three drilling transects at the Cascadia subduction zone. In addition to questions related to the state of stress and width of stress and strain accumulation in the incoming plate discussed above (see question 4 in section 6.1), important scientific questions related to the incoming plate that can be addressed through drilling include:

1. *How does the lithosphere evolve from birth at the mid-ocean ridge to the trench?* Hydrous minerals in the subducting sediments and alteration products in the basement contribute to fluid production in the forearc and volatile fluxes beneath the volcanic arc. ODP/IODP

Expeditions 168, 301, and 327 have cored the sediments and upper basement at 11 sites spanning crustal ages of 0.86-3.59 Ma offshore Washington. Long-term subseafloor observatories have been installed at several of these sites. The exceptional combined dataset provides a comprehensive characterization of the hydrologic architecture, hydration state, physical conditions, material properties, and composition of the basal sediments and upper basement in this region. ODP Site 888 and Site 174 recovered the upper sediment section to the Pliocene seaward of the deformation front offshore northern Washington and central Oregon, respectively. However, there is little direct information on the composition and physical state of the incoming crust between the Juan de Fuca ridge flank sites and Sites 888/174. Thus, it is critical to characterize how crustal alteration and hydration state changes from the mid-ocean ridge to the trench and how it varies along strike. The thermal state of the subducting lithosphere is a critical parameter required for models of subduction zone geodynamics and fluid production. Variations in fluid flow in the incoming igneous crust along strike would impact the shallow thermal structure of the subducting plate, as well as the physical and chemical properties of the subduction interface. Likewise, continued fluid circulation in the upper crust during subduction can transport heat and solutes from deeper within the subduction zone warming the incoming section near the trench. Accurate characterization of the thermal state along strike requires strong constraints on the recent sedimentation history near the deformation front, thus sedimentation rate histories at all input sites will be important.

2. *Are there observable changes in sedimentology, crustal alteration, structure, fluid-rock reactions, and fluid composition along strike on the incoming plate that are contributing to segmentation along the subduction zone? What is the nature of the deep high velocity sediments on the incoming plate in the southern and northern segments?* Differences in sediment velocity structure in these regions could reflect sediment mineralogy and cementation, differences in thermal state and/or stress state in the accretionary wedge near the deformation front.

3. *What is the extent of mineral dehydration in the incoming plate, and how does dehydration-related fluid production evolve in the forearc?* Clay mineral assemblages, in particular, are important for fluid production, and their contributions can be modeled down the trajectory of subduction if the initial composition and thermal conditions are well-constrained. Hydrous phases, bulk rock composition, and the thermal state in the incoming section and frontal thrust need to be thoroughly characterized.

Some Observations that can address the questions above:

1. Standard measurement program through logging while drilling and conventional coring. Coring of a representative section of the upper, altered basaltic basement at each transect. Penetration of at least the upper 100 m of basement is desired.

2. Detailed sedimentology and mineralogy of the sediment section and upper basaltic basement to characterize hydration state, composition-dependent frictional properties, and the structural characteristics and microfabric of the incoming sedimentary section, all of which exert a strong influence on fault zone development.

3. Porosity, permeability, heat flow, and pore pressure are critical to constrain the initial conditions for geodynamic and diagenetic models.

4. Biostratigraphy and magnetostratigraphy for sedimentation rates and age models. Constraints for the uppermost sediment section important for characterization of the thermal state of the incoming section.

5. Fluid and sediment organic and inorganic geochemistry will inform the nature and formation conditions of diagenetic phases, and how diagenetic reactions vary spatially and temporally.

6. Long-term monitoring of borehole pressure, temperature, flow rates, and fluid composition in sediments and upper basement to document secular and transient volumetric strain, the thermal state of the incoming crust, and the relationship between fluid flow and deformation.

The workshop attendees agreed that three transects are required to address questions related to variability in characteristics along strike and their role in governing segmentation at Cascadia. With incoming sediment thicknesses ranging from ~2.5 to 4 km, it will not be possible to continuously core the entire sediment section and upper basement at each transect. We have proposed a strategy where the upper basement and basal sediments will be cored at a site distant from the deformation front, and the upper sediment section will be cored at a site just seaward of the deformation front. This strategy would require two input sites per transect, but would provide a more complete reference sedimentary section and a representative section of the upper, altered basaltic basement for each transect.

Southern transect – latitude of Hydrate Ridge taking advantage of the OOI cabled observatory. The first input site would be located ~80 km from the deformation front, seaward of Site 174, coring ~1,000 m of sediment and ~100 m into the basement. The second site would be just outboard of the deformation front, and would recover a few hundred meters of sediment. These sites extend east and west of Site 174 filling in gaps in the lithostratigraphy and providing more recent sedimentation rate data needed for characterizing the thermal state of the incoming plate.

Central transect – The first site would expand upon the Leg 168 transect by coring east of Site 1027 penetrating ~1,000 m of sediment and the uppermost basement. The second site would be just outboard of the deformation front, south of Site 888, and would core the upper 800 m of the sediment section.

Northern transect – Transect at the Neptune Canada cabled observatory. Input site strategy would be similar to the central transect described above, possibly sharing the outboard reference site with the central transect.

Input site locations along each of the transects should consider proximity to existing seismic data, suitability for establishing future borehole observatories, and pre-existing data from ODP coring

6.3. Prism Structure and Characteristics of Fault Zone

A defining feature along virtually all of the Cascadia margin is a thick blanket of terrigenous clastic sediment on the incoming plate near the continental margin, much of which has been incorporated into a large accretionary wedge over the past 2 million years. Broadly speaking, the Cascadia forearc comprises two distinct phases of accretionary complex development with contrasting structural age, thickness and internal structure: an outer Plio-Pleistocene complex, and an older Miocene complex beneath the upper slope and shelf (e.g., MacKay, 1995; McNeill et al., 1997; Adam et al., 2004). Where these large thicknesses of sand-rich sediment reach the deformation front, especially in the Astoria and Nitinat Fan regions, the prism exhibits widely-spaced thick thrust sheets with relatively modest internal deformation, resulting in a wide accretionary prism with a very low surface taper overlying a decollement. Landward, beneath the shelf and upper slope, thick slope basin sediment accumulations overlie a zone of chaotic reflectivity known as the mélange and broken formation (MBF; McNeill et al., 1997), and interpreted as the Miocene and older accretionary prism that developed when incoming plate sediments were both thinner and less sandy than those of the outer prism.

