



The background is a detailed bathymetric map of the Pacific Northwest region, showing the Explorer Plate, Explorer Ridge, Middle Valley, Endeavor Ridge, and the North American Plate. It also labels the Pacific Plate, Gorda Plate, and various faults like the Explorer Fault and Mendocino Fault. A red box with the word 'RECONN' is overlaid on the top right, and a blue box with the full name of the network is overlaid on the middle left.

# RECONN

## Regional Cabled Observatory Network (of Networks)

Report of the  
**Cabled Regional  
Observatory Workshop**

Held October 2003



## Ocean Observatories Initiative

The National Science Foundation (NSF) Division of Ocean Sciences (OCE) established the Ocean Observatories Initiative (OOI) to facilitate the temporal and spatial exploration of the ocean. With proposed support from NSF's Major Research Equipment and Facilities Construction (MREFC) account, OCE plans to support construction of an integrated observatory network that will provide the oceanographic research and education communities with a new mode of access to the ocean. The OOI has three elements:

(1) regional cabled observatories on the seafloor spanning multiple geological and oceanographic features and processes, (2) globally distributed moorings that could be deployed in harsh environments such as the Southern Ocean, and (3) new construction or enhancements to existing facilities leading to an expanded national network of coastal observatories. The RECONN report addresses the regional cabled observatory (RCO) component, in particular the location of the first RCO and how the cable should be configured to best achieve the research objectives across all disciplines of ocean science.

# **RECONN**

## **REgional Cabled Observatory Network (of Networks)**

**Report of the Cabled Regional  
Observatory Workshop**

**October 7-10, 2003  
San Francisco, CA**

**A Report to the  
National Science Foundation**



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# OVERVIEW

For decades, progress in the ocean sciences has been limited by scientists' inability to observe and sample the ocean, and its attributes, on spatial *and* temporal scales required to characterize it. Notable attempts have been made to tackle this "aliasing" problem. Major strides have been made in ocean biogeochemistry as a result of data collected at the two long-time-series stations—Hawaii Ocean Time Series (HOT) and Bermuda Atlantic Time Series (BATS). But interpretation of data from these sampling sites, the first in biogeochemistry to overcome the limitations of inadequate temporal sampling, are limited by a profoundly inadequate spatial sampling—a single point. In marine geology, the FAMOUS project at the crest of the Mid-Atlantic Ridge stands out as an early example of the value of obtaining dense spatial sampling within a single area typical of an important process, in this case, crustal accretion. This project's lack of temporal sampling (only a single set of surveys were carried out), however, meant that decades would pass before exciting discoveries of the episodic nature of mid-ocean ridge processes could be made.

This fundamental truth—that the majority of the measurements that we make in the oceans are aliased in space or time—is well known, but is rarely articulated because practical limitations prevent meaningful response.

The concept of the Regional Cabled Observatory (RCO), using a few thousand kilometers of seafloor electro-optic cable located within a region of many hundreds of kilometers extent—including the deep ocean—is the first significant response by the ocean sciences community to this challenge. There is a need for instrumentation systems to be emplaced in a few

locations around the globe that have the capability to sample, *both in time and space*, on the scales at which the processes to be investigated are operating.

An RCO is not any set of sensors that are connected by a seafloor cable (thus providing a continuous data stream and overcoming the temporal sampling problem). Rather it is a *regionally distributed set of sensors linked by high-bandwidth seafloor cables* that permit investigators to overcome simultaneously both the temporal and spatial sampling problem.

From October 7-10, 2003, approximately 70 ocean scientists met at the National Science Foundation (NSF)-sponsored Cabled Regional Observatory Workshop in San Francisco, California to consider where such regional cabled observatories should be located, and in some detail, how the first such facility should be configured.

It is impractical to instrument all the world's oceans, and it is impossible to identify a single regional location at which *all* important ocean processes can be studied and observed adequately. Therefore, from the beginning the community plans a network of RCOs, distributed globally that will, in sum, address the highest-priority, process-oriented research questions.

## Science Drivers

RCOs will tackle the full range of important research problems in modern ocean sciences. RCO technology will transform the way that ocean scientists work. New approaches to many key problems in ocean science will be enabled. Progress will be dramatically accelerated toward understanding fundamental processes that control, for example, earthquake

generation, seafloor volcanism, air-sea exchange of greenhouse gases, biogeochemical cycling, and the impacts of climate change and human activities upon marine ecosystems.

Several of the most fundamental processes occurring in the oceans cannot be understood until the role of turbulence (at scales from millimeters to thousands of kilometers) is assessed quantitatively. Prime candidates for quantification include air-sea exchanges of greenhouse gases, the magnitude of thermohaline circulation, and fundamental frequencies and magnitudes of ecosystem dynamic parameters. RCO capability is essential to the advancement of ocean turbulence studies and their impact upon ecosystems, not only because of the bandwidth of spatial scales that must be addressed, but also because of the high power requirements of almost all the appropriate sensor and observation systems (e.g., large-scale eddy studies with acoustics, biological observations with multi-frequency acoustics and video/still photography).

An RCO is essentially the only known approach to the observation of ocean variability across the full spectrum of time scales from fractions of a tidal cycle to multiple decades and so is the only hope of reliably observing long-term changes and establishing a true “mean” picture of the ocean’s carbon cycle for selected regions. In the coming decades accelerating human impacts and climate change promise to impact marine ecosystems at unprecedented levels. The temporal and spatial sampling capabilities of an RCO coupled with its available power for sophisticated sensor suites will accelerate understanding of how biodiversity, biogeochemical cycling, functional ecology, and the structure and distribution of biological assemblages are altered, so offering the promise of the ability to forecast and perhaps mitigate the impact of these changes.

Although kinematics of Earth’s lithospheric plates is well known, many fundamental questions remain unanswered regarding forces acting on plates, how plate boundaries interact and deform, and linkages and feedbacks among the magmatic, tectonic, hydrothermal, and biological processes at plate boundaries. Only an RCO can collect the seismic, geodetic, and other geophysical data needed to tackle these problems over a region encompassing an entire plate over an extended period.

It is now known that novel microbial communities thrive in the absence of sunlight under anoxic conditions within the hot volcanic rocks of active mid-ocean ridge systems. These microbial communities exist within, and move through, the sediments that accumulate as the seafloor ages as well as within the accretionary prisms that accumulate along convergent margins bounding continents and volcanic arcs. Although individual components of these systems have been studied in detail, fundamental questions remain regarding process linkages in each of the environments at the scale of an entire plate ecosystem. Only the observational capabilities provided by an RCO will allow definitive approaches towards these complex questions.

## First RCO

The realization of the first integrated, regional-scale system requires the research community’s endorsement of a single geographic location for the initial RCO installation. The choice of this location must balance the importance of the science themes served by the RCO against the many practical issues associated with its engineering, implementation, and maintenance. Experience from previous smaller-scale observatory efforts highlight the many significant logistical concerns, which should be taken into account in the initial designs. At the workshop, many sites spanning the globe were considered with a mix of science and logistical opportunities. The Northeast Pacific Ocean has compelling scientific opportunities



in many different fields with relatively accommodating logistics. The Tonga-Kermadec island arc in the western Pacific region has compelling science opportunities but more challenges associated with the more remote location. Other regions near the United States and Canada provide feasible logistics (North Atlantic, sub-tropical Atlantic, sub-tropical Pacific coast), and excellent scientific questions for some fields, but lack compelling scientific questions for others. Polar regions present many fascinating scientific questions, but are the most challenging logistically.

