Plate Boundary Evolution and Physics at an Oceanic Transform Fault System – The Blanco Transform Fault Experiment
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Project Summary

Intellectual merit. Two broad issues are addressed by this project: 1) improve understanding of earthquake rupture physics in relation to material and fault zone properties along transform plate boundaries; 2) understand geodynamic effects of plate boundary evolution and reorientation on transform fault structure. The aim is to go beyond simple general tectonic characterizations of transform faults to a detailed process-oriented view. A strong motivation for the proposal comes from a successfully completed project using land-based recordings of larger earthquakes, which revealed unique details tied to Blanco Transform Fault Zone (BTFZ) complexity. The BTFZ, consisting of transform fault segments, pull-apart basins and a short intra-transform spreading center provides a range of scientifically interesting targets.

We propose a comprehensive investigation of seismicity, tectonics and lithosphere structure of an entire oceanic transform fault (OTF) system. The study consists of a deployment of 55 three-component ocean bottom seismometers and differential pressure gauges. The dense sea-floor network covers the entire BTFZ and operates for ~1 year to capture fine-scale OTF tectonics. The BTFZ is seismically very active, we anticipate detecting over 50,000 magnitude M≥1 earthquakes and capturing several larger M=5.0-6.5 earthquakes with their fore- and aftershock sequences. The large dataset offers opportunities to determine spatial and temporal variations in seismicity rate, accurate earthquake locations for active fault identification, and earthquake fault-plane solutions for deformation style investigation. We will derive 3-D lithosphere structure, covering the fault zone and surrounding intra-plate regions. In addition to body wave tomography, we will use receiver-function and ambient seismic noise analysis techniques sensitive to S-wave velocity structure and thus temperature and partial melt. OTFs are known for occurrence of slow earthquakes. At subduction zones, slow earthquakes involve non-volcanic tremor and our array is well suited to detect and locate tremors if they occur. We will also investigate wave-velocity anisotropy. Transform plate motion likely imparts crystal lattice alignments in the upper mantle and crust leading to shear-wave anisotropy. Hydrous minerals, like serpentine, are highly anisotropic and detecting anisotropy could be used to identify their presence, possibly indicating a mechanically weak fault zone.

The comprehensive dataset will allow us to address questions about OTF tectonics and earthquake rupture physics. One question is how fault segmentation and complexity affect seismicity and seismic moment release rates. The estimate of amount of seismic slip along parts of the BTFZ may depend on contributions from large numbers of small earthquakes; only ocean bottom instruments can detect these and resolve whether seismicity rates (b-values) are constant or roll-off at small magnitudes. A related question, requiring well-determined hypocenters, concerns the depth extent of ruptures with implications for thermal structure, fault zone rheology and mechanical strength, and the importance of hydrothermal circulation. For the BTFZ, we want to understand the causes for increased fault zone complexity at its western end, the origin and composition of the transform parallel Blanco Ridge, and the relation between sea-floor spreading, magmatism, and tectonism at the Cascadia Depression.

A study of this scope became feasible only with the establishment of the U.S. National Ocean Bottom Seismograph Instrument Pool. These new instruments allow long-term deployments for high-resolution fault-scale studies in the oceans akin to transformative IRIS PASSCAL land experiments and allow us to apply several novel analysis techniques that have not been widely attempted in oceanic studies.

Broader impacts. Our proposal is timely in relation to Neptune Canada, which includes OBS’s in the northern Juan de Fuca plate, and the planned MARGINS/EarthScope 3-year OBS deployment along Cascadia starting in 2011. Combined with our deployment, the full network would allow monitoring Juan-de-Fuca intraplate seismicity at unprecedented resolution. In addition to OBS data, we will acquire new multi-beam bathymetry, which is also of general interest.

Earthquakes associated with continental transforms (e.g., San Andreas, North Anatolian or Enriquillo-Plaintain Garden faults) pose a serious risk to heavily populated areas as witnessed with the 2010 Haiti earthquake. Improved understanding of earthquake rupture physics and interactions between various transform fault segments, can improve understanding of hazard in high-risk population centers. Another aspect of relevance, particularly in Cascadia, is to understand how large, proximal OTF earthquakes might load and possibly bring a subduction zone closer to rupture. The project involves graduate and undergraduate students and promotes teaching, training and learning. Experiments like this provide valuable, sea-going experience for MGG students.
Results from Prior NSF Support

Principal Investigator: John Nabelek, College of Oceanic and Atmospheric Sciences, Oregon State University, An Experiment in Regional Seismic Monitoring of the Juan de Fuca Plate and the Surrounding Ridge-Transform System; OCE 9521929; $226,000, 8/1995-7/1998.

The project was the first detailed long-term seismotectonic study of an oceanic ridge-transform system. Proximity of the Juan de Fuca plate and its plate boundaries provides a globally unique opportunity to study oceanic seismicity with high-dynamic range broadband data from a close-by, dense land seismic network. Primary objectives were to build a source parameter database (source mechanism, magnitude, depth) of magnitude M≥4.0 earthquakes and to increase resolution of seismotectonic models for oceanic plate and plate boundary behavior. Analyzing M=4.0 earthquakes is about one magnitude unit smaller than possible with traditional teleseismic techniques resulting in a roughly ten-fold increase in earthquakes that can be analyzed. During the 1994-1998 period of continuous monitoring about 400 events were analyzed (Fig. 1) – or about 80 events/year compared to 6 events/year (average over 30 years) obtained by the teleseismic Harvard CMT method.

Seismotectonic studies of offshore regions with land-based data are severely hampered by earthquake mislocations. Combining land and ocean bottom seismometer data showed that routine locations even for events close to the coast have large uncertainties and biases (Braunmiller et al. 1997). For specific targets (Explorer region and Blanco Transform Fault Zone), source parameters were combined with relocated epicenters and high-resolution bathymetry. Results revealing segmentation and fault zone complexity along the Blanco Transform Fault Zone (Dziak et al. 2000; Braunmiller & Nabelek 2008) of unmatched resolution for an oceanic transform fault are described in this proposal. Event analysis led to the first observation of earthquake-induced changes in a hydrothermal system on the Juan de Fuca ridge (Johnson et al. 2000).

