Earth Structure and Dynamics of Ocean Lithosphere
Working Group Report

The "Earth Structure and Dynamics of Ocean Lithosphere" Working Group was charged with identifying scientific priorities and developing plans for utilization of a regional cabled observatory to study plate-scale tectonics and geodynamics in the oceans. The members of this working group are listed in Appendix __. This report draws heavily on an excellent 1999 NEPTUNE Working Group White Paper "*Opportunities for Seismology and Geodynamics*". The SCOTS Workshop Report (2002) and a white paper from a 2003 NEPTUNE Pacific Northwest Workshop also provided valuable input to the working group's discussions.

1.0 Scientific Priorities and Questions

The movement and interaction of tectonic plates at the Earth's surface is responsible over geologic time for the formation of ocean basins, the uplift of mountain ranges and the rifting of continents. On human time scales these plate motions are the cause of earthquakes and volcanic eruptions that can have devastating consequences for the populations that live along plate boundaries. While the kinematics of plate motions are now well known, there remain many fundamental unanswered questions regarding the forces acting on the plates, how plate boundaries interact and deform, and the linkages and feedbacks among magmatic, tectonic, hydrothermal and biological processes at plate boundaries. Attacking these problems will require the collection of seismic, geodetic and other geophysical data at multiple scales over a region encompassing an entire plate over an extended period of time. In this section we outline four major research priorities for these plate-scale geodynamic studies.

<u>Understanding the dynamics of the lithosphere/asthenosphere system at the plate scale</u>

The pattern of mantle flow at the plate scale, the forces acting on plates and at plate boundaries and their variation with time are all still very poorly understood. 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 mantle 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. Testing and refining these models, and constraining the pattern of mantle flow, require the long-term deployment of seismological and other geophysical sensors in an array with an aperture comparable to the dimensions of the plate. A regional, plate-scale cabled observatory would provide an exceptional opportunity to address a number of fundamental questions regarding upper mantle dynamics and asthenosphere-lithosphere interactions including:

- How is mantle flow coupled to plate motion? Does the flow move faster or slower than the plate, i.e., does flow help drive the plate, or is it driven by the plate motion? What is the larger-scale mantle flow regime?
- How is episodic and time-variable deformation at plate boundaries coupled to larger scale plate motion?
- What is the pattern of mantle upwelling flow and melting beneath mid-ocean ridges?
- What is the pattern of small-scale convection beneath the plate?

- What is the origin of intraplate volcanism and large seamount chain volcanism?
- How does the subducted lithosphere alter as it moves to greater depths, and how is it eventually recycled into the mantle?

Understanding earthquake faulting and rupture processes at plate boundaries

Earthquakes at plate margins are the most important indicator of current stress and deformation. Our knowledge of the nucleation and rupture processes of earthquakes at faults in the oceans and along their margins is limited by the lack of stations in the immediate vicinity of ridge crests, subduction zones and oceanic transforms. Megathrust events in subduction zones are responsible for some of the most devastating earthquakes and tsunamis on Earth (Fig. 1). Their study is limited by most seismograph monitoring being limited to land stations. Offshore observations can provide constraints on the updip limit of the locked zone (which is a primary control on tsunamis) and on the length of the rupture zone downdip (which controls the magnitude of megathrust events). Earthquakes in the subducting slab are thought to be related to metamorphic processes in the slab. Long-term monitoring of seafloor seismicity and hydrothermal alteration will yield information on the initial state of the slab before underthrusting, the distribution and extent of faults in the subducting slab, and the stress regime in the subducting plate.

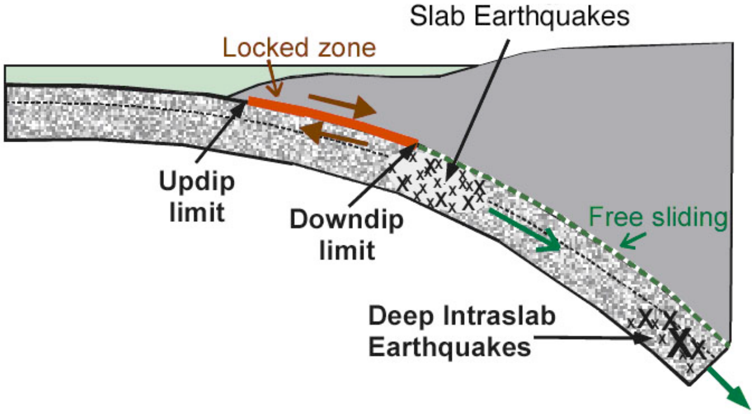


Figure 1. Schematic cross-section of a subduction zone. Megathrust events, which occur when the locked zone ruptures, are responsible for some of the most devastating earthquakes and tsunamis on Earth. Deep, intraslab earthquakes also present a major seismic hazard to cities located along convergent margins.

At spreading centers, a knowledge of the temporal and spatial pattern of seismicity and crustal deformation is key to understanding the processes that control the spatial and time variations in the generation of oceanic lithosphere. Seismicity is associated with dike intrusion and extensional faulting, and is the primary means of detecting magmatic/tectonic spreading events. Oceanic transform faults are the least studied type of plate boundary in the oceans despite their natural advantages for constraining the mechanical processes involved in faulting and lithospheric deformation. The simpler geologic, thermal, and tectonic conditions at oceanic transforms make them potentially useful sites for untangling many of the fundamental debates that remain unresolved in analogous continental environments. Questions in earthquake fault mechanics that can be addressed by a regional cabled observatory in the oceans include:

- What is the rupture area for megathrust earthquakes and how does it vary along the subduction zone? What is the associated stress regime and its variation through the earthquake cycle?
- What controls intraslab earthquakes and hazards?
- Why do accretionary prisms support giant events but no small earthquakes?

- How wide is the zone of deformation at ridges and transforms, and how is it coupled to mantle flow?
- Why is the seismic behavior of oceanic transforms different than large continental strike slip faults?