Workshop attendees reached a consensus that, although a clear need can be articulated for a globally distributed network of RCOs, the most favored location for the first such observatory is the Northeast Pacific in the vicinity of the Juan de Fuca Ridge. The rationale for this decision combined consideration of the range of research topics that can be tackled in this region, along with the logistical convenience of supporting the prototype engineering from nearby U.S. ports, the magnitude of the planning invested by the Neptune Project, and the substantial commitments to this region in place by Canadian Government funding sources.

## Recommendations

The workshop premise was that funding would be available to support emplacement of 20 to 30 primary nodes along ~ 3500 km of seafloor electro-optic cable. Within that context, attendees made the following recommendations:

- **Plan for a globally distributed network of RCOs.** The complexity of the dynamics of ocean and ocean-floor processes operating at the broadest range of temporal and spatial scales requires establishing a network of RCOs around the globe during the next several decades. Planning for this network should begin, entraining all interested nations even as the first prototype RCO is being designed and installed.
- **Locate the first RCO in the Northeast Pacific.** The first RCO should be located in the Northeast Pacific and should be designed optimally to tackle the broadest range of important process-oriented research themes that span all ocean science disciplines.
- **The First RCO – Design.** Recommendations concerning sensor types and sites are included in figures shown in the report. Consideration must be given to the wide use of “extension cables” that, when judiciously located away from the primary nodes of the main cable, permit great flexibility to locate sensors over very large areas of the ocean floor. Resource limitations inevitably require identifying a set of highest-priority sensors and observation sites that should be populated as part of the “first deployment” plan to insure timely production of exciting and important results. This “first deployment” plan described in the report includes five sites and transects to tackle crustal and lithospheric problems and twelve “super sites” to address water-column physical, chemical, and biological processes.

Other key recommendations are described more fully in the body of the report, including:

- Observe the full water column
- Use this unique infrastructure to support the highest quality research and education
- Develop new sensor technologies
- Build strong linkages between observations and other key research approaches
- Maintain a quality infrastructure.

# INTRODUCTION

This report describes proceedings of one of a series of NSF-sponsored planning activities in support of the Ocean Observatories Initiative (OOI). The Cabled Regional Observatory Workshop, which took place in San Francisco from October 7-10, 2003 and has come to be known as RECONN (REgional Cabled Observatory Network (of Networks)), addresses the RCO component of the OOI. The workshop's charge was to identify where the first RCO should be located on the ocean floor and to consider how, given the special characteristics of that location, the cable should be configured to best achieve the research goals across all sub-disciplines of ocean science.

The OOI is one component of a broader program called Ocean Research Interactive Observatory Networks (ORION). Whereas the OOI is only associated with observatory infrastructure funded through NSF's Major Research Equipment and Facilities Construction (MREFC) account, the ORION Program will encompass a broader range of activities. They include operation and maintenance of systems established under the OOI as well as existing observatory sites, instrumentation for OOI infrastructure, mobile platforms, research funding, and education and outreach activities.

**Table 1: OOI-Related Reports**

- *Autonomous and Lagrangian Platforms and Sensors*  
[www.geo-prose.com/ALPS](http://www.geo-prose.com/ALPS)
- *Coastal Ocean Processes and Observatories: Advancing Coastal Research*  
[www.skiio.peachnet.edu/coop/materials/COS\\_report.pdf](http://www.skiio.peachnet.edu/coop/materials/COS_report.pdf)
- *Enabling Ocean Research in the 21st Century: Implementation of a Network of Ocean Observatories*  
[books.nap.edu/catalog/10775.html](http://books.nap.edu/catalog/10775.html)
- *Illuminating the Hidden Planet*  
[www.nap.edu/catalog/9920.html](http://www.nap.edu/catalog/9920.html)
- *Implementation Plan for the DEOS Global Network of Moored-Buoy Observatories*  
[www.coreocean.org/deos](http://www.coreocean.org/deos)
- *An Information Technology Infrastructure Plan to Advance Ocean Sciences*  
[www.geo-prose.com/oiti/report.html](http://www.geo-prose.com/oiti/report.html)
- *Ocean Observatories Initiative brochure*  
[www.geo-prose.com/projects/ooi\\_broch.html](http://www.geo-prose.com/projects/ooi_broch.html)
- *Ocean Sciences at the New Millennium*  
[www.joss.ucar.edu/joss\\_psf/publications/decadal](http://www.joss.ucar.edu/joss_psf/publications/decadal)
- *Real-time, Longterm Ocean and Earth Studies at the Scale of a Tectonic Plate, NEPTUNE Feasibility Study*  
[www.neptune.washington.edu/pub/documents/documents.html](http://www.neptune.washington.edu/pub/documents/documents.html)
- *Science Planning for the NEPTUNE Regional Cabled Observatory in the Northeast Pacific Ocean: Report of the NEPTUNE Pacific Northwest Workshop*  
[www.neptune.washington.edu/pub/workshops/PNW\\_Workshop/ws\\_reports\\_documents.html](http://www.neptune.washington.edu/pub/workshops/PNW_Workshop/ws_reports_documents.html)
- *SCOTS: Scientific Cabled Observatories for Time Series*  
[www.geo-prose.com/projects/scots\\_rpt.html](http://www.geo-prose.com/projects/scots_rpt.html)

Continued refinement of the OOI implementation plan has grown from several community-wide scientific planning efforts (Table 1). An important scientific justification for OOI science is provided in the report, *Ocean Sciences at the New Millennium* (Brewer and Moore, 2001). In that report, the community strongly advised that, “New fixed (cabled or moored buoy) and mobile (ROV, AUV, drifter) ocean-observing systems are an essential complement to ships and satellites, and must be deployed if critical events are to be captured.” To make the next, significant step forward in understanding of the oceans and the seafloor below, we need to be able to continuously observe these phenomena at spatial and temporal scales appropriate to the processes and systems being studied.

A report issued by the National Research Council (NRC) in 2000 also recommended that NSF initiate a seafloor observatory program. The NRC committee’s conclusions paralleled those of the Millennium Report committee, stating that, “The scientific problems driving the need for seafloor observatories are broad in scope, spanning every major area of marine science.” “The scientific benefit of seafloor observatory research has been recognized for many years.” A follow-on NRC study (NRC, 2003) provided NSF with advice on various implementation issues related to the establishment of an ocean observatory network.

To engage the community in a dialog to determine what science questions would benefit most from establishing a network of ocean observatories, where key observatories should be located, and how an ocean observatory program should be managed, NSF’s Division of Ocean Sciences established the Dynamics of Earth and Ocean Systems (DEOS) Steering Committee. This committee continues to advise NSF on OOI planning and implementation. In early 2004, the DEOS committee will be replaced by the ORION Project Office whose primary tasks will be to establish a scientific and technical advisory structure, develop a project implementation plan for the OOI, and continue community outreach.

The Scientific Cabled Observatories for Time Series (SCOTS) workshop, held in August 2002, specifically addressed the regional cabled observatory aspect of the OOI. The workshop focused on scientific questions that require, or would most effectively be addressed, by networks of multidisciplinary cabled observatories in three generic domains: open ocean, geologic plates, and coastal. The five scientific working groups at the Cabled Regional Observatory Workshop took the science identified in the SCOTS report (Glenn and Dickey, 2003), with the exception of coastal observatory studies (which was the subject of a separate NSF-funded workshop), and considered the optimum location for establishing the first RCO. This report synthesizes the five individual RECONN scientific working group reports, and organizes the information presented in them. The five scientific working groups were:

- Earth Structure and Dynamics of the Oceanic Lithosphere
- Fluids and Life in the Oceanic Crust
- Turbulent Mixing and Biophysical Interactions
- Ecosystem Dynamics
- Ocean, Climate, and Biogeochemical Cycling.

