Note: The meetings of the NEPTUNE ad hoc science working groups were brainstorming sessions that allowed groups of creative scientists to explore the research possibilities that will be created by NEPTUNE's capabilities, as well as to better constrain those capabilities. Each working group white paper summarizes the results of these meetings. The ad hoc groups were not asked to prepare exhaustive lists of experiments nor to focus on the priorities of the experiments discussed. Such decisions, which require more detailed assessments, will be determined by peer-review decisions during Phase 2.

NEPTUNE Working Group White Paper

Opportunities for Seismology and Geodynamics

Table of Contents

1. Summary

The Juan de Fuca / Gorda / Explorer plate system incorporates a remarkable array of plate tectonic features within a relatively small area, including all major types of oceanic plate boundary. As a consequence, the seismic and geodetic component of the proposed NEPTUNE seafloor fiber-optic network will provide an opportunity to study a wide range of geophysical processes. In June 1999, a small ad hoc working group met in Seattle to discuss the scientific rational and requirements for seismic and related observations in NEPTUNE.

The last great earthquake along the Cascadia subduction zone occurred three centuries ago and there is considerable interest in improving our understanding of subduction zone seismogenesis and hazard. Seafloor seismometers and geodetic observations will lead to improved constraints on the earthquake cycle, the width of the locked zone and its variations along the margin and can also contribute to an improved understanding of deep intraslab earthquakes. Long-term observations are required for multidisciplinary experiments to understand the relationships between earthquakes, fluid flow in the accretionary prism, and catastrophic sediment transport events. At the Juan de Fuca and Gorda mid-ocean ridge, seafloor seismic observations are essential for understanding the relationship of seismicity to magmatism and hydrothermalism. Both seismic and geodetic measurements will be an important part of the long-term observatories that have been envisioned for the Juan de Fuca Ridge. At present, our understanding of tectonism and deformation on oceanic transform faults is also limited. This setting may be particularly important for studies of earthquake physics since many earthquakes on transforms appear to have anomalously slow rupture characteristics.

At the plate-scale, observations of seismicity and deformation will constrain many important processes including the nature and causes of variations of stress with time across the plate, the styles and causes of intra-plate earthquakes, and the coupling of forces across plate boundaries. A plate-scale seismic array will also facilitate studies of the structure and evolution of the lithosphere-asthenosphere system. Such work would contribute to our understanding of mantle melting, the coupling of the mantle to the lithosphere, the pattern of return flow from trench to ridge, the nature of mantle flow near plate boundaries, and the rheology of the mantle.

Because many of the problems of interest require observations at the plate scale, the first priority for a seismic network is to deploy a fiber-optic backbone across the entire Juan de Fuca / Gorda / Explorer plate system instrumented with ~30 broadband seismometers spaced about 100 km apart at each primary junction box. In order to develop a fully two-dimensional network that spans the plate boundaries, 30-40 additional broadband sensors will eventually be required at distances of 50-100 km from the nearest primary junction box. In selected areas of seismic interest, local networks of intermediate band seismometers should be deployed to supplement the regional network. There are a variety of seafloor geodetic techniques at various stages of development that can be used to study motions near plate boundaries and plate scale deformation. Such observations will complement the seismic network and should be an important component of NEPTUNE.

2. Introduction

The movement and interaction of lithospheric plates gives rise to many of the Earth's most dramatic and hazardous geologic features. In the Pacific Northwest, the processes accompanying the creation of the oceanic Juan de Fuca plate and its eventual subduction beneath North America result in mountain building, damaging earthquakes and explosive volcanism. Understanding the causes of such geologic hazards, as well as the processes responsible for the formation, evolution, interaction, and destruction of tectonic plates is a central goal of the geosciences. The Juan de Fuca / Explorer / Gorda plate system (Figure 2.1) represents a natural laboratory for addressing many questions related to this goal since it incorporates a remarkable array of plate tectonic features within a relatively small area.

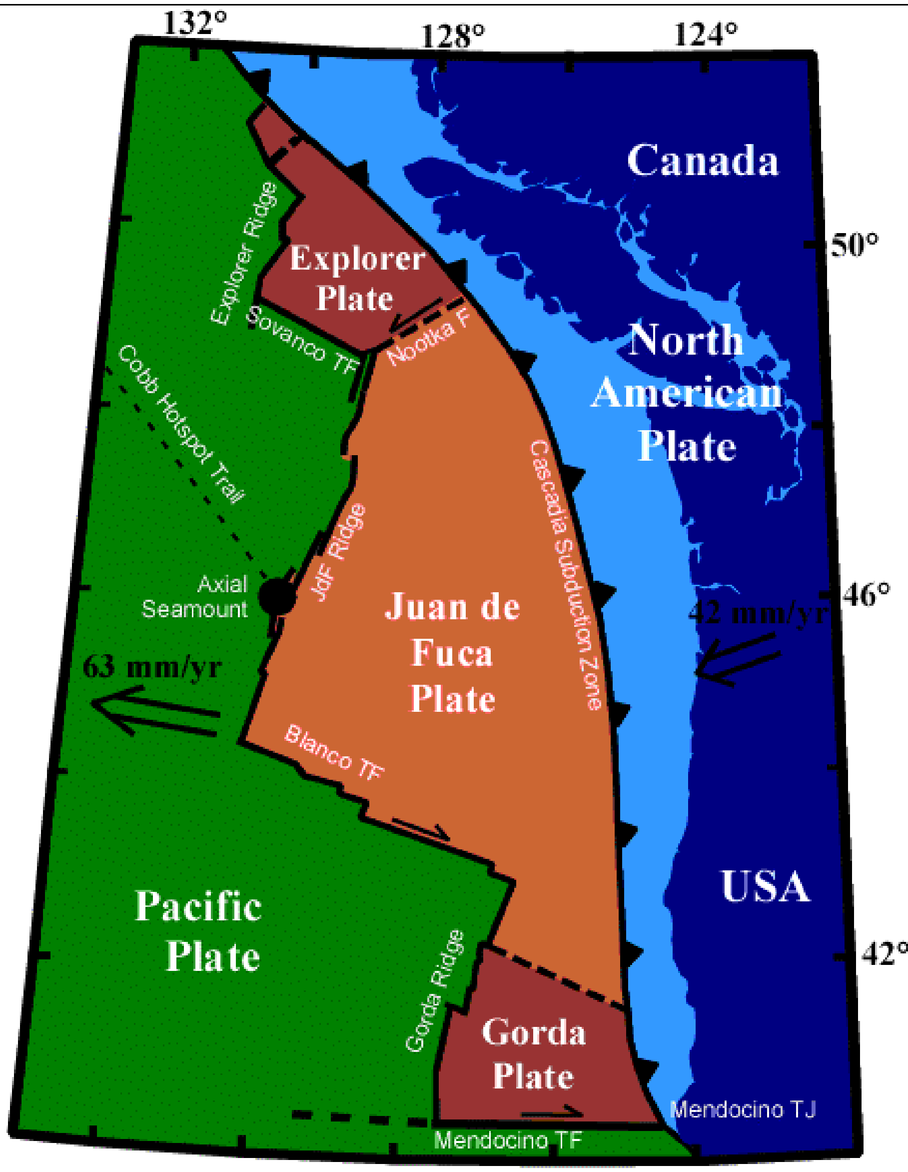


Figure 2.1. Location of plates and plate boundaries in the Pacific Northwest. The velocities of the Pacific and North American plates are shown relative to the Juan de Fuca Plate. Acronyms are as follows: JdF - Juan de Fuca; TF - transform fault; TJ - Triple Junction; and F - fault.

In western North America, large regional land seismic networks have been in operation for about 30 years (Figure 2.2). Long-term observations have provided a comprehensive view of the distribution and style of continental seismicity and of the seismic structure of the continental lithosphere. The seismic sensors in these networks are currently being upgraded from narrow band geophones designed to identify arrival times to broadband sensors and there are plans to increase the total number of stations. Data from broadband stations facilitates a wide variety of advanced studies involving the analysis of seismic waveforms. In the past decade, geodetic networks that utilize GPS have also been deployed (Figure 2.2) and as they grow, they are providing an increasingly detailed and complementary picture of crustal strain rates. However, in the Pacific Northwest much of the seismicity and deformation associated with the Pacific / Juan de Fuca / North America plate boundary system occurs offshore. Even the most extensive land-based networks can provide only a partial and one-sided picture of this process.

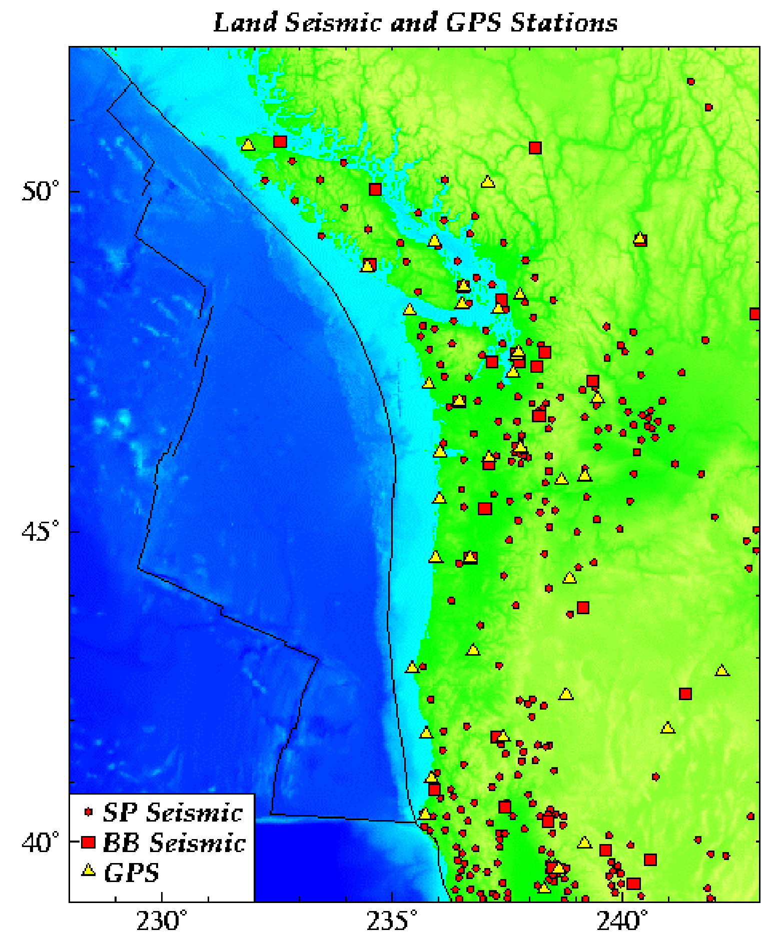
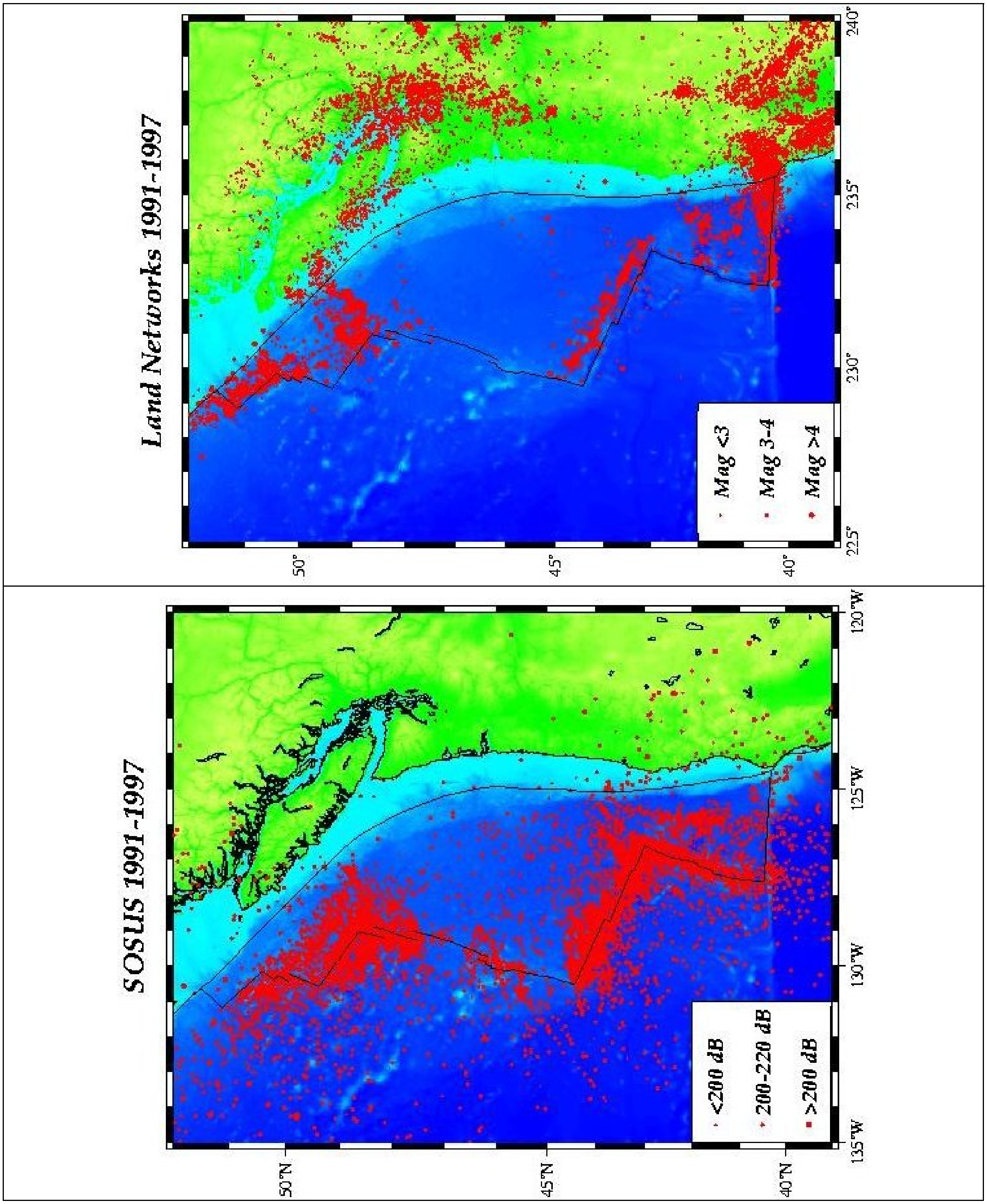


Figure 2.2. Distribution of land seismic and permanent GPS stations in the Pacific Northwest. Broadband (red squares) and short period (red circles) seismic station are shown for the Pacific Northwest Seismograph, Canadian National Seismograph, Northern California Seismic, Berkeley Digital Seismic, Boise State University Seismic and Western Great Basin Seismic Networks. GPS stations (yellow triangles) are shown for the Pacific Northwest Geodetic Array (PANGA) and the Bay Area Regional Deformation (BARD) / Northern California Continuous GPS Network.


SOSUS 1991-1997
<200 dB
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>200 dB
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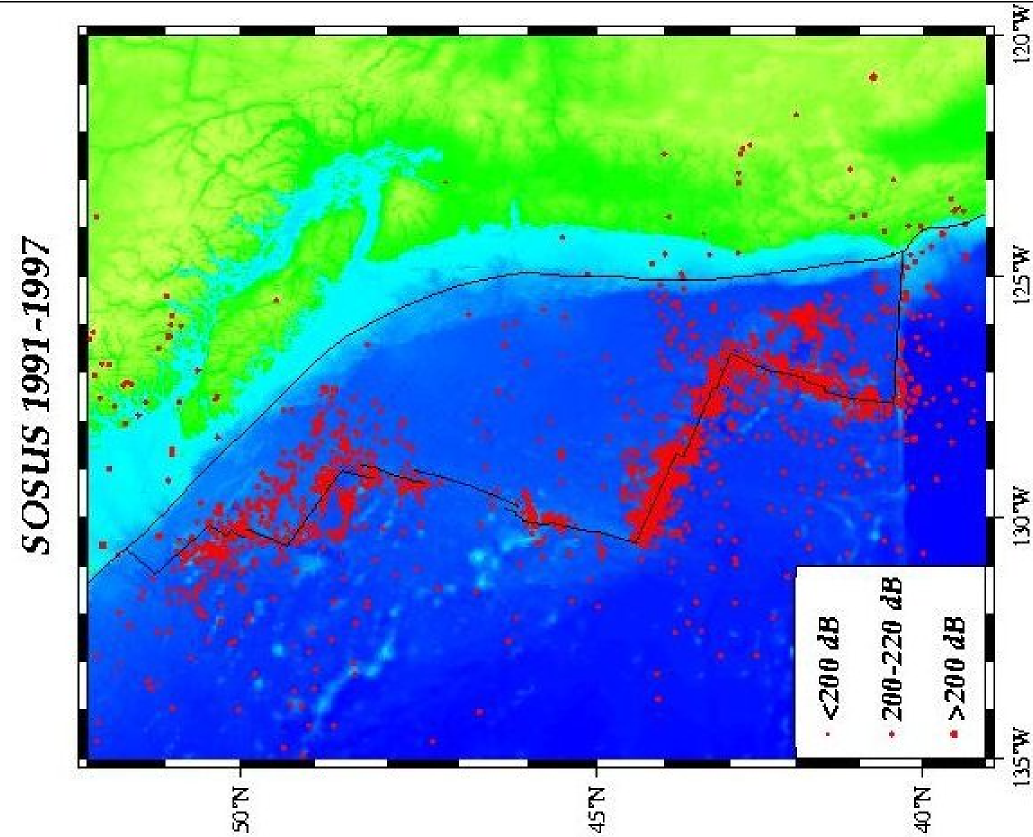

Figure 2.3. Earthquakes epicenters for the period August 29, 1991 - December 31, 1997 determined using (top) land seismograph data from the Pacific Northwest Seismograph Network, Canadian National Seismograph Network, and the Northern California Seismic Network and (middle, bottom) T-phases recorded by underwater hydrophones in the U.S. Navy's SOund SUrveillance System (SOSUS) and analyzed by NOAA/PMEL. The middle plot shows locations determined for three or more SOSUS arrays while the bottom plot shows more accurate epicenters derived for those events recorded by four or more arrays.

To date, seafloor seismic and geodetic experiments in the area have been limited to short deployments of local ocean bottom seismometer (OBS) arrays mostly on the Juan de Fuca Ridge and a number of pilot geodetic experiments. Since 1993, the availability of continuous T-phase data from the US Navy's SOSUS hydrophone arrays has significantly reduced the detection threshold for submarine earthquakes in the Pacific Northwest (Figure 2.3). The SOSUS data shows that there is considerable seismicity in the Juan de Fuca / Explorer / Gorda plate system and has been central to efforts to detect and respond to submarine eruptions on the Juan de Fuca Ridge. However, the detection threshold for the SOSUS data is still poorer than within a good regional network and the epicenters are only accurate to a few kilometers. The T-phase data provides only qualitative information on earthquake depth, no constraints on focal mechanisms, and cannot be used to image earth structure. Focal mechanisms can be derived with broadband seismometers on land but are limited to the small number of earthquakes with magnitudes greater than about 4 (Figure 2.4). A complete picture of the seismicity and seismic structure of the Juan de Fuca plate can only be obtained from seismometers deployed on the ocean floor.