<u>Understanding the mechanisms of intraplate deformation and plate boundary interaction</u>

Intraplate earthquakes, faulting patterns and *in situ* crustal stresses can provide important clues on the forces acting on the plate and on intraplate deformation. Observations of seismicity and deformation across a whole plate will provide a unique opportunity to understand the balance of forces acting on the plate. From work on land it is now clear that stress transfer is a fundamental mechanism controlling fault interaction, aftershock clustering, as well as earthquake shadows. There are also hints from recent studies that oceanic plates can transmit stresses rapidly over many hundreds of kilometers. For instance, a 400-km-long band of intense mid-plate seismicity in the Gorda plate observed in 1991-1992 (Fig. 2 left panel) ceased following a magnitude 7.2 earthquake in the Cape Mendocino region (Fig. 2 right panel). It has been proposed that the high levels of intra-plate seismicity prior to August 1992 reflected an accumulation of stress in the Gorda plate that was reduced by movement in the adjacent subduction zone during a Cape Mendocino earthquake. This intriguing study suggests that oceanic plates can transmit stresses over many hundreds of kilometers, but the mechanism by which this happens is poorly understood.

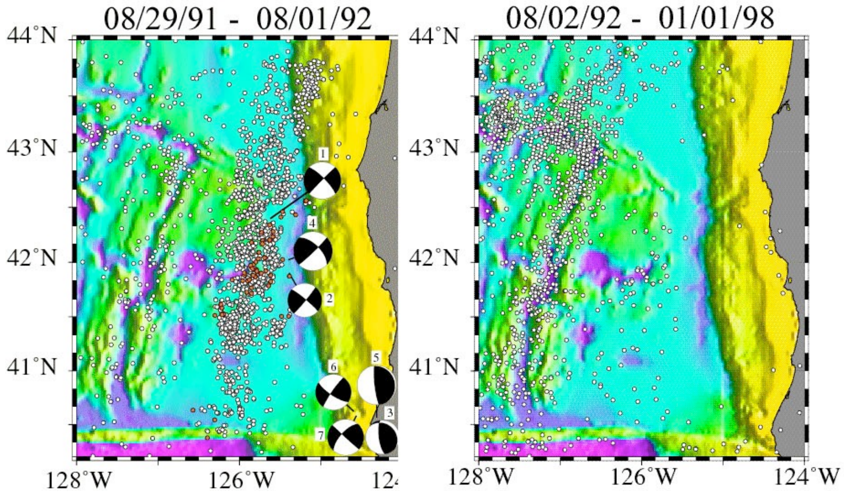


Figure 2. Distribution of earthquake epicenters in the Gorda Plate region derived from both land-based networks (red dots and focal mechanisms) and hydrophone arrays (white dots). The left-panel shows events recorded from August 29, 1991 through August 1, 1992. The right-hand panel shows events recorded from August 2, 1992 through January 1, 1998. Note the high levels of seismicity in the Gorda Plate that ceased after July 1992. (from Fox and Dziak, 1999)

If stress transfer on this scale is possible in the oceans then a large subduction zone earthquake might cause stress perturbations in the far field that could lead to strike slip events on a transform or trigger volcanic sequences on a ridge crest. Similarly a ridge or transform earthquake might increase the probability of a megathrust subduction zone event. In order to understand the mechanisms involved in plate boundary interactions, it is critical to measure the temporal effects of far field stress changes, and how the responses fit into the longer-term record of “background” activity. Coincident observations across an entire plate will be necessary to investigate these linkages and address the following questions:

- What forces act across plate boundaries and on plate interiors?
- What are the styles of intraplate deformation?

- How and why do stresses vary with time across the plate (as indicated by small earthquakes and *in situ* stress measurements)?
- What are the spatial scales over which variations in plate boundary stresses act?
- Do oceanic plate boundaries interact by transmission of stresses over long distances?

Understanding magma-tectonic-hydrothermal-biological interactions at plate boundaries

Strong interactions between tectonic, magmatic, hydrologic and biological processes on a local scale have recently been documented at both oceanic ridges and at subduction zones. On ridges there is a correlation among volcanic intrusion-spreading events, earthquakes, and fluid flow carrying microbial blooms. In subduction zones, large earthquake shaking may result in fluid expulsion (liquefaction and consolidation?) carrying methane upward to produce gas hydrate in the upper several 100 m below the seafloor. The mechanisms responsible for these interactions are not clear. Simultaneous time-series observations at plate boundaries will better define, and have the potential to elucidate, the mechanisms for these interactions. The coupling between fluid pressure changes and strain events/earthquakes will improve our understanding of the triggers of large events. In particular, are large earthquake cycles controlled by a combination of strain buildup that increases the shear stress on the fault and pore pressure buildup that reduces fault strength? There also is the potential through time series studies to understand how magmatic or tectonically induced changes in crustal permeability affect the microbial biomass in the subsurface and hydrothermal fluxes.

Spreading Ridge Processes. At spreading centers, ocean crust and an underlying depleted mantle lithosphere are created by upwelling and melting processes that are still poorly constrained. Spreading occurs by a combination of brittle fracturing, mainly in normal faults, and by magma intrusion. Both processes vary with time along the ridge. At intermediate and fast spreading ridges, spreading mainly occurs in magmatic-tectonic events lasting days to weeks with time intervals of tens of years and involving ridge lengths of 10's of kilometers. Some important questions are:

- How is spreading partitioned between magmatic and amagmatic extension?
- What is the role of fluids in fault rupture processes?
- What is the space-time variation of magmatic and tectonic activity associated with creation of oceanic crust?
- How do magmatic and tectonic processes influence fluid flow and biological activity at active plate boundaries.
- What are the biological responses to ongoing and large event hydrothermal fluid expulsion? What is their relative importance in ocean productivity and ecology?
- What is the total amount, distribution, and nature of fluid incorporated in the oceanic crust and upper mantle (free pore fluid, larger scale fracture/rubble porosity, bound in hydrothermal minerals)?

Subducting Plate Processes. Large amounts of water are incorporated in the incoming oceanic plate at the ridge and in mid-plate settings by fracturing, hydrothermal circulation, and formation of hydrated mineral assemblages. Plate bending fracturing just seaward of the trench also may increase the porosity and permeability of the crust. At subduction zones this water is progressively removed by mechanical collapse and by mineral dehydration processes as the pressure and temperature increase. Key questions relating to subducting plate processes are:

- What are the processes of dehydration of the incoming plate and at what depths (temperature and pressure) do they occur?
- How do dehydration processes control or affect seismicity?
- How do dehydration processes and mantle flow control arc volcanism?
- How do lithospheric age and convergence rate affect subduction processes?