As many subdisciplines as possible were represented in the working groups given workshop space limitations. Unfortunately, however, there were a number of important omissions, especially in the areas of sediment dynamics and in the study of megafauna, including marine mammals. These subdisciplines should receive particular attention during the later, more-detailed planning activities that are essential to this initiative’s successful progress.

Full copies of the working group reports are available at [http://www.geo-prose.com/cabled\\_wksp/](http://www.geo-prose.com/cabled_wksp/).

## What is a Regional Cabled Observatory (RCO)?

“A cabled observatory is an unmanned system located in a fixed region that uses electrical/fiber optic cables either laid on or buried just below the seafloor to provide substantial electrical power and real-time, two-way communication links between a shore base and, often, multiple measurement platforms deployed offshore. The observational assets supported by the cable system will generally include a variety of stationary and mobile platforms enabling coherent, interdisciplinary measurements over temporal and spatial scales sufficient to study a broad suite of processes in regions selected for particular scientific interest.” (Glenn and Dickey, 2003).

A regional cabled observatory takes the cabled observatory concept and extends the network over an area of many hundreds of kilometers or more out to the deep ocean. Along the length of the cable are “nodes” to which a variety of instrument packages, including water-column moorings, may be connected. Sensor networks of secondary cables (< 100 km long) and mobile platforms will be used to provide the necessary sampling between primary nodes. This is the only way that large regions of the ocean can be monitored over long time periods, providing ocean scientists with the ability to sample—simultaneously—at the spatial and temporal scales at which the physical, chemical, biological, and geological processes to be investigated are operating.

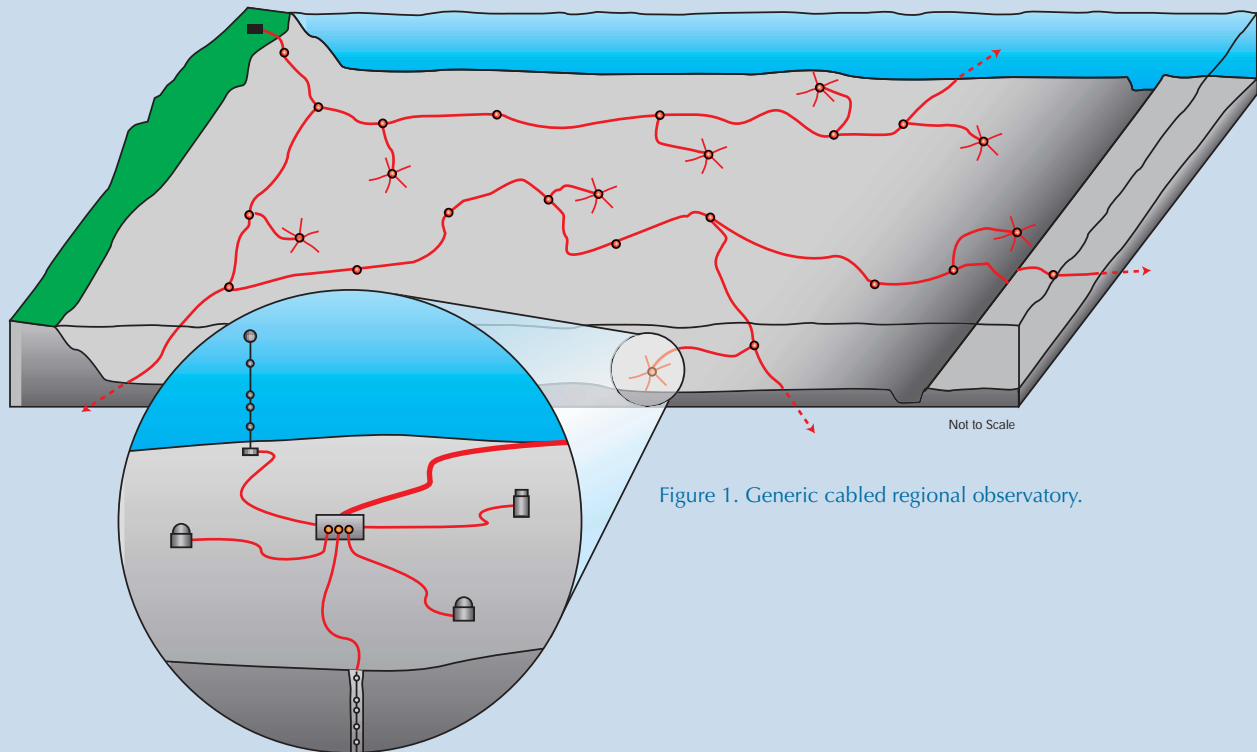


Figure 1. Generic cabled regional observatory.

# SCIENTIFIC RATIONALE

The coupled dynamics of the land-ocean-atmosphere systems establish and maintain Earth's habitability. Key processes ranging from plate tectonics to air-sea gas exchange to ocean water mass formation to controls on the production and consumption of organic matter vary on multiple and independent temporal and spatial scales, from millimeters to thousands of kilometers and seconds to millennia. Furthermore, many key processes are episodic in time or heterogeneous in space, and must therefore be measured continuously to obtain accurate integrated assessments. Unfortunately, undersampling is a fact of life in oceanography; neither the spatial nor temporal coverage of observations is sufficient to achieve a comprehensive understanding of many of these key processes, and thus how Earth might change in response to greenhouse gas-induced warming or other global environmental forces. The planned establishment of RCOs at strategic oceanic sites will provide an opportunity to view Earth processes through a new window of opportunity. These remote, long-term measurement programs are ideally suited for investigations of subtle habitat changes, irregularly spaced stochastic events, and the many complex interactions that dominate in the marine environment.

Historically, marine scientists have used ships to observe oceanic processes. The advent of remote-sensing technologies, including Earth-orbiting satellites, autonomous underwater vehicles, floats and drifters, and other unattended instruments has begun to provide the scientific community with high-temporal-frequency data sets and synoptic views in a large spatial domain. In designing the next generation of ocean observatories it is imperative to consider that the temporal and spatial scales of variability for key geological, chemical, physical, and biological phenomena

may be very different. This places a significant burden on those planning and coordinating these interdisciplinary observation programs.

For example, a complex set of inter-related processes determine the nature and evolution of the oceans and the underlying lithosphere. Hydrothermal vents result from volcanic and tectonic processes: cold seawater is drawn down into the oceanic crust, to then be heated by magmas beneath mid-ocean ridge spreading centers. These vents support unusual biological communities, and also pump heat and minerals into the ocean, which are then moved around the globe by ocean circulation. Hydrothermal vents are ephemeral, and thus so are the biological communities that they support. New ones spring up where magma moves close to the seafloor (preceded by volcanic earthquakes), while others die out as the seawater cools the new crust and hard, cold basalt replaces it.