Off Vancouver Island and central Oregon, the outer prism is dominated by seaward-vergent thrusting typical of accretionary wedges globally. However, off northern Oregon and Washington, the frontal region of the prism is dominated by landward-vergent thrusting above a decollement that lies at or near the basement-sediment interface (Silver, 1972; Seely, 1977; MacKay, 1995). The existence of this landward-vergent zone is spatially associated with the thickest sediment accumulation between the two major fans and has long been interpreted as evidence for extremely low basal frictional strength due to very high pore fluid pressure at the decollement (Tobin et al., 1993; MacKay et al., 1995; Saffer and Bekins, 2006; Fisher et al., 1999).

Because the locked zone of the plate interface lies largely or entirely offshore along all of the Cascadia margin, the potentially seismogenic and tsunamigenic shallow plate boundary fault system is the decollement and associated thrust splays and duplexes of the accretionary prism. The extremely low taper angle implies a weak plate boundary fault (e.g., Saffer and Bekins, 2006). A fundamental question is whether a weak fault zone hosted in prism sediments is more likely to inhibit or enhance earthquake rupture propagation to shallow levels. It has long been assumed that weak prism sediment faults would absorb rupture energy in megathrust events leading to an "up-dip limit" (e.g., Byrne et al., 1988; Hyndman, 1997); however the 2011 Tohoku magnitude 9 earthquake showed that quite the opposite may be true under some conditions (Ito et al., 2011), and laboratory experiments support unstable slip even in weak sediments under certain conditions (Faulkner et al., 2011). On the other hand, recent large earthquakes off central Chile (2010 Maule, 2014 Iquique and 2015 Illapel) show at most very limited evidence for slip to the trench, and the sequence of earthquakes in 2007 and 2010 near Padang, Indonesia, show that seismogenic slip to the trench can be delayed relative to slip on the plate boundary farther down-dip.

The most urgent questions from the perspective of hazard and tsunamigenesis are therefore:

1. How does the outer wedge respond during a megathrust earthquake?

2. Can along-strike variations in vergence, coupling, wedge morphology, wedge strength and mechanics, sediment inputs, and sediment load affect the likelihood of shallow slip or rupture arrest?

3. Where in the sediment section and/or basement does the decollement form?

4. What factors result in the development of splay faults?

Progress on understanding the response of the outer wedge hinges on documenting its composition, physical properties, fault structure, pore fluid pressure, and stress state, which requires drilling and sampling. In general, the decollement level is not reachable by drilling unless very deep (2.5 to 5 km) drilling is possible, which would require riser capability. However, thrust faults that splay from it can be accessed, the sediments and pore fluids within and adjacent to these faults can be sampled, and the in situ temperatures, pressures and pore water compositions can be monitored with observatory installations. In addition to addressing questions related directly to the tsunami potential of the Cascadia margin, drilling here would contribute to understanding more general questions about accretionary wedge mechanics and structure with answers that could be applied to a global understanding of this tectonic environment.

7. Details of proposed transects

A combination of well imaged geologic structure and proximity to cable connection points is offered at two locations along the Cascadia subduction zone, one off central Oregon, and one off south-central Vancouver Island, British Columbia. Extensive site-survey operations and drilling, targeting primarily shallow structure and gas hydrate accumulations, have been carried out at both (e.g. Westbrook et al., 1994; Tréhu et al., 2006; Riedel et al., 2006b; Davis et al., 2010). Through extensive discussions at the workshop, it was concluded that both are excellent candidates for deeper drilling and the establishment of borehole and seafloor observatories for geodynamic studies and clear contrasts in sedimentological and structural properties between the sites provide the opportunity to test hypotheses. The capability that cable connections can provide to support long-term monitoring with real-time data and limited ship and submersible operations for site servicing is of unquestionable valuable, and the structure at each site is ideal for establishing transects across the outer parts of the seismogenic zone.

A third transect across the Washington margin is also proposed. Here, the forearc wedge structure is very different from that off Vancouver Island and off central Oregon, as discussed in section 3.1 Because of the absence of any prior drilling along the entire landward-vergent segment of the Cascadia subduction zone and the consequent lack of timing constraints to reconstruct the timing of events leading to this structure, the primary drilling target here is to establish a transect of sampling sites to constrain the nature and age of sedimentary materials. How this portion of the forearc responds to slip on the plate boundary has critical implications for tsunamigenesis.

7.1. Vancouver Island

Characteristics of the northern site are illustrated in Figures 15 and 16, which show the local seafloor bathymetry and subseafloor structure at the deformation front in the vicinity of two of the NEPTUNE Canada nodes from which extension cables can be laid. While variable on a scale of ~10 km, the structure at the toe of the accretionary prism is locally simple along both profiles. The incoming igneous oceanic crust seaward of the prism toe is smooth and buried by roughly 2.5 km of turbidite and hemi-pelagic sediment, and anticlinal structures are developed over the seaward-most parts of underlying landward-dipping thrust faults.

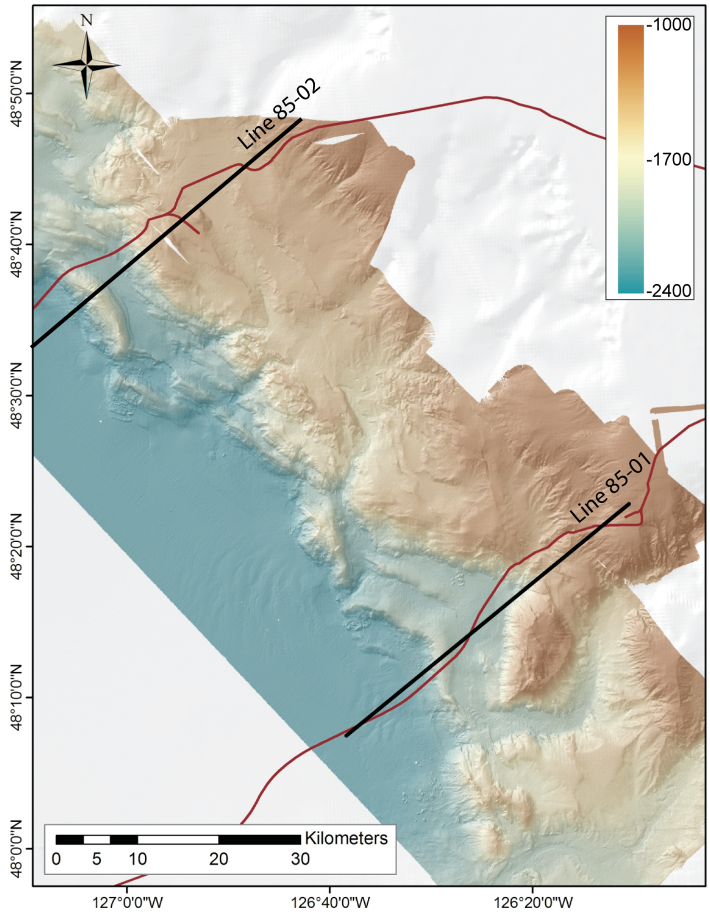

Figure 15. Bathymetric map of the continental margin off Vancouver Island showing the cable route for the NEPTUNE Canada cable observatory (red line) and the position of the two reflection profiles shown in Figure 16 (black lines).