Accretionary Prism Processes. Accretionary prisms are a modern analogue of ancient fold and thrust belts that are common on land. Therefore, they are an important source of information on the coupled processes of stress, pore pressure, earthquakes and shaking that control faulting, folding, and small-scale deformation processes (Fig. 3). Accretionary prism dewatering processes due to pressure and increasing temperature are inferred to be a critical control on deformation. These processes are also important for transporting and concentrating the biogenic methane (and thermal hydrocarbons) formed in accertionary wedge sediments into gas hydrate. Key questions include:

- What is the interaction among stress and pore pressure that control faulting, folding, and small-scale deformation processes within accretionary prisms?
- What is the role of strong earthquake shaking in triggering both deformation processes, and in expelling fluid (and methane) upward? (the sedimentary wedge lies immediately above the megathrust earthquake source so the shaking is very large)?
- How are the biological processes associated with fluid motions and responsible for the upward methane formation-hydrate dissociation process?

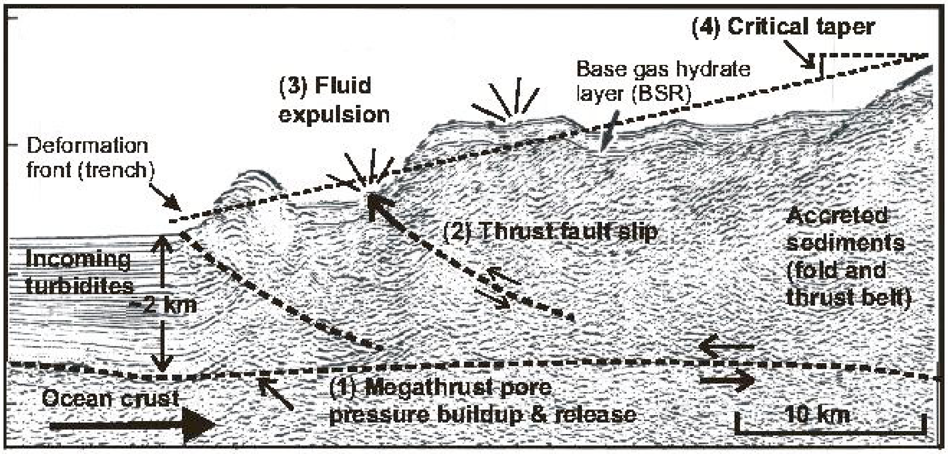


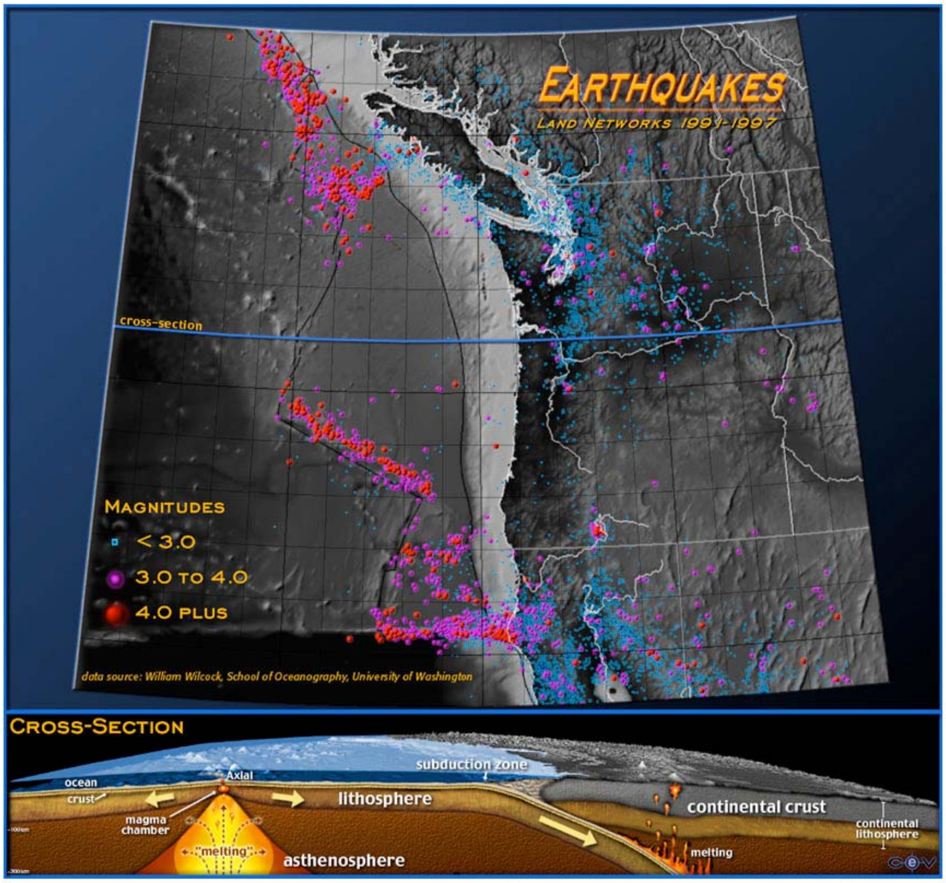
Figure 3. Accretionary prisms are an important source of information on the coupled processes of stress, pore pressure, earthquakes and shaking that control faulting, folding, and small scale deformation processes.

<u>Seafloor Sedimentary and Geotechnical Processes</u>

The working group lacked the expertise to address seafloor sedimentary processes, including problems of slope stability, erosion etc. along continental margins.

2.0 Experiments and Locations

The Juan de Fuca/Gorda/Explorer plate system includes a remarkable array of tectonic features within a relatively small area, including all of the major types of plate boundaries, making it a unique natural laboratory with which to study plate-scale tectonic processes and geodynamics (Fig. 4). The Juan de Fuca plate formed over 20 Ma ago as a remnant of the Farallon plate that broke into several distinct lithospheric units when sections of the Farallon-Pacific plate spreading axis were subducted beneath North America. The Juan de Fuca plate is forming along the Juan de Fuca Ridge and subducts beneath the North America plate along the Cascadia margin. Strike-slip motion occurs along the Sovanco and Nootka fault in the north, and the Blanco and Mendocino transform faults in the south. On a geologic time scale the Juan de Fuca Ridge is slowly migrating towards the subduction zone beneath North America and as the triple junctions at the north and south edge of the plate slowly migrate towards each other, the Juan de Fuca plate will eventually be consumed.



data source: William Wilcock, School of Oceanography, University of Washington

Figure 4. The Juan de Fuca/Gorda/Explorer plate system incorporates a remarkable array of plate tectonic features within a relatively small area including all three major types of plate boundaries (ridge crests, transform faults, subduction zone).