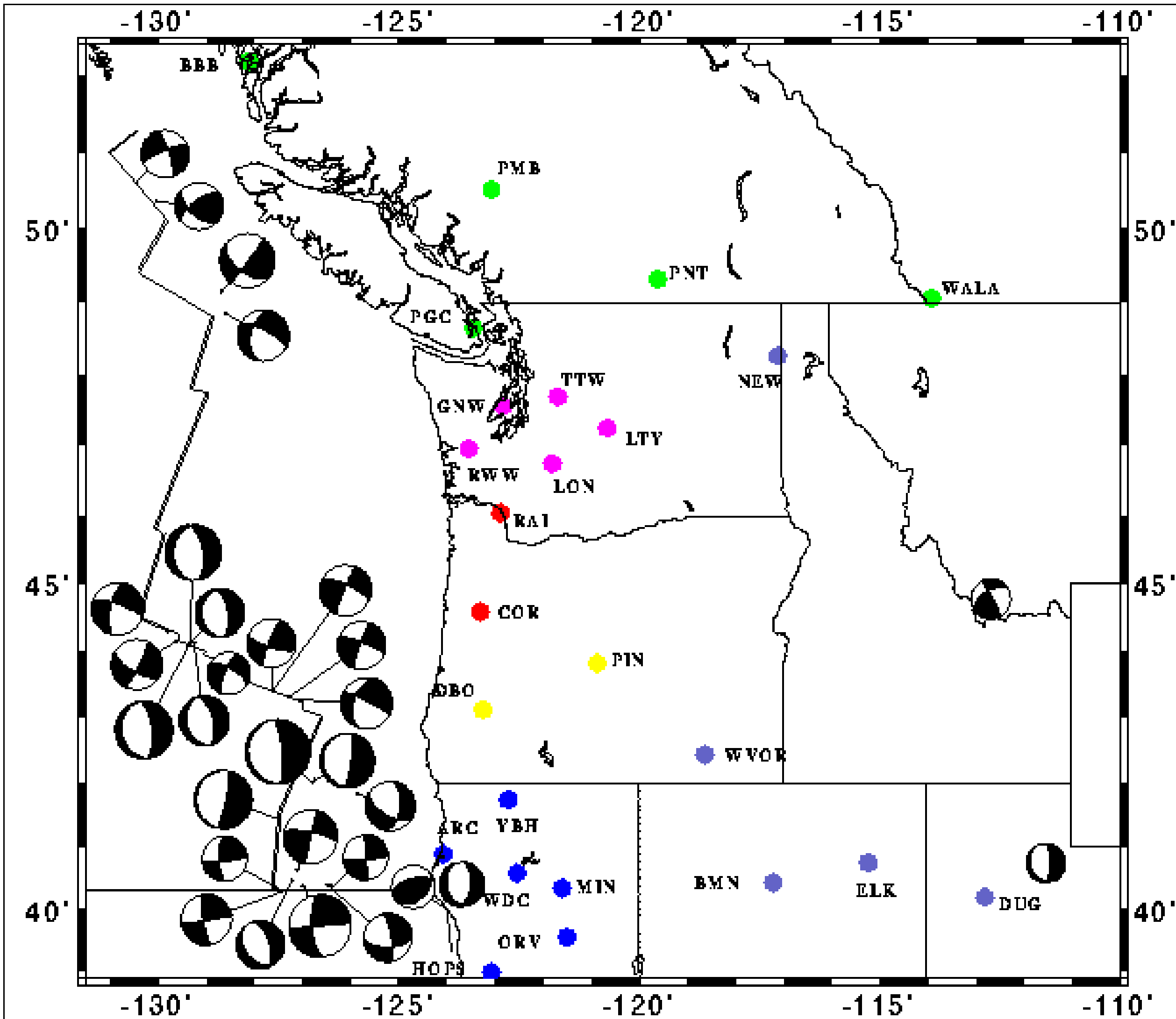

Figure 2.4. Focal mechanism determined for magnitude >4 earthquakes in the Pacific Northwest using waveform data from broadband stations on land (from Nabelek and Xia, 1996). Note that most of the larger earthquakes in the region are located offshore in the environs of oceanic transform faults, the Gorda ridge, and the Gorda plate.

The NEPTUNE Project is an ambitious plan to deploy a fiber optic cable network on the Juan de Fuca plate. This system will provide the power and communications necessary to support instrumentation for a wide-range of long-term geological, oceanographic, and ecological studies. From the standpoint of geophysics, it will provide a unique opportunity to deploy a long-term regional plate-scale network of seafloor seismometers and related geodetic instruments in the Pacific Northwest. This report explores the scientific rational and technical requirements for such observations. It is based on a small meeting held in Seattle in June 1999 together with contributions from several scientists who did not attend.

3. Major scientific issues

3.1 The Seismic Potential of the Cascadia Subduction Zone

The Pacific Northwest from Northern California to Southern British Columbia is subject to a large earthquake hazard. As with other subduction zones, there are three potential earthquake source zones: the continental crust, the downgoing oceanic plate, and the thrust fault marking the plate boundary (often termed the megathrust). NEPTUNE can contribute to our understanding of all three sources. It is especially important for addressing questions related to the megathrust earthquake cycle and for improving our understanding of earthquakes in the downgoing oceanic plate.

Megathrust Earthquakes

Although there is no historical record of large megathrust earthquakes in Cascadia, there is mounting evidence that they have occurred as recently as 300 years ago (e.g., Hyndman, 1995). Elsewhere, these earthquakes are responsible for the most devastating earthquakes and tsunamis. Long term observations are required to understand the physical processes preceding and accompanying megathrust events in order to develop a framework for predicting ground motions. Seismometers are needed to detect and locate the small but tectonically important earthquakes currently missed by onshore networks, and to provide better constraints on the depths and focal mechanisms of larger events. Geodetic observations can provide critical information on the nature and extent of offshore deformation in the megathrust zone. Other sensors are needed to measure fluid flow and pore pressures, since fluid processes are likely to be an important factor controlling earthquakes and will affect the ground motion and slope instability resulting from earthquakes.

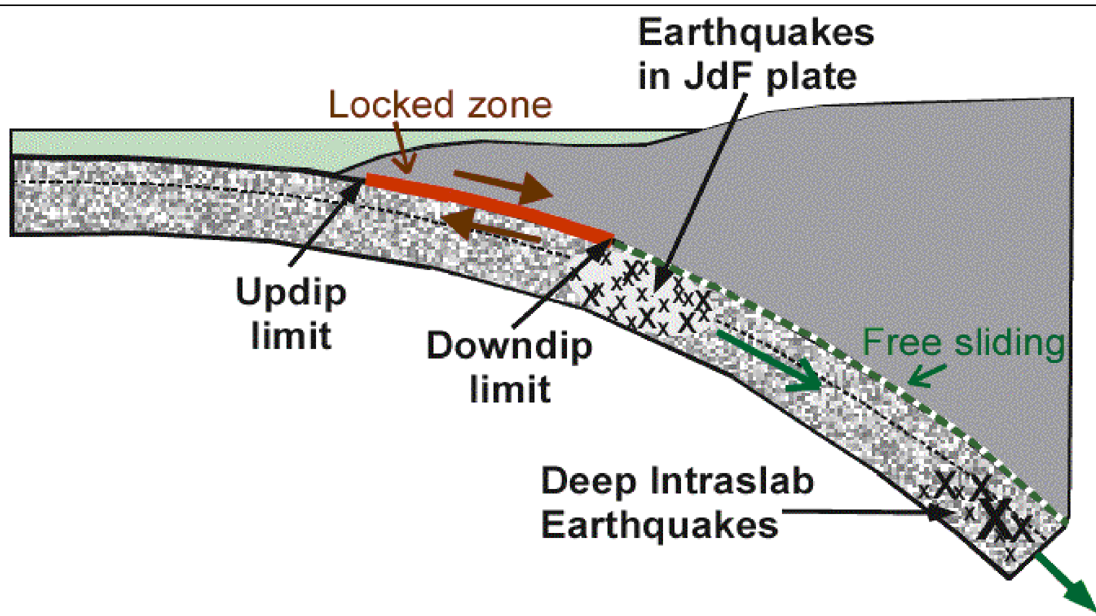

Figure 3.1.1. Schematic cross-section of the subduction zone. Earthquakes in the subducting oceanic plate beneath the inner continental shelf may define the downdip limit of the megathrust rupture zone (i.e., the zone that is presently locked) and their mechanisms may evolve from downdip compression after a great event to downdip tension later in the earthquake cycle. Deep intraslab earthquakes are believed to be a result of metamorphic processes.

What is the rupture area for megathrust earthquakes and how does it vary along the subduction zone?

The landward and seaward limits of the seismogenic or locked part of the megathrust (Figure 3.1.1) are important parameters controlling the hazards from subduction zone earthquakes (Hyndman et al., 1997). The landward rupture limit is the closest approach of the earthquake source to inland cities and is thus very important for predictions of earthquake shaking; the seaward limit is important for tsunami generation. Variations in these seismogenic limits may also partially explain why some subduction zones have maximum earthquake magnitudes of less than 7.5 while others support earthquakes of magnitude greater than 9.

<u>Landward limit:</u> At present, the main constraint on the downdip limit of the locked portion of the megathrust comes from modeling land geodetic data (Figure 3.1.2). The models assume that the

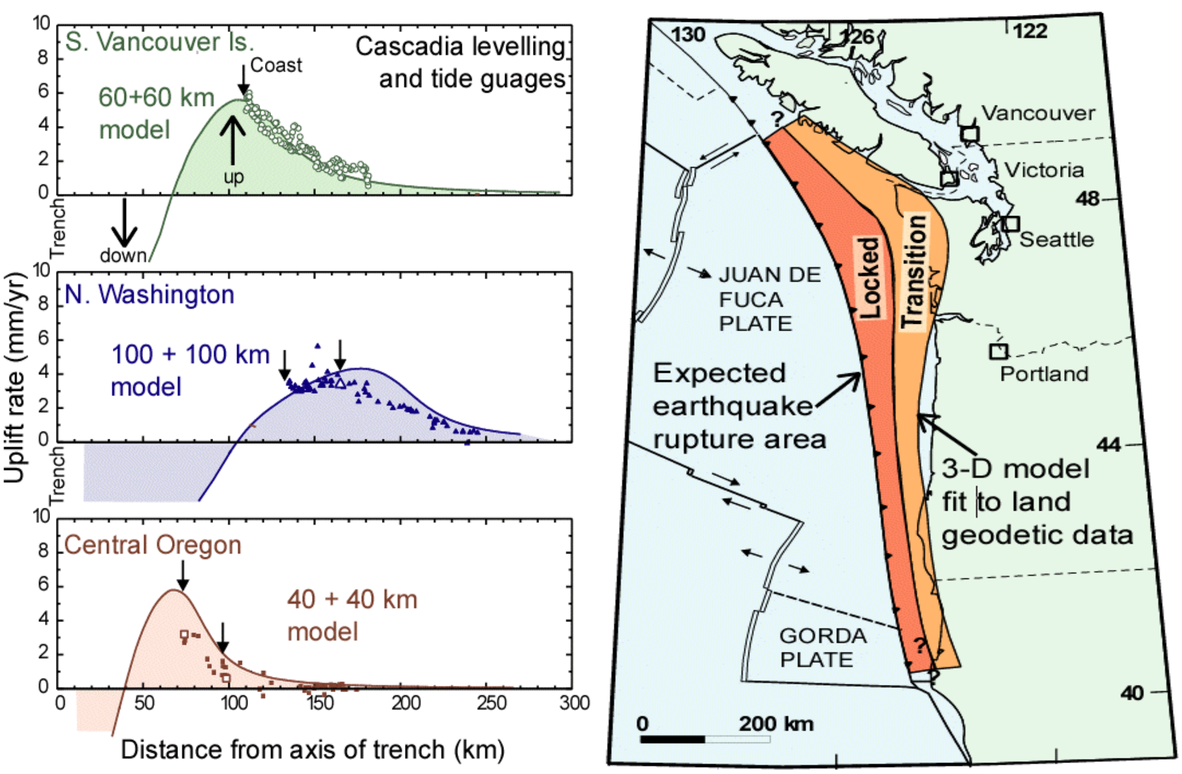

Figure 3.1.2. Elastic dislocation model of the interseismic deformation produced by a locked subduction zone. The left figure shows the fit of a two-dimensional model to vertical deformation data at three locations along the subduction zone (Hyndman and Wang, 1995). Clearly the models would be better constrained with seafloor data. The right figure shows the areas of the locked and transition zones for a three-dimensional model (Fluck et al., 1997). Note that the seaward limit of the locked zone is not constrained by the geodetic data and the boundary between the locked and transition zones is chosen on the basis of thermal constraints. GPS data is now providing improved constraints on the locked zone and future models should include a more realistic viscoelastic rheology.

downdip limit is determined by a critical temperature and that steady subduction occurs at greater depths (i.e., greater temperatures) by ductile flow. Since most of the deformation associated with the locked zone occurs offshore, seafloor geodetic observations in the subduction zone would help test the assumptions underlying these models and would provide the constraints necessary for more sophisticated models.

Data from seafloor seismometers also can test these models. Any small earthquakes that are accurately located on the subduction thrust will provide direct constraints on the extent of the seismogenic zone. The concentration of seismicity in the downgoing plate beneath the west coast of southern Vancouver Island and northern Washington (Figure 3.1.3) may also constrain the downdip limit. It has been postulated that these earthquakes are caused by stress concentration at the downdip end of the locked zone (Figure 3.1.1). This model predicts a change from mainly downdip compression immediately after a great earthquake, to downdip tension as the increasing shear stress on the locked zone is transferred to the deeper slab. Offshore seismic stations are needed to obtain accurate event locations and fault mechanisms to test this prediction. If it proves to be correct, these earthquakes may be of particular importance since they will allow us to determine where we are in the great earthquake cycle.

If the landward limit of the locked zone is controlled by a critical temperature, it should differ depending upon the composition of the rocks across the subduction thrust fault. Most of the locked zone is believed to lie beneath the accretionary prism, which has a relatively constant clastic composition. However, off central Oregon the mafic Siletz terrain extends seaward beneath the continental shelf and geophysical data suggest that there may be a buried mafic ridge on the subducting plate. Since the critical temperature is likely to be higher for mafic rocks and the buried ridge may act as an asperity, the locked zone may extend considerably further landward. Historically, this region has had a very low level of seismicity and geodetic data are sparse and give apparently contradictory results. Accurate locations for small offshore microearthquakes are essential if we are to determine the width of the locked zone in this region.

Seaward limit: The seaward limit of rupture is a primary control on the tsunamis generated by great earthquakes. The limit is very poorly known for the Cascadia margin because there have been no historical great earthquakes. The land geodetic data cover only about one third of the zone of plate boundary shortening (Figure 3.1.2) and as a result the seaward portions of dislocation and other earthquake cycle models are very poorly constrained. At present, our only constraints on the tsunami wave amplitudes come from records in Japan for the last great event (in 1700), and from paleotsunami studies along the Cascadia margin. Offshore microearthquake and geodetic data would place strong constraints on the updip rupture limit and tsunamogenic potential of the Cascadia subduction zone.

Can the accretionary prism support earthquakes?

Earlier studies concluded that accretionary prisms were aseismic world wide, and that the portion of the megathrust beneath accretionary prisms was also aseismic. Indeed, this was one explanation given for the aseismic updip zone observed for most great subduction earthquakes. Along most of the Cascadia margin, most if not all of the seismogenic portion of the megathrust is inferred to lie under the accretionary prism. In this region it is particularly important to understand the seismic behavior of accretionary sediments to determine whether great earthquakes can occur beneath accretionary prisms. No earthquakes have been unequivocally recorded in the Cascadia accretionary prism. However, this may be just a consequence of the high magnitude threshold for detecting offshore earthquakes with the land networks and of the

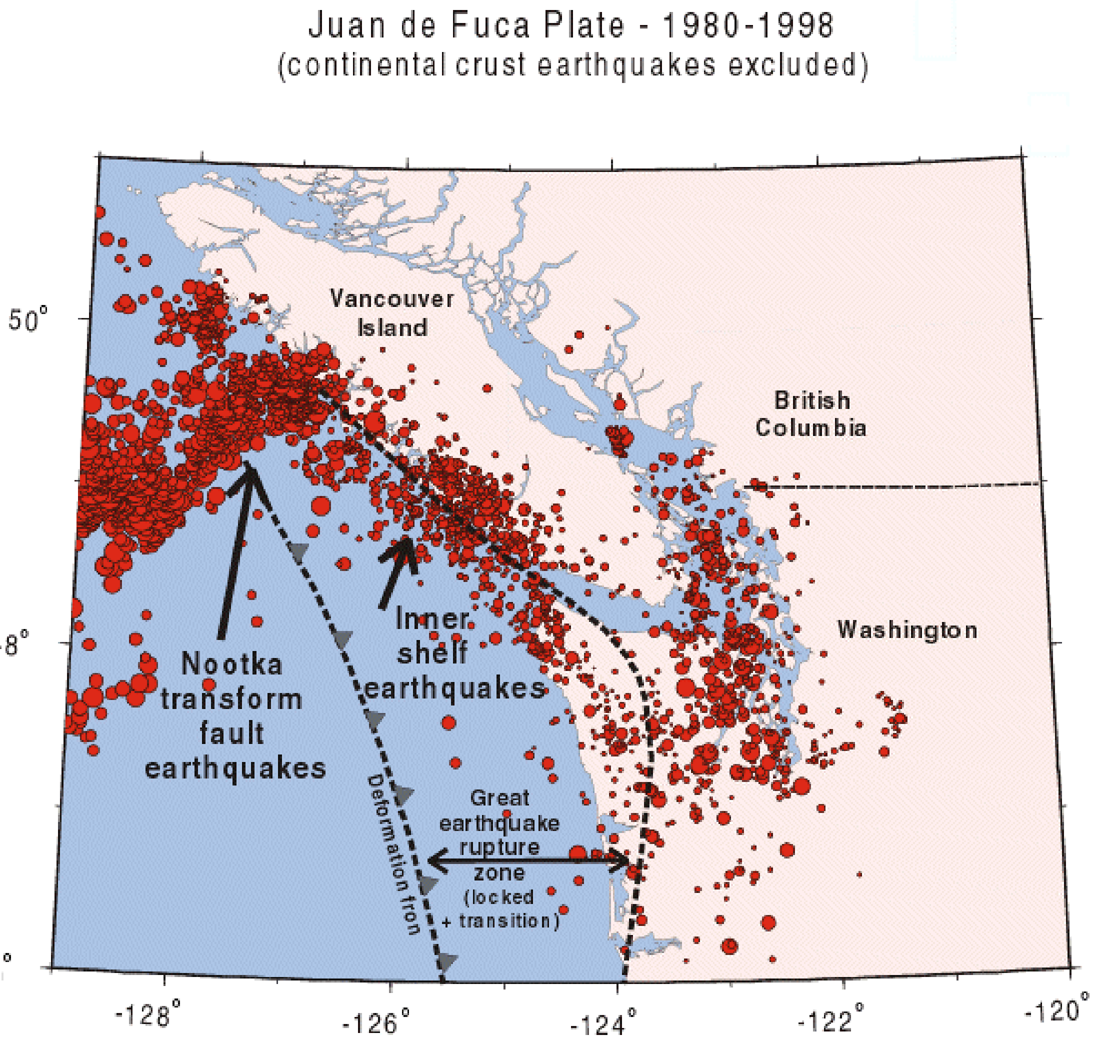

Figure 3.1.3. Earthquakes in the Juan de Fuca plate beneath the north Cascadia margin (earthquakes in the continental crust have been excluded). The inner shelf earthquakes may mark the landward limit of the locked portion of the subduction thrust fault. The Nootka transform fault is a strong shaking source beneath the accretionary prism.

poor depth accuracy for the locations. Offshore seismographs will allow detection and accurate location of small earthquakes. The presence of microearthquakes in the prism would confirm that well-consolidated accretionary sediments can support the seismic behavior (velocity weakening) required for great events.