At Line 85-01 (Figure 16 bottom) the crest of the frontal anticline is elevated 475 m above the adjacent abyssal seafloor, and roughly 1 km above the level of the underlying primary frontal thrust, which at this location can be traced landward through nearly the full thickness of sediment to the top of the igneous crust of the Juan de Fuca plate. Two protothrusts are present roughly 3 and 5 km seaward of the primary thrust, but these do not displace sediment layers in the upper few hundred meters and thus appear to be currently inactive.

Deformation at the frontal anticline at Line 85-02 (Figure 16, top) is more extreme and internal structure is less visible, although a landward-dipping thrust can be seen roughly 1.5 km below the crest of the frontal anticline which here rises 750 m above the adjacent seafloor. Only hints of deformation are seen seaward of the frontal structure along this profile. Hence, it appears that current deformation at the prism toe is concentrated at the frontal structures both here and along Line 85-01.

Landward of the frontal region, the prism structure becomes incoherent at both locations (particularly across Line 85-02). Loss of internal reflectors is nearly complete, presumably as a result of small-scale fault and fold deformation, and reflections from the oceanic crust are largely obscured, possibly the result of some combination of scattering by structural complexities and absorption by gas-bearing sediment. Diffuse reflected energy appears at a depth of roughly 4.5 s two-way-time beneath the outer prism along Line 85-02; sharper reflections reappear beneath the outer- to mid- continental shelf along both lines.

Extensive drilling operations have been carried out previously in this region. In 1993 (ODP Leg 146), efforts focused on characterizing the composition, structure, physical properties, and thermal state of the incoming sediment section (Site 888 along Line 85-02, cored and logged to roughly 570 mbsf), and the outer accretionary prism, including the gas hydrates accumulated there (Sites 889 and 890, near Line 85-02) (Westbrook et al., 1994). In 2005, IODP Expedition 311 focused primarily on the distribution and characteristics of gas hydrates with a systematic transect of drilling sites also along line 85-02 (Riedel et al., 2006a). In 2010, Expedition 328 provided an opportunity to install a multi-level ACORK at a location structurally equivalent to Site 889 (Davis et al., 2010). Pressure monitoring has been underway since the time of drilling (Davis et al., 2013b), and downhole instruments for monitoring tilt, seismic motion, and temperature are to be installed inside the cased hole (sealed near the bottom at roughly 300 m) in 2016 by J. McGuire, J. Collins, and K. Becker.

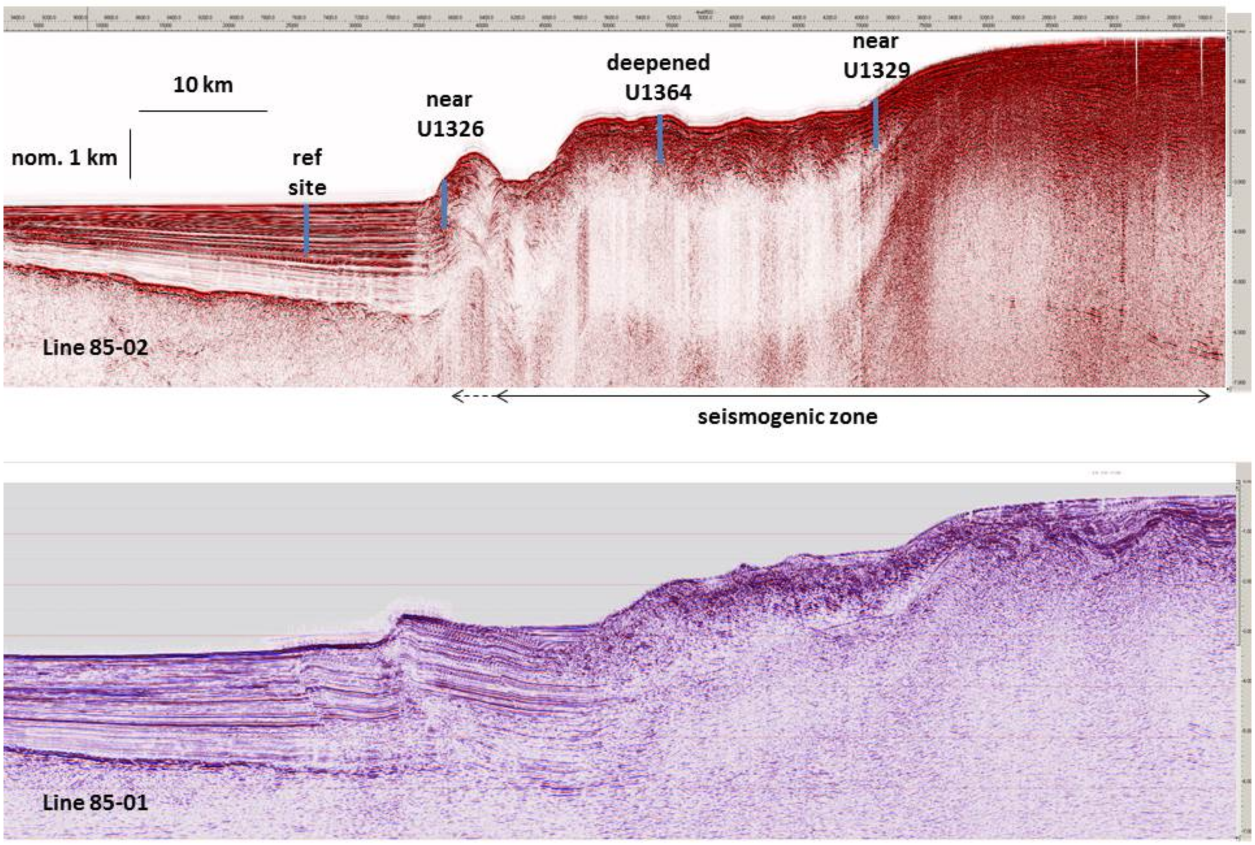

Figure 16. Reflection profiles (top) 85-02 and (bottom) 85-01 across the deformation front off Vancouver Island with the former showing potential drilling sites.