A regional-scale cabled observatory in the Northeast Pacific would provide a unique opportunity to investigate the inter-related processes that control the formation, evolution and destruction of the Juan de Fuca plate and its interactions with the North American continental margin. Understanding these processes will require a series of experiments to address processes at a variety of scales, ranging from plate-scale monitoring (using arrays with an aperture of about 1000 km) to more local experiments with apertures on the order of kilometers to a few tens of kilometers. The general locations of instruments proposed for both the plate-scale array and several local, plate boundary experiments are shown in Figure 5. These observatory experiments are described in more detail in the following sections.

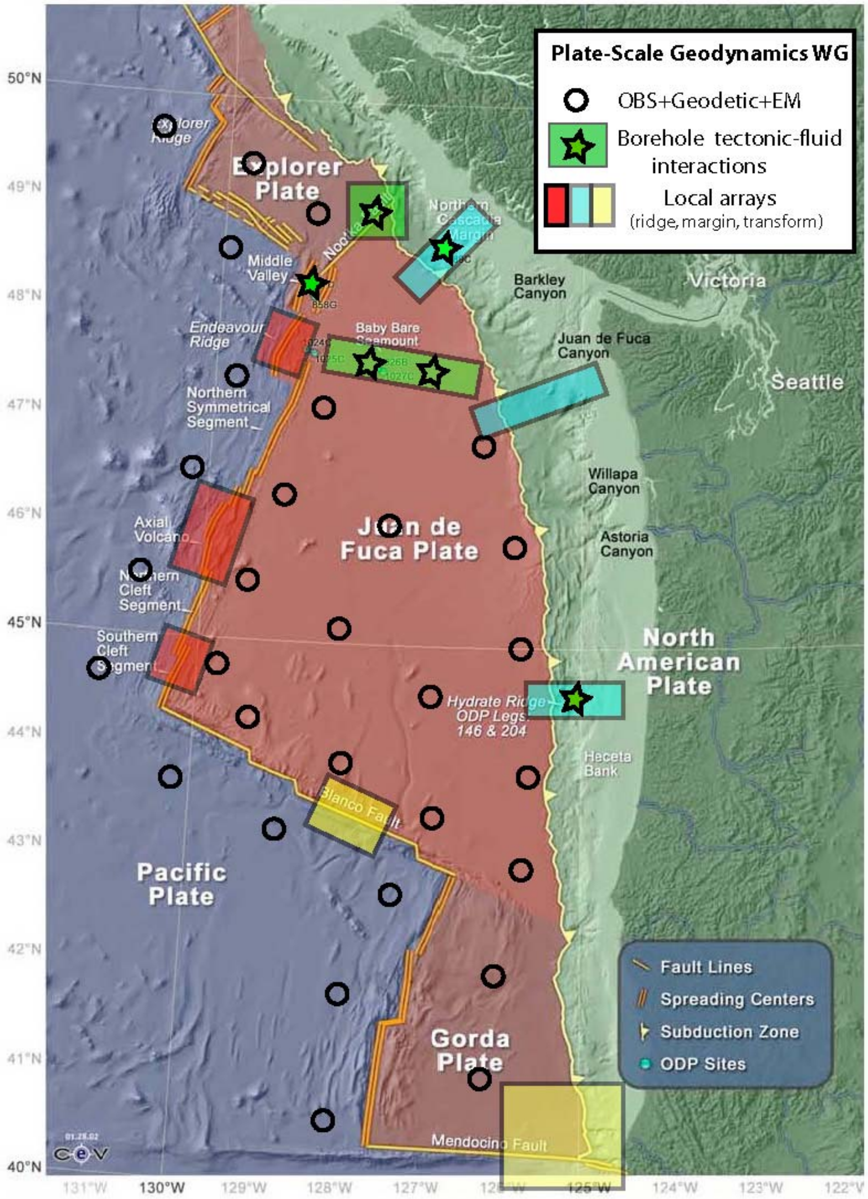


Figure 5. Location of instrument sites for earth structure and plate dynamic studies in the Northeast Pacific

2.1 A Plate-Wide Geodynamics Observatory

A distribution of seismic, geodetic and electromagnetic instruments around the entire boundary of the Juan de Fuca plate is essential to the goal of studying the tectonics of an entire oceanic plate, imaging the structure of the underlying mantle, determining deformation along the plate's boundaries, and constraining plate boundary interactions. The black open circles in Figure 5 show a possible plate-scale observatory design. Instrument spacing is ~100 km (~150 km in the plate interior) with ~30 sites covering the entire Juan de Fuca, Explorer and Gorda plates and extending onto the adjacent Pacific plate in order to ensure good resolution of the structure of the Pacific-Juan de Fuca plate boundary, and the accurate determination of Pacific, Juan de Fuca, and America relative plate motions. Each node of this plate-wide geodynamical observatory should consist of a broadband, 3-component seismometer with a buried sensor, a hydrophone or vertical hydrophone array, transponders for acoustic/GPS plate motion measurements, and sea floor magnetometers and electric field instruments for electromagnetic studies. The highest priority sites are those straddling the Pacific-Juan de Fuca plate boundary, sites located at the base of the continental slope (and outer shelf if available), and sites in the interior of the Explorer and Gorda plates. The array design shown in Figure 5 is notional – a modeling study is recommended to define the optimal array geometry for plate-wide geodynamic studies before an array like this is installed.

A regional seismic network like that shown in Fig. 5 will not be able to characterize the seismicity associated with individual dike extension events along the Juan de Fuca ridge system; a denser concentration of instruments is needed across and along the ridge. Additional short period or intermediate band seismometers should be spaced no more than 30-50 km apart on either side of the spreading center along its length (Fig. 6). A cross-ridge seismic, magnetotelluric and geodetic array should be installed on a part of the plate boundary with no evidence of recent magmatic or hydrothermal activity to contrast with the ridge crest experiments at Endeavour and Axial seamount described below.