We now know that marine ecosystems are variable in time and space; both the population structure and the rates of ecosystem metabolism and biogeochemical cycling—including carbon dioxide sequestration—vary considerably, and in large part in response to climate variability and other physical forcing mechanisms. For example, basin-scale climate variations such as the El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and North Atlantic Oscillation (NAO), with time scales ranging from subseasonal to decadal, are known to cause changes in wind forcing, nutrient loading, primary and secondary productivity, and carbon export in the impacted habitats. Repeat or continuous observations of the coupling of the large-scale climate processes to the more local/regional scale fish production, for example, will yield both the mean or climatology as well as the perturbed state. These anomalies will provide

the data necessary to calibrate and improve existing biogeochemical models, which can then be used to predict future states of the global ocean under anthropogenic greenhouse-gas forcing of climate change.

These links among biological, chemical, physical, and geological processes are not new discoveries. Observing them and measuring them at the temporal and spatial scales appropriate to each process, and understanding the mechanisms underlying their behavior, does, however, pose a great challenge for ocean scientists. Cabled observatories, which would provide the power required for instruments to remain operational for extended periods, and thus would provide the long-time-series information required to understand the links among the different processes, will open new and exciting research avenues in the future.

At the RECONN meeting, five working groups discussed the scientific problems that would require, or most effectively be addressed by, RCOs. The working groups used the SCOTS report (Glenn and Dickey, 2003) as a basis for these deliberations. While we have, for organizational purposes, broken down the science into themes, there was considerable discussion among meeting attendees regarding the close links among the different disciplines. Key science considerations are as follows:

## Earth Structure and Dynamics of the Oceanic Lithosphere

The movement and interaction of tectonic plates at Earth's surface is responsible over geologic time for the formation of ocean basins, uplift of mountain ranges, and rifting of continents. On human time scales these plate motions cause earthquakes and volcanic eruptions that can have devastating consequences for populations that live along plate boundaries. Although 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 collection of seismic, geodetic, and other geophysical data at multiple scales over a region encompassing an entire plate over an extended period.

## Fluids and Life in the Oceanic Crust

Some of the most novel organisms on Earth live within one of the most extreme environments on our planet along the global mid-ocean ridge spreading network. These microbes produce and utilize volcanic gases and thrive in the absence of sunlight under anoxic conditions within the young, hot volcanic rocks. Evidence indicates that deep microbial communities and consortia also exist within, and move through, the sediments accumulating on the seafloor during crustal aging, and within accretionary prisms that accumulate along convergent margins bounding continents and volcanic arcs. At major plate boundaries associated with transform faults, recent discoveries of carbonate vent systems indicate that a methane-dependent suite of microbial communities may be linked to the exothermic, hydrogen- and methane-generating interaction between seawater and mantle peridotite. The microbiological communities within these transform fault systems are dramatically different from those associated with submarine volcanism, and they represent a new biotope that does not require volcanic heat. Although individual components of these plate systems have been studied in detail, fundamental questions remain regarding process linkages in each of the environments and at the scale of an entire plate ecosystem. The relative significance of the carbon fluxes and the carbon fixation associated with these systems is unknown. In addition, recent responses of instruments in Ocean Drilling Program holes show that from a deformation-hydrological perspective, linkages occur over distances >100 kilometers requiring long-term, plate-scale observations. An RCO would permit questions and priorities to be ad-

dressed that focus on understanding the links among plate-scale ecosystems, deformation, and fluid flow in a variety of tectonic settings.

## Turbulent Mixing and Biophysical Interactions

Ocean turbulence occurs at a variety of scales, from microscale (millimeters) to mesoscale (hundreds to thousands of kilometers). Turbulence in the ocean has significant consequences for carbon fluxes, ecosystem dynamics, and marine biodiversity through direct and indirect effects on the marine ecosystem. In addition, turbulence has profound effects on air-sea exchanges of greenhouse gases and on the magnitude of the thermohaline circulation. Ignorance of the processes and locations of turbulent mixing in the ocean has such serious implications for global climate modelling and climate change projections that the *Millennium Report* (Brewer and Moore, 2001) identifies turbulence as one of the remaining “big questions” in ocean science.

Cabled systems are essential for tackling problems in small-scale turbulence and its interactions with all levels of the marine ecosystem. The ability of cabled systems to collect data during periods when sea state prohibits measurements from ships will be critical in detecting rare but intense mixing events and in assessing the physical and biological responses to turbulence over the full range of conditions that occur in the ocean. Both the ample power and, especially, the broad bandwidth that will be provided by cabled systems are required by present methods for measuring turbulence quantities (dissipation scales with microscale sensors or large-eddy scales with acoustics), and for those biological techniques (such as multi-frequency acoustics, spectral analysis of inherent and apparent optical properties, and video/still photography) that can provide detail sufficient to adequately delineate ecosystem responses. More importantly, high bandwidth and power will facilitate applica-

tion of emerging technologies that use laser sheets and holography to simultaneously measure turbulent flows and distributions and behavioral responses of biota. An RCO with an adequate footprint is necessary for the investigation and comparison of turbulent mixing regimes with very different characters—deep-sea mixing driven by tidal flow over steep topography, upper mixed layers subject to very different combinations of wind and buoyancy forcing, and shelf regimes strongly influenced by tidal bottom boundary mixing. The character of embedded ecosystems also varies dramatically: a challenge is to discover how much of the bio-geographical variability arises through direct and indirect effects of small-scale turbulence.

## Ecosystem Dynamics

An issue central to studies of the ecology of populations, communities, and ecosystems is the role that biological and physical factors play in the distribution and abundance of organisms and in patterns and rates of energy flow through biological systems. In the last decade, oceanographers have made significant progress in understanding marine ecosystem dynamics, including factors altering the abundance and distributions of organisms, complexity of marine food webs, and rates of processes governing population growth and energy transfer within marine communities. In particular, links between climatic variability and ecosystem processes have been investigated in several systems. The coming decades, however, will present exceptional challenges as accelerating human impacts, climate change, and potentially more frequent and severe weather events threaten to impact marine ecosystems at unprecedented levels. An understanding of how biodiversity, biogeochemical cycling, functional ecology, and the structure and distribution of biological assemblages are altered on a variety of temporal and spatial scales is needed to understand, forecast, and possibly mitigate these changes. Responses of ecosystems to various scales of climatic and oceanographic variability (i.e., storm, seasonal, interannual, North Atlantic Oscillation, El Niño

Southern Oscillation, Pacific Decadal Oscillation, and secular climate warming) is expected to differ both within and among ecosystems.

An RCO gives scientists the opportunity to observe a variety of time-space scales of environmental and ecosystem variability and infer mechanism and future behavior from the correlations and patterns in these time series. The high power available through the RCO may allow manipulative experiments nested within this context, and through the use of specialized sensors and tools, to test hypotheses concerning the mechanisms and dynamics of the ecosystem itself. These approaches can be used to both develop and test predictive models concerning ecosystem function in relation to internal and external controls. The interaction between modeling and the understanding of underlying dynamics may be one of the more powerful synergies to arise from the creation of RCO-scale science opportunities.

## Ocean, Climate, and Biogeochemical Cycling

An RCO offers new opportunities to observe and sample coherently oceanic variability from tidal to decadal frequencies, and to both observe long-term changes and establish a “mean” picture of the ocean’s carbon cycle for selected regions. An RCO that encompasses several distinct bathymetry roughness environments is needed for observing and determining the role of ocean margins in vertical mixing and exchange of heat and other properties over ocean basins. An RCO would be used: to observe the regional oceanic response to external forcing from tidal periods and below to interdecadal time scales, and determine the effects of climate variability on selected regions; to quantify the contribution of the region to the global carbon cycle (Are ocean continental boundary systems sources or sinks of atmospheric carbon?); and, to determine the role of regional features and processes in physical transports

and biogeochemical cycles. An RCO also offers great potential for real-time adaptive sampling, an emerging methodology.