Current tectonics of the Explorer region the northernmost part of the Juan de Fuca system were a topic of recent debate. One model predicted independent Explorer plate motion while a second postulated the region is cut by a transform fault forming the Pacific-North America plate boundary with Explorer plate’s remnants now permanently attached to either side. Quality earthquake source parameters and relocations show present strike-slip motion directions require an independent Explorer plate and imply a recent plate motion change (Fig. 2) resolving the debate (Braunmiller & Nabelek 2002).
Plate Boundary Evolution and Physics at an Oceanic Transform Fault System – The Blanco Transform Fault Experiment

1. Introduction and Rationale

Oceanic transform fault (OTF) systems are a first order plate-boundary type connecting mid-ocean ridge spreading centers along a total length of ~45,000 km (Bird et al. 2002). The role of transform faults in plate tectonics was recognized first by J. Tuzo Wilson (1965). Comprehensive studies of OTF systems, however, are difficult to perform due to their remoteness. Previous long-term seismicity studies used data recorded at distant stations resulting in low spatial resolution of OTF seismic properties. Higher-resolution studies with ocean bottom seismometers (OBS) have been short-term and small in extent until now and thus provided only glimpses of OTF complexity. Compared to mid-ocean ridge studies, OTF systems have received little attention. Morphological studies (Pockalny et al. 1988; Embley & Wilson 1992; Ligi et al. 2002) revealed fault zone complexity – segmentation, step-overs with intervening pull-apart basins or short intra-transform spreading ridges, releasing and constraining bends, parallel fault strands, etc. But relatively little is known how morphological complexity is reflected in crust and upper-mantle structure (except for a 3-D seismic refraction study of the Clipperton transform fault, northern East Pacific Rise; Van Avendonk, et al. 2001; and two recent refraction lines across the Quebrada and Gofar transforms; Roland et al. 2009) or how it affects distribution, size and depth-extent of earthquakes, their mechanisms and occurrence rates. Resolving the issues would improve understanding of OTF tectonics significantly as well as contribute in general to understanding earthquake rupture processes and fault behavior. We
propose a comprehensive investigation of OTF seismicity and structure by placing a dense network of seismometers on the ocean floor along the length of the Blanco Transform Fault Zone (BTFZ) (Fig. 3).

The BTFZ is a natural laboratory to study a long (350 km), seismically active and fairly fast-moving (5.6 cm/yr) OTF that consists of several transform-fault segments offset by extensional basins (Embley & Wilson 1992) offering a wide range of study targets. The BTFZ is probably the tectonically best-studied OTF to-date and therefore an ideal site for a comprehensive, long-duration ocean seismic instrument deployment. Embley & Wilson (1992) provided detailed analysis of BTFZ morphology and tectonic history from SeaBeam bathymetry and magnetic anomalies (Wilson 1993). Our study (Braunmiller & Nabelek 2008), using land-based seismic data, showed complexities in seismicity distribution, earthquake depths, frequency-size distribution, and deformation style at unmatched resolution; results (see below) provide a strong basis for an OTF-scale long-duration passive seismic experiment to reach the next-level in fine-scale resolution of seismicity and structure. Seismicity along the BTFZ is high and we expect over 50,000 earthquakes during a ~1-year deployment that very likely includes several magnitude M=5.0-6.5 events.

A high-resolution passive seismic experiment of an OTF became feasible only recently when the U.S. National Ocean Bottom Seismograph Instrument Pool (OBSIP) was created. The OBSIP provides wide-band and short-period OBS and differential pressure gauges (DPG) that can operate up-to ~15 months. Results from the MELT (MELT Seismic Team 1998) and the PLUME experiments show that the new OBS and DPG sensors provide quality seismic data over a wide frequency range including long-periods (e.g., Forsyth et al. 1998; Webb & Forsyth 1998; Hammond & Toomey 2003; Laske et al. 2007; Wolfe et al. 2009) necessary for surface wave studies. The Ocean Seismic Noise Pilot Experiment (Collins et al. 2001; Stephen et al. 2003; Crawford et al. 2006) also reported quality wide-band recordings suitable for local and teleseismic earthquake detection. The first large-scale OBS deployment along the Quebrada, Discovery, and Gofar transforms on the East Pacific Rise (PIs J. McGuire and J. Collins) was completed in late 2008. Compared to the Blanco transform, these are ultra-fast transforms (~14 cm/yr) with very different overall geometry. Both transform studies are complementary and promise to provide exciting results towards a general understanding of OTF seismicity and mechanics.
We summarize initial highlights from the one-year deployment along the EPR transforms (McGuire et al. 2009) to show how exciting and diverse OTF seismicity is. Over 100,000 earthquakes were detected. A magnitude M=6 earthquake, forecast to occur during the experiment (McGuire, pers. comm.; 2008), ruptured the western Gofar transform, which consists of four segments. Before the M=6 event along the west segment, seismicity was concentrated at a barrier separating the quiet east from the west segment. The westernmost segment near the ridge intersection ruptured later during a 2-day swarm with earthquake size below M=5.5. Seismicity in the barrier was greatly reduced after the M=6 event. Interestingly, events reaching into the mantle occurred in this region, difficult to reconcile with thermal models for fast-slipping faults and suggestive of extensive hydrothermal cooling. The first results reveal the spatial-temporal evolution of seismicity over a one-year period for one OTF system. The BTFZ system offers the same range of structural diversity with the western and eastern BTFZ showing low, respectively, high seismic coupling analog to the Quebrada and the Discovery and Gofar transforms, respectively, with difficult to explain deeper events in the central inter-OTF spreading center, with possible segmentation of the highly coupled Blanco Ridge (Boettcher & McGuire 2009) similar to the western Gofar transform, and with complex, multi-stranded, possibly swarm-like activity along the western BTFZ. Only one detailed, long-term OBS study has been conducted along all existing OTF systems to date; we propose a second study along the medium-fast BTFZ, probably the best understood OTF globally.

The proposed project is timely in relation to the MARGINS/EarthScope Cascadia amphibious array that includes the deployment of ~60 OBS along the Cascadia margin planned for the period 2011-2014. A concurrent deployment combined with the already existing Neptune Canada OBS sites (Fig. 1) offers the unique opportunity to study plate-scale seismicity in the Juan de Fuca plate for free in addition to the main science goals of each individual project. The BTFZ is by far the seismically most active region in the Cascadia region; only a dense local BTFZ network can provide high-resolution event locations for the BTFZ and it could also be helpful in separating Cascadia signal from other seismic sources. Details of the Cascadia deployment are currently open; if funded, we will coordinate closely with the Cascadia array PIs to ensure optimum network configurations.

This proposal is a re-submission. The original proposal received high ratings from the reviewers and the panel for being transformative in terms of its science. The panel concluded with that this proposal “should receive highest priority for funding.” The most significant change concerns our proposed experiment plan, which we reduced from 2 to 1 deployment to drastically reduce the costs of the proposal, ship and OBS deployment fees also reflected in a reduction from a four- to a three-year proposal. Ideally, we would prefer our original plan, but belief the science objectives are reachable with a shorter experiment by increasing the number of instruments from 40 to 55 and by maximizing the deployment period from 12 to ~15 months. We updated the discussion on serpentinization and hydrothermal circulation along parts of the BTFZ in response to panel’s question about their resolvability. The panel noted that the EM-300 multi-beam system looses some resolving power for water depths over 3000 m and we thus propose to use a ship equipped with EM-120 for at least one leg; we added a figure comparing close-ups of newly acquired EM-302 relative to 25+ -year old bathymetry to illustrate that EM-300 systems work adequately for most parts of the BTFZ and to highlight a need for new bathymetry to advance morphotectonic interpretation.