What is the intensity of shaking at inland cities for megathrust earthquakes?

Seismic hazard estimates for the larger cites in the Cascadia forearc (Portland, Seattle, Vancouver, Victoria) are presently affected by large uncertainties in the expected attenuation with distance of megathrust events and in the focussing of energy landward. In this structurally complex region, the standard relations for ground motion attenuation with distance from earthquake sources could have a large error. In particular, the energy from great earthquakes may be reflected from the Moho in the shallowly subducting oceanic plate and it has been postulated that the inland cities may be at the critical distance where this phase is strongly focussed. Well-located small to intermediate offshore earthquakes lying in the oceanic crust or overlying accretionary prism (i.e., above oceanic Moho) can be used to calibrate the attenuation relations and assess the importance of focussing. More accurate ground shaking estimates from great earthquakes might thus be possible.

Intraslab Earthquakes

In the past century, the most damaging earthquakes in the Pacific Northwest have been intraslab events, earthquakes that occur within the subducted Juan de Fuca plate at depths of 30 to 70 km. Examples include the magnitude 7.1 Olympia earthquake, 1949, and the magnitude 6.5 SeaTac earthquake, 1965. These earthquakes are believed to be related to metamorphic processes in the slab (Kirby et al., 1996). The oceanic crust created at the mid-ocean ridges is hydrothermally altered and hydrated. During subduction, the hydrated basalts and gabbros are transformed into the higher density eclogite and this induces deviatoric stresses. The metamorphic transformation also releases significant amount of water (1-2% by weight) that elevates pore fluid pressure. The combination of the stress and fluid pressure increases may reactivate some pre-existing faults and cause earthquakes.

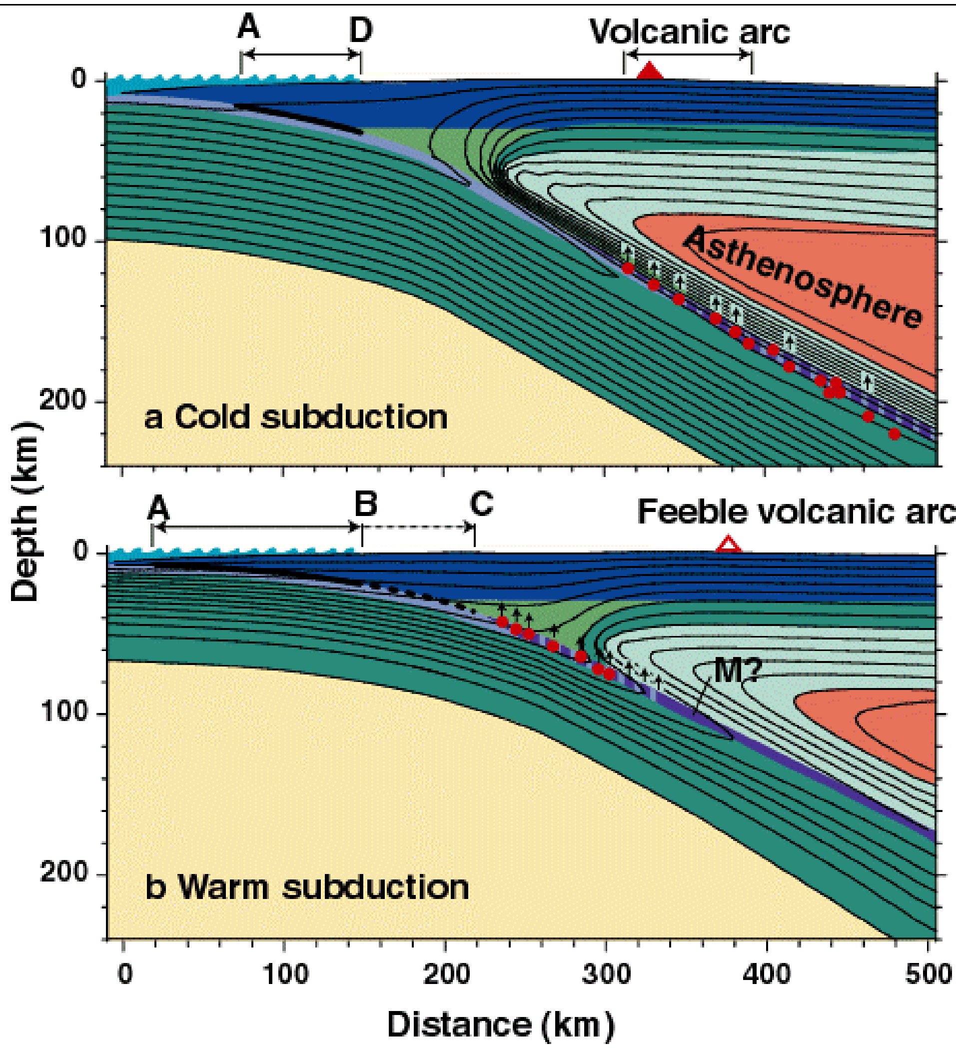

Figure 3.1.4. Cross-sections of cold and warm subduction zones. In warm subduction zones such as Cascadia, arc volcanism is sparse and dehydration due to the basalt-eclogite transformation and intraslab earthquakes (red dots) occur at shallower depths (from Kirby, 2000).

It has been well documented that the subduction zone thermal regimes have a strong influence on intraslab earthquake processes (Figure 3.1.4). Peacock and Wang (1999) studied the NE Japan and SW Japan subduction zones, typical examples of cool and warm subduction zones, and concluded that the higher temperature in the SW Japan subduction zone caused the basalt-eclogite transformation and hence intraslab earthquakes to take place at much shallower depths. Other consequences include a shallow termination of a low seismic velocity layer representing the untransformed crust, sparse arc volcanism, and possible melting of the slab. The Cascadia subduction zone is a warm subduction zone because of the young age of the subducting Juan de Fuca plate, and is very similar to SW Japan.

What controls intraslab earthquakes and hazards?

NEPTUNE will provide an opportunity to improve our understanding of intraslab earthquakes and will allow us to assess their hazard along the Cascadia margin. NEPTUNE will host studies of seafloor hydrothermal activity on the Juan de Fuca ridge and it flanks and these observations will contribute to our understanding of the degree and depth extent of the hydration of the oceanic lithosphere prior to subduction. Long term monitoring of seafloor seismicity will yield information on the distribution and extent of faults in the subducting slab. In addition to constraining the characteristics of the plate prior to subduction, seafloor seismic observations can be used to study the slab after subduction. For this margin, the intraslab stress regime is rather poorly constrained at depths between 10 and 50 km, partly due to the lack of seismic observations offshore. By recording and analyzing seismic waves that are generated by intraslab events and that propagate along the slab, it will be possible to constrain the seismic velocity structure of the slab and thus infer its thermal structure and petrology. Such information is essential if we are to constrain downdip and along-strike variations in the metamorphism and earthquake processes in the slab. In the long term, a better understanding of the mechanism of intraslab earthquakes and the slab thermal and mechanical structure will facilitate a more rigorous hazard study for these earthquakes.

3.2 Mechanisms of Plate Deformation and Interactions

While the theory of plate tectonics is now several decades in the making, earth scientists have only just started to attempt to monitor plate scale deformation on continents. Even when these efforts are successful, they will only provide a partial picture of plate tectonics on the Earth. There are many important questions that can only be addressed by plate scale observations in the oceans.

What is the style of deformation along plate boundaries?

We know from observations on land, that continental plate boundaries are associated with wide zones of deformation. For instance, the deformation associated with Pacific-North American plate boundary extends over the western third of North America. In comparison, plate boundaries within the oceans appear relatively narrow. Qualitatively, this difference must reflect both the different characteristics of the plate boundaries and the high strength of oceanic lithosphere relative to the continents. Because the Juan de Fuca plate includes every type of plate boundary, NEPTUNE can provide the long-term observations necessary to quantify the width and style of deformation along oceanic plate boundaries.

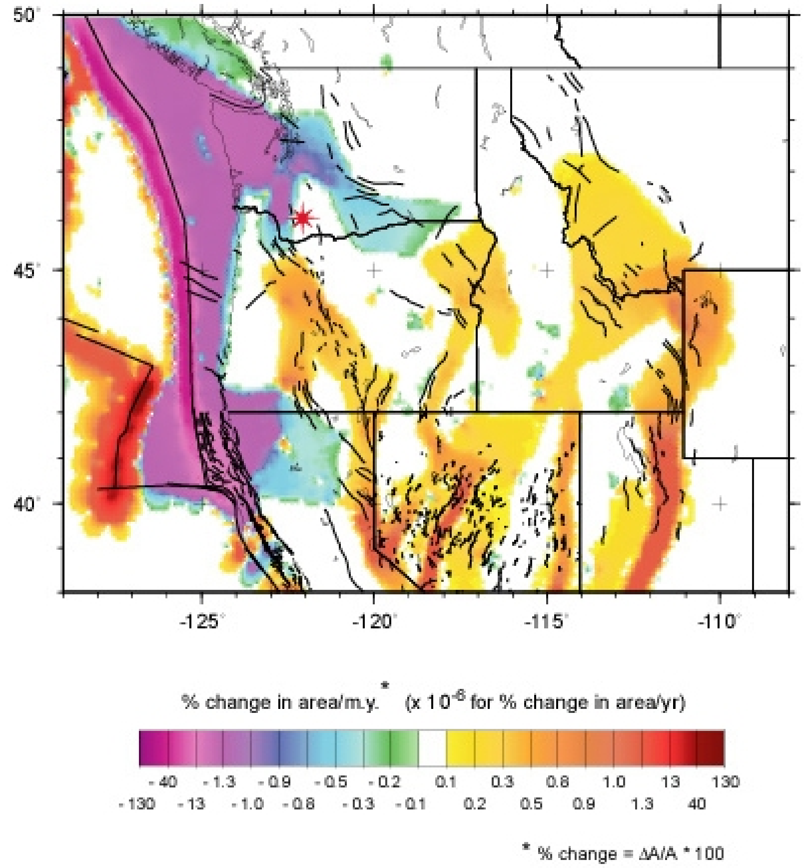

Figure 3.2.1 Isotropic strain map for the Pacific Northwest from the finite element modeling of Hemphill-Haley (1999). Warm colors (red) indicate a gain in area and cool colors (blue) a loss of area. Much of the strain associated with the Cascadia subduction zone is located offshore.

Figure 3.2.1 shows a model of isotropic strain map (Hemphill-Haley, 1999) derived by combining land GPS observations with a finite element model that explicitly includes known faults. The model shows that the much of the compression associated with subduction is located offshore. However, the model is only constrained offshore by global plate-tectonic kinematic models. Here the model cannot be refined without local observations constraining the width of the deformation zone and the stresses imparted by the overriding plate in the subduction zone. Similarly, improved mechanical models of deformation at spreading centers and oceanic transform faults require improved observations of the nature of deformation at these boundaries.

How and why do stresses vary with time across the Juan de Fuca plate system?

Epicenter data derived from SOSUS by NOAA/PMEL reveal patterns of increasing and decreasing seismicity over large areas and over a time scale of several months. For instance, Fox and Dziak (1999) show that activity in a 400-km-long band of intense mid-plate seismicity in the Gorda plate ceased following a magnitude 7.2 earthquake in the Cape Mendocino region (Figures 3.2.2 and 3.2.3). They propose that the band of mid-pate seismicity reflected an accumulation of stress in the Gorda Plate that was reduced by movement in the adjacent subduction zone during the Cape Mendocino earthquake. This intriguing study suggests that oceanic plate can transmit stresses over many hundreds of kilometers but the mechanism by which this happens is poorly understood.

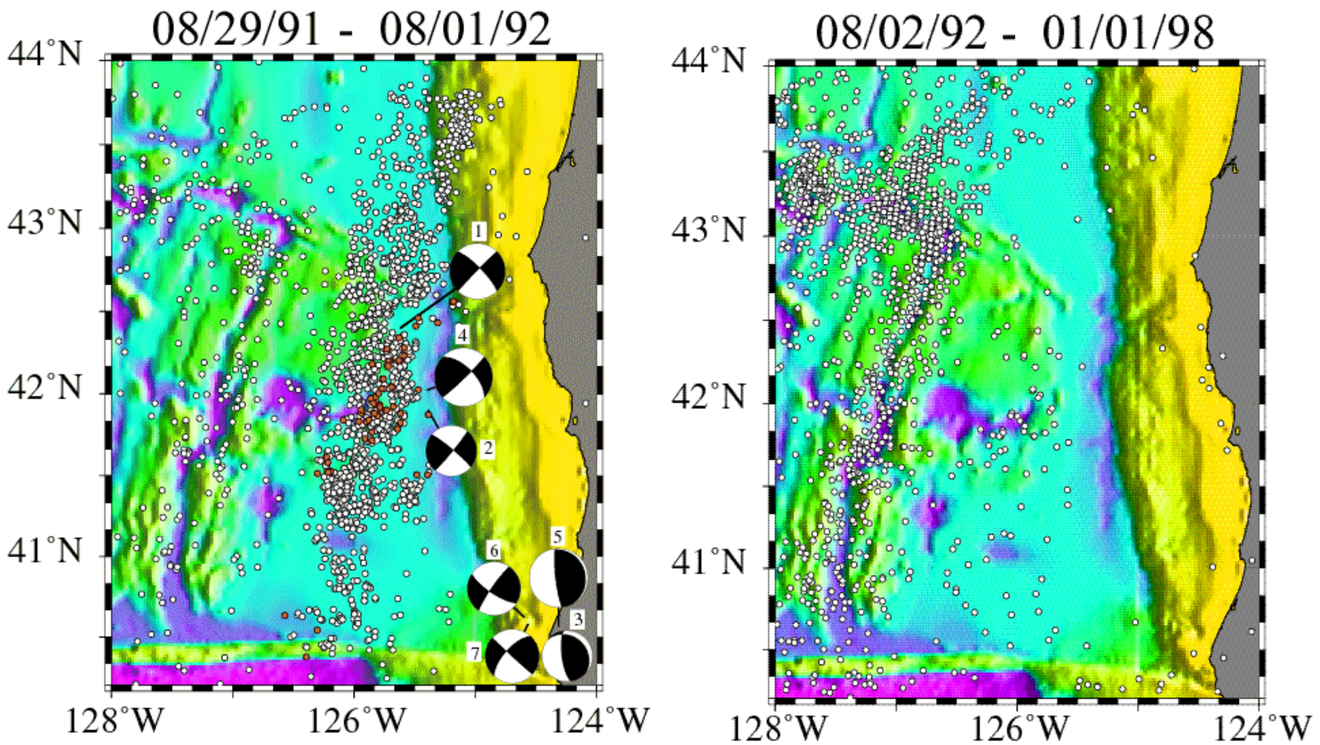

Figure 3.2.2. Distribution of earthquake epicenters in the Gorda Plate region derived from both land-based networks (red dots and focal mechanisms) and hydrophone arrays (white dots). The left-hand map shows events recorded from the beginning of hydrophone monitoring on August 29, 1991 through August 1, 1992. The right-hand map shows events recorded from August 2, 1992 through January 1, 1998. A band of hydroacoustically recorded microearthquakes in the middle Gorda Plate can be clearly seen in the left-hand map but has effectively ceased after July 1992. The mechanisms in the left-hand map are lower-hemisphere, equal-area projections with the compressional quadrant shaded. The diameters of mechanisms are proportional to the earthquake magnitude (from Fox and Dziak, 1999).

The Juan de Fuca plate is still relatively competent and undeformed, and it is not unreasonable to speculate that it may be able to transmit stresses over very large distances. A plate scale seismic and geodetic network would allow us to understand how stresses couple across the plate and how they vary with time. For instance, do earthquakes on the Blanco transform affect stresses in the subduction zone? How rapidly are stress perturbations transmitted into the far field? Does the volcanic topography of the spreading centers significantly modify the strain pattern over the plate? Are earthquakes or volcanic sequences triggered by phenomena in the far field and if so under what circumstances?

What are the causes and styles of intraplate deformation?

We know from the distribution of epicenters recorded by land networks and SOSUS and from seafloor morphology that the Gorda and Explorer plates are undergoing internal deformation (Figures 2.1.3 and 3.2.2). While less frequent, intraplate earthquakes also occur on the Juan de Fuca plate. Some of the intraplate earthquakes are recorded on land and mechanisms can be inferred for a few large events (Figure 2.4). However, these observations are insufficient to resolve some fundamental issues. For example, it is unclear whether the Explorer plate is still a discrete microplate as shown in Figure 2.1 or whether it is being reworked as part of a regional

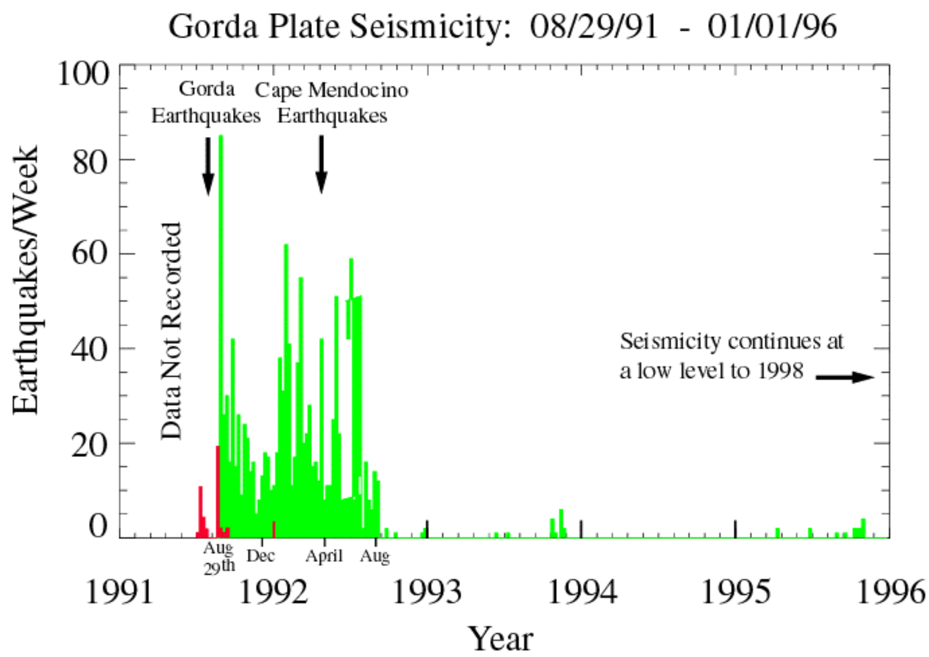

Figure 3.2.3. Histogram of the number of earthquakes per week in the Gorda Plate microseismicity band detected by SOSUS (green) and land stations (red). The location of the microseismicity band can be seen in the left map of Figure 3.2.2. The times of occurrence of the teleseismically-detected earthquakes from the Gorda Plate and Cape Mendocino are labeled. It is inferred that the decrease in the level of microseismicity in the Gorda Plate is the result of stress reduction induced by the Cape Mendocino earthquakes in the adjacent subduction zone (from Fox and Dziak, 1999).