## Getting to a Consensus

A principal goal of the RECONN workshop was to build a consensus for the location of the first RCO. As a starting point for discussion, the workshop chairs used the region around the Juan de Fuca Plate off the coasts of the northwestern United States and Canada as a model for consideration. This region has been the focus of substantial planning, including a National Oceanographic Partnership Program (NOPP)-supported feasibility study (NEPTUNE Phase I Partners, 2000). This region has also been selected by the Canadians as the location for a major national initiative (NEPTUNE Canada) to instrument the ocean floor.

It was clear from workshop discussions that to optimally study ocean phenomena requires instrumenting several places in the oceans covering a range of tectonic, oceanographic, and ecosystem settings. A variety of different areas was proposed in addition to the Northeast Pacific, such as the Southwest Pacific and Arctic. Workshop attendees moved quickly, however, to the consensus that the first RCO should be established in the Northeast Pacific Ocean. The extensive workshop discussion of the first RCO forms the basis of this report. Additional proposed sites are reviewed after that.

Workshop attendees noted that while RCOs are a critical facility for extending knowledge of the oceans and seafloor below, their utility will be greatly enhanced by additional observations provided by autonomous underwater vehicles (AUVs), drifters, gliders (Rudnick and Perry, 2003), satellites, and ship-based instrumentation. The enabling infrastructure provided by an RCO would also help programs such as the Integrated Ocean Drilling Program, EarthScope, RIDGE 2000, and MARGINS achieve their goals.



# NORTHEAST PACIFIC REGIONAL CABLED OBSERVATORY

## SETTING

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 (Figure 2A). 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.

Topographic relief along the Juan de Fuca Ridge produces barriers to turbidites from the continental margin, resulting in the accumulation of sediment burying the eastern flank of the Juan de Fuca Ridge within Cascadia Basin. Oceanic basement is exposed to the west, where the crust is young, and the sedimented seafloor is relatively flat to the east, except over seamounts. East of the Endeavour Segment, basement relief is dominated by linear ridges and troughs that are produced by faulting and variable magma supply. Basement relief is relatively low ( $\pm$  100-200 m) near the ridge, and higher ( $\pm$  300-700 m) to the east. Low-permeability sediment limits advective heat loss, leading to strong thermal, chemical, and alteration gradients in basement.

Oceanographic variability in this region is considerable over multiple spatial and temporal scales. The large-scale pattern includes the West Wind Drift (WWD), the major eastward-flowing, wind-driven current that forms the boundary between the subtropical and sub-arctic gyres in the central North Pacific, and bifurcates within the study area to produce the Alaska Current and California Current (Figure 2B). The position and intensity of the WWD shifts over years to decades scales, leading to variation in the volume of transport for its daughter currents. Variation in these large-scale features influences strongly the patterns of productivity in the California Current and Alaska Current, including very large shifts in community structure throughout the trophic web. Smaller scales of variation in ocean physics also characterize the region, such as mesoscale circulation, turbulence, and mixing induced by interactions of large-scale flows with bathymetric features (e.g., Juan de Fuca Ridge), shifts in the position and depth of the California Undercurrent, upwelling events, the El Niño Southern Oscillation, and seasonally intense inputs of river runoff.

The bathymetry and physical oceanographic patterns in the Juan de Fuca Plate region structure a diverse set of pelagic and benthic marine ecosystems. The continental shelf environment is relatively narrow, yet extensive, and includes submarine canyons, sites with strong land/ocean interactions such as the Columbia River, and important coastal upwelling sites (Vancouver Island, Cape Blanco). A typical shelf section includes a distinct surf-zone community, a nearshore sand community, a midshelf-silt commu-

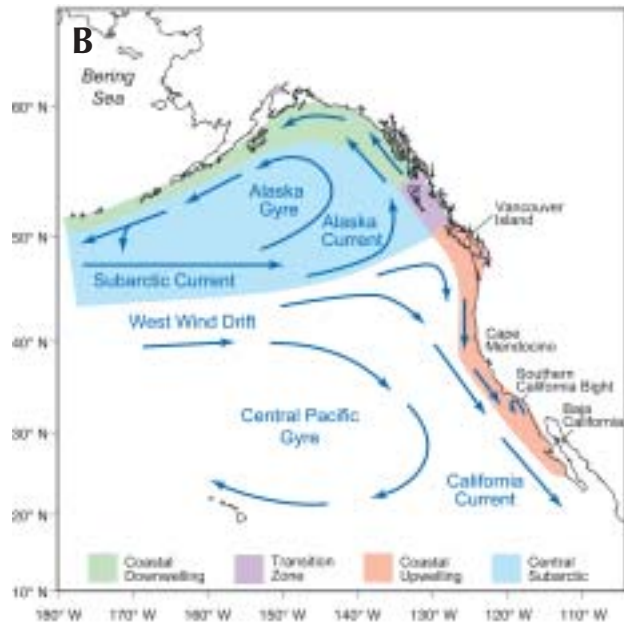
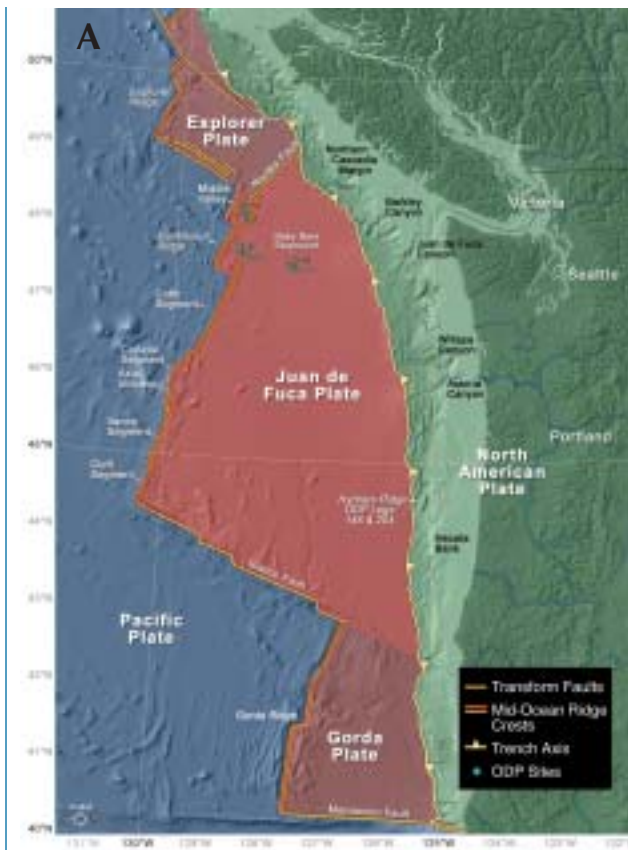


Figure 2. A) Map showing the distribution of tectonic features in the Northeast Pacific, including active spreading centers, transform faults, and subduction. Note that along the ridge crest there are active sediment-covered hydrothermal systems and hydrothermal systems that are sediment free. B) Regional circulation in the Northeast Pacific, from Howe et al., 2003.

nity, and an outer-shelf community on relict sands. Planktonic communities include one in the surf zone, a nearshore community within 5 km of shore where effects of upwelling are restricted, and a deeper shelf community strongly influenced by upwelling events. The continental slope in the region is incised with numerous submarine canyons where shelf/slope transport processes are focused. The slope and shallow abyssal plains are locations of historic deep-sea benthic sampling. The bathyal basin of the Juan de Fuca Plate is largely surrounded by the Juan de Fuca Ridge crest and Blanco Transform Fault. Seaward of the plate boundaries the seafloor slopes to abyssal depths, but is peppered with seamounts, particularly to the northwest. These seamounts are noted for their rich and diverse faunas. The region can be characterized biologically as one of many community transitions and strong gradients in ecosystem structure.