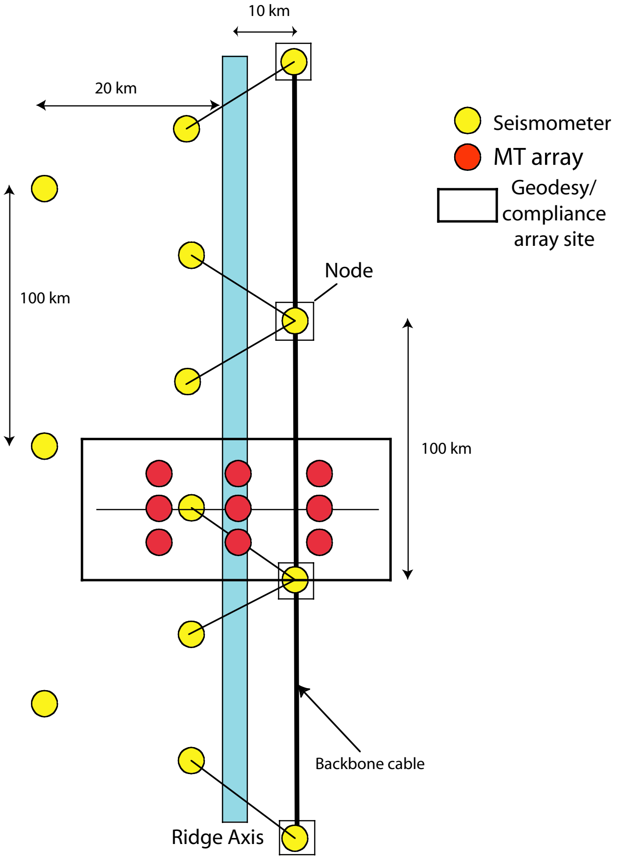


Figure 6. Schematic diagram of distribution of seismic, geodetic and magentotelluric instruments along the Juan de Fuca/ Gorda ridge system for monitoring ridge magmatic and tectonic activity.

2.2 Local Ridge Crest Observatories

A knowledge of temporal and spatial patterns of seismicity and crustal deformation is key to understanding the processes that control the generation of oceanic lithosphere. At shallow depths spreading occurs by dike intrusion and extensional faulting, both of which produce earthquakes, as well as uplift and extension of the crust that can be measured geodetically. Seismicity is also a primary source of information for monitoring and detecting magmatic/ tectonic spreading events along the ridge axis. Earthquakes also provide constraints on the mechanical properties of the forming crust. Fracturing and faulting creates permeability that controls hydrothermal circulation in the ridge and perhaps flank regions. Thus, long-term and detailed seismic and geodetic monitoring is essential to understand the coupling between tectonic, magmatic, and hydrothermal processes at mid-ocean ridges. In order to study the interactions among seismic activity, crustal deformation, and hydrogeologic processes that accompany oceanic crustal formation, array apertures of a few kilometers will be required. Since this will not be feasible over the entire plate boundary, the Working Group identified 4 areas along the Juan de Fuca ridge for detailed study – Endeavour Segment, Axial Seamount, Cleft Segement and Middle Valley.

Endeavour Segment. The well-studied central portion of the Endeavour Segment is a site of particular interest because it hosts five large hydrothermal vent fields that are spaced 2-3 km apart within a small axial valley. A recent multichannel seismic study shows that these hydrothermal fields are underlain by a mid-crustal axial magma chamber. However there is no evidence for recent eruptions, and in contrast to other intermediate- and fast-spreading ridges the magma lens is overlain by a zone of extensive seismicity that has been interpreted as a zone of intense hydrothermal cooling. In 1999 a large seismic swarm in this areas was probably associated with magma intrusion and perturbed the temperatures and chemistry of the vent fluids. One of the key goals of the Endeavour Observatory will be to characterize future tectonic and volcanic events and understand how these impact the hydrothermal systems and the biological communities they support. The local seismic network on the Endeavour Segment must provide accurate locations and focal mechanisms for small microearthquakes along a 10- to 15-km-long section of the ridge that encompasses the vent fields. This will require at least a dozen seismometers spaced 2-3 km apart. The majority should be short-period 3-component seismometers but several broadband seismometers will also be required to record long period tremor signals that are often produced by fluid flow in volcanic regions. An array of acoustic geodetic sensors should also be deployed to record the distribution of extension across the rise axis. Tilt meters, absolute pressure gauges and perhaps absolute gravity meters will record the surface deformation associated with magmatic inflation/deflation and larger earthquakes. Magneto-telluric instruments can measure fluid and magma movement in the sub-seafloor.

Axial Seamount. Axial Seamount, an area of anomalous volcanism, lies near the intersection of Cobb-Eickelberg seamount chain and the Juan de Fuca Ridge (Fig. 5). A summit caldera is surrounded by several hydrothermal vent sites and is underlain by an extensive shallow magma body. There is also evidence for smaller magma bodies beneath the volcano flanks. Over the past decade Axial Seamount has been the locus of two eruptive events. In 1993, a dike propagated 40-km northwards from the north flank to feed a small eruption on the Co-Axial segment. In 1998, a dike propagated southwards from an eruption site in the caldera. The local seismic network on Axial Seamount will have two objectives. It must record the seismicity in the summit region surrounding the caldera and it must characterize the earthquake swarms associated with diking events that may propagate tens of kilometers along the rift zones. The first objective can be satisfied with a network similar to the one described above for the Endeavour segment. The second objective could be accomplished with chains of short period seismometers deployed 2-3 km apart on either side of the rift zone, but it might also be accomplished by a more broadly distributed network. Because Axial Seamount is so magmatically active, geodetic measurements of vertical deformation and tilt will be particularly important at this site. An array of acoustic strain meters will be necessary to measure the two-dimensional pattern of extension associated with diking events and should cover the summit and the rift zones.