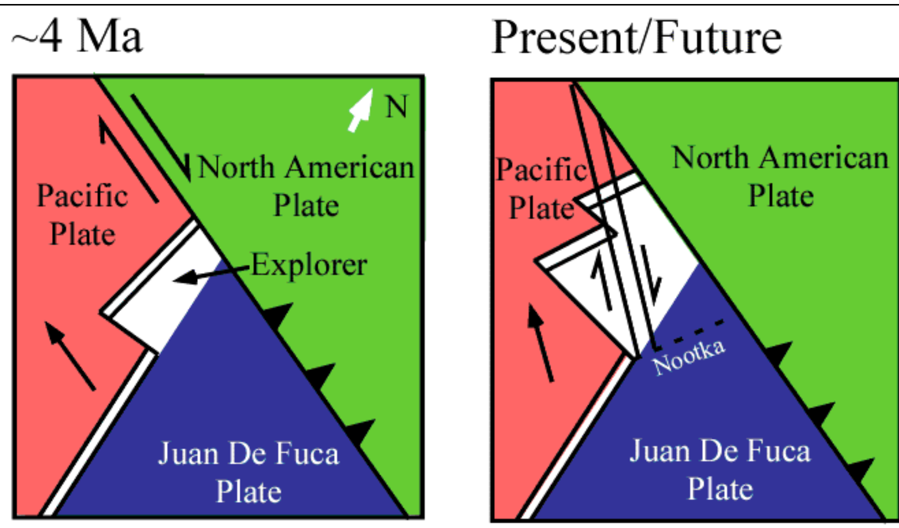

Figure 3.2.4. One possible tectonic model of the Explorer region. Following a 20 degree rotation of the Juan de Fuca ridge between 4 and 5 Ma, the Explorer Ridge split off as the three major plate boundaries try to form a stable geometry. This is being accomplished by the southward extension of the Queen Charlotte Fault (Pacific / North American plate boundary) into oceanic crust and dismemberment of the Explorer plate. For this model the eastern part of the plate now appears to be part of North America and the Ridge will probably be extinct within a few Ma (from Rohr and Furlong, 1995).

simplification of the plate boundaries as shown in Figure. 3.2.4. The Explorer plate region is characterized by ridge jumps, complex topography, indecipherable magnetic anomalies, large hydrothermal deposits and faulted sediments all associated with high rates of diffuse seismicity (Wilson, 1965; Barr and Chase, 1974, Hyndman et al., 1979; Riddihough et al., 1981; Davis and Riddihough, 1982; Davis and Currie, 1993; Wilson, 1993; Rohr and Furlong, 1995; Kreemer et al., 1998). Better constraints on the characteristics of this diffuse seismicity are essential to determine whether the region's rapid evolution over the last 5 Ma has been prompted by the resistance of young plate to subduction or a change in plate motion.

What are the boundary forces on the Juan de Fuca plate and how do the plate boundaries interact?

Because NEPTUNE will provide observations of seismicity and deformation across a whole plate, it will provide an opportunity to understand the balance of forces acting across the plate boundaries (Figure 3.2.5). Offshore focal mechanisms and seafloor faulting patterns suggest that the maximum compressive stress changes from N-S on the Gorda plate to NE-SW or E-W off northern Oregon. Elastic and elastic-perfectly plastic plate-stress models suggest that the right lateral shear motion of the Pacific and North American plates is primarily responsible for this stress pattern (Wang et al., 1997). The stresses appear to reflect the balance of compression across the Mendocino fault and horizontal resistance to margin parallel motion at the subduction zone. NEPTUNE will provide the data necessary to develop more refined mechanical models of plate stresses that incorporate data from the entire Juan de Fuca / Explorer / Gorda plate system

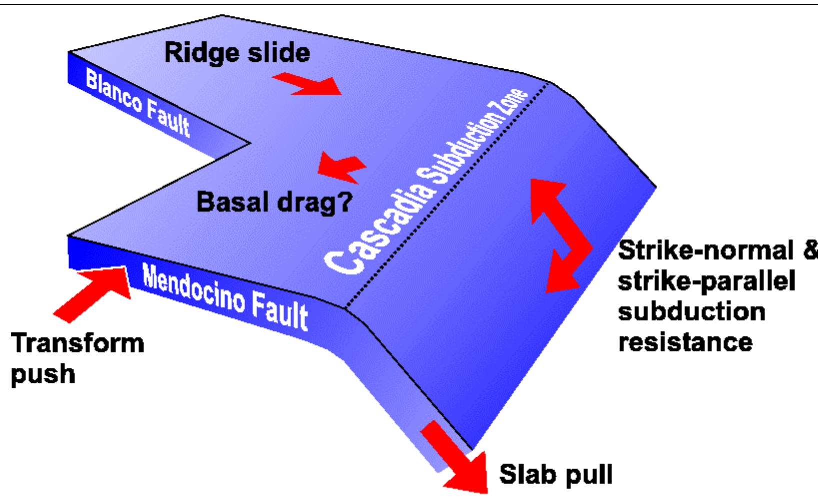

Figure 3.2.5. Cartoon illustrating the balance of forces acting on the Juan de Fuca plate (from Wang et al., 1997).

Answers to the above questions will require systematic long-term seismic and geodetic monitoring at scales ranging from plate scale down to local geologic features. This is because individual geologic features as well as the larger scale tectonic plate may respond to forces either elastically (earthquake rupture) or in a ductile fashion (slow creep of rock structures) and because such deformation is spatially variable. Only through long term seismic and geodetic monitoring will it be possible to determine the division between these styles of deformation. Additionally, the length of monitoring is crucial since geologic deformation rates are slow (mm/year) and patterns of stress and geologic activity often vary in response to local structure and events. Spatial coverage is also vital, since the level of deformation within a plate interior is significantly less than along the plate boundaries. In regions of particularly intense and potentially threatening deformation, geodetic and seismic instruments must be densely deployed and, again, a long period of observation is necessary to achieve statistically significant results.

3.3 Structure and Evolution of the Lithosphere/Asthenosphere System

The NEPTUNE Project on the Juan de Fuca plate provides a unique opportunity to address questions about the nature of plate-scale mantle flow. We know the directions and rates of motions of the oceanic plates from the pattern of magnetic anomalies, earthquake focal mechanisms, geodetic measurements, and the geometry of the plate boundaries, but we know very little about what happens beneath the surface. There are many theoretical models that predict the pattern of mantle flow beneath plates, but these models depend heavily on assumptions about the rheology of the lithosphere and asthenosphere. Laboratory experiments indicate that the rheology or viscosity should be a function of temperature, pressure, composition, melting temperature, melt fraction present in the mantle, and degree of depletion, but the form of this dependence is poorly known. For example, the temperature and melt content are expected to depend on the pattern of mantle flow making it a non-linear problem in "circular" reasoning. To test the models and constrain the pattern of mantle flow, we need seismological observations that require a long-term deployment of many instruments.

How much of the oceanic mantle moves with and is coupled to the surface plate?

Recent laboratory experiments suggest that the viscosity of the mantle may increase by orders of magnitude when completely dehydrated (Hirth and Kohlstedt, 1996). Thus, when the upwelling mantle beneath spreading centers begins to melt and the partial melt migrates to the surface to form new oceanic crust carrying with it essentially all of the water, the residual mantle left behind should be much stiffer than the original, undepleted mantle. If substantial melting begins at a depth of 60-80 km, then beginning right at the axis there may be a thick depleted, chemical boundary layer that is coupled to the surface plate and moves with the plate. A thermal boundary layer beneath young seafloor would be much thinner. The Juan de Fuca plate is an ideal area to test the hypothesis of a coupled chemical boundary layer because the absolute plate motion direction is much different than the direction of relative motion between the Pacific and Juan de Fuca plates (Figure 3.3.1). Seismic anisotropy in a coupled layer should be aligned parallel to the fossil spreading direction revealed by magnetic anomalies (Figure 3.3.2), but anisotropy in the underlying asthenosphere should be aligned by the relative motion between the plate and the deeper mantle.

What is the pattern of return flow from trench to ridge?

Plates transport material from the ridges to the trenches as part of the earth's convective system. To preserve mass balance, somewhere there has to be a return flow that resupplies the ridge. The Juan de Fuca plate may be too small and subduction too shallow for there to be a direct, local, return flow directly opposite the surface plate motion, but there may be local effects from the westward motion of the North American plate causing trench rollback or flow around the ends of the subduction zone. Is the form of the deep anisotropy the same beneath the Pacific and Juan de Fuca plates? Their directions and rates of absolute plate motion are very different; does the anisotropy associated with the overall return flow pattern just ignore the local geometry of the surface plates or does it show differences that could be attributed to a local flow pattern? In the MELT Experiment, shear wave splitting was found to be nearly twice as large beneath the Pacific plate as beneath the Nazca plate, in rough proportion to the velocity of the plates in the

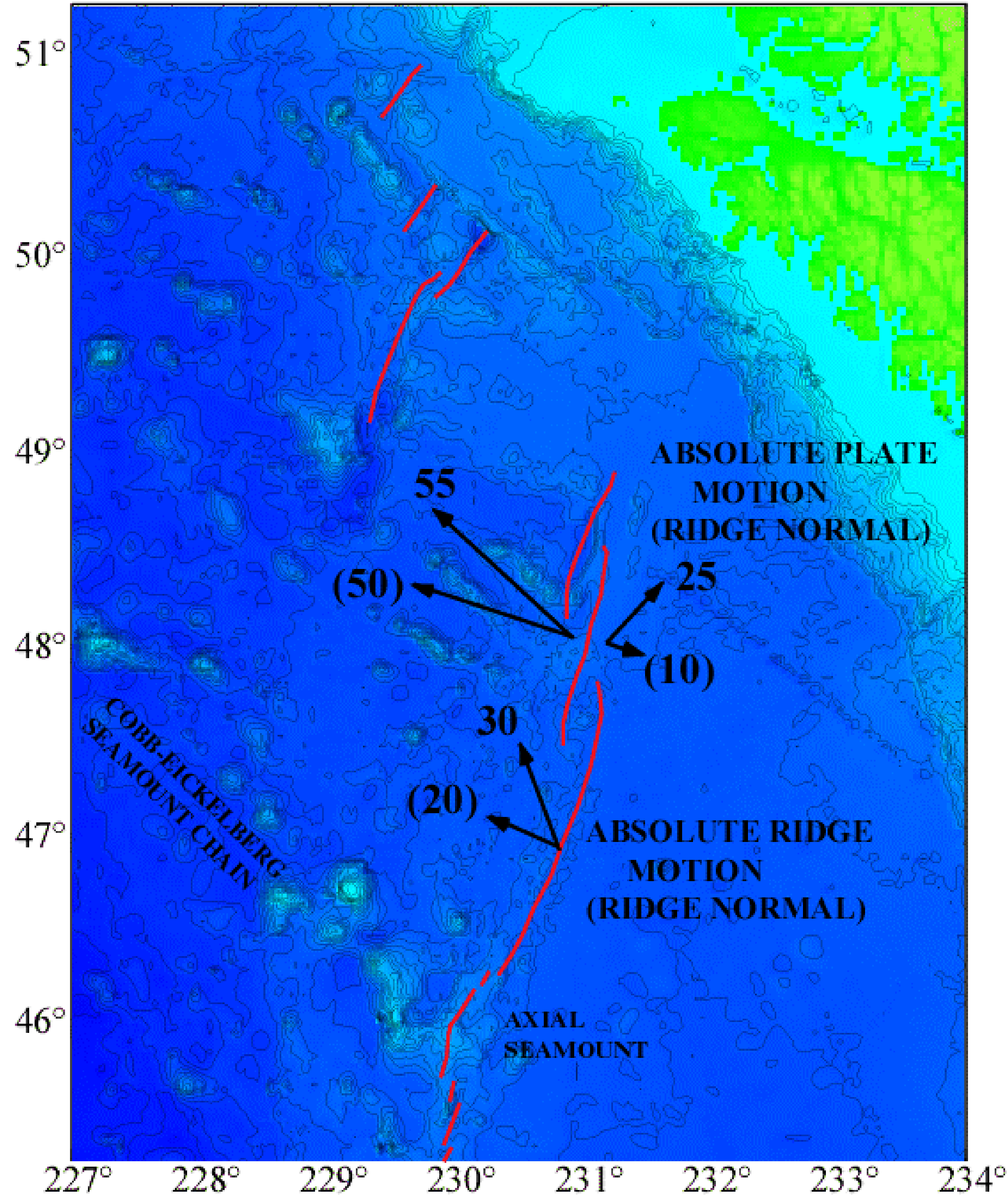

Figure 3.3.1. Bathymetry of the Juan de Fuca ridge crest and its flanks. Red lines show the location of the spreading centers and arrows show the absolute motions of the plates and ridge in the hotspot reference frame. Across the Juan de Fuca Ridge the relative plate motion is approximately symmetric and perpendicular to the ridge, but absolute plate motion is highly asymmetric and the Juan de Fuca plate is moving at large angle to spreading direction. Note the asymmetry in seamount population, with Cobb-Eickelberg chain leading to the Axial seamount confined largely to the Pacific plate west of the ridge (figure based on Davis and Karsten, 1986).

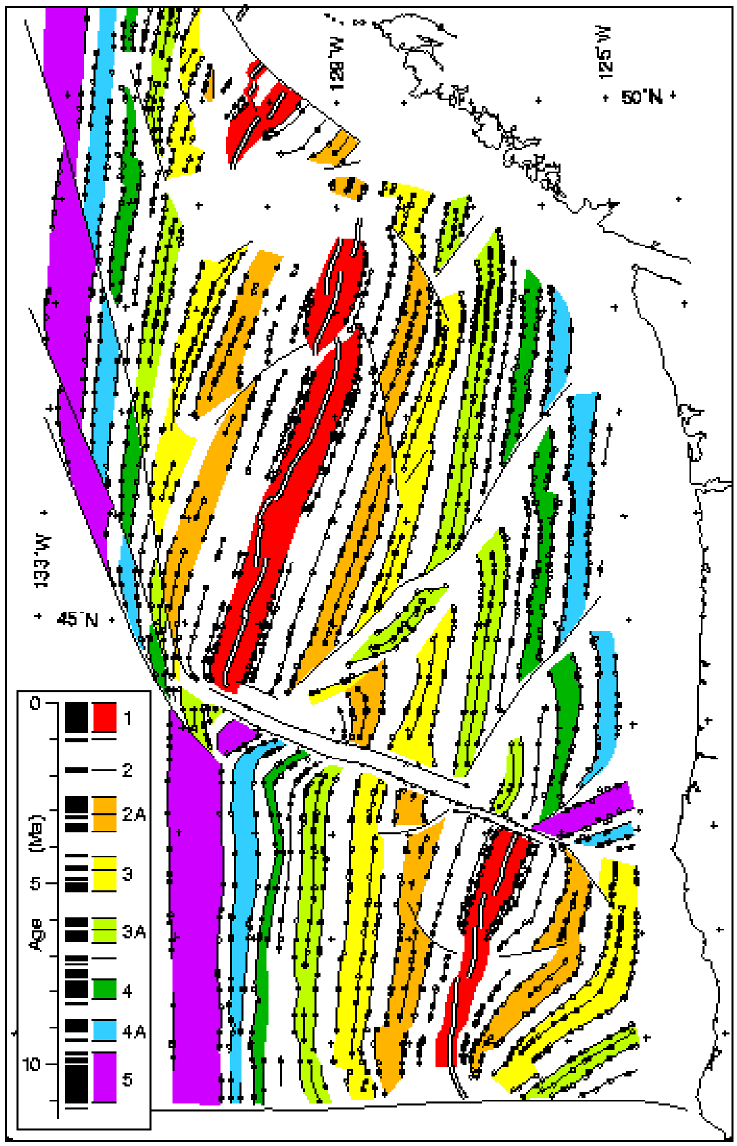

Figure 3.3.2. Magnetic anomalies in the Juan de Fuca region (from Wilson, 1993). Note the V-shaped discontinuities that mark the tips of ridge segments that propagate away from Axial seamount at 46 degrees N. Double lines show spreading centers.

hotspot coordinate frame (Figure 3.3.3). The change occurs fairly abruptly near the ridge axis, so there is a strong possibility that a local flow pattern could be detected.

Does mantle upwelling associated with a spreading center continue beyond a ridge-transform intersection? What are the patterns of flow near plate boundary intersections and intra-transform spreading centers? How wide is the transform zone at depth?

Simple models of asthenospheric flow predict that the abrupt transitions in motion that occur at plate boundaries should broaden with depth. Passive upwelling beneath a spreading center may extend across a transform offset beneath the adjacent, older seafloor (Phipps Morgan and

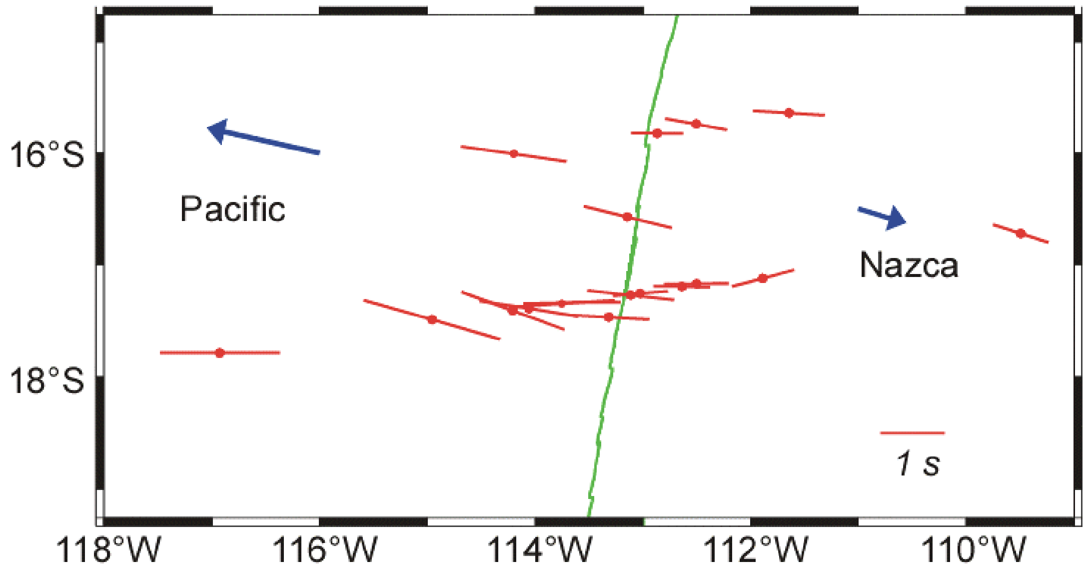

Figure 3.3.3. Shear wave splitting and anisotropy on the East Pacific Rise (from Wolfe and Solomon, 1998). A green line shows the East Pacific Rise. Red lines indicate fast direction of propagation for vertically travelling S waves, and length of line is proportional to splitting delay between fast and slow phases. The scale bar shows a 1-s delay. The Pacific plate is moving approximately twice as fast as the Nazca plate in the hotspot or absolute coordinate frame (blue arrows). This asymmetry in plate motion relative to the deeper mantle may be responsible for the contrast in shear wave splitting between the two plates.

Forsyth, 1988). At some ridge-transform intersections, there seems to be renewed volcanic activity and crustal thickening on the older plate (Barth et al., 1994), but it is not clear whether this activity reflects the lateral transport of magma across the transform at crustal levels or the vertical ascent of melt produced by upwelling beneath the older plate. A similar problem is the nature of upwelling associated with intra-transform spreading centers like those that are found in the Blanco transform fault. Even though these spreading centers may be very short and isolated from the rest of the ridge, normal mid-ocean ridge basalts are often produced (Karsten et al., 1998). This question of the pattern of flow around intersections between different types of plate boundaries can be extended to the Mendocino triple junction and intersections at the trench. The pattern of flow at the termination of a plate boundary may reveal more about the dynamics of flow and rheology of the mantle than the flow in the vicinity of a continuous, uniform boundary. We still have no measurement, however, of the width of the shear zone as a function of depth beneath a transform, which would yield a direct indication of the rheological structure of a plate.