The WWD bifurcates as it approaches the Straits of Juan de Fuca to form the headwaters of the California Current and the Alaskan Current. The variety of sediments, topography, and tectonic activity interact with this pelagic complexity to weave a complex tapestry of benthic communities.

# SCIENCE, LOCATION, SENSORS

## Earth Structure and Dynamics of the Oceanic Lithosphere

Robert Detrick, Woods Hole Oceanographic Institution and Roy Hyndman, Geological Survey of Canada

The Earth Structure working group identified four major research priorities for plate-scale geodynamics studies:

**1. Understanding the dynamics of the lithosphere/asthenosphere system at the plate scale.** 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 very poorly understood. Many theoretical models predict patterns 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 theoretical 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 exceptional opportunity to address a number of fundamental questions regarding upper mantle dynamics and asthenosphere-lithosphere.

**2. Understanding earthquake faulting and rupture at plate boundaries.** Earthquakes at plate margins are the most important indicator of ongoing stress and deformation. Knowledge of the nucleation and rupture processes of earthquakes at faults in the oceans and along their margins is limited by lack of

stations in the immediate vicinities of ridge crests, subduction zones and oceanic transforms. Megathrust events in subduction zones cause some of the most devastating earthquakes and tsunamis on Earth. Their study is hampered by the restriction of most seismograph monitoring 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.

At spreading centers, knowledge of the temporal and spatial pattern of seismicity and crustal deformation is key to understanding processes that control spatial and temporal 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 mechanical processes involved in faulting and lithospheric deformation. The simpler geologic, thermal, and tectonic conditions at oceanic transforms make them poten-

tially useful sites for untangling many of the fundamental debates that remain unresolved in analogous continental environments.

**3. Understanding mechanisms of intraplate deformation and plate boundary interaction.** Intraplate earthquakes, faulting patterns, and *in situ* crustal stresses can provide important clues to 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 controls fault interaction, aftershock clustering, and earthquake shadows. There are also hints from recent studies that oceanic plates can transmit stresses rapidly over many hundreds of kilometers, but how this happens is poorly understood.

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. To understand 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.

**4. Understanding magma-tectonic-hydrothermal-biological interactions at plate boundaries.** Strong interactions among tectonic, magmatic, hydrologic and biological processes on a local scale have recently been documented at both oceanic ridges and 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 hundred meters below the seafloor. The

mechanisms responsible for these interactions are unclear. Simultaneous time-series observations at plate boundaries will better define the events themselves, and have the potential to elucidate the mechanisms for these interactions. The coupling between fluid pressure changes and strain events/earthquakes will improve 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 create and sustain habitats that are suitable for the growth of microorganisms.

The RCO experiments described below address these scientific priorities. Additional detail can be found in the full working group available at [http://www.geoprose.com/cabled\\_wksp/](http://www.geoprose.com/cabled_wksp/).

## Plate-Wide Geodynamics Observatory

An RCO 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 (Figure 3).

A regional seismic network like that shown in Figure 3 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

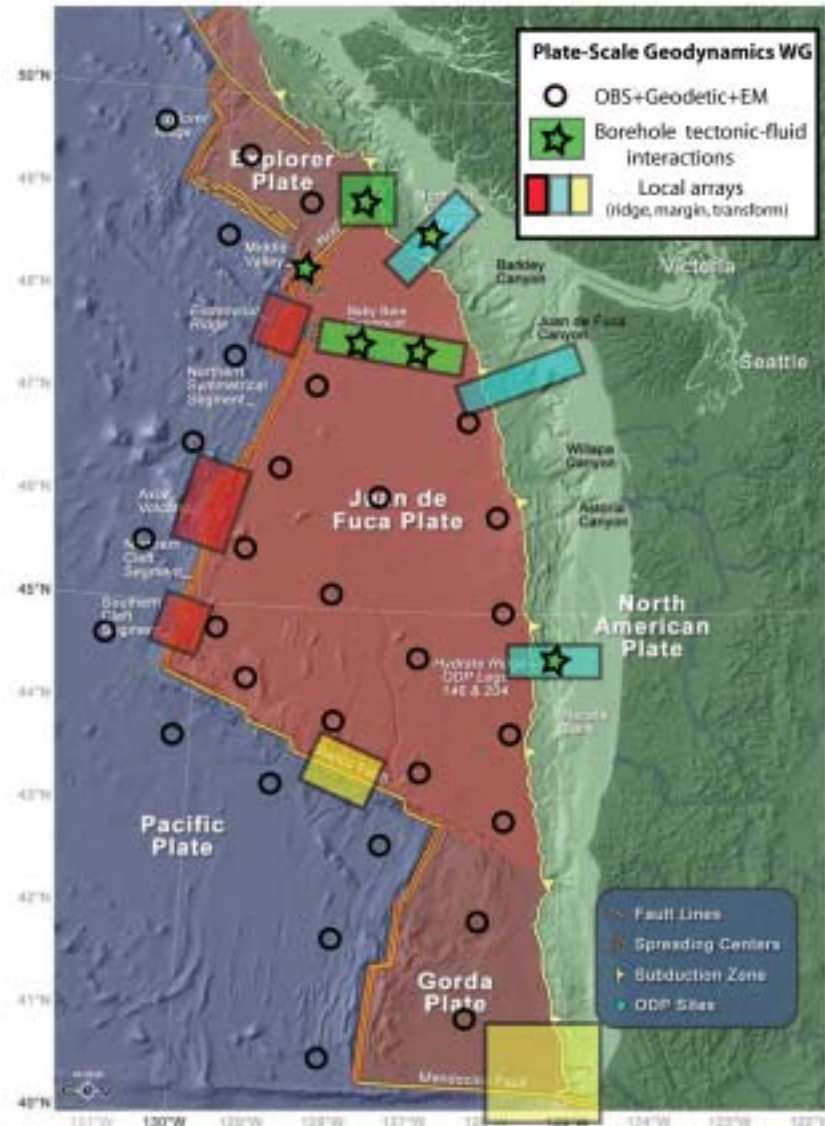
km apart on either side of the spreading center along its length (Figure 4). A cross-ridge seismic, magnetotelluric and geodetic array should be installed on a part of the plate boundary with no evidence of recent magmatic or hydrothermal activity to contrast with the ridge-crest experiments at Endeavour Ridge and Axial seamount.

### 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 among tectonic,

Figure 3. Primary measurement sites recommended by the Earth Structure and Dynamics of the Oceanic Lithosphere working group. The black open circles show a possible regional cabled 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 to ensure good resolution of the structure of the Pacific-Juan de Fuca plate boundary, and the accurate determination of the relative motions of the Pacific, Juan de Fuca, and America Plates. 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 seafloor magnetometers and electric field instruments. 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.