Information gained from these drilling, coring, logging, and instrumentation efforts have provided an excellent foundation for further work that will expand the depth of sampling, and the breadth of representative coverage for observatory experiments. While no specific sites were discussed at any locations along the Cascadia subduction zone at the workshop, it was generally agreed that a compromise was needed between depth of penetration and the total number of instrumented holes. Previous observations show that a minimum depth of roughly 600-800 m of penetration is required for borehole-hosted observations to be sensitive to strain. At the same time, it is also necessary to establish transects, including a reference site seaward of the subduction prism toe, and at least two sites in the prism itself. Tentative sites along line 85-02 are shown in Figure 16 top, for the purpose of discussion. Such a transect would allow the current thermal and pressure state of the accretionary prism to be documented, along with secular strain accumulation and short-term transient changes in state if interseismic deformation were to occur at Cascadia, as has been observed at Nankai and Costa Rica. The holes target the incoming plate, the seaward-most frontal thrust and its hanging-wall anticline, and the mid- to inner accretionary prism as far landward as the location of a possible fault separating the recently accreted section from older rocks of the inner prism. The inner two holes are almost certainly over where the plate-bounding fault is seismogenic. Whether the outermost part of the fault is seismogenic or tsunamigenic is an important question for assessing hazards, and thus is a high priority for the observatory transect, as is the reference site. The frontal fault/anticline site also provides an opportunity for sampling deeply sourced fluids transported up the thrust fault from a level much deeper in the prism than can be practically penetrated by drilling. The middle site is coincident with Hole 1364A, where the ACORK is currently in operation. This hole could be reoccupied for deeper penetration and observations, which would save considerable time and possibly allow the four sites to be completed in a single drilling expedition.

7.2. Central Oregon (Hydrate Ridge)

The central Oregon margin shows considerable along-strike variation in seafloor morphology and structure. Figure 17a shows the bathymetry and the distribution of gas hydrate as inferred from the presence of a BSR in the grid of seismic profiles that was acquired as a site survey for ODP Leg 146 (Zwart et al., 1996). Sites were drilled on the first ridge and near the crest of North Hydrate Ridge (NHR on Figure 17a) during ODP Leg 146 (Carson and Westbrook, 1995). In contrast to the Vancouver margin, where almost all of the sediment is being accreted, off central Oregon only the upper part of the sediment is currently being accreted at the deformation front, and the lower part of the incoming sediment is subducted, although it may be accreted to the upper plate through duplexing within a few 10s of km of the deformation front (Figure 17b). Variability in the amount of sediment underplating, as well as well as seamount subduction (Tréhu et al., 2012), may be responsible for the pronounced along-strike topographic variability along this segment of the margin as well active seismic activity (Tréhu et al., 2015).

ODP returned to this region for Leg 204 to understand how subsurface stratigraphy and structure controls fluid flow and the distribution of gas hydrate within an accretionary ridge. The black box around the South Hydrate Ridge summit (Figure 17a) outlines the footprint of a high-resolution 3D seismic site survey that was used to locate 9 drill sites that sampled a variety of structural and stratigraphic conduits interpreted from the seismic data (Tréhu et al., 2006). Figure 17c is a slice through that volume and shows the setting of 4 of the ODP Leg 204 sites, which were on an east-west transect across the northern flank of the southern summit. South Hydrate Ridge was chosen for Leg 204 because methane venting at the summit was vigorous and focused (e.g., Suess et al., 1999; Heeschen et al., 2003) and Leg 146 site survey data suggest that this was because the incoherent and presumably highly fractured and permeable accretionary complex (AC in Figure 17c) was covered by less permeable slope basin sediments (colored units in Figure 17c). Another distinctive feature of SOUTHERN HYDRATE RIDGE is the presence of a thick (~2 m) high porosity ash layer that may be the primary conduit focusing gas from the accretionary complex and channeling it to the summit. Leg 204 indicated that gas concentration within this layer may be high enough to generate pore space connectivity, resulting in gas pressures high enough to drive rapid vertical migration and expulsion of free gas (Tréhu et al., 2004; Liu and Flemings, 2007). The shape of this surface and its seismic reflectivity are shown in Figure 17d along with the location of Leg 204 drill sites. Migration of high amplitude patches on this surface between 2000 and a high-resolution 3D survey in 2008 suggests updip gas migration along this horizon of >100 m between 2000 and 2008 (Bangs et al., 2011).