Is there a hotspot or center of upwelling beneath Axial Seamount?

If there is a hotspot, how does it affect mantle flow beneath the Juan de Fuca Ridge? Axial Seamount is a prominent feature on the Juan de Fuca Ridge that connects to the Cobb-Eickelberg seamount chain (Figure 3.3.1). The magnetic anomaly pattern indicates that propagating rifts have migrated away from Axial Seamount both to the north and to the south (Figure 3.3.2), which is typical of hotspot-influenced ridges. On the other hand, basalt chemistry does not indicate an anomalous degree of melting beneath Axial Seamount (Shen and Forsyth, 1995) and there is no comparable seamount chain on the Juan de Fuca plate, as would be expected if Axial were a ridge-centered hotspot. As has been suggested for the Foundation seamount chain in the

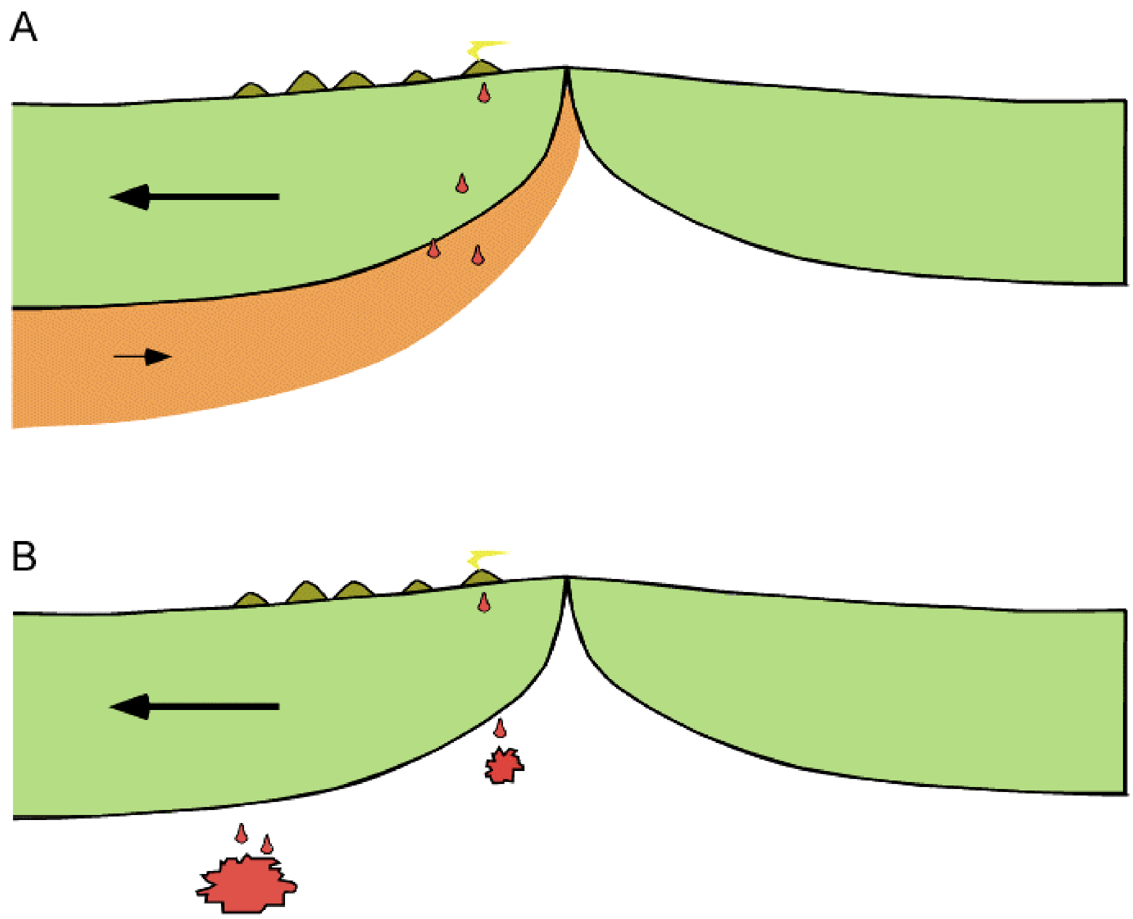

Figure 3.3.4. Models for the asymmetric production of seamounts. (A) An off ridge hotspot beneath the Pacific plate feeds warm material (orange) towards the ridge and some of the melt produced in this region of channeled flow leaks through the plate to form seamounts. (B) Alternatively, embedded heterogeneities that melt more easily than the surrounding mantle produce magma that migrates vertically to the surface creating a seamounts. Because the Pacific plate (to the left of the ridge in this diagram) is moving more rapidly than the Juan de Fuca plate, most of the upwelling and melt production is to the west of the axis. The asymmetric motion causes the ridge to migrate westward (to the left) over already melted residual mantle, so that whatever upwelling does occur beneath the Juan de Fuca plate will involve fewer enriched heterogeneities (Davis and Karsten, 1986).

South Pacific (Hekinian et al., 1999), one possibility is that there is an off-ridge hotspot beneath the Pacific plate that feeds material back toward the ridge axis along the sloping bottom boundary of the plate. Some of the melt produced in this channeled flow could leak through the plate to the surface, producing an asymmetric distribution of seamounts, with many forming off-axis.

Because there are numerous other small seamount chains on the Pacific plate to the west of the spreading center, an alternative model has been suggested in which the seamounts form by melting of chemical heterogeneities embedded in the upwelling mantle (Figure 3.3.4). In this model, the asymmetry in seamount population arises because the Pacific plate is moving much faster to the west than the Juan de Fuca plate is moving to the east. The faster translation of the Pacific plate causes more upwelling and melting beneath that plate. It also causes the ridge to migrate to the west relative to the deeper mantle, so that upwelling induced beneath the Juan de Fuca plate involves mantle that has already been flushed of its easily melted heterogeneities by prior upwelling beneath the Pacific plate. These two models involve much different flow patterns and imply distinctly different lithospheric and asthenospheric structure and are testable with seismic observations.

All of the above questions related to mantle flow and structure of the lithosphere and asthenosphere can be addressed with observations of seismic anisotropy, velocity, and attenuation. Seismic anisotropy can be constrained by shear wave splitting, azimuthal variations in surface wave velocity, and Love-Rayleigh discrepancies. Anisotropy is a particularly powerful tool, because anisotropic structures arise from alignment of olivine crystals or melt pockets accompanying deformation in mantle flow. Seismic velocities and attenuation give indications of mantle flow primarily through their dependence on temperature and the presence of melt, and can be measured with observations of both body and surface waves at a network of ocean-bottom observatories.

Questions of mantle flow and plate structure require the deployment of instruments outside the Juan de Fuca plate itself in order to be able to image structures beneath the boundaries and the pattern of flow around the edges. Long-term deployments of five years or more are required, particularly for shear-wave splitting. Variations in anisotropy with depth can be detected with incoming shear waves, but only if many high quality waves are received from a variety of azimuths or with a variety of polarizations. Typically, only a few high quality signals of the right type are received each year. To fill in gaps in azimuthal coverage normally requires several years of waiting for earthquakes to occur in the right spots around the globe. Similarly, to resolve both azimuthal and lateral variations in surface wave velocity requires as wide a distribution of sources as possible. A backbone of "permanent" stations is ideal for gathering this type of data. Shorter, supplemental experiments will be needed to provide the details of structure near plate boundaries in some areas, but these will be interpreted best in combination with the regional picture supplied by the backbone of long-term stations.

3.4 Earthquakes and Geological Processes at Plate Boundaries

Mid-Ocean Ridges

A good knowledge of temporal and spatial patterns of seismicity is key to understanding the processes that control the generation of oceanic crust. At shallow depths, seafloor spreading occurs by a combination of dike intrusions and tectonism and both these processes produce earthquakes. Diking events must penetrate brittle rock and they create additional earthquakes because the intrusion modifies the surrounding stress field. Tectonic extension occurs by slip on ridge parallel normal faults. The fracturing that accompanies diking and faulting creates permeability that controls the patterns of hydrothermal cooling and thus feeds back into the mechanical properties of the crust. At present our knowledge of mid-ocean ridge seismicity is limited to monitoring T-phases which constrain epicenters to within a few kilometers but provide little information on the depth or style of faulting and to short-term deployments of OBSs over periods that may not be fully representative of long term processes. NEPTUNE has the potential to revolutionize our understanding of the coupling between tectonic, magmatic and hydrothermal processes at mid-ocean ridges.

What is the nature of seismicity associated with diking-eruptive events?

The primary style of eruptions on the Juan de Fuca ridge system appears to be the emplacement of dikes along axis from a central source in a crustal magma chamber. The propagation of dikes along axis has been tracked using arrival times of T-Phases observed on the US Navy SOSUS arrays. The best observed diking events on the Juan de Fuca ridge have been the eruptions of the Coaxial segment in 1993 (Fox et al., 1995) (Figure 3.4.1) and Axial Volcano in January, 1998 (Dziak et al., 1999). For each of these events, the earthquake locations migrated tens of kilometers over a few days as the dike propagated along axis from a magma chamber source at mid-crustal depths. Investigations following these seismic detected fresh eruptions on the seafloor and intense hydrothermal activity.

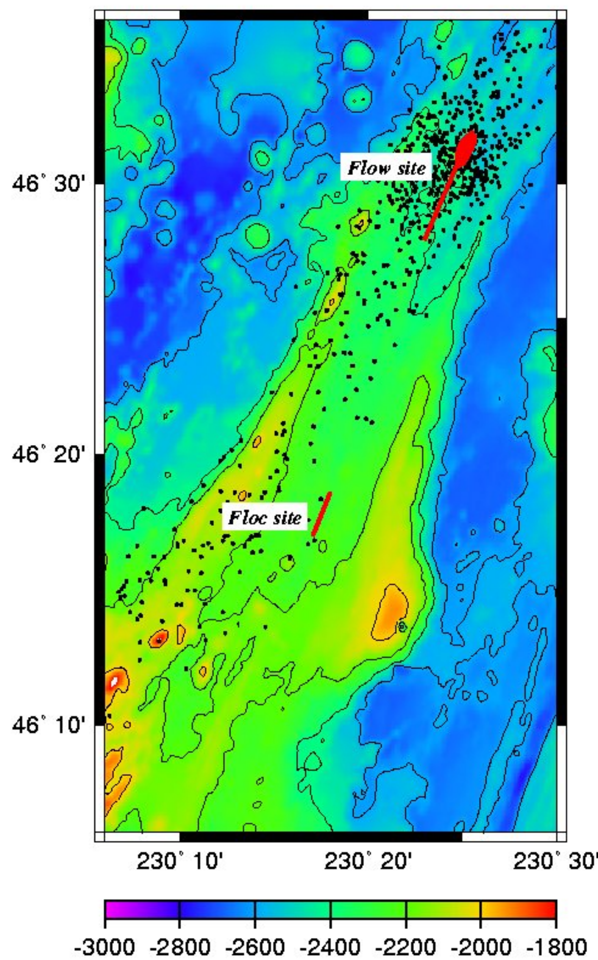

Figure 3.4.1. SOSUS epicenters for the June 1993 lateral dike injection on the CoAxial segment of the Juan de Fuca Ridge. The swarm originated on the north volcanic rift zone of Axial Seamount and migrated over 60 km to an eruptive site (Flow site) where field observations confirmed the presence of fresh lava flows and hydrothermal activity at the eruptive site.

Attempts to deploy ocean bottom seismometers for more detailed seismicity studies in response to diking events detected by SOSUS arrays (Sohn et al., 1998b; Sohn et al., 1999) have only been partly successful. Most of the seismicity occurs within a few days and it is very difficult to install an array on the seafloor rapidly enough. NEPTUNE would allow for monitoring of the geological, geothermal, biological and oceanographic effects of complete eruptions and for their interpretation in the context of ground truth inferred from accurate knowledge of seismicity. Sub-Arrays of 10 to 20 seismometers deployed near the ridge axis in a few key regions would record numerous eruptions over the lifetime of NEPTUNE. The arrays would locate seismic events much more accurately than SOSUS and would resolve earthquake depths and mechanisms to better delineate the region associated with magma movement. Theoretical considerations suggest that earthquakes will be concentrated near the top and bottom boundaries of propagating dikes where the tensional stresses are highest (Rubin and Gillard, 1998). Accurately located earthquakes would thus map out the extent of the dike. Earthquakes are also associated with removal of magma. Several very large earthquakes (magnitude 4) were detected during the eruption of Axial Seamount and were associated with the collapse of the caldera floor as magma moved into the dike.

Geodetic observations will also be critical along magmatically active ridge segments. Magma inflation leads to progressive seafloor uplift and changes in tilt while eruptive events are accompanied by sudden deflation. Diking emplacement is accompanied by both horizontal and vertical strain. The distribution of strain can be used to infer the depth and extent of magma bodies (e.g., Rubin, 1992; Arnadottir et al., 1998).

What are the relationships between mid-ocean ridge seismicity and hydrothermalism?

Small earthquakes are also associated with long-lived hydrothermal circulation. Swarms of microearthquakes observed below vent fields may be associated with stresses imposed by thermal contraction of rock as heat is mined from the hot rock or from a cooling magma chamber. Recently, a distinct change in temperature (and possibly chemistry) was detected at a vent near 9 degrees 50' N on the East Pacific Rise a few days after a swarm of very small microearthquakes (Figure 3.4.2) located 1 km beneath the vent field (Sohn et al., 1998a, 1999).

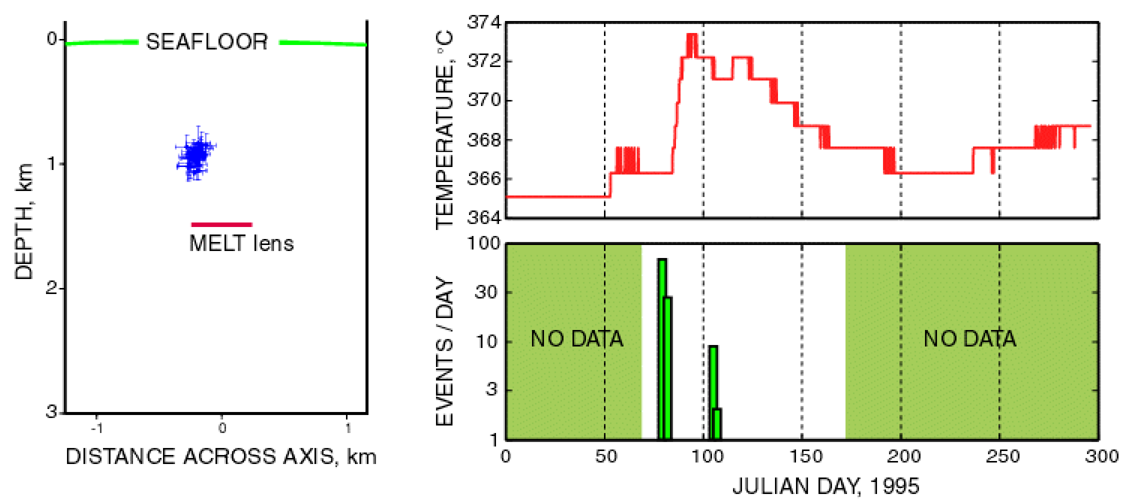

Figure 3.4.2. A seismic-hydrothermal even on the East Pacific Rise (from Sohn et al., 1999). The left-hand figure shows the earthquakes locations (plotted as 2-σ error bars) for a seismic swarm 1 km below the seafloor of the East Pacific Rise and 500 m above an axial magma lent. The right-hand figure shows the temperature records for a high temperature vent and the number of events recorded per day. A seismic swarm was followed by a 7 degrees Celsius increase in temperature 4 days later.

The temperature perturbation persisted for a few weeks, consistent with the mining of heat from a slightly hotter region not previously accessible to the hydrothermal system.

Unlike the East Pacific Rise and the Axial seamount and Cleft segments on the Juan de Fuca Ridge, Middle Valley and the Endeavour segment of the Juan de Fuca Ridge are not believed to be underlain by a shallow crustal magma chamber. Short microearthquake studies show that the hydrothermal systems on these segments of the Juan de Fuca Ridge are underlain by substantial microseismicity at depths of 2-4 km. This observations suggests hydrothermal circulation penetrates the lower crust. In June 1999, the SOSUS network detected a large swarm of several hundred earthquakes on the Endeavour segment including several earthquakes that were large enough (magnitude ~4) to be recorded by land networks (Chris Fox and Bob Dziak, personal communication). Since the epicenters are distributed over a region that extends about 30 km along axis and 15 km across axis, it is probable the several faults were active during this swarm. Most of the SOSUS epicenters are located west of the ridge axis but time series observations in the axial valley show that the onset of the swarm was followed about a week later by an increase in the intensity of diffuse venting at several sites (Paul Johnson, personal communication). High-temperature fluid samples recovered at the end of the summer showed a marked increase in carbon dioxide and helium concentrations (Marv Lilley and John Lupton, personal communication). It appears that either the earthquake swarm was accompanied by the emplacement of fresh magma near the base of the hydrothermal system or that the earthquakes opened up new hydrothermal pathways to a magma body. In the absence of local seismic observations it is not possible to distinguish between these two possibilities or deduce the subsurface geometry of this complex event.

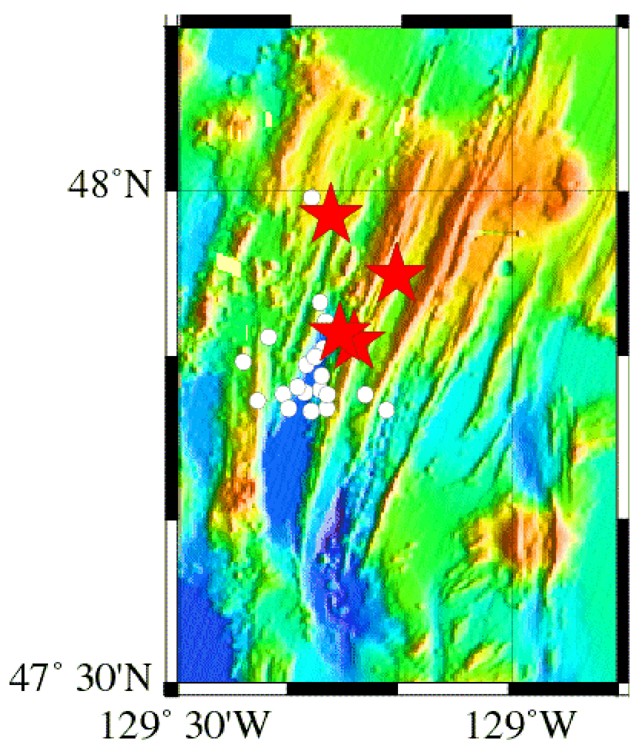

Figure 3.4.3. Location of SOSUS epicenters (red stars and white circles) for the June 1999 swarm on the Endeavour segment of the Juan de Fuca Ridge. Red stars show earthquakes that were also detected by land networks. (Figure courtesy of Chris Fox and Bob Dziak).

These exciting results demonstrate the importance of monitoring seismicity near vent fields in conjunction with measurements of the vent fluid properties. This can be accomplished with small sub-arrays of about ten seismic sensors spaced a few hundred meters apart near vent fields of particular interest. Permanent NEPTUNE local networks could also provide the fixed infrastructure necessary to support 4-D active source seismic experiments to image temporal changes in seismic velocity structure resulting from changes in temperature, melt, or crack distribution.