2. Background

Global Seismological Studies of Oceanic Transform Fault Systems


Broadly speaking, the depth-extent of seismogenic faulting in oceanic lithosphere seems to be governed by its simple composition and well-understood thermal field. The observed earthquake cut-off depth near the 600ºC isotherm (Wilcock et al. 1990; Abercrombie & Ekström 2001; 2003; McKenzie et al. 2005) implies brittle faulting reaches into the uppermost mantle. Experimental data on strength and frictional behavior of olivine agree with transition from unstable to stable sliding at ~600ºC (Boettcher et al. 2007). Most results relating earthquake depth and temperature were derived from half-space cooling
models (e.g., Turcotte & Schubert 2002), but recent 3-D finite-element simulations with more realistic rheology obtain similar thermal structures (Behn et al. 2007). No observational study thus far could verify continuous seismicity extending through the mid-lower crust into the mantle as expected for strong dry crust (Searle & Escartin 2004 for discussion). Whether hypocenters deepen towards an OTF mid point also remains controversial, e.g., Tréhu & Solomon (1983) found deepest events along the Orozco TF near the ridge-transform intersection at odds with cooling models.

Good agreement between plate motion rates and cumulative seismic moment has been reported for the Gibbs fracture zone (Kanamori & Stewart 1976; Kawasaki et al. 1985) and the Romanche, Jan Mayen, Bullard and Conrad transforms (Brune 1968; Stewart & Okal 1981). These OTFs appear seismically fully coupled, i.e., seismic moment release accounts for full plate motions. However, on the Eltanin fracture zone, seismic moment release accounts for less than 10% of predicted slip (Stewart & Okal 1983; Okal & Langenhorst 2000). Moreover, recent global studies suggest seismic moment release along OTF systems in general accounts only for small parts (~15%) of plate motions (Bird et al. 2002; Boettcher & Jordan 2004). Inferred low seismic coupling could potentially be due to overestimating the seismic zone width. The zone could be narrower and thus seismically fully coupled, e.g., as a shallow zone underlain by aseismic, pervasively serpentinized peridotite (Willoughby & Hyndman 2005) or a narrow zone just above the 600°C isotherm with stably sliding crust on top. Another possibility is lateral variability of seismic and aseismic patches akin to locked and creeping segments of the San Andreas Fault. Resolving the issue requires high-quality hypocenters along an entire OTF.

Seismic moment release and degree of seismic coupling are also affected by the earthquake frequency-magnitude distribution. The slope b of the distribution describes the ratio of small to large earthquakes. With teleseismic data, b-values are usually averaged over entire OTFs. Langenhorst & Okal (2002) suggested b-values increase with plate motion rate, while statistical analysis of Bird et al. (2002) concluded that b=1 is constant. OBS deployments provide an opportunity to investigate b-values of much smaller sized events. Long-term local observations along an entire OTF are required to resolve spatial b-value variations to infer coupling variations and fault-zone complexity.

Strike-slip faulting with slip parallel to the plate motion direction is the dominant faulting style along OTF segments (e.g., Bergman & Solomon 1988; 1992; Engeln et al. 1986; Goff et al. 1986; Wolfe et al. 1993; Abercrombie & Ekström 2001; 2003). Wolfe et al. (1993) studied unusual OTF events and found they occur at geometrical complexities of transform segments, e.g., compressional jogs or extensional offsets. Fault-plane solutions are important for estimating stress-field orientation. The San Andreas Fault “heat-flow paradox” (Lachenbruch & Sass 1980; 1992; Zoback 1987; Saffer et al. 2003) – no anomaly near the San Andreas – suggests fault slip at low resolved shear stress along a weak transform. Support for weak oceanic transforms comes from micro-earthquake fault plane solutions recorded by OBS’ showing extension across the Kane transform (Wilcock et al. 1990) and from rotated strike-slip mechanisms at the Mendocino transform (Wang et al. 1997). Numerical modeling including weak coupling (Behn et al. 2002) fits observed patterns of strike-slip and oblique normal faulting near ridge-transform intersections (Huang & Solomon 1988; Wolfe et al. 1993). Anomalous fore- and aftershock behavior has been reported for East Pacific Rise transform faults from hydrophone array data (McGuire 2003; McGuire et al. 2005). The hydrophone array has an earthquake detection threshold near M=2.5–3.0 (Fox et al. 2001). The data show foreshock activity possibly related to stress changes driven by slow aseismic slip or other fault preparation processes (McGuire et al. 2005). Conversely, larger OTF earthquakes have fewer aftershocks than continental events (Boettcher & Jordan 2004; McGuire et al. 2005); the aftershock decay rate, though, follows a modified Omori law (Bohnenstiel et al. 2002). In addition, larger earthquakes along these ultra-fast transforms show high-periodicity supporting the seismic cycle concept (McGuire 2008). Recently, Boettcher & McGuire (2009) suggested a ~14 year repeat cycle for two distinct patches along BTFZ’s Blanco Ridge based on teleseismic relocation of M≥6 events. More studies are needed to verify an anomalous nature of OTF foreshock and aftershock sequences, to develop a physical model for their origin, and to obtain precise, local earthquake locations to confirm the repeat nature of large OTF events.

Low seismic coupling and anomalous foreshock behavior could be tied to slow earthquakes, which are common along OTFs (Kanamori & Stewart 1976; 1979; Okal & Stewart 1982, Prozorov & Sabina 1984; Beroza & Jordan 1990; Ihmle & Jordan 1994). Slow earthquakes consist or include a phase of low rupture velocity that may precede and initiate normal fast ruptures (Ihmle & Jordan 1994; McGuire et al. 1996; McGuire & Jordan 2000). Such events are often found in connection with episodic non-volcanic tremors in subduction zones (Dragert et al. 2001; Obara 2002; Miller et al. 2002; Kao et al. 2005; Shelly et al. 2006).
Non-volcanic tremor was also detected at the San Andreas Fault where heightened tremor activity precedes bursts of normal local earthquakes suggesting a causal relation (Nadeau & Dolenc 2005). Our data are ideally suited to scan for tremor signals along an OTF.

The Blanco Transform Fault Zone (BTFZ)

The 350-km-long BTFZ forms the Pacific-Juan de Fuca plate boundary between the Gorda rise and the Juan de Fuca ridge. Seismicity is high and fault plane solutions (Tobin & Sykes 1968; Chandra 1974) agree with right-lateral strike-slip motion. Earthquakes located by land stations, though, are systematically biased ~30 km to the northeast (Dziak et al. 1991; Cronin & Sverdrup 2003). Locations with sonobuoy (Johnson & Jones 1978) and hydrophone arrays (Dziak et al. 2000), in fact, agree with bathymetry. The bathymetry shows northwest-trending lineations punctuated by right-stepping offsets and depressions making the BTFZ an oceanic analog to continental wrench-fault systems (Embley & Wilson 1992).

Cascadia Depression, at BTFZ's center, is the largest depression. It subsides tectonically at a rate of 1.8 cm/yr (Griggs & Kulm 1973) and is seismically active (Johnson & Jones 1978). Seismic reflection data and bathymetry reveal back-tilted blocks and basement doming in its center indicating active seafloor spreading (DeCharon 1989; Embley & Wilson 1992). Other smaller basins along the BTFZ, though, seem to be oceanic analogues to continental pull-apart basins (Embley & Wilson 1992).