There are two other ridge crest sites of secondary interest. The Cleft segment at the southern end of the Juan de Fuca ridge was a focus of early hydrothermal studies in the RIDGE program and is the site of several long-term geodetic experiments that should be incorporated into the regional observatory. A seismic network could be added to support hydrothermal observations and record future volcanic events. Middle Valley at the northern end of the Juan de Fuca ridge is of high priority for hydrothermal studies, but also has important tectonic objectives. It is a sedimented site that was the locus of plate spreading until a recent change in plate boundaries. It is hydrothermally active and, like the Endeavour Segment, the hydrothermal fields are underlain by extensive seismicity. Several ODP drill holes penetrate the hydrothermal system. A small seismic network at this site would complement hydrological observations in these drill holes by characterizing the seismicity and current tectonics.

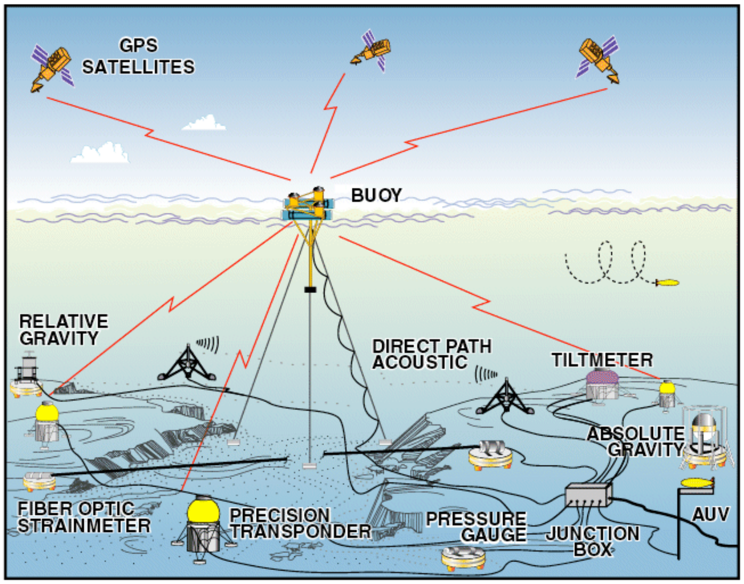


Figure 7. Types of seafloor geodetic measurements that can measure vertical and horizontal deformation of the crust, and larger scale plate motion.

2.3 Subduction Thrust and Accretionary Prism Observatories

Long-term observations are required to understand the physical processes preceding and accompanying megathrust earthquakes. Seismometers are needed to detect and locate small but tectonically important earthquakes currently missed by onshore networks. Geodetic observations can provide critical information on the nature and extent of offshore deformation in the megthrust zone. Other sensors on the seafloor and in boreholes are needed to measure fluid flow and pore pressures. The roles of fluid pressure and transport are especially important. Fluid pressure may control megathrust and smaller earthquake rupture, and fluid transport may control gas hydrate formation. The effects of temperature and sediment chemical changes landward also may be important since fluid processes are likely to be an important factor controlling earthquakes, slope stability and ground motion amplification factor.

Two main subduction and accretionary wedge observatory sites are proposed (Fig. 5), primarily to correspond to existing ODP and planned IODP boreholes off southern Vancouver Island and Oregon (Hydrate Ridge). An additional site off Washington state could address differences in accretionary wedge structure (landward and seaward vergent thrusts) along the Cascadia margin. A fourth site of interest is over the subducting Nootka transform fault (Fig. 5). This site has primary objectives associated with strong frequent earthquake shaking, especially the effects of this shaking on fluid processes in the prism. Much of the prism deformation and fluid/biological processes may be concentrated at the time of very strong shaking from great subduction zone earthquakes. This process cannot readily be studied because of the very large time interval between events (~500 years for Cascadia megathrust events). However, the Nootka fault provides much more frequent large (but not giant) earthquakes. These earthquakes produce strong shaking at time intervals of a few years so are amenable to study by a cabled observatory.

Each subduction and accretionary wedge observatory is a transect ~ 50-75 km long crossing the shelf-slope. In each transect ~10 broadband seismometers and strong motion accelerometers would be deployed. Geodetic sensors will be particularly important in order to measure tilt and vertical uplift associated with accumulation of strain in the overlying plate. Additional sensors needed for these observatories include magnetic and electric field instruments, borehole temperature and pressure sensors, and instruments for fluid monitoring and sampling.

2.4 Transform Fault Observatories

Oceanic transform faults are the least studied type of plate boundary in the oceans despite their natural advantages for constraining the mechanical processes involved in faulting and lithospheric deformation. Oceanic transforms also appear to have behaviors that differ from similar fault systems on land. A cabled observatory with a 30 year lifetime presents an outstanding opportunity to quantitatively investigate the interaction between rock type, thermal structure, and hydrothermal alteration that controls the spatial variation in the failure mode (seismic vs aseismic) of oceanic faults, and to observe a fault through an entire large earthquake cycle.

Blanco Transform Fault. The Blanco transform is a 350 km long right-lateral strike-slip fault with a geologic slip rate of about 7 cm/yr that forms the boundary between the Juan de Fuca and Pacific plates (Fig. 5). The longest segment and arguably the most seismically active portion of the Blanco transform is the Blanco Ridge, a ~150 km long transform ridge located at the eastern end of the transform between the Gorda and Cascadia Depressions. Submersible investigations of the Blanco Ridge found it to be composed of upper oceanic crust and gabbro. Additionally, modeling of gravity and magnetic profiles across Blanco Ridge further suggest a low density and possibly induced magnetization beneath the ridge, characteristic of a serpentinized root. Five M>6 earthquakes located between 127.75 and 128.25W have occurred since 1968. It is difficult to say that a particular point on the Blanco Fault ruptured during a specific earthquake owing to uncertainties in location, depth extent, and rupture length for events not recorded by a local network. However, t-phase derived aftershock locations and standard stress drop values suggest that instrumenting the ~50 km long section of the Blanco Fault around 128°W as part of a Northeast Pacific cabled observatory would capture several large (>M6) earthquakes during its lifespan. An array of broadband and strong motion seismometers combined with geodetic systems will be able to determine the depth range of background seismicity, the rupture area and propagation velocity of large earthquakes, and the region of the fault that slips aseismically. These observations of the fault rheology will be compared with rock mechanics predictions based on the spatial variations of rock type and thermal structure. The seismometer station spacing should be a maximum of about 10 km along strike with stations both directly on top of the fault and ones located approximately 10 km away from the fault. Thus a minimum of ~8 OBS sites (with both a broadband seismometer and strong motion accelerometer) is required. Acoustic-GPS sites should be located on both sides of the fault and direct-path ranging systems should span the fault at a minimum of two locations within the OBS array.