How far does tectonic deformation extend off axis at intermediate spreading ridges?

At the detection threshold of the SOSUS system (magnitude ~2), the southern Juan de Fuca Ridge is aseismic except during magmatic events. However, SOSUS does record many tectonic earthquakes on both the northern Juan de Fuca and Gorda Ridges. A two-month OBS experiment on the Endeavour segment detected microearthquakes up to 20 km off axis (Wilcock et al., 2000). These events are located in a region of ridge-parallel normal faults but their cause is unclear. They may be characteristic of a intermediate-spreading rate ridge in a phase dominated

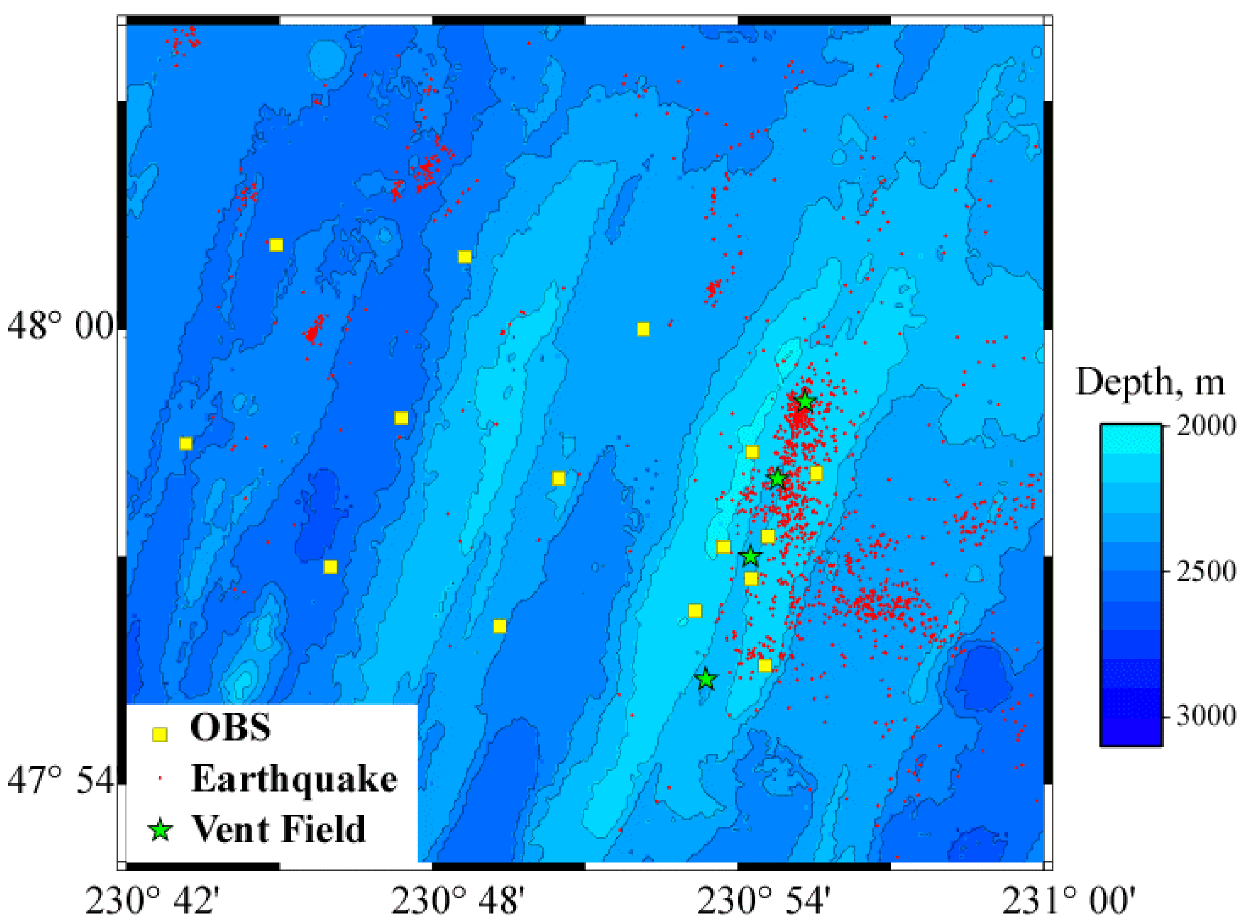

Figure 3.4.4. Epicenters recorded during a two-month microearthquake experiment on the Endeavour segment. Note that in addition to extensive activity beneath the axial vent fields, there are several swarms on the western flanks at distances of up to 20-km off-axis.

by tectonic as opposed to magmatic extension. This would suggest that the zone of active extension is fairly broad, a result that could have important implications for the patterns of mantle upwelling. Alternatively, off-axis earthquakes may be a result of regional stresses associated with the breakup of the Explorer plate to the north and the complex tectonics of the Sovanco transform. NEPTUNE will provide the long-term observations that are essential to understand the tectonism of this region and the style of deformation at mid-ocean ridges.

Subduction Zones

What are the geological effects of great earthquake shaking on the continental margin?

In addition to the direct earthquake hazards discussed in Section 3.1, great subduction zone earthquakes may have a profound effect on many geological processes on the accretionary prism (Figure 3.4.5). The continental margin shows scars indicative of massive slope instabilities that may have been triggered by earthquakes. Such events can trigger tsunamis, destroy offshore facilities and release large volumes of methane into the ocean. The effect of ground shaking on gas-charged and gas hydrate-bearing accretionary complex sediments must be measured in order to develop a predictive understanding of how this hazard is linked to seismic activity. NEPTUNE can play an important role in correlating these processes with earthquake ground shaking.

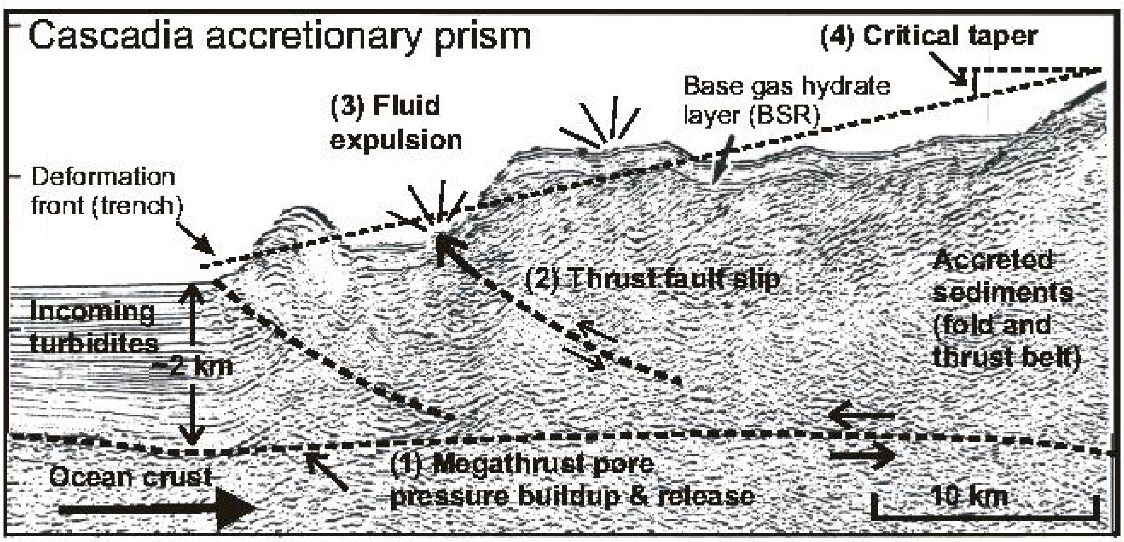

Figure 3.4.5. Many important processes may be limited to short time intervals during and immediately following great thrust earthquakes including: (1) pore pressures build up and release on the megathrust; (2) thrust faulting in the overlying accretionary prism; (3) regional sediment consolidation due to fluid expulsion; and (4) slope failures that control the angle of the seafloor.

<u>The Nootka Fault/Mendocino Triple Junction Experiment</u>: Ideally, the processes that are initiated by great thrust earthquakes in and beneath an accretionary prism would be observed through such an earthquake. Unfortunately, the frequency of occurrence of such great events is too low for practical monitoring times. A good proxy is available at sites where strong shaking is generated more frequently by other earthquake sources lying beneath the accretionary sedimentary prism. The Nootka and Mendocino transform faults (Figure 2.1), which bound the Cascadia subduction zone, exhibit especially frequent magnitude 6 to 7 events (the intense

seismicity of the Nootka fault zone is shown in Figure 3.1.3). Both regions are characterized by rapid sedimentation and the formation of gas hydrates. Earthquake statistics suggest that shaking of at least 10% g should occur in a recording time of a few years. NEPTUNE could monitor a wide range sedimentary and fluid processes to better understand how they are linked to earthquakes. Some processes could be monitored on the seafloor, but ideally the experiment would include instrumented deep boreholes.

Transform Faults

What is the style of deformation along transform faults?

Large offset oceanic transform faults represent a major class of plate boundary found throughout the oceans. They are an important source of large earthquakes and since oceanic crust is strong under compression they probably play an important role in guiding the directions of plate motions (Richards and Lithgow-Bertelloni, 1996). The Juan de Fuca region includes three major transform faults with contrasting properties, the Blanco, Mendocino, and Sovanco faults. The Blanco transform is a leaky transform; a small component of extension across the fault results in several short intra-transform spreading centers. Conversely the Sovanco is undergoing transform parallel compression, perhaps as a result of plate reorganization in the Explorer region (Rohr and Furlong, 1995). Large earthquakes occur on all three faults (Figure 2.4) and cumulatively they tend to dominate the annual seismic moment release for the region. Accurate focal mechanisms can be determined for the larger earthquakes using data from broadband stations on land (Figure 2.4) but there are many important questions that can only be addressed by local observations. For instance, knowledge of the depths of microearthquakes and their variation along the transforms would improve constraints on the thermal structure and nature of lithospheric cooling of the transforms. Local observations are necessary to constrain the width of the transform displacement zone and understand the effects of transform perpendicular motions. They are essential if we are to fully understand the origin of such basic morphological features as the transform valley, inside corner highs and median ridges. The mechanisms of small earthquakes in the plates adjacent to the transform will constrain the state of stress in the vicinity of the transform and by inference the strength of the fault (Wilcock et al., 1990).

Earthquake Physics

What is the physics of earthquake nucleation and rupture propagation for different types of plate boundaries?

There is substantial evidence that some plate boundaries show different or unusual styles of earthquake nucleation and rupture. For example, earthquakes along oceanic transform faults frequently have longer durations and slower rupture propagation than expected, and occasionally have slow precursors (McGuire et al., 1996). In addition, some earthquakes along the shallow thrust zone of subduction zones show slow rupture properties (Kanamori and Kikuchi, 1993). Large earthquakes of this type are commonly called "tsunami earthquakes" because their tsunami excitation is much larger than their high frequency seismic radiation. The factors controlling the rapidity of rupture propagation and strain release are unknown. One hypothesis for "tsunami earthquakes" is that they are ruptures at the uppermost edge of the seismogenic zone and the slow rupture velocity is a result of the low shear modulus of the sediments and other shallow layers (Pelayo and Wiens, 1992).

Our knowledge of the nucleation and rupture properties of earthquakes is limited by the lack of stations in the immediate vicinity of oceanic transform and subduction zone plate boundaries. As a consequence, only large earthquakes can be studied and the resolution of rupture parameters is limited. Recently, considerable progress has occurred through study of the rupture properties of small earthquakes along the San Andreas fault in California, including observations indicating a seismic nucleation phase (Ellsworth and Beroza, 1995) and evidence of fault healing with time (Vidale et al., 1994). NEPTUNE will allow detailed observations of oceanic transform fault and shallow thrust zone earthquakes to be made by a nearby array of high quality sensors for the first time, elucidating the similarities and differences between earthquake rupture properties in these settings. These results may provide important clues about the controls that mechanical and material properties exert on earthquake initiation and propagation.

4.0 Seismic Network

4.1 Design and Priorities

Even a single seismometer located on the seafloor in the subduction zone would provide useful data. However, from the standpoint of seismology and geodynamics, the strongest justification for NEPTUNE comes from the fact that it has been conceived as a plate-scale facility. Geodynamics is inherently plate scale. If we are to understand the plate-tectonic processes that deform and recycle the earth's crust, we must make observations at this scale. The Juan de Fuca / Gorda / Explorer plate system includes many tectonic features in a relatively small region and it juxtaposes major seismic and geodetic networks on-land. The Cascadia subduction extends the full length of this system and represents a major societal hazard that is incompletely observed from land.

The working group agreed unanimously that the first priority should the deployment of a complete backbone covering the Juan De Fuca / Gorda / Explorer plate system with a broadband three-component seismic sensor located at primary junction boxes spaced ~100 km apart. Once the backbone is deployed, additional seismic sensors will be needed both to complete the plate-scale network and to establish local networks. The working group agreed that these two objectives should receive equal priority.

Figure 4.1.1 illustrates a possible network design. It is based on the cable configuration scenario developed for the conceptual design and engineering feasibility study. It should be emphasized that the final design will require extensive planning to ensure that the network is optimized for seismic detection and characterization. The design should be based on our existing knowledge of the plate-scale distribution of seismicity (Figure 2.3) and the development of a community-wide consensus on the priority of the scientific problems to be addressed.

Even a quite extensive fiber-optic backbone, such as the 3000-km 30-node configuration envisioned in Figure 4.1.1, will not provide a complete regional network if the seismometers are only deployed at sites along the cable. There will be large gaps in the interior of the Juan de Fuca plate and smaller station spacings are desirable in the vicinity of the subduction zone. In addition, stations are also required further west on the Pacific plate, since good seismic observations of the plate-boundaries require a network that spans the boundary. For this reason additional broadband sensors should be deployed at distances of 50-100 km from primary junction boxes. Figure 4.1.1 shows one possible configuration for 36 additional sensors.

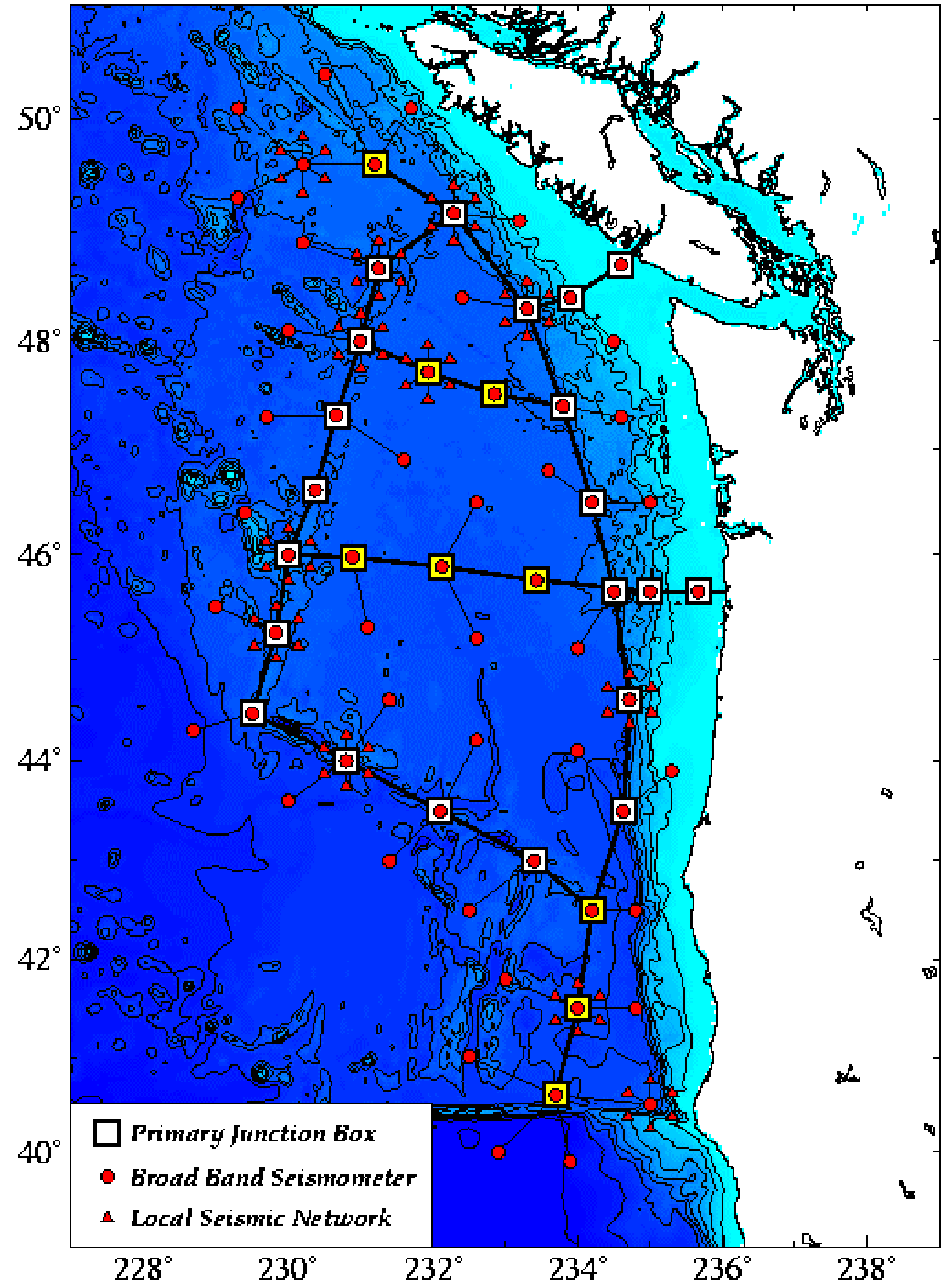

Figure 4.1.1 Possible network design based on a configuration used for the conceptual design and engineering feasibility study (yellow symbols show junction boxes that have been modified from that study). The first priority is the deployment of a broadband seismometer (red circles) at primary junction boxes (open squares) spaced about 100 km apart and covering the Juan de Fuca, Explorer, and Gorda plates. A fully two-dimensional plate-scale network, which spans the plate boundaries, will require the deployment of additional broadband stations at distances of 50-100 km from the primary junction boxes. High-resolution local networks comprising 10 or more closely spaced intermediate period sensors (red triangles) will be installed around a number of nodes in regions of particular interest.

Local networks comprising 10 or more sensors should be deployed at selected nodes to make high-resolution observations in regions of particular interest. The following sites will be strong candidates.

Axial Seamount
Blanco transform (near a ridge-transform intersection)
Central Oregon (near hydrate sites and "Goldfinger" faults)
Cleft Segment
Endeavour Ridge
Explorer Plate
Mendocino triple junction Middle Valley
Mid-plate on Gorda or Explorer plates
Mid-plate ODP drill hole
Nootka Fault
Offshore Vancouver Island

At many of these sites, the local networks will form part of larger multidisciplinary experiments. At others they may be motivated primarily by problems of seismological interest.

4.2 Sensor Choices and Installation

Broadband Seismometers

Although many regional land networks are still dominated by short-period sensors, these are being replaced by broadband instruments that allow for a much greater variety of studies. Broadband instruments will be essential for many of the studies envisioned for the NEPTUNE network. Given the relatively small cost of seismometers compared to the cable infrastructure, three-component broadband sensors (~500 s - 50 Hz) such as the Guralp CMG-1 of CMG-3 should be used for the entire regional network. For the local networks an intermediate band (~30 s - 50 Hz) sensor such as the Guralp CMG-40 would be adequate.