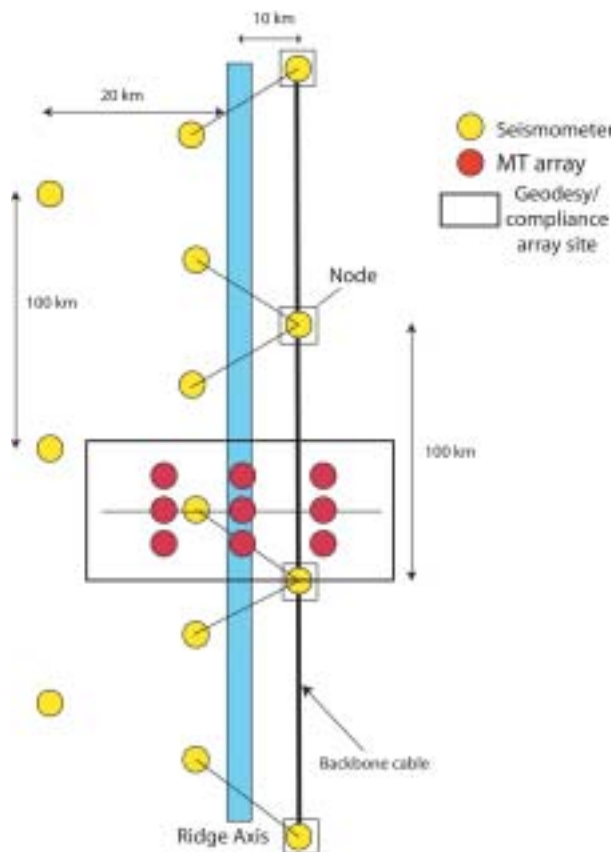


Figure 4. Schematic diagram of distribution of seismic, geodetic, and magnetotelluric instruments along the Juan de Fuca/Gorda Ridge system for monitoring ridge magmatic and tectonic activity.

magmatic, and hydrothermal processes at mid-ocean ridges (Figure 5). 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 resolution will not be feasible over the entire plate boundary, the Earth Structure Working Group identified four areas along the Juan de Fuca Ridge for detailed study—Endeavour Segment, Axial Seamount, Cleft Segment, 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. 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 that they support. The local seismic network on the Endeavour Segment must provide accurate locations and focal mechanisms for small micro-earthquakes along a 10- to 15-km-long section of the ridge that encompasses the vent fields. It 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. Tiltmeters, absolute pressure gauges, and perhaps absolute gravity meters will record the surface deformation associated with magmatic inflation/deflation and larger earthquakes. Magnetotelluric 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 (Figure 3). 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. 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

Figure 5. Cartoon of a seafloor geophysical observatory that contains seismometers and a variety of geodetic instruments.

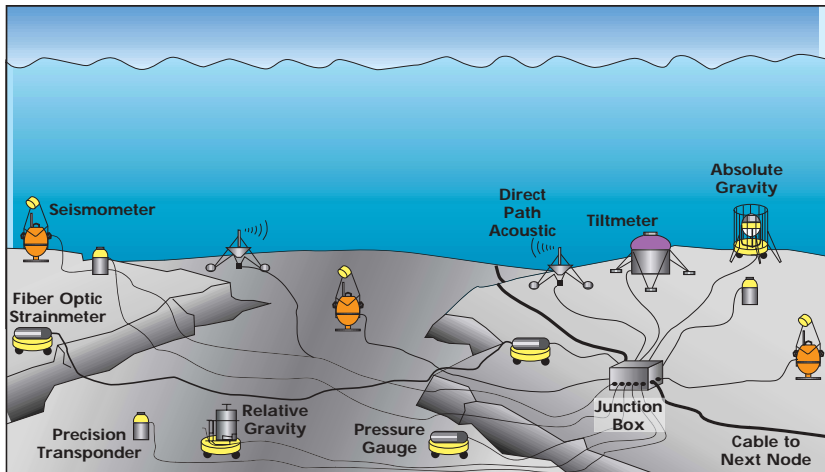
the two-dimensional pattern of extension associated with diking events and should cover the summit and the rift zones.

**Cleft Segment.** 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.** 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 Ocean Drilling Program (ODP) drill holes penetrate the hydrothermal system (Figure 2). A small seismic network at this site would complement hydrological observations in these drill holes by characterizing the seismicity and current tectonics.

### 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 megathrust 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 (Figure 2), primarily to correspond to existing ODP and planned Integrated Ocean Drilling Program (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. 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 earthquakes. These earthquakes produce strong shaking at intervals of a few years so are amenable to study using 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.

## 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-yr 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 (Figure 3). 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. 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. Seismometer station spacing should be  $\leq 10$  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 ocean-bottom seismometer (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 Mendocino. This region produced magnitude greater than 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.

It is worth noting that with the exception of some geodetic sensors (e.g., fiber-optic strainmeters, 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.



# Fluids and Life in the Oceanic Crust

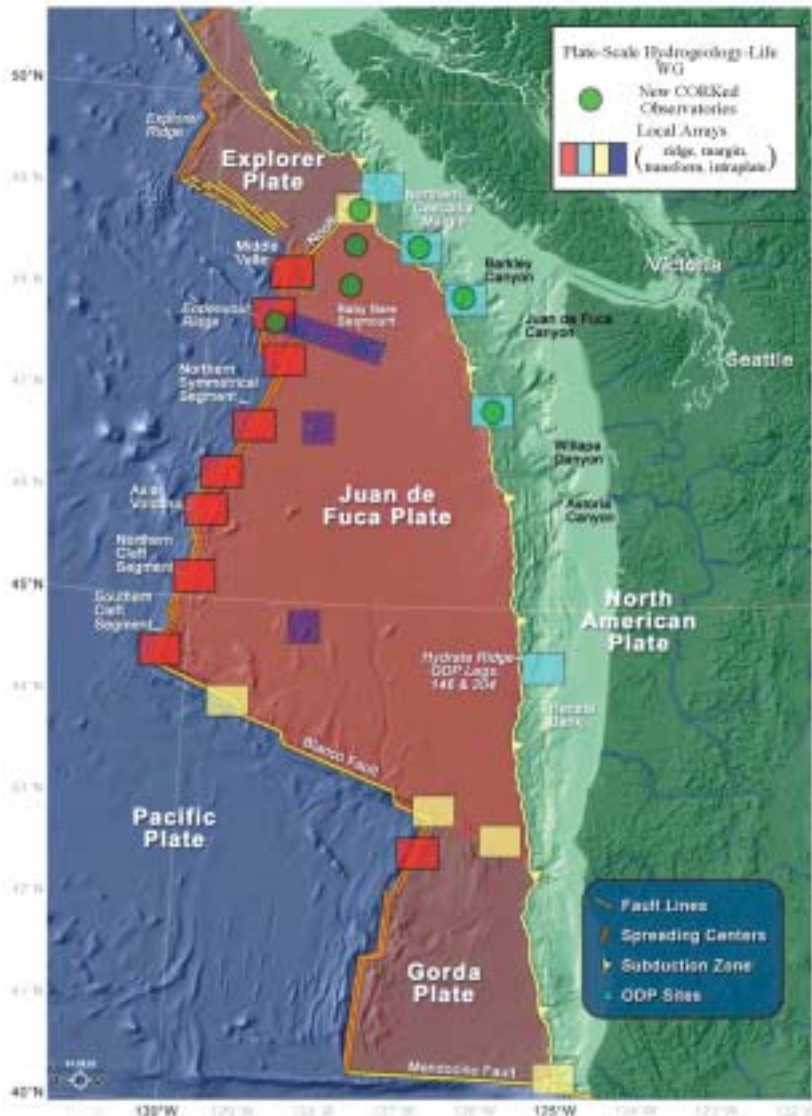
John Delaney and Deb Kelley, University of Washington and Barbara Bekins, United States Geological Survey\*