Mendocino Triple Junction Region and Transform Fault. Instrumenting the Mendocino region will contribute to understanding earthquake rupture dynamics, seismic hazard, and the interaction between plate boundaries. A high rate of seismic activity is distributed over a relatively broad region extending approximately 100 km north and 100 km west of Cape Mendicino. This region produced M>6.5 earthquakes on the subduction zone thrust interface, the transform boundary with the Pacific Plate, and internally within the Gorda Plate during the 1990s. A broad seismic and geodetic network with a station spacing of ~20 km covering the southeastern corner of the Gorda Plate would be desirable for studying the suite of structures accommodating deformation and to examine the interaction and stress transfer between them. The stress state within this region is known to vary rapidly over time and these variations can be inferred through earthquake rates and focal.

3.0 Instrumentation Needs

A plate-scale geodynamic observatory has a variety of instrumentation needs. Each observatory node should be equipped with the following “core instruments”:

Hydrophone (or hydrophone array)
Temperature
Conductivity
Current meter

“Community instruments” required for plate-scale geodynamic studies include:

Broadband seismometers (buried sensors)
Short or intermediate period, 3-component seismometers
Strong motion accelerometers
Acoustic/GPS transponder array
Seafloor tiltmeters
Absolute pressure gauge
Fiber optic strain meters
Acoustic strain meters (direct and indirect path)
Relative and absolute gravity meters
EM and MT instruments
Seafloor compliance instruments
Borehole seismometers, strain meters and fluid samplers

It is worth noting that with the exception of some geodetic sensors (e.g. fiber optic strain meters, absolute gravity meters), these are all mature instrument systems that are ready for deployment at an ocean observatory. No major instrument development is required for a geodynamic observatory.

4.0 Seafloor Maps and Site Surveys

A key related need for a geodynamic observatory is improved seafloor swath bathymetry and backscatter maps of the Juan de Fuca plate and adjacent areas, and more detailed local site surveys. Currently, high-resolution bathymetric maps are only available for the axial region of the Juan de Fuca Ridge, much of the margin, and a few other selected regions (quality is variable). Acquiring high-resolution bathymetry and side scan sonar imagery over the whole Juan de Fuca plate should be a high priority before installation of geodynamic observatories. Detailed local site surveys and repeat bathymetric and seismic reflection surveys of selected plate boundary areas will be another useful tool for determining change in plate boundary systems.

5.0 Highest Priority Community Instrumentation for Installation with the Observatory Infrastructure

The establishment of the complete plate-scale geodynamic observatory as outlined above will take several years. The highest priority community instrumentation for installation with the observatory infrastructure is outlined below. This instrumentation would provide an early scientific payoff by establishing one geodynamic observatory on each of the three major types of plate boundaries in the Northeast Pacific and a regional seismic and geodetic array for defining plate-scale processes and plate boundary interactions. Exciting results that could emerge in the first few years include new constraints on mantle dynamics at the plate-scale, new information on the links between fluid flow and earthquake activity, "capturing" a diking event at the Juan de Fuca leading to a better understanding of the coupling between tectonic, magmatic, and hydrothermal processes, or the documentation of new evidence for stress transfer over long distances and interactions between plate boundaries (e.g. events on the Blanco transform triggering events on the Juan de Fuca Ridge or Cascadia margin).

The community instrumentation recommended for installation with the observatory infrastructure includes:

- Broadband seismometers at each node, and at some additional sites on the Pacific plate (~30 sites total)
- Acoustic geodetic sensors at a subset of the nodes for plate scale geodynamic observatory (~10 sites)
- Endeavour ridge crest observatory instrumentation (~12 seismometers, geodetic, MT and compliance instruments)
- Instrumentation for one subduction megathrust transect (~10 broadband seismometers, geodetic instrumentation)
- Blanco fracture zone observatory instrumentation (6-8 broadband seismometers and geodetic instrumentation)

6.0 Additional Sites for Regional Cabled Observatories

A regional scale observatory in the Northeast Pacific provides the opportunity for conducting multidisciplinary and contemporaneous observations over a whole tectonic plate and at finer scales along the three basic types of plate boundaries. However, there are numerous fundamental questions on lithosphere/asthenosphere dynamics, physical and chemical oceanography, biogeochemistry, microbiology, biogeography, and climate change that can be addressed only by extending and contrasting the observations obtained in the Northeast Pacific with multi-disciplinary observatory data in other tectono-volcanic, oceanographic and biogeographic settings. Several additional sites for regional cabled observatories of particular interest for studies of earth structure and geodynamics are discussed below, some of which are priority areas for other major US geoscience programs (R2K, MARGINS, IODP, OMD, EARTHSCOPE)

6.1 Intra-oceanic arc and back arc systems

Intra-oceanic arc and back arc systems provide a very different and complementary tectonic setting to the Juan de Fuca plate for studying “Earth Structure” processes. Two plate-scale regional cabled observatories are recommended that would enhance existing global focus areas of the US RIDGE 2000 (East Lau Spreading Center) and MARGINS (Mariana Subduction Factory) Programs. Both may be able to re-use existing telecommunication cables (Pacrim East and GPT, respectively) as a means of rapid progress towards establishing these observatories.

Common themes:

- Deformation, fluid flow and serpentinization (?) associated with subduction of the oldest (Mesozoic) oceanic crust,
- Tectonic erosion, and fluid flux through non-accretionary forearc,
- Backarc spreading processes and how they differ from mid-ocean ridges
- Biosphere, hydrothermal circulation and metallogenesis of both submarine arc volcanoes and back-arc spreading centers (with varying arc proximity/influence),
- Mantle wedge circulation, composition, rheology, and melting,
- Lithosphere subduction through the 670 km discontinuity

The Tonga-Kermadec region has additional features of interest from a geodynamic perspective including a hotspot at American Samoa at its northern end; continental shelf and slope off NE New Zealand in the south; and the fastest global rates of subduction and transform faulting (240 mm/yr). The Mariana has the additional characteristic of forearc serpentinite mud volcanism.