Dziak et al. (1991) reported seismicity differences between the eastern and western BTFZ. The largest earthquakes (moment magnitude $M_w=6.5$) occur along Blanco Ridge, the longest (150 km) continuous transform segment located in the eastern BTFZ (Dziak et al. 2000). Blanco Ridge is a transform-parallel ridge, also found elsewhere. Mechanisms for their origin involve serpentinite intrusions, extensional volcanism, and dip-slip faulting due to plate motion changes (Thompson & Melson 1972; Bonatti 1976; 1978; Bonatti et al. 1994; Pockalny et al 1996; Pockalny 1997). Blanco Ridge origin has been attributed to serpentinite diapirism (Embley & Wilson 1992; Dziak et al. 2000). However, petrological samples from the BTFZ include only lower crustal gabbros, indicating uplift, but no serpentinite (Dziak et al. 2000).

The western BTFZ is broad compared to the narrow Blanco Ridge suggesting a more complicated fault configuration with possibly several active transform strands (Delaney et al. 1981; Embley & Wilson 1992; Juteau et al. 1995; Dauteuil 1995; Dziak et al. 2003). A response effort to swarm-like earthquake activity within East Blanco Depression, a pull-apart basin, led to the discovery of the first active hydrothermal vent along an OTF (Dziak et al. 1996). Another strong earthquake ($M_w=6.2$) at the westernmost BTFZ caused a drop in fluid temperature at hydrothermal fields at the southern Juan de Fuca ridge (Dziak et al. 2003) about 40 km from the event's epicenter.

Several studies (Hyndman & Weichert 1983; Dziak et al. 1991; Boettcher & Jordan 2004; Willoughby & Hyndman 2005) investigated seismic coupling. Significant differences in their results are mainly due to different assumptions about depth extent of earthquake rupture. Boettcher & Jordan (2004), for a 10-km seismic width, found only 10%-15% of slip is seismic. Hyndman & Weichert (1983) and Willoughby & Hyndman (2005), though, suggest seismic slip accounts for all plate motions, but they assume a seismic width of only 3 km. (However, even for same widths, inferred rates would differ by a factor of 2 because of differences in the earthquake catalogs and magnitude-to-moment conversion).

An unusual swarm with over 600 earthquakes started in March 2008 about 70 km north of the western BTFZ (Merle et al. 2008). This was the first intraplate swarm detected by SOSUS hydrophones in the Juan de Fuca plate. A rapid response cruise found no water column anomalies indicative of an eruptive episode, but found recently (Holocene) active faults consistent with active seismics results (Nedimovic et al. 2009). Also, throughout 2008 seismicity along the BTFZ was unusually high (shown later in Fig. 6), which raises the question if events on the BTFZ and the nearby intraplate swarm activity are connected?

Results From Our BTFZ Investigations

Establishment of a broadband seismic network along the northeast Pacific coast during the 1990's provided the impetus for our earlier study (Braunmiller & Nabelek 2008). Regional data allow source parameter estimation (seismic moment tensor, depth, and rupture history) of $M_n\geq4.0$ earthquakes along the entire BTFZ; the low threshold is unique for any OTF. We combined 126 moment-tensors with relative earthquake locations (Douglas 1967; Dewey 1972) and SeaBeam bathymetry for unmatched resolution images of OTF seismic deformation and tectonics (Fig. 4).
The globally most significant result is documentation of spatially highly variable seismicity. Seismicity correlates with deformation style changes that reflect fault zone segmentation evident in bathymetry (Fig. 4). OTF complexity is further manifested by sub-parallel active transform fault strands, variation of maximum earthquake size and frequency-magnitude relation between segments, and variable but spatially stationary long-term seismic energy release (Fig. 5). BTFZ’s complexity, comparable to continental transforms, shows average models are misleading when describing OTF system behavior.

Fig. 4 shows fault-plane solutions and epicenter relocations on SeaBeam bathymetry. Source parameter changes between strike-slip and normal faulting agree with BTFZ morphology and indicate several transform segments offset by extensional step-overs. Extension is parallel to Pacific-Juan de Fuca motion in the Cascadia Depression (128.75ºW) consistent with active spreading (DeCharon 1989; Embley & Wilson 1992). Extension in active pull-apart basins (127ºW and 129.25ºW) is rotated by ~45º consistent with stress-axes of strike-slip events. Largest normal-faulting events reach M_w=5.5.

The eastern Blanco Ridge (127º–127.75ºW) is seismically most active. Largest BTFZ earthquakes (M_w=6.5; a M_w =6.3 event occurred on January 10, 2008) nucleate near the transition to the western Blanco Ridge and possibly rupture unilaterally towards west. A second, possibly older, fault-strand north of Blanco Ridge, indicated by a lateral offset of a turbidite channel, seems still to be active. Strike-slip earthquakes along western BTFZ (west of 129.25ºW) are more widely spread even after relocation. Teleseismic location resolution cannot resolve which fault strands are active, but the spread implies several. This is supported by subtle, but definite, differences in slip-vector directions, consistent with fault trends deduced from bathymetry, possibly indicating on-going small plate-motion re-adjustments. Maximum event size in the western BTFZ is smaller (M_w=6.2) reflecting finer fault segmentation.

Figure 4. BTFZ close-up with fault plane solutions and well-relocated epicenters on SeaBeam bathymetry. Solid and dashed lines mark inferred (Embley & Wilson 1992) locations of active and inactive faults, respectively.

The earthquake depth distribution and rupture extent (assuming circular ruptures and constant stress drop) are shown in Fig. 5 (right bottom). Centroid depths are less than 10 km with uncertainties of about ±3 km. For average crustal thickness of ~6 km (Chen 1992), a distribution of 4–9 km (depth <4 km not resolved) implies seismicity in the crust and uppermost mantle. Centroids near Cascadia Depression (128.75ºW) and along the eastern Blanco Ridge are deeper than near the ridge-transform intersections where depths do not exceed 6 km. Rupture areas are above the 600ºC isotherm (calculated for half-space cooling), consistent with observations (Abercrombie & Ekström 2001; 2003) and experimental data on olivine frictional stability (Boettcher et al. 2007). Active spreading with a shallow magma chamber should reset isotherms, but centroids at Cascadia Depression are deep, probably indicating intermittent magma supply and rapid hydrothermal cooling after dike emplacement (Coogan 2001). Similar to our
depths, micro-earthquakes at the northern Gorda Ridge reach 11 km depth (Solano 1985) and between 4-8 km along various parts of the slow-spreading MAR (Barclay et al. 2001).