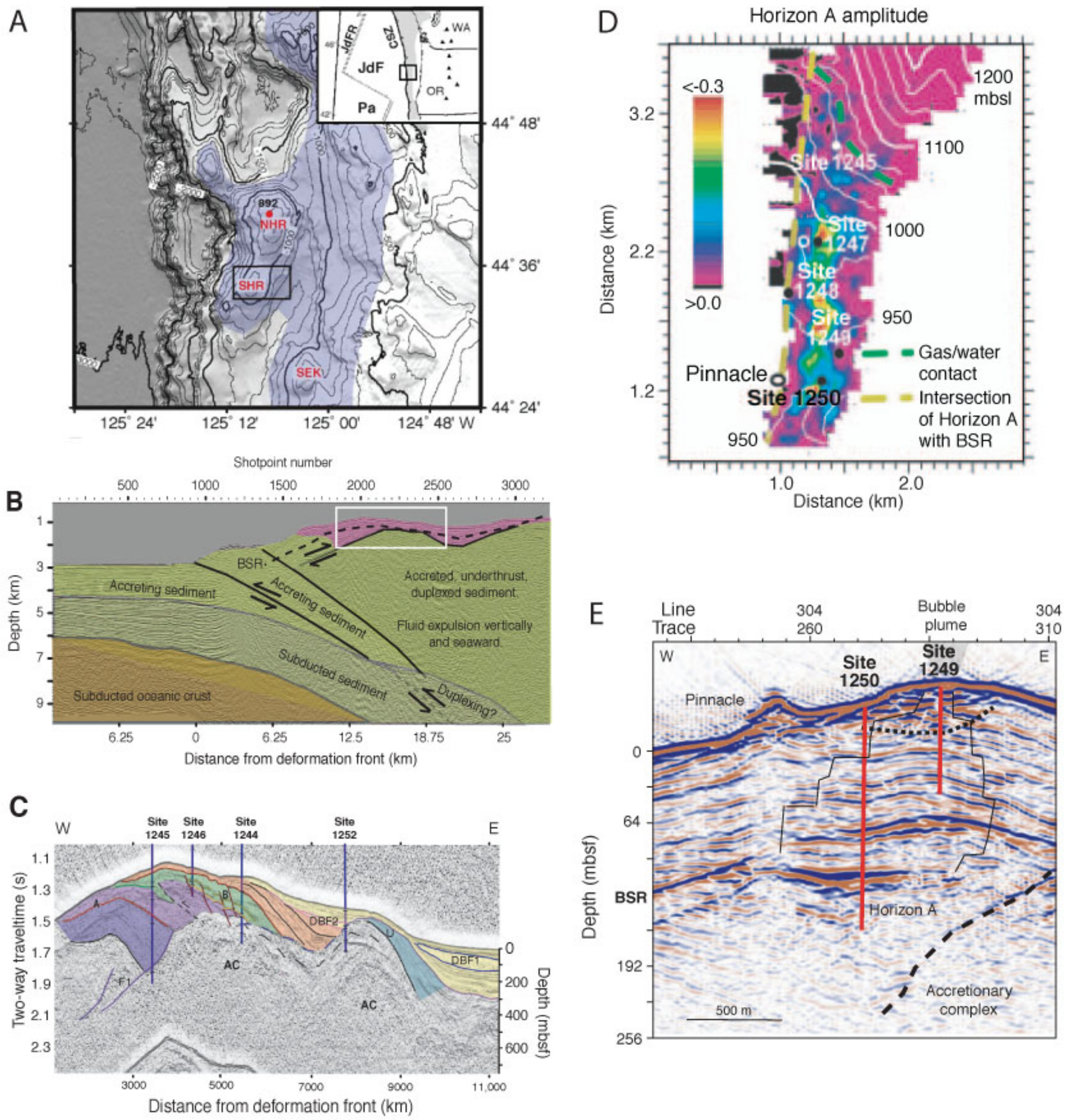

Figure 17. Overview of the structure of South Hydrate Ridge on the central Cascadia margin offshore Oregon as derived from a seismic site survey data and drilling during ODP Legs 146 and 204. A. Topographic map showing the regional extent of a clear BSR (violet shading). B. Interpreted cross-section across the deformation front. The white box shows the region shown in C. C. Interpreted cross section across the northern flank of South Hydrate Ridge. D. Map showing the depth beneath the sea surface and the amplitude of Horizon A (see C and E), a 2-3 m-thick, ash-rich stratigraphic horizon that is interpreted to be the primary conduit feed gas to the southern summit of Hydrate Ridge (adapted from Tréhu et al., 2006).

This relatively well-imaged and well-understood plumbing system feeding a massive gas hydrate deposit and vigorous methane vent (Figure 17e; Kannberg et al., 2013; unpublished data) provides a target for installation of an observatory to study the interaction between venting and tectonic activity. It is important to note that SOUTHERN HYDRATE RIDGE is also a node in the Regional Cabled Observatory of the Ocean Observing Initiative, providing the infrastructure needed to access data from a borehole observatory in real time as well as important complementary data (e.g. a small-aperture network of 3 short-period seismometers around a broadband seismometer).

A critical difference between the central Oregon segment of Cascadia and the margin to the north is the difference in interseismic locking behavior indicated by onshore GPS and leveling data and the level of earthquake activity in the nominally locked zone (Figure 6c-d). The data from the central Oregon segment can be fit equally well a very narrow, offshore locked zone or a distributed zone of intermediate locking, depending on how the inversion is constrained (Schmalzle et al., 2014). This is the most seismically active segment of the plate boundary between the Blanco and Nootka fracture zones, with seismicity characterized by clusters of earthquakes on or near the plate boundary (Tréhu et al., 2015). The combination of these characteristics suggests that the plate boundary here is creeping, thus providing a distinct contrast in geodynamic setting compared to the two other transects proposed during the workshop.

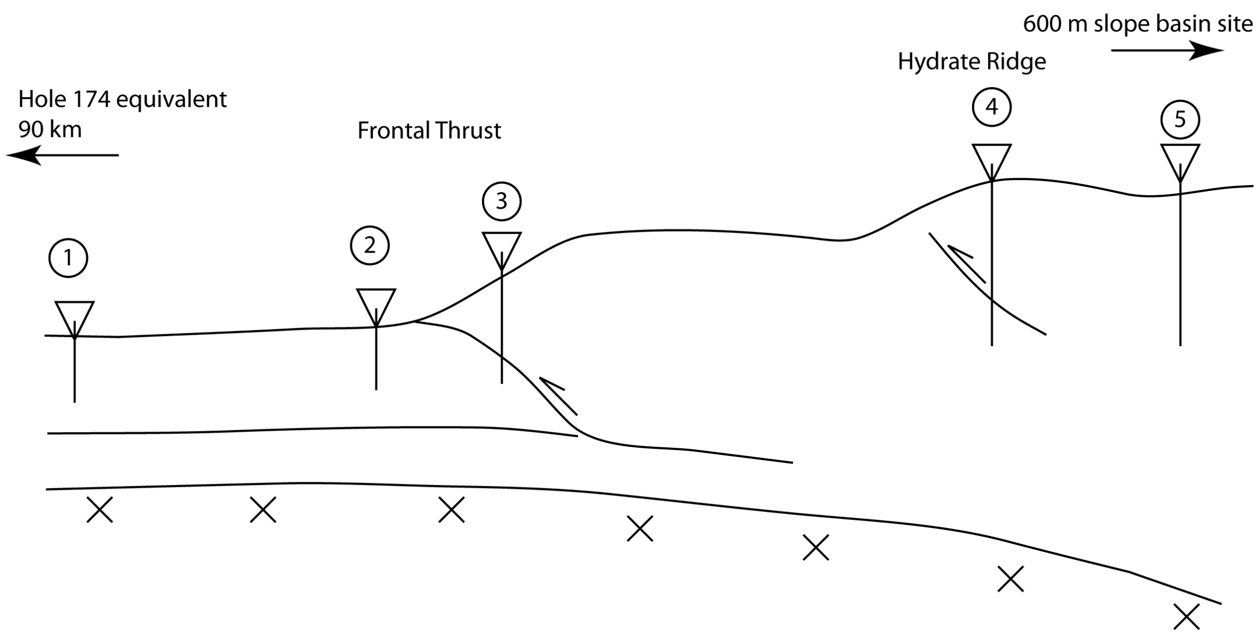

Figure 18. Cartoon illustrating the possible configuration of drill holes on a profile off central Oregon.

Figure 18 shows a schematic plan discussed at the workshop. This plan includes an input control site, a site that penetrates the frontal thrust which could be connected to an RCN node on the Juan de Fuca plate immediately seaward of the deformation front, and a primary observatory site on the summit of SOUTHERN HYDRATE RIDGE that would monitor the influence of earthquake activity and fluid flow associated with the massive gas hydrate formation and vigorous methane venting that has been documented here. A proposal for an observatory here was previously submitted, reviewed and highly ranked, but not scheduled. That proposal has been retracted and we expect that it will be superseded by a new proposal informed by recent experience and technological developments.