6.2 California Borderlands and Gulf of California Observatory

Earthquakes and faulting in southern California occur to a large extent along the San Andreas fault system between the Pacific and North American plates. This fault system extends from Cape Mendocino, where it reaches the triple junction bordering the southern end of the Gorda plate, to the Gulf of California where it intersects the rifted margin forming the Gulf of California. The proposed Northeast Pacific Observatory will cover the plate boundaries north of Cape Mendocino.

A California Borderlands Observatory would cover the Pacific-North America plate boundary to the south of the Mendocino transform. Nearly all of the control on faulting parameters, earthquake locations and deformation for this plate boundary are obtained from seismic and GPS stations to the east of this fault system. Seismic stations in the ocean to the west of the plate boundary would add greatly to the precision of locations, particularly for earthquakes occurring near and under the ocean, and for delineation of fault mechanics. Earthquakes along the Mendocino transform would also be much better resolved than is possible with only land stations. The scientific uses for such an observatory would include seismic monitoring, plate boundary structural investigations, submarine landslide studies, and tsunami detection. This would constitute the oceanic compliment to the Plate Boundary Observatory of EARTHSCOPE. The Gulf of California – Salton Sea is one the MARGINS focus sites for continental rifting and initial sea floor spreading.

6.3 Slow and Ultraslow Spreading Centers (Mid-Atlantic Ridge, Reykjanes and Gakkel Ridges)

From a solid Earth perspective, the spreading rate at a divergent plate margin provides a fundamental boundary condition and control on magma supply. The conventional, steady-state view of the thermal state of the oceanic lithosphere held that at slow spreading centers there would be insufficient magma supply to support the existence of sustained crustal magma chambers. By extension it was reasonable to anticipate that hydrothermal venting sites would be rare or non-existent in such settings. In recent years, however, a magma chamber has been detected along the slow spreading Reykjanes Ridge, a northern extension of the MAR. The Gakkel Ridge, in the Arctic basin, is the slowest spreading of all oceanic ridge systems, yet the magmatic heat budget appears sufficient to support extensive venting at multiple sites. A fundamental problem is therefore arising in balancing plate dynamics and evolution against the problem of magma supply. A sustained observing program along the MAR, and also north into the Gakkel Ridge area, could be used to contrast these slow and ultra-slow spreading and ostensibly magma-starved spreading ridges with the intermediate spreading, more magma-rich Juan de Fuca system.

Mid-Atlantic Ridge - The Mid-Atlantic Ridge southwest of the Azores Archipelago (also known as the MOMAR region) contains four sites of high-temperature hydrothermal venting related to magmatic heat sources. The area is also located close to sites of venting linked to serpentinization of the upper mantle (Soldanha and Lost City). The vent sites are located along a section of the ridge crest convenient to access from the Azores in varying geological settings and at a range of different depths/pressures. The Lucky Strike vent sites are distributed around a lava lake in the caldera of an axial volcano. The Lucky Strike segment has been designated by InterRidge as a region for detailed multidisciplinary investigations in a range of seafloor environments, all within ready reach of the Azores.

The MOMAR area is also of interest to researchers in water-column processes. This section of the MAR exhibits a complex hydrography that is further affected by the ridge topography, the Mediterranean water tongue and the Azores current and front. The water column overlying the ridge crest within the MOMAR area is noted for an increased biomass, perhaps linked to local upwelling around the islands as the ridge-crest shoals toward the Azores Archipelago. The intrinsically high biodiversity observed within the mid-water fauna at these latitudes attracts the interest of a wide spectrum of scientists studying biogeochemical cycles.

Reykjanes Ridge - A number of sites at different stages of a tectonomagmatic cycle may be instrumented further north on the slow spreading Reykjanes Ridge region where there is no present evidence for hydrothermal venting. An E-W oceanographic instrument array centered on the southernmost Reykjanes Ridge could measure the structure and transport of deep boundary currents on either side of the ridge. These current systems play a fundamental role in transport of heat in the North Atlantic conveyor system and exert a moderating influence on climate in this region. Physical oceanographic and upper ocean biogeochemical data can be provided by vertical sub-arrays, distributed from WNW to ESE across the axis of the Reykjanes Ridge, and extending laterally for hundreds of km and vertically throughout the water column. A transect of time series across the ridge offers an opportunity to study the boundary between two North Atlantic biogeochemical provinces, the Atlantic Arctic province to the Northwest and the North Atlantic Drift province to the southeast.

Gakkel Ridge – The Gakkel ridge is the slowest spreading ridge on the planet yet shows unexpectedly high levels of hydrothermal activity. Multi-disciplinary data collected by an Arctic regional cabled observatory would be able to address fundamental questions regarding the dynamics of the upper mantle and sea floor spreading, and associated magmatic and hydrothermal processes at ultraslow spreading rates. This information will provide the basis for a new generation of predictive geodynamic models of mantle matrix flow, melt generation and melt extraction that take full account of time variations and their interactions with ridge segmentation.

6.4 Cable Re-use Opportunities for Additional Cabled Regional Observatories

There is currently an opportunity to acquire and use retiring fiber optic submarine telecommunications cable systems to provide infrastructure for ocean observing systems. The cable systems are being retired well before their design lifetime because of conditions in the industry. Assuming that the cables can be acquired for scientific use, and that technical and engineering issues surrounding their reuse for ocean observatories can be solved, several of these cables could be moved to locations where they could provide the infrastructure for additional regional observatories.

TAT-10 - The possibility exists to reuse the second generation fiber optic telecomunications cable TAT-10, which runs from New Jersey, crosses the MAR in the mid-40's N latitude, and enters European marginal seas north of the UK, where it branches into spurs landing in Germany and Denmark. The section of cable from the European continental margin break could be recovered and moved to serve the Reykjanes or Mid-Atlantic Ridge observatories described above.

HAW-5 - The Hawaii-4 optical cable between Hawaii and California was retired in October, 2003. AT&T is offering the cable system to the scientific community for re-use to support ocean observatories. One option for observatory use is to move the eastern half of the cable from its current location to the ocean off California from north of Mendocino to the Mexican border, with 10 to 12 instrumented nodes along the cable.

A second cable, TPC-5, will likely be retired within a few years. This cable could be used to circle Baja California providing observatory infrastructure on both sides of Baja California. Cable infrastructure running up the Gulf of California would be of interest for monitoring activity on the spreading centers and transform faults that constitute this plate boundary.