We determined seismic slip rates by summing seismic moments of all earthquakes during the period 1964-2005. Instead of averaging as before (Hyndman & Weichert 1983; Dziak et al. 1991; Boettcher & Jordan 2004; Willoughby & Hyndman 2005), we corrected for land-based mislocation (~30 km to NE) and size bias (body-wave magnitudes \(m_b\) are 0.5 units smaller than \(M_w\)) to project slip of each earthquake onto the BTFZ. Then summed over all events to obtain the spatial slip rate distribution (Fig. 5 upper right), which shows tremendous spatial variability that tests indicate is temporally stable. The distribution follows segmentation seen in bathymetry and fault plane solutions. Earthquakes account for only 15% of plate motions in normal faulting areas requiring mostly aseismic deformation. Motion along Blanco Ridge is essentially fully seismically coupled. Along the western BTFZ, observed seismicity accounts for only about 25% of plate motions. The degree of variability shown here had not been known to exist for any OTF. The average BTFZ seismic rate is 2.0 cm/yr (36% of plate motion), however, this value was not observed for any segment indicating averaging over an entire OTF is a gross oversimplification.

Figure 5. Top left. Epicenters (open circles, line ends at original locations) relocated using the joint epicenter determination technique to avoid known bias of routine locations. Star shows reference event. Relocations are tighter and coincide with bathymetric features. Top right. Seismic slip rate distribution along the BTFZ for a 7-km uniformly wide seismic zone. Solid line at 5.6 cm/yr is full plate motion rate (Wilson 1993). Stars and circle are \(M \geq 6\) events. Dashed lines are four segment averages. High seismicity during 2008 (Fig. 6) had no significant effect on the distribution since all events were \(M < 6\), except the \(M_w=6.3\) event on the fully coupled Blanco Ridge segment. Bottom
left. Seismicity rates along four segments. Panels show a histogram of event magnitudes above the frequency magnitude relation. Linear regression applied in range covered by solid line. Bottom right. Map of centroid depth distribution, SS, NF are strike-slip and normal faulting. Below are cross-sections with circular earthquake rupture areas superimposed on half-space cooling isotherms; ruptures are bound by the 600°C isotherm. The Mw=6.5 Blanco Ridge event seems to violate a 600°C cut-off; for large events circular rupture is incorrect and actual rupture probably had a large length-to-width ratio. Thermal reset at Cascadia Depression (bottom) is inconsistent with observations.

Frequency-magnitude relations for four BTFZ regions from teleseismic earthquakes are shown in Fig. 5 (left bottom). Their slope b, though not very well constrained due to small sample size, varies from 1.1 for Blanco Ridge to 1.6 for the western BTFZ. Self-similarity allows estimating the seismic moment release of all, observed and unobserved, earthquakes from a catalog that is complete only for certain magnitudes via seismic activity and b-value (Molnar 1979). Large b-values (~1.5) indicate smaller events not recorded by land stations (Mw≤4.8) might contribute significantly to the moment release such that seismicity could account fully for plate motions. Along Blanco Ridge, large events dominate moment release. We suspect b-value differences also reflect fault zone complexity with large values in heavily faulted areas with short faults. Based on these intriguing results, we now like to improve b-value resolution significantly, which requires local seismic observations.

Throughout 2008, BTFZ seismicity was unusually high. At M≥4.5, where detection by land stations is complete, activity was ~4 times higher than usual for the entire BTFZ, and a blistering ~7 times higher for the western BTFZ (Fig. 6). Whether 2008 represents an anomaly or foreshadows upcoming large events in the western BTFZ is unknown. Given the apparent slip deficit in the western BTFZ, chances of recording M=5.0-6.5 events up close during a 15-month OBS deployment are high.

3. Experiment Objectives

The broad experiment objectives are to significantly improve understanding of physics of earthquake ruptures in relation to material and fault zone properties and of plate boundary evolution on fault structure and dynamics along an OTF. We chose the BTFZ as example of an OTF, because it is long, seismically active, contains transform and extensional areas characteristic for such systems, and background knowledge, not available for any other OTF, exists. We cover four thematic areas to reach our objectives:

**BTFZ Complexity.** High-precision epicenters define active faults. Which faults are active? Are parallel fault strands active? Does epicenter distribution change from segment to segment? Do ridge-transform intersections at the Juan de Fuca and Gorda ridges affect seismicity? Is activity along transform segments more focused than in extensional basins? What is the seismicity signature in pull-apart basins relative to the Cascadia Depression spreading center? Is there off-transform seismicity?

The epicenter distribution can define active faults and identify fault zone complexity as is done on land within dense seismometer networks like at the San Andreas Fault system. This requires high-resolution locations of many earthquakes from active faults, which do not exist for any OTF. Acquiring such data requires a dense OBS array operating long enough to capture an accurate image of overall seismicity; we thus propose a ~1+year deployment. A dense array also provides high-quality data to search for unusual fore- and aftershock behavior of OTF events at much smaller magnitudes than previously possible.

**BTFZ Mechanical Properties.** The amount of seismic vs. aseismic motion has important implications for rheologic-mechanic models of fault zones and their lithology. Estimating seismic motion requires determining seismicity rates (b-values). Their spatial variations are possibly related to fault zone heterogeneity, pervasiveness of faulting, and hydrothermal circulation. Reliable estimates require a large, complete dataset only achievable with a dense long-duration OBS array. Questions to ask: Are rates
affected by fault zone complexity, length of fault segments or deformation style? Is seismicity scale-invariant, i.e., are b-values from micro-earthquake and teleseismic data identical? How much motion do small events account for? Do regions lacking large events 'compensate' with abundant small events to reach full seismic coupling? And what causes different mechanical properties?

Slow slip events, possibly connected with non-volcanic tremors, may account for large parts of plate motions in regions of low coupling. Do such tremors indicative of slow slip occur along the BTFZ? Our proposed array allows detection and location of tremors.

Inner fault zone properties, such as amount of fault gauge, can affect transform fault mechanics, particularly seismic coupling. We like to place some stations in the fault zone to record trapped guided waves, which carry information about inner fault-zones (Li et al. 1994; Hough et al. 1994; Ben-Zion 1998).

**BTFZ Thermal State and Deformation Patterns.** Precise hypocenters are required to determine the depth distribution of earthquake nucleation. What is the depth extent and can simple thermal models explain variations? What are lower and upper cut-off temperatures? Is lower oceanic crust aseismic and weak or not? Are depths related to transform fault segment length? How deep are events beneath the Cascadia Depression spreading center and the pull-apart basins? What do depths imply for thermal structure, magma supply and tectonic extension? Do ridge-transform intersections affect event depth? Do fault zone composition and degree of peridotite serpentinization affect depth and fault strength?

The dense OBS array allows high-precision absolute and relative hypocenter depth determinations. Additional constraints on earthquake depth will come from waveform modeling. Modeling also allows retrieval of earthquake source parameters (fault plane solution, seismic moment, non-shear source parts), which reveal deformation modes and shed light on fault strength. Some open questions are: Do normal and strike-slip faults bend towards each other near a ridge-transform intersection? Are off-fault mechanisms rotated relative to events on main transform segments? Are oceanic transform faults weak? Are effects of lithosphere thermal subsidence observed during earthquake rupture?