7.3. Washington

In contrast to the Hydrate Ridge and Vancouver transects, there has been no previous drilling of any part of the off-Washington region where the locked seismogenic zone is likely widest, most completely locked, and extends the furthest landward (Figure 6c-d) (Schmalzle et al., 2014). Furthermore, coverage with high-quality MCS reflection images is relatively sparse and widely spaced (Figure 7) (Fisher et al., 1999; Adam et al., 2004; Flueh et al., 1998; Holbrook et al., 2012).

The offshore portion of the margin here exhibits an unusual structure (Silver, 1972). The frontal deformation is dominated by a series of widely-spaced landward-vergent thrust sheets that have shortened the ~2.5 km thick incoming Cascadia Basin sediments, abutted by a little-deformed lower slope plateau (Figure 19) in which flat-lying, undisrupted sedimentary packages are imaged all the way to the down going plate reflector in some locations. Individual thrust sheets are variably buried with super-wedge sedimentation and piggyback basins. The overall geometry is an extremely low-taper-angle outer wedge (~1 degree of surface taper and < 3 degrees of overall taper to the base of the steeper continental slope) that appears to have rapidly developed in Plio-Pleistocene sediments; one objective of drilling is to constrain the timing of accretion and deformation via dating of sediments in piggyback basins and deformed thrust sheets.

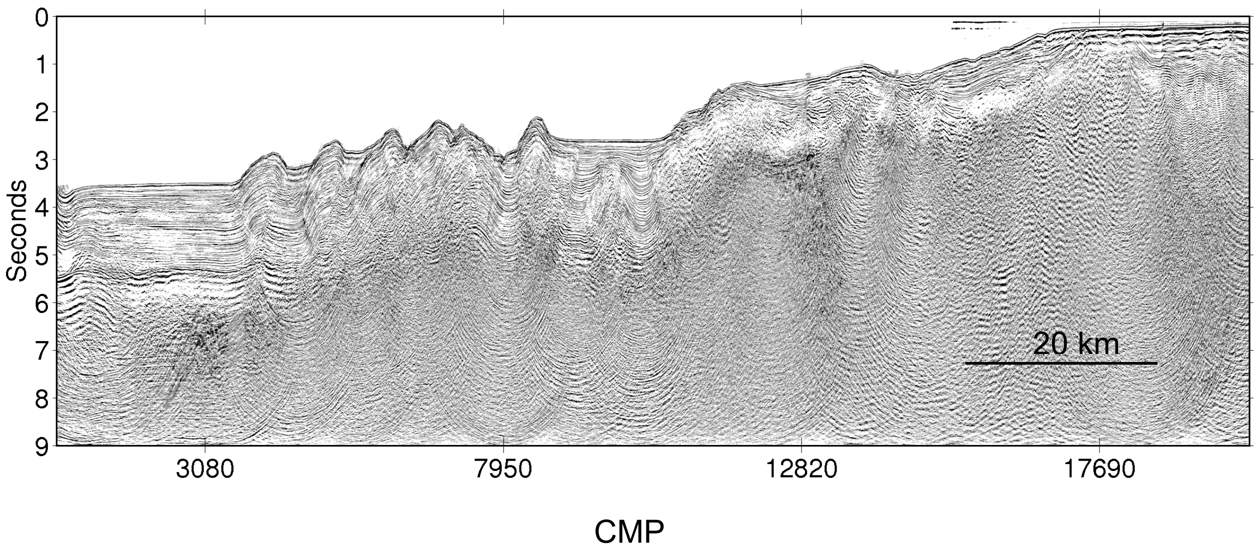

Figure 19. A seismic section across the Washington margin for Line 6 of the COAST experiment (Holbrook et al., 2012). This profile is migrated and plotted after applying a 6-70 Hz band-pass filter and 1-second automatic gain control. Figure downloaded from the Academic Seismic Portal (ASP) at UTIG (http://www-udc.ig.utexas.edu/sdc/).

Landward of this outer wedge is an inner zone that forms the shelf and steep slope, with an acoustically chaotic zone (MBF of McNeill et al., 1997; Fisher et al., 1999) interpreted as the older mélange wedge of Miocene age, overlain by thick younger slope basin sediments, in many places exhibiting normal faulting accommodating margin perpendicular extension (McNeill et al., 1997). The plate boundary underlying this inner wedge domain is poorly imaged at best in seismic reflection and refraction studies.

A narrow taper and the dominance of landward vergent thrusting point to a weak decollement forming the shallow plate boundary fault zone (e.g., Seely, 1977; MacKay et al., 1992; Fisher et al., 1999). Because the locked zone is largely offshore and underlies the slope and at least some portion of this outer wedge, a major open question is how the weak shallow wedge responds to megathrust slip propagating from depth. End-member possibilities include (a) the weak sediments act as slip absorbers, forming an up-dip boundary to seismogenic and tsunamigenic slip (e.g., Oleskevich et al., 1999) and tending to retard slip to the trench, or conversely (b) the weak shallow detachment slips easily in response to propagating earthquake rupture (e.g., Faulkner et al., 2011), promoting trenchward displacement and tsunami generation. A further complexity is understanding how the mid-slope terrace and landward vergent zone would accommodate megathrust displacement, and what component might be transferred into seafloor displacement.

Therefore, the key objectives for drilling the transect off Washington differ from areas to the north and south. A transect of holes to establish the relative timing of formation of individual thrust sheets and the age of sediments in piggyback basins is needed (Figure 20). This will shed light on the sequential vs. simultaneous propagation of the thrusts, and the timing of development of the individual slope basins relative to thrusting. This in turn will permit evaluation of the relative strength of the wedge materials vs. the plate boundary at the base. Physical properties data from cores and logs would be used in concert with this age and sediment accumulation rate information to understand state of stress and pore fluid pressure in the developing wedge. Such physical properties data (porosity, density, P-wave velocity, and their pressure dependence) can be used to calibrate MCS seismic interval velocities to extrapolate away from boreholes.