The recent Ocean Seismic Network pilot experiment in deep water 200 km from Hawaii compared the performance of three broadband seismometers over a four month period (Stephen et al., 1998). One seismometer was deployed on the seafloor, another was buried in sediments just below the seafloor, and the third was deployed in a borehole 240 m beneath the seafloor. Figure 4.2.1 and 4.2.2 show typical noise spectra from this experiment and from Global Seismic Network station KIP on Hawaii for both vertical and horizontal channels. The results (see Figure 4.2.1) show that burying the seismometer at shallow depths produces a large reduction in noise levels at longer periods (10-20 s). At high frequencies (>0.2 Hz), the borehole seismometer is markedly quieter than both the seafloor and shallow buried instruments. Nevertheless, the buried instrument was sufficiently quiet, that at least 10 teleseismic records from this experiment have pickable short-period P waves. The horizontal channels (Figure 4.2.2) of the borehole seismometer are also quieter at short periods but are quite noisy at longer periods. From the standpoint of NEPTUNE it should be relatively straightforward to deploy all seismometers below the seafloor either by inserting them into sediment or using a rock drill at unsedimented sites. Where boreholes exist, an additional broadband seismometer should be deployed ~200 m below the seafloor.

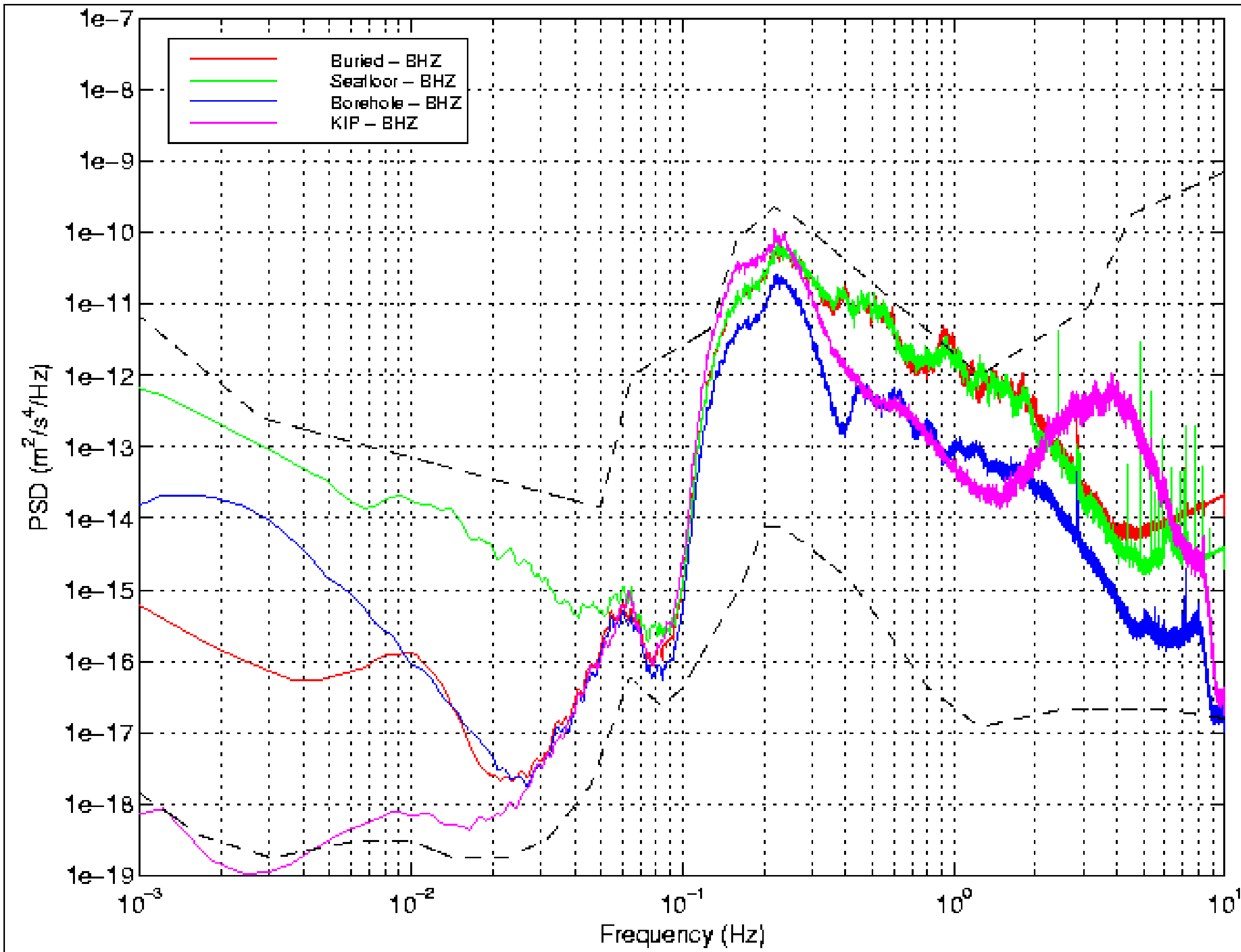

Figure 4.2.1. Examples of broadband vertical noise spectra recorded for the OSN pilot experiment and GSN station KIP. The seafloor seismometer is very noisy at long periods while at short periods borehole instrument is markedly quieter than either the seafloor or shallow buried seismometers.

Since broadband seismometers have already been successfully deployed in the oceans, there are no large technological obstacles to adding them to the NEPTUNE network. In most land applications it is relatively straightforward to access the sensor for maintenance. Some thought should be given to ensuring that all seismic sensors deployed in NEPTUNE have a maintenance free lifetime of many years.

Other Seismic Sensors

In addition to the broadband seismic network, a seafloor hydrophone should be included with each installation. Strong-motion accelerometers should be deployed at sites where there is a significant possibility of strong shaking (e.g., near the subduction zone and the transforms). Hydrophones in the SOFAR channel can continue the acoustic monitoring efforts of NOAA/PMEL should the Navy decommission the SOSUS arrays. T-phases can be used to monitor seismicity outside the network and may lower the detection thresholds in parts of the network. Data from vertical and horizontal hydrophone arrays can be stacked to reduce noise and beamform signals. Cabled hydrophone arrays around structures of geological interest (e.g.,

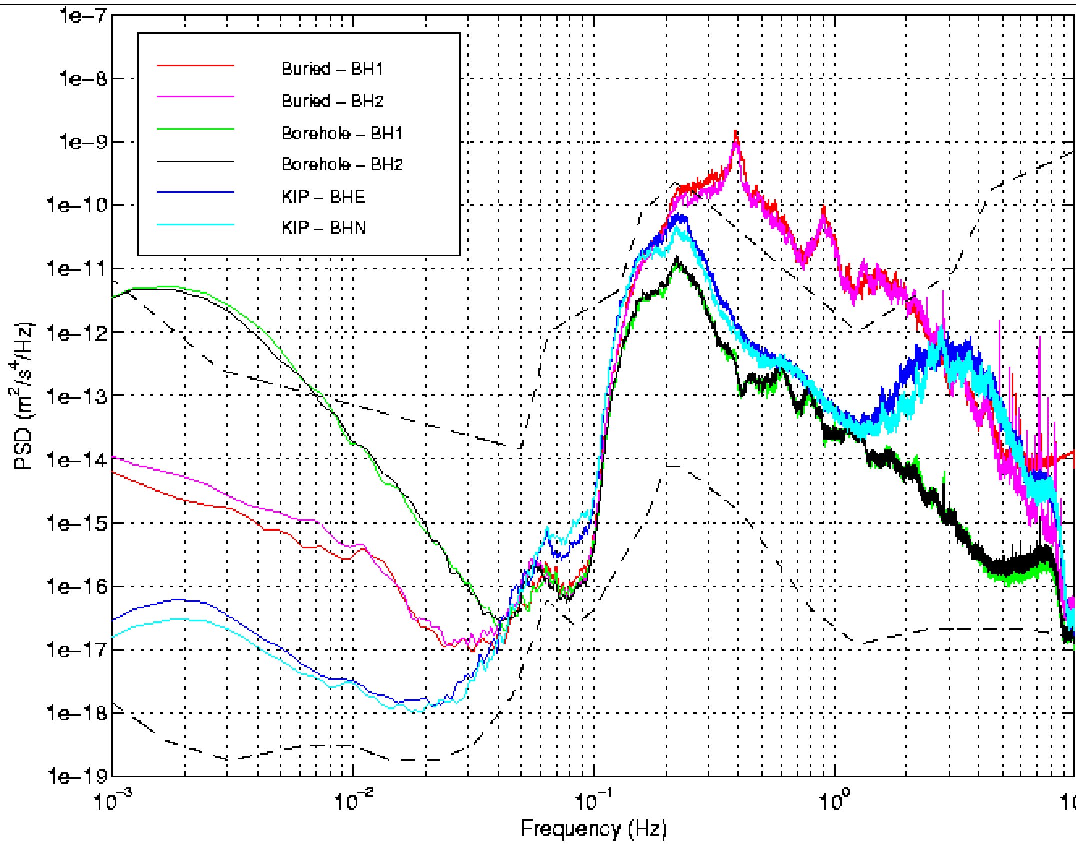

Figure 4.2.2. Examples of broadband horizontal noise spectra recorded for the OSN pilot experiment (note that data is not shown for the seafloor seismometer) and GSN station KIP. As for the vertical channels (Figure 4.2.1), the borehole instrument is markedly quieter at short periods. At long periods the borehole instrument is very noisy. This may be the result of either inadequate seismometer installation or convection-generated noise.

hydrothermal vent fields) could facilitate fine-scale 4-D seismic studies. Pressure sensors on the seafloor can be used for tsunami early warning systems.

4.3 Network Operations

All the seismic data from the network should be freely available to anyone. The seismological community has considerable experience operating regional and global networks and thus, the operation of the NEPTUNE seismic network can follow the established procedures.

In addition to maintenance, network operations will involve basic analysis of transient events, quality control, and data archiving and distribution. Data processing will involve the automatic detection, location and evaluation of transient events such as earthquakes, volcanic eruption signals and submarine landslides. Timely information on such events is of widespread societal interest and will be of importance to interactive experiments. The results can be made available through electronic means such as e-mail, FTP, and web pages. Long-term catalogs of earthquake locations and parameters calculated in a consistent manner are one of the most valuable scientific products of seismic networks. Time-series data can be made available in real-time (or nearly so) at the data collection center. The data collection center should also have the capability to set up custom continuous automatic feeds of selected channels. For instance, data from near-coastal stations should be shared with the appropriate land networks. Data archiving could follow the procedures adopted by the IRIS Data Management System in which the data collection center packages and quality checks the incoming data before turning it over to a data management center who arrange for its long term archiving and recovery for later use by researchers.

NEPTUNE could seek to establish its own seismic data processing and management centers, but it would probably be most cost effective to take advantage of existing facilities. The IRIS Data Management Center (DMC), which is based in Seattle, is already set up to provide long term archiving and distribution of seismic data. In the global seismology community, the IRIS DMC has proved very capable and responsive to maintaining a large inventory of data and providing easy access to research seismologists. In addition, data analysis and quality control for all or part of the NEPTUNE network could be combined with the operations of one or more of the regional land networks.

5. Seafloor Geodesy

In addition to supporting a seismic network, NEPTUNE provides a unique opportunity to obtain complementary long-term measurements of crustal deformation for the entire life cycle of a plate from creation to subduction. Geodetic instruments will be concentrated near the plate boundaries but it is also important to incorporate techniques to measure plate scale deformation. Compared to land-based observations, seafloor geodesy is in its infancy. However several techniques (Figure 5.1) are emerging to measure both the vertical and horizontal deformation and the continued development of these techniques is important for NEPTUNE

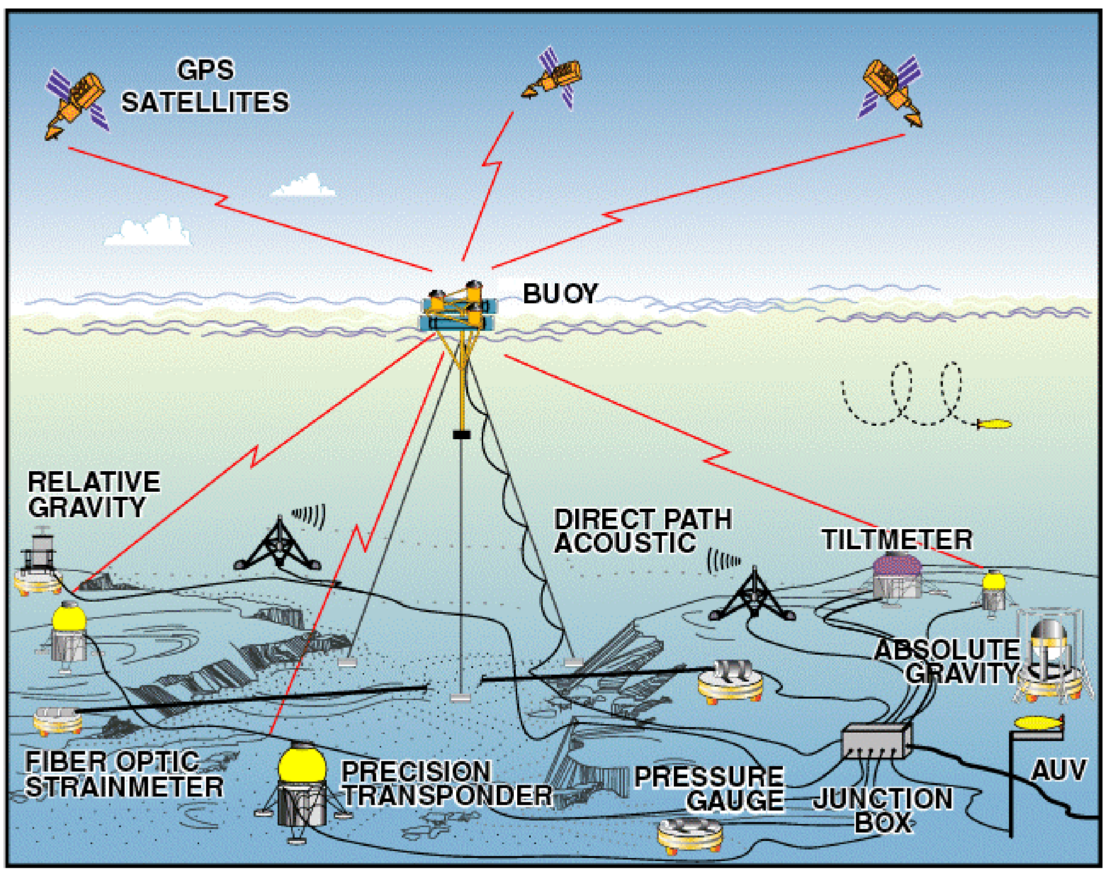

Figure 5.1. Cartoon showing the different types of geodetic measurements that would be incorporated into NEPTUNE.

Vertical Deformation

Three approaches have been demonstrated to measure vertical deformation: pressure, gravity and tilt. Relative pressure meters measure the weight of the water column above a seafloor site, with a repeatability of a few centimeters. Time series measurements are subject to long-term drift and thus, the technique is most suitable for observing rapid events. For instance, Fox (1990,1999) has used autonomous pressure gauges to observe deflation events at the Axial volcano.

Absolute/relative gravity measures distance to the earth's center as well the effects of local crustal density variations. Relative gravimeters measure the displacement of a bean supported by a zero-length spring. They can achieve high precision but are subject to long term drift. Absolute gravity meters use an optical method to measure the acceleration of an object falling in a vacuum and are not subject to drift. A compact absolute gravimeter has been developed for submersible deployments and measurements with this instrument approach a repeatability of 10 cm in elevation (Zumberge and Canuteson, 1994). Land based measurements using larger but still portable systems can achieve much higher repeatability (< 1 cm), and it is not unreasonable to think that observations of similar accuracy will eventually be possible on the seafloor. Absolute gravimeters are power hungry instruments and long-term time series observations will be greatly facilitated by NEPTUNE. Continuous measurements would be particularly useful in the subduction zone since could provide a key constraint to improve estimates of the width of the locked zone (Figure 3.1.3)

Seafloor tiltmeters measure local crustal inclinations with resolutions of a few micro-radians. Tolstoy et al. (1998) and Anderson et al. (1997) used short-baseline (~1 m) and long-baseline (~100 m) instruments to constrain inflation of Axial Seamount to be below 0.5-1.0 micro-radian per day during mid-1994. Tilt meters will form an important component of any instrument array designed to monitor diking-eruptive events.

Horizontal Deformation

Four approaches have emerged to measure horizontal deformation with centimeter repeatability over distances of 1 to 100 km. The first two, direct-path acoustics and fiber optic strain meter operate over distances of approximately 1 km. A third approach uses the indirect acoustic path between an intermediate deeply towed transducer and seafloor transponders separated by about 4 km within networks spanning 10 km. A fourth approach incorporates the acoustic path from seafloor transponders to a sea-surface transducer - located with the Global Positioning System - to position seafloor points separated by 100s km.

Direct-path systems measure the propagation time of an acoustic signal between transducers and converted the travel time to distance with knowledge of the ocean sound speed. Chadwell et al. (1999) and Hildebrand et al. (1999) use transponders on towers 3.5 m high and 715 m apart to observe no motion (-3 +- 5 cm/yr 2-sigma) across axial cleft of the southern Juan de Fuca Ridge from 1994 to 1999 (Figure 5.2). Chadwick (1999) used a system that spaces adjacent instruments approximately 100 m apart forming a baseline up to 1 km to observed deformation associated with the 1998 eruption of Axial volcano. This technique could also be applied to study the characteristics of the transform deformation zone.

An alternative to direct-path acoustic approaches which are limited by upward refraction and knowledge of ocean sound speed is a fiber optic strainmeter (Zumberge, 1997). The distance is measured along an elastic fiber by observing the time of flight of a light pulse along the fiber. The fiber is stretched under modest tension between two seafloor anchors. A spreading event stretches further the elastic fiber increasing the path length, measured travel time and distance.

A third system uses the indirect acoustic path between an intermediate deeply towed transducer to extend the horizontal coverage from 1 km to 5 km. In the deep ocean, the sound speed increases with depth causing acoustic rays to be refracted upward. The vertical distance the ray is offset is proportional to the square of the horizontal distance separating the ray ends. For example, a 1000-m horizontal separation between transducers requires mounting transducers on towers 3-4 m high above the seafloor. This is the practical limit of direct path systems because towers higher than 3-4 m make it difficult to insure tilting of the tower is not misinterpreted as horizontal deformation. The horizontal separation can be increased to 5 km by including 3 or more seafloor transponders and interrogating from a transducer towed 100 - 300 m above the seafloor. Centimeter-level displacements can be measured between the seafloor units provided sound speed variations can be measured to a few parts in 10^5 (Spiess and Hildebrand, 1995).