**BTFZ Structure.** Determine 3-D crust and upper mantle velocity models to infer fault zone composition and structure relative to surrounding oceanic lithosphere. Is the fault zone strongly serpentinized? How deep does hydrothermal circulation extend and how is it related to depth of serpentine? What is the crustal thickness? Is crust under extensional basins thinner than elsewhere? Is there a connection between fault zone structure and seismicity? What is the nature of the deep West Blanco Depression right at the ridge-transform intersection; it is not a pull-apart or a spreading ridge? Is structure more complex in areas of recent plate boundary changes along western BTFZ than elsewhere?

Main tools for determining crust-upper mantle P- and S-wave velocity structure will be joint local and teleseismic earthquake tomography, waveform modeling and combined inversion of ambient seismic noise and receiver functions. Combining constraints from structure and seismicity potentially leads to a comprehensive model of OTF behavior. Lateral plate motion along transforms likely imparts strong crystal lattice alignments in the upper mantle and crust leading to shear-wave anisotropy (e.g., Wolfe & Solomon, 1998; Rümpker et al., 2003). One can expect anisotropic fabric to vary based on the age of the transform segment, temperature and style of deformation. Hydrous minerals, such as serpentinite, are highly anisotropic and thus anisotropy can be potentially used to identify their presence.

### 4. Experiment Plan

The experiment will deploy 55 ocean-bottom seismometers and differential pressure gauges for the maximum instrument operation time of about 15 months. The average inter-station distance is about 25 km, similar to dense land networks.

**Instrumentation.** We will use 55 ocean-bottom seismic instruments provided by the OBSIP. 30 will be equipped with a wideband (0.03 Hz to 50 Hz), 3-component seismometer plus a differential pressure gauge (DPG) to record low frequency to about 0.01 Hz; and 25 with a short-period, 3-component seismometer plus a DPG. All instruments have a 24-bit data logger. High sampling rates (50-100 Hz) are required for precise picking of local P- and S-wave arrivals. Ideally, all sites would be equipped with wideband seismometers. However, given their high demand, we believe short-period seismometers together with DPGs can serve our goals. The short-period instruments are adequate for detecting/locating earthquakes, tremors and tomography. Based on own experience deconvolving instrument responses from short-period data, we expect quality data up to at least 5-sec periods for large teleseisms, which can be used for receiver-function analysis (see also Collins et al. 2001). DPGs are important for analyzing long-period surface waves from earthquakes and ambient noise, and for local earthquake moment-tensor
analysis. At this point OBSIP does not routinely equip short-period instruments with DPGs. If at the time of the deployment there are not enough DPGs available to equip both wideband and short-period instruments, we plan to transfer the DPGs from wideband to all short-period instruments to achieve wide-band recording capabilities for each site. We schedule fieldwork to begin during late summer 2011 when an adequate number of wideband OBSIP instruments are available.

**Experiment Design Rationale.** The BTFZ is seismically very active. A 15-month duration is likely to provide a characteristic distribution of micro-earthquake epicenters and sizes as well as to record several larger events. A 15-month deployment is adequate for recording a sufficient number of large global earthquakes for receiver function analysis and sufficient amounts of ambient noise for unbiased cancellation of spurious arrivals. Wind speed will affect short-period noise levels (e.g., Wilcock et al. 1999) and thus detection thresholds seasonally. We chose a dense station spacing to achieve a uniform threshold for event detection near magnitude M=1 (detection and size from a single observation) and for event location near M=2 for the entire study area. The deployment plan is based on knowledge of BTFZ earthquake distribution; and is aimed to capture narrow event distribution along the eastern and wider distribution along the western BTFZ, to study Blanco Ridge composition, and to verify deeper hypocenters in the central Cascadia spreading center. Four wide-band OBS will be placed about 100 km north and south of the BTFZ. This increases network aperture and allows location of events significantly off the main BTFZ; seismicity from standard databases (USGS) and different relocation procedures show a few such events, but it is not clear how good these locations actually are. The off-axis instruments will also constrain the Juan de Fuca and Pacific intra-plate crust and upper-mantle structure.

**New Multi-beam Bathymetry.** An important aspect of the proposal is the acquisition of new multi-beam bathymetry taking advantage of ship time in the BTFZ region. Existing coverage was obtained with the 1980’s 19-beam system and primarily land-based navigation. The existing swath is narrow and does not reveal fault strands clearly for structural interpretations. Utilizing a modern 135-beam system with backscatter capability will substantially improve existing resolution and more than double areal coverage.

![Figure 7. Comparison of (top) new EM-302 multi-beam (Okeanos Explorer; courtesy S. Merle, R. Embley) versus (bottom) existing 1980’s bathymetry. The new data from a shakedown cruise cover only a small part of the BTFZ. Their resolution is visibly higher even for areas with >3000 m water depth like the Cascadia Depression (left) significantly aiding structural interpretation for the BTFZ.](image-url)

After consulting in-house experts (C. Goldfinger and R. Embley) and based on the NSF panel advice, we suggest using Simrad EM-300 in water less than ~3000 m deep and EM-120 in deeper water. Modern multi-beam systems produce considerably higher quality data than the old 19-beam system (Fig. 7). Goldfinger and Embley affirmed that EM-300 data alone would significantly increase resolution compared to existing bathymetry; Embley agreed to assist in all aspects of data acquisition and processing. We note our primary objective is the OBS deployment and multi-beam data collection will be performed on as time
permits basis. The experiment’s success does not hinge on new multi-beam data, though they would be very useful. For example, bathymetry with discernable active faults could be used to verify the location of the active transform along the Blanco Ridge (Dziak et al., 2000) and to aid tectonic interpretation in general. New multi-beam bathymetry will be made available to the community as soon as processed.

**Logistics.** The estimated number of “Science Days” for the deployment and pickup cruise is 17 days. The estimates are based on consultations with J. Collins, J. McGuire, J. Babcock and on own experience using OBSIP instruments. We also consulted with colleagues in our college about working at sea in the northeast Pacific. Time required for OBS shipboard operations are about 3.5 hour/site for deployment and recovery for deep-water (~3000+ m) sites. A 3.5-hour/deployment time includes OBS drop, sinking to the seafloor and subsequent echo sounder surveying for precise OBS location. Transit times between sites are based on average inter-site distances and normal ship cruising speeds. This results in 14 days of ship time. Several recent experiences with OBSIP instruments come from the equatorial Pacific with ideal deployment conditions. We have been strongly warned about the high likelihood of bad weather in the northeast Pacific and were advised to add at least 3 days for weather related and other contingencies.

The R/V Thompson, equipped with a modern 135-beam system (EM-300) with backscatter capability, is our vessel of choice for one leg. We will request the R/V Melville or R/V Revelle for one leg because their EM-120 multi-beam system is superior to EM-300 in deep water. We expect a 13-member scientific crew. OBSIP will provide technical support for instrument operation (section G). OSU will provide helpers and watch-standers according to OBSIP guidelines and will operate the multi-beam system. The ship operator will provide a marine technician.