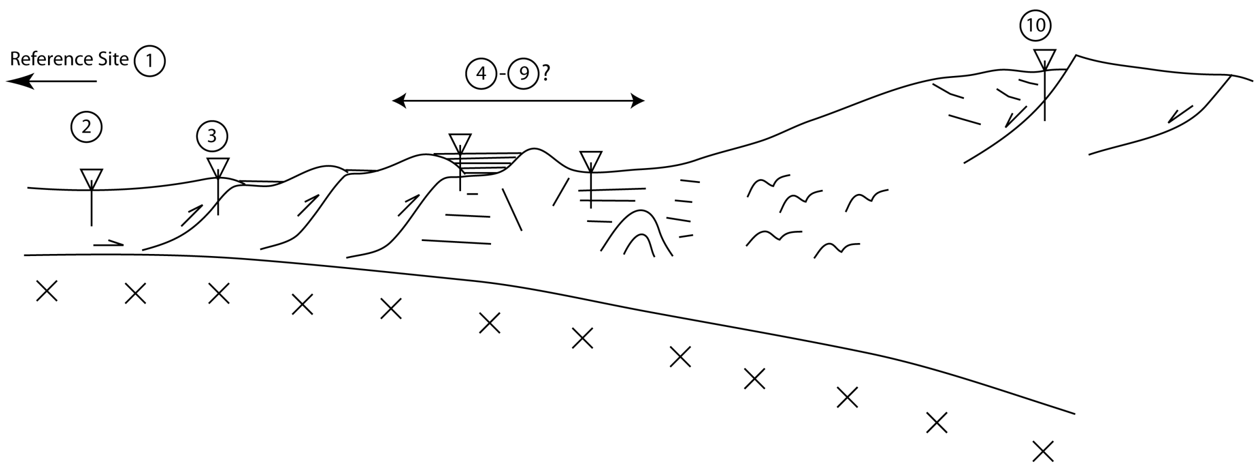

Figure 20. Cartoon illustrating the possible configuration of drill holes on a profile off Grays Harbor, Washington.

Sampling across the thrust faults that splay from the main plate boundary decollement (Figure 20) will allow for studies of evidence of conditions during fault slip, including possible past co-seismic frictional heating (e.g., Sakaguchi et al., 2011; Yamaguchi et al., 2011) shown by chemical alteration in faulted sediments and rocks. Documenting the mechanical state of the prism sediments, rocks, and fault zones of this outer prism will inform models for slip propagation into the shallow deformation front region, with implications for the tsunamigenic potential. For example, a weak and easily deformed wedge may distribute and dissipate focused plate boundary slip, lessening the severity of seafloor displacement, while a strong wedge over a weak plate boundary could promote transfer of focused displacement to the seafloor, promoting tsunami generation. Data on the mechanical properties of wedge materials would help discriminate between these alternatives.

Fluid samples, establishment of the geothermal gradients, and/or long-term temperature monitoring would permit evaluation for or against the hydrogeologic linkage of these faults to the deeper plate boundary, fueling fault zone stress state modeling. Seaward vergent thrusts may tap fluids from the plate boundary at depth; landward-vergent thrusts may tap only the deeper portions of the incoming section and upper basement, or may also be linked to the plate boundary at depth. Chemistry of the water and hydrocarbon fluids in the fault zone can distinguish among these alternatives.

One or more borehole observatories are clearly important for geodetic and seismologic observations in this portion of Cascadia as well. In comparison to sites to the north and the south, the hypothesized more complete and wider locking of the plate boundary here should be detected as a difference in microseismic activity, geodetic strain of a borehole, and slow slip or tremor if detected.

8. A Plan for Moving Forward

8.1. Where do we start?

The *JOIDES Resolution* will not be in the north Pacific until after 2020 (IODP call for proposals for April 1, 2006 - https://www.iodp.org/call-for-proposals). Nevertheless, given the long lead-time for drilling proposals, the need for down hole instrumentation, and the requirement for adequate studies to identify the optimal drilling sites, it is important to start planning now. The first step in a drilling proposal is the submittal of a Preliminary Proposal (Pre-proposal) and this should be done soon in order to get feedback from the Science Evaluation Panel.

While there have been extensive investments in onshore and offshore geophysical monitoring and imaging studies in Cascadia, there are some significant gaps offshore and which if filled would benefit planning for drilling. As noted in section 3.3, seafloor geodetic observations in Cascadia are almost entirely confined to land. Expanding and adding to the nascent efforts in offshore geodesy would lead to improved constraints on the width, characteristics and along-strike variations of the locked zone and thus help determine the optimal sites for boreholes instrumented to measure signals related to strain rates. As discussed in section 3.4, the existing seismic reflection images along most of the subduction zone were obtained in the 1980s and 1990s. Modern reflection images obtained across the margin with the *R/V Marcus Langseth* are limited to the COAST experiment off Grays Harbor Washington. Expanding such coverage to the other potential drilling transects would add important data for site selection.

8.2. Funding an ambitious program.

Funding drilling in Cascadia will be a challenge. As a result of a decadal review (National Research Council, 2015), the NSF Division of Ocean Sciences is working to reduce infrastructure costs so that science and infrastructure costs are appropriately balanced, while ensuring that the infrastructure is well aligned with science priorities. For IODP, the review suggested a 10% cut to IODP. This may decrease the number of legs that are fully funded by NSF and its international science partners but it also provides potential opportunities for projects that can obtain at least partial funding from other sources. The Cascadia subduction zone represents a significant natural hazard to the Pacific Northwest that spans an international boundary and which has recently received significant public attention (e.g., Schulz, 2015). Drilling has the potential to play an important role in better characterizing and mitigating this hazard. While there are no established sources of funding outside of NSF to support drilling, it seems worth pursuing opportunities for interagency and international collaborations that might provide new sources of funds.

In addition to a successful drilling proposal, significant funds must be obtained to acquire and maintain downhole instrumentation. Within NSF, potential sources of funds include the core Marine Geology and Geophysics program and the GeoPRISMS program. The Ocean Technology and Interdisciplinary Coordination Program and Major Research Instrumentation Program are potential sources of funds to support development and acquisition of instrumentation. The new cross-disciplinary solicitation in the Prediction of and Resilience against Extreme Events (PREEVENTS) may provide an additional source of funds.

It should also be noted that, because both the US and Canada have established expansive offshore cabled observatories that cross the Cascadia margin, future drilling efforts can leverage these established facilities (as some existing instrumented drill holes are already doing for the NEPTUNE Canada cabled observatory) to pursue downhole science objectives that specifically require real time monitoring and/or high power and bandwidth. Pursuing such objectives in locations without established observatories would be prohibitively expensive.