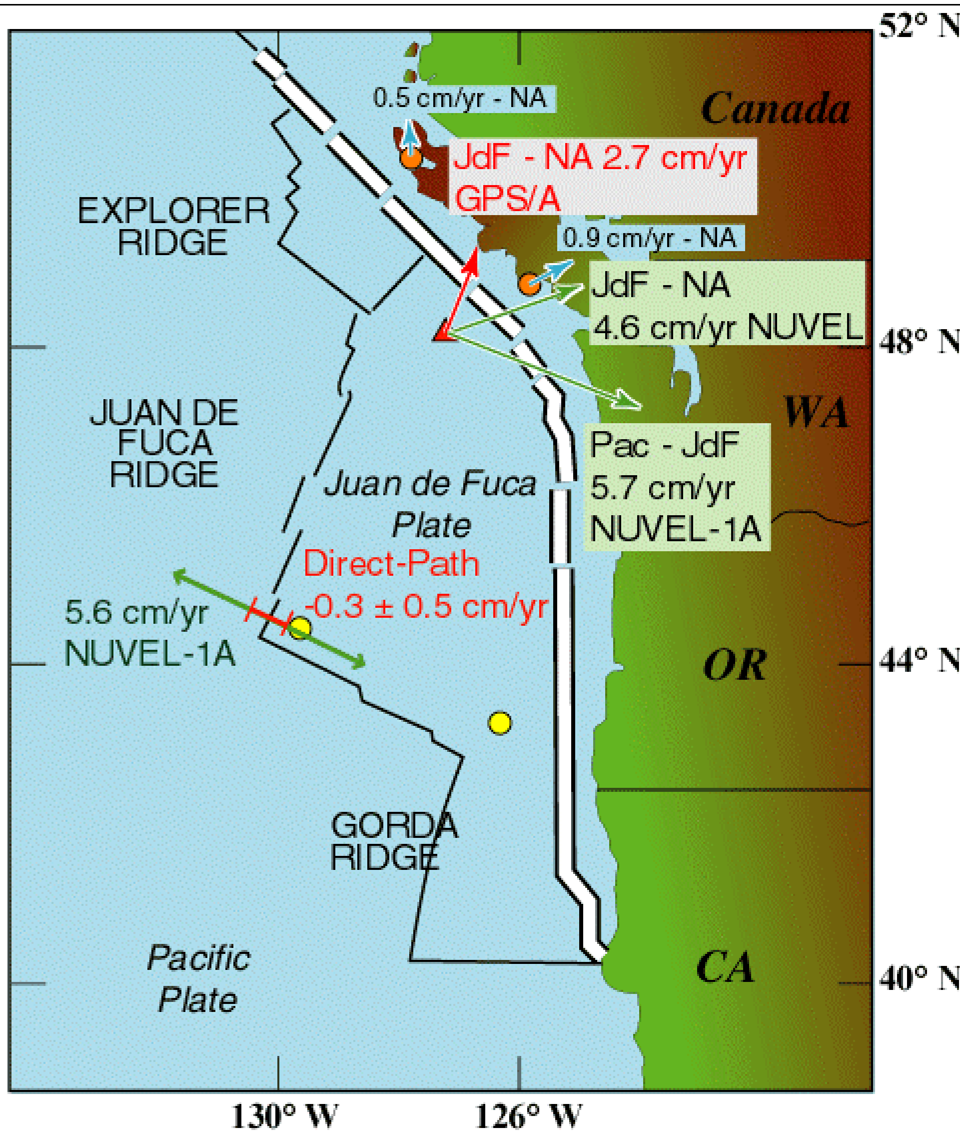

Figure 5.2. Results of geodetic experiments on the Juan de Fuca Plate. Direct path measurements have detected no extension across the axis of the southern Juan de Fuca Ridge between 1994 and 1999 (Chadwell et al., 1999). A GPS-acoustic measurement on the northern part of the plate shows that the plate motion is significantly different than predicted by global plate models. Further measurements are planned at two more sites (yellow circles).

Since it is envisioned that the NEPTUNE system will incorporate a significant number of autonomous underwater vehicles (AUVs), it should be feasible to use these as the intermediate vehicle for acoustic geodesy (Figure 5.3). Indeed, acoustic 'beacons' will be required to navigate the AUVs. Just as the GPS satellites are used for both navigation and geodesy on land, a network of acoustic transponders could serve a dual purpose in the oceans. At reasonable intervals the AUV can swim through the transponder network collecting travel times. At the end of the survey, the AUV can dock at an underwater station offload the data for transmission over the NEPTUNE facility to shore, and be recharged and reprogrammed for other tasks.

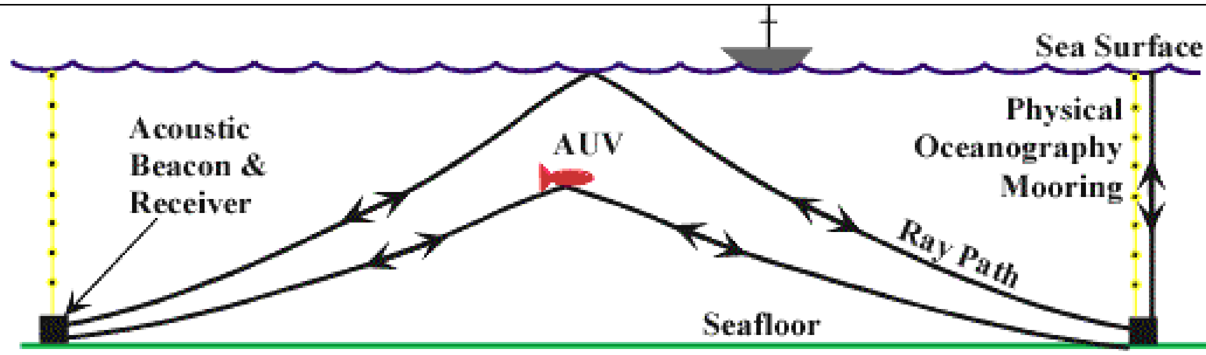

Figure 5.3. Acoustic beacons will be required in NEPTUNE to navigate AUVs and might also be used in for geodesy using either surface-bounce paths or the AUV as an intermediate vehicle.

It is also worth considering whether acoustic techniques could eventually be used over baselines longer than ~5 km. In the northeast Pacific Ocean acoustic rays that reflect downwards from the sea surface once or that are relayed by an AUV below the thermocline (Figure 5.3), can travel horizontal distances up to ~40 km in water depths of 2500 m. To use this phase for geodetic measurements would require a very accurate equation of state for the speed of sound though seawater. It would be necessary to calculate large corrections for a number of effects including changes in the sea surface height, varying water column velocity structure, and internal gravity waves. Since NEPTUNE will provide accurate timing, the capability to average many measurements, and physical oceanography data to correct for water column structure, it is worth considering whether it would be possible to calculate the corrections sufficiently accurately to make it a feasible geodetic technique.

A fourth approach the Global Positioning System - Acoustic (GPS-A) technique globally locates seafloor markers with centimeter-level repeatability over hundred-kilometer scale baselines. The technique combines simultaneous GPS dynamic positioning of a surface platform and precision acoustic positioning of an array of seafloor transponders to measure the horizontal position of the seafloor site. The GPS-system is composed of three receivers attached to a rigid platform (ship/buoy) whose submerged portion contains an interrogating hydrophone. GPS data is collected at a one-second rate at the three antennas and at two or more receivers on shore to determine the position and attitude of the platform and thus the location of the hydrophone on a second-by-second basis.

The transponder array is composed of three or more seafloor units arranged in a circle with radius approximately equal to the water depth. About every 10 seconds the interrogating hydrophone transmits a coded acoustic signal that is received at the seafloor units and then retransmitted and received at the interrogating hydrophone. By correlating the received signal with the transmitted signal, the two-way travel time can be determined with a few microsecond resolution. The travel times are converted to range using a model for the sound speed. Knowing the GPS-determined location of the hydrophone at transmission and reception permits the estimation of the seafloor positions. This approach has been used to measure the centimeter-level motion of the Juan de Fuca plate relative to North America (Spiess et al., 1998) (Figure 5.2)

NEPTUNE would permit long-term continues GPS-A measurements of seafloor sites, by mooring a buoy with GPS receivers and interrogating hydrophone at the center of a seafloor transponder array (Figure 5.1). Both the transponders and the buoy are connected to the NEPTUNE facility through seafloor junction boxes and in the case of the buoy by extending the fiber up the mooring line. Power to and data from the GPS receivers and buoy-mounted transducer would travel over the mooring-line fiber to the seafloor cable and back to shore for processing. With this configuration daily positions of the seafloor sites can be estimated with centimeter-level precision. This is analogous to the now several-year-long daily solutions for 100s of GPS stations at continental sites.

Borehole Strainmeters

Strainmeters are instruments that are used to make point measurements of crustal deformation near active faults and volcanoes. Strain is detected either with differential capacitance tranducers for tensor strainmeters or linear voltage displacement transducers with mechanical amplification for dilational strainmeters. Because the surface of the earth is unstable, strainmeters are deployed either in boreholes where they detect movement of the walls or at the surface where they measure the strain between two deep anchors spaced about 10 m apart. Strainmeters are most sensitive at periods of about an hour to a month and, thus, they fill the gap between seismic observations at short periods and conventional geodetic baseline techniques whose accuracy increases linearly with time. They are of particular importance in understanding slow earthquakes, including the slow slip that may proceed or accompany regular earthquakes.

Currently, numerous instruments have been installed along the San Andreas fault, in the Long valley Caldera, and near active faults and volcanoes in Japan, China, and Iceland. As an example of their use on land, Linde et al. (1996) report a slow earthquake sequence that occurred on the San Andreas in central California. Over about a week a slow earthquake sequence produced slip equivalent to a magnitude 4.8 earthquake. The largest regular earthquake was only magnitude 3.7 and the total moment release by normal earthquakes was negligible.

In the Summer of 1999, ODP leg 186 successfully deployed borehole strainmeters (as well as tiltmeters and seismometers) in sediments 1100 m below the seafloor at two locations in the Japan trench (Linde et al., 1999; Suyehiro et al., 1999). At present these systems are operating in a standalone mode using a seawater battery, but since the power requirements are high (~10 W) and there is a desire to access data in real time they will eventually be connected to a fiber optic cable. The objective of these deployments is to understand the seismogenesis of the Japan trench since the slip accompanying large earthquakes accounts for only about one third of the plate convergence in this subduction zone

Within the NEPTUNE array, strainmeters could be usefully deployed at many locations. In combination with seismometers, they would provide a tool to study the slow rupture properties of the shallow parts of the Cascadia subduction thrust as well as other faults in the accretionary prism such as the Nootka or Mendocino faults. For example, it is well established that the 1960 Chile earthquake was preceded by a slow precursor. Along the transform faults strainmeters could be used to investigate earthquake nucleation and rupture processes, which teleseismic records suggest can be anomalously slow. At ridge sites, strainmeters would be a useful geodetic components of volcanic observatories. Finally, within the plate interior, strain meters could be used to investigate the transmission of stresses across the plate. Seafloor strainmeters will require boreholes and ideally they should be deployed ~100 m below basement or very deep in the sediments.

6. Scientific linkages

6.1 Linkages to Other NEPTUNE Working Groups

Ridge Crest Working Group: As discussed in section 3.4, local seismic networks will form an integral part of the multidisciplinary observatories that will be established by NEPTUNE to study hydrothermal, magmatic, and tectonic processes on the Juan de Fuca Ridges. In addition, section 3.3 discusses several questions related to mantle flow and melt production beneath the ridge that will be addressed by the plate-scale seismic network.

Subsurface Hydrogeology and Biogeochemistry Working Group: The subsurface hydrogeology and biogeochemistry working group notes that "coordinated hydrogeologic and seismic monitoring will be critical for a number of objectives". At the sedimented Middle Valley site on the Juan de Fuca Ridge, two boreholes already penetrate a seismically active hydrothermal system. Long-term seismic and hydrogeologic monitoring at this site is likely to provide new insights into the coupling between tectonism and fluid flow. Similarly, at ridge flank borehole sites, small intraplate earthquakes may produce detectable hydrological effect that can be interpreted in terms of formation properties. Section 3.4 of this report describes the scientific motivation for coupled seismic, hydrological, and sedimentary observations in a portion of the accretionary prism that undergoes frequent strong ground shaking.

Cross-Margin Particle Fluxes Working Group: Earthquakes can trigger catastrophic slope instabilities in the accretionary prism leading to the formation of debris flows and turbidites. From a logistical standpoint, the sediment transport working group has a particular interest in working off the coast of southern Oregon and northern California (i.e., the Gorda plate) because this region has high sediment fluxes and a narrow continental shelf. This region is also seismically active and, thus, of interest to seismologists.

Subduction Zone Processes (Fluid Venting and Gas Hydrates) Working Group: Fluid release at convergent margins is attributed to tectonic overpressuring of pore fluids and is probably focused through high-permeability fault zones within the subduction complex. Subduction zone earthquakes will lead to large increases in the pore pressure driving flow and landslides may trigger the catastrophic release of gases trapped as hydrated phases.

Water Column Processes Acoustics is the preferred technique for studying processes at long range in the ocean. Hydrophone sensors deployed for seismic monitoring can be readily applied to marine mammal tracking, acoustic tomography, and other applications. The sensor instrumentation required for acoustic studies is relatively inexpensive and consistent between applications, but data processing needs differ. For example, seismic applications generally require continuous, low frequency data acquisition, while marine mammal studies require a much broader frequency band while tomography requires a narrow band-pass. Acoustic efforts between the various NEPTUNE core working groups will be carefully coordinated to assure that the sensor needs of each group is met.

Fisheries and Marine Mammals Working Group: Hydrophone arrays deployed for seismic monitoring can be applied directly to monitoring large cetaceans in the open ocean. Large whales, in particular blue whales and fin whales, vocalize in frequencies below 50 Hz, and while highly endangered, their distribution and abundance is very poorly known since they spend most of their life histories in the open ocean. Recent work has shown the applicability of low frequency acoustic monitoring to marine mammal studies (Moore *et al.*, 1998; Stafford *et al.*, 1998; McDonald and Fox, 1999; Stafford *et al.*, submitted). In particular, recent results (Stafford *et al.*, in press) clearly show a migration corridor for blue whales from the eastern tropical Pacific through the Northeast Pacific. Acoustic sensors planned for NEPTUNE would provide an unprecedented ability to monitor and track in real-time migratory blue whales. The ability to continuously monitor at higher frequencies (up to 1 kHz) would allow studies of many other species including humpback whales, and the application of high-frequency click detectors would provide information on sperm whales, killer whales, beaked whales, and dolphins.

6.2 Linkages Outside NEPTUNE

The objectives of the NEPTUNE Seismology and Geodynamics working group are very complementary to a number of other programs. The links between NEPTUNE and the Ocean Drilling, RIDGE and MARGINS Programs in NSF's Division of Ocean Sciences are fairly transparent and extend well beyond the scientific objectives of this working group alone. Similarly the links with the NOAA Vents program, which monitors the SOSUS data and is developing the New Millenium Observatory (NeMO) on Axial Seamount, are fairly clear. However, there are two major national initiatives outside ocean sciences that have strong linkages to the seismic and geodynamic objectives of NEPTUNE and these are discussed below.

EarthScope - A Look into Our Continent

EarthScope is a major effort to enhance the facilities for observing the structure and deformation of the North American continent. Like DEOS it has been developed for submission to NSF's Major Research Equipment (MRE) Program and is being promoted heavily by the Division of Earth Sciences. It is a package of several initiatives, namely USArray, the Plate Boundary Observatory (PBO), the San Andreas Fault Observatory at Depth (SAFOD), and Interoferometric Synthetic Aperture Radar (InSAR). The first phase of Earthscope comprises USArray and SAFOD and has already been submitted internally within NSF for MRE consideration in FY 2000. If this is proves successful, the second phase PBO may be submitted as early as FY 2001. While some aspects of EarthScope are still in their formative stages and detailed plans are still being developed, it is already clear that both USArray and PBO have strong scientific linkages to the objectives of NEPTUNE.

USArray is a proposed enhancement to the infrastructure for seismological investigations of the North American continent. The heart of the facility will be a transportable seismic array that will systematically cover the entire US and provide order-of-magnitude improvement in the quality of seismic images of the crust, lithosphere and deeper mantle. A flexible component of USArray will complement these synoptic views with higher resolution investigations of regional structures. The main scientific goal of USArray is to address continental structure, evolution, and deformation by imaging crustal and mantle structures over a wide range of scales to obtain an integrated "whole continent" view of the North America. In addition, the facility aims to improve seismic hazard assessment in North America; imaging of deep-Earth structure (e.g., lower mantle and core-mantle boundary); and Earth Science education and outreach. These objectives are very complimentary to NEPTUNE. The "whole continent" focus of USArray will be complemented very well by the oceanic plate-scale approach adopted by NEPTUNE. One of the weaknesses of USArray as initially conceived is that the high-resolution seismic imaging stops at the coastline and thus ignores many processes of geodynamic interest. In the Pacific Northwest, USArray data should be combined with data from the NEPTUNE seismic network to provide a complete image of the subduction zone.

The Plate Boundary Observatory (PBO) is a proposed facility for investigating active tectonic and magmatic processes of the Pacific/Juan de Fuca - North American plate boundary through measurements of crustal deformation. The chief observational requirement is a characterization of the three-dimensional deformation field over the maximum ranges of spatial and temporal scales. The PBO is designed to study long-term, regional tectonic processes as well as shorter-term, smaller-scale processes that may be more closely related to natural hazards, such as earthquakes and volcanic eruptions. In addition to advancing our basic scientific knowledge of active tectonic processes, the facility aims to improve seismic and volcanic hazard assessment and contribute to earth science education and outreach. Although the planned infrastructure and specific scientific objectives are presently not as fully developed as for USArray, it is clear that geodetic measurements in the western US will be complemented by seafloor seismology and geodesy within NEPTUNE. Indeed seafloor measurements are essential to get a complete picture of deformation along the North America / Juan de Fuca plate boundary. Careful attention needs to be paid to ensuring that geodetic data from NEPTUNE is merged with regional land geodetic data both from the existing geodetic networks and from the proposed PBO.

Advanced National Seismic System

A major upgrade, expansion and modernization of the permanent earthquake monitoring networks may be taking place within the next five to ten years. At the request of Congress the US Geological Survey, with participation by many industrial and university groups, drafted a document in 1999 assessing the state of seismic monitoring in the US and its future needs. This document recommends a widespread overhaul of the current monitoring infrastructure with particular emphasis on replacing obsolete 30-year-old seismic stations with modern digital instruments capable of both broadband and high dynamic-range recording of ground motion. These instruments will be run by a combination of regional operational centers and the USGS National Seismic Network run out of Golden Colorado with strict standards for data quality and compatibility. Using modern computer networking technology, data will be exchanged in real-time between adjacent regional centers and the national network forming an integrated, uniform "Advanced National Seismic System" (ANSS). Clients of the ANSS will be scientists, emergency managers, civil authorities, engineers, the press and public.

One of the regional recording systems for the ANSS will almost certainly be the University of Washington which currently hosts the recording system for the "Pacific Northwest Seismograph Network" (PNSN), a conventional seismograph network covering most of the states of Washington and Oregon. The PNSN operates 135 old-fashioned short-period analog stations and about a dozen modern broadband stations. It is slowly upgrading its stations and telemetry system now and will be well positioned to become a major component of an ANSS in the future. The PNSN currently exchanges some seismic data in real-time with networks in the neighboring states of California, Nevada, Montana, and with the USGS National Network and the Alaska Tsunami Warning center and will soon be exchanging data with the western Canadian network operated by the Pacific Geoscience Centre. Such exchanges improve the uniformity and completeness of geographic coverage of the region by forming overlapping and partially redundant networks. The PNSN is well positioned to exchange data with a NEPTUNE network in real-time to improve coverage along the west coast of Washington and Oregon. Land-based station data imported into NEPTUNE would contribute to the detection, location, and study of events along the eastern part of the subduction front. Similarly NEPTUNE data merged with the

PNSN data would improve coverage along this network's western side. The merged catalog for the two networks would be quite uniform and complete at a common magnitude level right across the continental margin, a result not found anywhere else in the world.

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