5. Analysis Plan

**Event Detection and Location.** Main goals: mapping of seismicity rate (b-value), high-resolution hypocenter location to identify active faults and to constrain depth extent of seismogenic layer. The 3-component data are recorded continuously at high sampling rate. We will use Boulder Real Time Technologies’ Antelope software for automatic arrival-time picking, event association, and preliminary location. We used the software for earthquake detection and location for the Hi-CLIMB experiment in Nepal and Tibet. With the dense array, we expect to detect M≥1 and to locate M≥2 earthquakes. Our earlier BTFZ study (and Fig. 6) shows ~5 M≥5 earthquakes per year and a b-value of ~1.0 or greater; projecting to small events, we expect ~50,000 detected and ~5,000 located events. Such large datasets are necessary for statistically significant b-value mapping and active fault identification. For determining spatial b-value variations, we will include events detected by only one or two sites to extend the magnitude range covered. Objectives are to investigate whether b-values vary from segment to segment and whether b-values are magnitude-dependent (Aki 1987; Boettcher et al. 2009).

Stepwise event location will result in a subset of refined highly accurate locations. Automatic picks will be manually adjusted and additional secondary arrivals will be picked. Each event will be located and its magnitude determined. Improvements in absolute location will be considered as part of local earthquake tomography (see below). We will employ ray tracing to constrain hypocenter depth from time differences between direct and secondary phases (successfully applied to Cascadia earthquakes by Trehu et al. 2008) and perform polarization analyses to further confirm selected locations. Selected event clusters will be relocated, using waveform cross-correlation for accurate arrival times (VanDecar & Crosson 1990; Deichmann & Fernandez 1992; Dodge et al. 1995) and double difference location (Waldhauser & Ellsworth 2001; Waldhauser 2001; Menke & Schaff 2004; Hauksson & Shearer 2005) to constrain spatial event relations at ~10’s of m resolution to map active faults. Table 1 summarizes projected resolution improvements relative to current estimates.

<table>
<thead>
<tr>
<th>Event Category</th>
<th>Current Status</th>
<th>Projected Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake Detection Threshold</td>
<td>Land: m_b ~3.0-3.5;</td>
<td>OBS: M_L ~1.0; M_L ~0 near station</td>
</tr>
<tr>
<td></td>
<td>SOSUS: m_b ~2.5</td>
<td></td>
</tr>
<tr>
<td>Earthquake Location Threshold</td>
<td>Land: m_b ~3.5-4.0;</td>
<td>OBS: M_L ~1.5-2.0</td>
</tr>
<tr>
<td></td>
<td>SOSUS: m_b ~3.0</td>
<td></td>
</tr>
<tr>
<td>Locations per Year</td>
<td>~50 based on USGS data</td>
<td>~5,000-10,000</td>
</tr>
</tbody>
</table>
Waveform Modeling. Main goals: determine fault plane solutions and seismic moments, additional constraints on depths. We will invert three-component waveforms at wide frequency bands for the seismic moment tensor to analyze variations in deformation style (Nabelek & Xia 1995). Analysis with regional land-based data has been performed for larger BTFZ events (section Background). The threshold for complete waveform analysis for a land network with inter-site spacing like the proposed ocean array is near M=3 (Roten & Braunmiller 2002; Deichmann et al. 2004). For higher noise oceanic environments we expect slightly lower performance depending on actual signal-to-noise levels at OBS and DPG sensors. Inversions using only the stable vertical component data can be performed. We will also use an extension of the original method to smaller events developed by Schurr & Nabelek (1999) that inverts seismogram windows at P- and S-arrivals allowing analysis down to M=1. We expect several hundred local moment tensors. The solutions, combined with quality locations, will provide a detailed image of deformation style for the entire BTFZ. The inversion searches for non shear-faulting contributions to earthquake sources, possibly important in extensional regimes. The inversion provides seismic moment useful to tie amplitude-based magnitudes to physically meaningful moment (Braunmiller et al. 2005).

Earthquake depth from waveform inversion is determined via grid-search. Even for simple models, depths are well determined with absolute uncertainties of a few kilometers (Szönyi et al. 2005). Complete waveforms sample crust-mantle structure differently than body waves. Depth from modeling thus complements estimates from event location. We will test viability of hypocenter depth estimates by comparing synthetic and observed seismograms for earthquakes with well-determined focal mechanism.

Strike-slip fault zones are known to channel waves along them (Li et al. 1994, Hough et al. 1994). These guided waves can be used for investigations of inner fault structures such as the extent of the brecciated damage zone, fault-gauge produced by continuous slip or the fault zone serpentinitization. We plan to have several instruments directly in the fault zone perfectly suited for such an investigation.

Tomography. Main goals: improved event location, overall P- and S-wave crust-upper mantle velocity structure. For selected well-located events, we will invert subsets simultaneously for location and best-average 1-D structure (Kissling 1995) followed by 3-D structure and location inversion (Thurber 1983). Step-wise processing stabilizes the inversion (Kissling et al. 1994; Solarino et al. 1997) and results in best-constrained, best-resolved locations. Similar steps were employed for dense OBS deployments at mid-ocean ridges (Barclay et al. 2001). We will add regional arrivals, teleseismic delay times, which can be detected even at relatively noisy ocean floor sites based on Ocean Seismic Network Pilot Experiment (Collins et al. 2001) results, and later arriving local phases to the inverse problem to improve resolution of upper mantle model parts. With ~25 km station spacing and local earthquakes following the BTFZ quite narrowly, we do not anticipate to obtain a high-resolution 3-D crustal image. Our main objective is to resolve structural differences across and along the BTFZ at depth, particularly in trying to determine the lithospheric extent of the transform. Given the station spacing, the shallow structure is not expected to be well-resolved using tomography. The crustal structure is likely dominated by subhorizontal layering, for which receiver functions and ambient noise dispersion are better-suited techniques.

Ambient Seismic Noise and Receiver Functions. The ambient seismic noise field analysis (Campillo & Paul 2003; Shapiro & Campillo 2004; Shapiro et al. 2005; Sabra et al. 2005; 2006) can be used to resolve 3-D crust-upper mantle structure from continuous long-term recordings of long-period (~0.1-0.02 Hz) seismic noise. A fully diffuse wavefield allows extraction of inter-site Green's tensors by cross-correlation of seismograms recorded at receiver pairs (Fig. 8). The assumption of randomly distributed noise sources requires cross-correlation of long time series and/or stacking cross-correlations. Earthquakes actually are unwanted signal (they are not random sources and their signal dominates seismograms) and are eliminated (e.g., Derode et al. 1999; Campillo & Paul 2003; Herrmann et al. 2005).

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Table 1. Projected resolution improvements. Land, SOSUS, OBS are land, hydrophone, and OBS based earthquake detection and location thresholds for the BTFZ. MT: from moment tensor analysis.
Frequency-time analysis (Dziewonski et al. 1969; Levshin et al. 1972; Herrmann 1973) of the dispersive signal agrees excellently with group-velocities from earthquake data verifying that low-frequency ambient noise data, indeed, contain information about Earth structure. Dispersion measurements (Fig. 8) can be inverted for 2-D group velocity maps. This “seismology without source” provides tremendous possibilities for improving resolution of seismic images within a dense network. Conventional surface wave analysis is limited by event distribution, low resolution due to averaging over long event-station distances and difficulties to obtain accurate short-period dispersion measurements due to multi-pathing. Ambient noise analysis has been applied to OBS data only recently (Harmon et al. 2007), but has been extensively used, e.g., in association with the EarthScope TA-seismic array, for high-resolution images of continental crustal-scale structure (e.g., Yang et al. 2008).