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Appendix B. Meeting Agenda

April 29 – Day 1
NHS Hall, Center for Urban Horticulture, University of Washington

8:00	Light continental breakfast available	
8:30	Welcome and meeting goals	Organizers
8:40	Cascadia geology, segmentation & recurrence intervals	Chris Goldfinger
9:10	Borehole hydrological observatories	Earl Davis
9:40	Seismic and geodetic monitoring off Japan	Eiichiro Araki
10:10	JFAST temperature observatory and results	Patrick Fulton
10:30	Break	
10:50	The Seismogenic zone in Costa Rica	Susan Schwartz
11:10	Subduction zone hydrogeology	Liz Screaton
11:30	Predicted geodetic signals in Cascadia	Kelin Wang
11:50	Recent geophysical experiments off Cascadia	Anne Tréhu
12:10	Seafloor geodesy in Cascadia	Dave Chadwell
12:30	Lunch	

1:20 Breakout: Scientific Questions
3 groups on same topics with participants pre-assigned to provide a breadth of expertise in each group
What are the scientific questions that can be addressed by a multi-component ocean drilling effort in Cascadia? Which are most important? How might drilling and post-drilling observations be complemented by non-drilling (seafloor and land-based) observations?

Group A (Red): Barbara Bekins and Susan Bilek
Group B (Yellow): Paul Johnson and Rachel Lauer
Group C (Green): Suzanne Carbotte and Glen Spinelli

3:10 Break

3:25 Plenary: Scientific Questions

3:55 Lightning presentations
(3 minutes with no more than 2 slides to highlight an important idea or research result)

5:30 Adjourn

6:30 Dinner at UW Club

April 30 – Day 2
NHS Hall, Center for Urban Horticulture, University of Washington

8:00 Light continental breakfast available

8:30	Goals for the Day	Organizers
8:35	Infrastructure for early warning	John Vidale
8:50	NEPTUNE Canada	Martin Heeseman
9:05	NEPTUNE US	Deb Kelley
9:20	JOIDES Resolution capabilities and possibilities for use of Chikyu	Keir Becker
9:50	Plans for Breakout Groups	Organizers

10:00 Break

10:20 Breakout: Drilling Priorities, Locations, and Experimental Strategies Part I
Up to 4 groups focusing on different topics selected based on Day 1 breakout
Possible topics: Present day deformation, the incoming plate and history of the accretionary prism, fault zone drilling.

What are the highest priorities for drilling?
What are the best locations and strategies to address the scientific questions?

Tentative Group Organization:
Group I. Miriam Kastner and James Sample: *Defining the chemical and physical composition and properties of the incoming plate and prism*
Group II Rob Harris and Masako Tominaga: *Determing the incoming plate and prism states through downhole measurements and logging*
Group III Jeff McGuire and Lisa McNeil: *Seismologic and geodyanamic monitoring*
Group IV Harold Tobin and Kelin Wang: *Prism structure and characteristics of fault zones*

12:10 Lunch

1:10 Plenary: Drilling Priorities, Locations and Experimental Strategies Part I
Brief update of the status of each group

1:25 Breakout: Drilling Priorities, Locations and Experimental Strategies Part II

Building on the morning's discussions: What are the optimal experiment designs including drill hole locations and configurations, downhole instrumentation and complementary experiments?

3:15 Break

3:35 Plenary: Drilling Priorities, Locations and Experimental Strategies Part II

4:05	Science funding sources	Thomas Janecek
4:15	Hazards funding sources	Joan Gomberg

4:25 Breakout: How do we fund it?

3 groups

Group 1. David Schmidt: *Hazards funding*

Group 2. John Delaney: *Non-traditional funding sources*

Group 3. Adam Schultz: *How to prioritize with limited science budgets*

5:15 Plenary: How do we fund it?

5:30 Adjourn

May 1 – Day 3

Marine Sciences Building Room 123, School of Oceanography, University of Washington

8:00 Light continental breakfast available

8:30 Plenary: Discussion and Assignment of tasks

9:00 Group meetings to further develop drilling ideas and outline / write sections of report and drilling proposal

12:00 Plenary: Meeting wrap up

12:30 Adjourn

Appendix C. Scientific Questions

The following is a list of questions compiled by merging the output of the breakout groups that met on the first day of the meeting.

Plate Interface

- Is the seismogenic zone currently fully locked?
- Over what width across the subduction zone does strain accumulation take place?
- Does the degree and width of locking vary along strike and if so what controls this segmentation?
- Is the updip portion of the plate interface creeping or undergoing episodic slow slip?
- Does any of the slip associated with down-dip episodic slip at Cascadia propagate through the seismogenic zone, or is it arrested at a fully locked fault?
- What portion of the fault will slip during a megathrust earthquake?
- Are there precursors to large earthquakes?
- What is the seismic and tsunamagenic hazard associated with a megathrust earthquake?
- Why are levels of seismicity so low?
- Are there any indicators of deformation of which we are currently unaware?
- What is the absolute state of stress on the megathrust?
- What are the fluid pressures on the plate interface? Can they be inferred indirectly?

Incoming Plate

- How does the lithosphere evolve from birth (MOR) to recycling (SZ/arc/deeper)?
- What are the inputs to the subduction zone, and how does that affect the volcanic arc?
- Are there geologic/structural/fluids and other observable changes along strike on the incoming plate that are contributing to the segmentation of the subduction zone?
- How are hydrological processes coupled across the plate and how does this impact the subduction zone?
- What is the role of basement in the transfer of fluids, heat, and mass?
- What is the nature of basement alteration farther from ridge where the thickness of the sediment blanket is greater?
- What is the extent of mineral dehydration on the incoming plate?
- What are the properties of the sediments at the plate interface?
- What is the cause of the seismic velocity increase in deep sediments as they approach the deformation front?

- Over what breadth across the incoming Juan de Fuca plate do stress and strain accumulate through an earthquake cycle?
- What is the absolute state of stress in the incoming plate?

Overriding Plate

- What are the mechanical properties of the outer Cascadia accretionary prism?
- How do deep fluids and presence of hydrocarbons (methane, thermogenic gases) affect prism properties?
- How do sediments properties in/on the accretionary prism affect slope stability and failure?
- What causes landward vergence and why does the vergence change along strike?
- Are splay faults important in deformation and how is slip partitioned between them?
- What can be learned from non-thrust faulting?
- What is the role of splay faults/normal faults in dewatering of the prism?
- How does the high sand content affect physical properties and fluid flow relative to other margins with lower sand content?
- Do deeply sourced fluids with diagnostic compositions travel up faults and reach to levels that can be accessed, either at the seafloor or in boreholes, and can these lead to insights into steady or episodic deformation?
- How do deeply derived hydrocarbons from relatively organic-rich sediments and high heat flow impact the deep biosphere?
- What is the absolute state of stress above and below the frontal thrust of the prism?
- How has the structure of the prism evolved through geological time?