Figure 8. Stacked ambient noise correlograms from 49 Hi-CLIMB stations relative to station H017. Each line is a stack of many day correlograms. (right) Rayleigh-wave group-velocity dispersion for stations 104 km apart.

Teleseismic receiver function analysis (Langston 1977) will be used to obtain independent Moho depth, crustal structure and average $V_p/V_s$-ratio estimates. Analysis requires 3-component seismic data; due to high noise levels, particularly for horizontal OBS data, we expect only large events (M>6.5) will provide useful receiver functions. We will stack these to get simple station averages for Moho depth to constrain depths for a joint 3-D inversion with ambient noise derived group velocities. Receiver functions are also sensitive to anisotropy. Both lead scientists have experience with receiver function analysis (e.g., Nabelek et al. 1993; 2005; 2009; Lombardi et al. 2008).

We will derive a 3-D crust-upper mantle S-wave velocity model by jointly inverting group-velocities and receiver functions extending 1-D (Özalaybey et al. 1997; Du & Foulger 1999; Julia et al. 2000) and 2-D methods (Vergne & Nabelek 2008). Dense station spacing provides very good path coverage to allow ~5 km lateral S-velocity resolution. We are eager to apply noise analysis to ocean bottom observations. Cross-correlation to extract Green’s functions is best performed with data from stable vertical sensors. We request DPG sensors because of their wideband low-noise characteristics. Analysis procedures of Shapiro and Campillo have been implemented and applied to Hi-CLIMB data (Vergne & Nabelek 2008).

We are interested in comparing the earthquake tomography model with noise-receiver function results (possibly leading to a joint inversion). The tomography model probably resolves P-wave structure better, while the noise-based/receiver-function model will provide S-wave structure. A major concern for our experiment design is to derive reliable structural information for the fault zone area relative to the Pacific and Juan de Fuca plate interiors. Blanco Ridge is a transform parallel ridge, which Dziak et al. (2000) suggested has a core of serpentinitized peridotite implying near-surface high P- and low S-wave velocities and likely high anisotropy. Resolving Blanco Ridge composition would help unravel the cause of its origin.

Anisotropy, especially in the upper mantle, can be studied using birefringence of SKS phases from distant large earthquakes (e.g., Wolfe & Solomon, 1998). Investigation of crustal anisotropy is better achieved with receiver functions and with local earthquake waveforms, which are also expected to show birefringence but at much higher frequencies.
Detection of non-volcanic tremor. Slow creep-like motions observed in subduction zones are often associated with non-volcanic high-frequency tremors. Slow-slip events in OTF systems (e.g., Beroza & Jordan 1990; Ihmle & Jordan 1994) may represent a similar phenomenon and may be associated with tremor. Low frequency, slow-slip signals will be problematic to detect by our array but tremor detection and localization is feasible. Tremor signals consist of intermittent weak, long-duration signals (up to a few weeks; Kao et al. 2005) in a 1-8 Hz frequency band without clear P and S phases (except for periods with relatively impulsive arrivals called 'low frequency earthquakes' [Katsumata & Kamaya 2003]). The chaotic signal character makes traditional phase based hypocenter locations impossible requiring signal-stacking techniques that scan a grid for best-possible location (Kao & Shan 2004).

6. Additional Relevance and Broader Impacts

Our study has several tiers of broader impacts. The scientific impact will be via the comprehensive analysis of seismicity and structure along the BTFZ. The improved multi-beam bathymetry acquired during the experiment will be of general interest to structural geologists and other investigators of the Blanco transform system. Exciting new deployments of OBS either already in place along the northern Juan de Fuca plate (Neptune Canada) or planned along the Cascadia subduction zone (joint MARGINS/EarthScope Cascadia amphibious array) combined with a concurrent BTFZ deployment would provide an unprecedented opportunity for monitoring intra-plate seismicity in the Juan de Fuca plate.

OBS-based earthquake locations provide an independent check of location accuracy provided by Navy's offshore hydrophone arrays (SOSUS). Previous comparisons (Cronin & Sverdrup 2003; Braunmiller & Nabelek 2008) indicated differences between SOSUS and relative earthquake locations, however, relative locations used only low-resolution teleseismic data. We have close ties with the NOAA-PMEL team in Newport, Oregon, which produces SOSUS locations, and will continue collaboration to resolve why SOSUS and land seismic locations differ. Precise local earthquake locations are useful to calibrate station-corrections. Land-based BTFZ earthquake locations are consistently ~30 km northeast of the fault zone an artifact due to uneven station distribution and improper Earth models. Calibration would improve BTFZ event location accuracy by land stations significantly. Precise locations would be extremely helpful to calibrate paths from the BTFZ to stations along the U.S. Pacific coast for waveform modeling.

Societal relevance. The rheology at OTF systems is simpler than for their continental counterparts; it is thus likely that a better understanding of earthquake mechanics and fault interaction along different fault segments can be gleaned from OTF systems. Ultimately, the findings can be extrapolated to continental transform fault systems, like the San Andreas, North Anatolian and Enriquillo-Plaintain Gardens faults, that cut through densely populated regions and pose significant earthquake hazard. Another hazard aspect is the relation of eastern BTFZ earthquakes to and their consequences on the Cascadia subduction zone; large BTFZ events potentially bring critically loaded faults closer to breaking either as a plate interface earthquake (the next Cascadia earthquake) or as a plate bending outer-rise earthquake (like the 2007 M=8.1 Kuril or the 2009 Samoa earthquakes) with devastating consequences to local communities and posing a circum-Pacific tsunami threat. Knowing maximum event size (M=6.5 or 7?), likely location and rupture characteristics could help to estimates BTFZ earthquake influence on Cascadia.

Education and outreach impact. The OBS deployment will provide seagoing experience for two graduate students, who will analyze the resulting dataset, as well as for four other students, who will help during deployment and recovery. Rachel Roberts, an undergraduate Math major at OSU, has been working in our lab for over a year analyzing regionally recorded earthquakes in Juan de Fuca plate region. She has been very productive and, motivated by the hands-on learning experience, is now planning to pursue a higher degree in seismology. We hope to entice other OSU undergraduates to follow her footsteps in this project. The public in Oregon, Washington and Northern California is concerned about strong felt earthquakes originating offshore in the Juan the Fuca plate. We have provided radio interviews and presentations at local schools after such events. Jochen Braunmiller's involvement in the EarthScope National Office at Oregon State University provides means for outreach activities among informal educators and teachers. Our college and university have active publication and outreach offices. We will use these offices to communicate our findings to wider audiences.