The Juan de Fuca Plate region provides unparalleled opportunities for studying many processes active on and below the seafloor (Figure 6). From geodynamic and seismic perspectives, all types of plate boundaries are present, and their mutual proximity allows meaningful observations to be made concerning the influence of events at one boundary on the conditions along adjacent boundaries or in the plate interior. From a crustal fluid flow or hydrologic perspective,

this simple compression of geodynamic scales is augmented by the effects of rapid sedimentation. The accumulation of sediments on the Juan de Fuca Plate serves thermally to insulate the underlying igneous crust and hydrothermal systems, and hydrologically

\*The authors of this chapter thank A. Fisher and the co-proponents of IODP Proposal 545Full3 for their suggestions for active hydro-geologic experiments.

Figure 6. Primary measurement sites recommended by the Fluids and Life in the Oceanic Crust working group. The Juan de Fuca Ridge is an ideal place to resolve the variability in the style and intensity of magmatism, tectonism, and hydrothermal activity along a mid-ocean ridge. It contains four distinct areas along its length that represent “end-member” conditions: Cleft Segment, Axial Seamount, the Endeavour Segment, and Middle Valley. Experimental designs that best address the temporal and spatial diversity of these systems and linked processes must include a basic seismic array, and a suite of instruments in a representative set of vents at each site that span the range in fluid chemistry, temperatures, and venting styles. The Juan de Fuca eastern flank is an excellent place to resolve first-order questions of crustal hydrogeology and evolution. High gradients result in strong signals that rise above natural and experimental noise. The high sedimentation rate allows work on crust that is much younger than could be studied otherwise, providing indications of ridge-crest and ridge-flank properties, and allowing study of sites in different hydrologic settings that are in close proximity.



to partially isolate the systems from exchange with the overlying ocean. As a consequence, temperatures in the sediments and upper igneous crust range from nearly zero to almost 300°C. Crustal fluid compositions range from relatively oxidized to strongly reduced in a simple and predictable way over the few-hundred-kilometer distance from the spreading axis of the Juan de Fuca Ridge to the Cascadia subduction zone. In addition, hydrological systems play key roles that influence hydrocarbon migration, and are strongly linked with biological processes that control the formation of gas hydrates at accretionary margins at subduction zones. As a result, the plate offers a rich matrix of lithologies, temperatures, fluid compositions, and flow regimes that is geographically compressed, and thus perfectly suited for sustained, in-depth study using a cabled observatory network.

## Understanding Crustal Formation and Life: Spreading Centers and Intense Flow

Among the most challenging problems to address along the mid-ocean ridge are the spatial scales at which geological, chemical, and biological processes are linked and the issue of how these processes vary and co-vary through time. Chief among the many attributes that make the Juan de Fuca Ridge an ideal study site is the variability in the style and intensity of magmatism, tectonism, and hydrothermal activity along the ridge (Figure 7). The Juan de Fuca Ridge contains four distinct areas that represent end-member conditions. The southern Cleft Segment has high magmatic flux with elevated ridge topography, it erupted in 1987, it is hydrothermally active, and there exists a set of good time-series measurements. Axial Seamount is the highest topographic feature along the ridge. It is volcanically and hydrothermally active and has enhanced magmatic output with a well-developed magma chamber and caldera. Scientists from NOAA's Pacific Marine Environmental Laboratory have

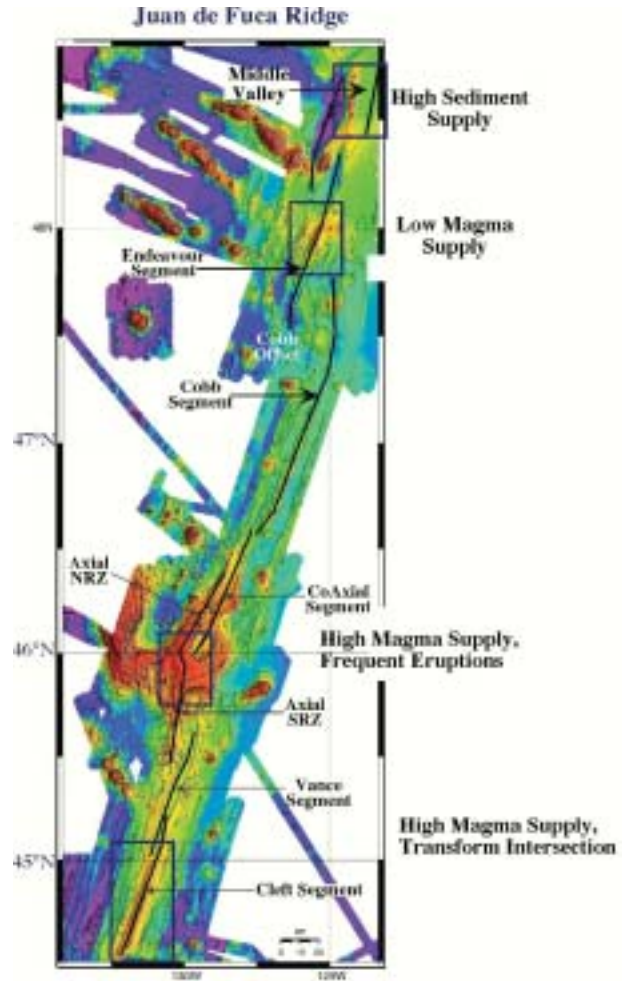


Figure 7. Sonar image of the Juan de Fuca Ridge from the Blanco Transform (south) to Middle Valley (north). The boxes identify locations of four distinctly different major geodynamic variations typical of many ridges world wide, within a ridge length of approximately 450 km.

established the NeMO observatory on this actively volcanic site. Axial Seamount also has an excellent suite of time-series measurements collected over the past decade including regular sampling for microbiological characterization. Endeavour Segment is one of the most seismically and hydrothermally active areas along the entire global mid-ocean ridge, and it has a dense and diverse macrofaunal community. It is a RIDGE Integrated Study Site, and has more than a decade of sustained time-series vent water analyses and microbiological studies as well. Middle Valley is a sediment-covered spreading center, and hosts several

instrumented Ocean Drilling Program (ODP) holes that contain borehole seals, or “CORKS.” Middle Valley has significant metal deposition below the seafloor, is hydrologically well-characterized, and holds some seafloor microbial communities that have been partially documented.

In addition to these intense, focused sites, other sites should be instrumented with a more limited subset of instruments so that we can monitor the ridge system as a whole. We have much to learn about how these systems evolve, the effects of local and more distal perturbation events to the entire ridge system, and how hydrologically connected the ridge may be. Experimental designs that best address the temporal and spatial diversity of these systems and linked processes must include a basic seismic array at each site. A suite of additional instruments should be placed in a representative set of vents that span the range in fluid chemistry, temperatures, and venting styles. Instruments should include *in situ* chemical sensors (e.g., hydrogen, resistivity, pH, CO<sub>2</sub>, CH<sub>4</sub>, Eh, H<sub>2</sub>S) and fluid-microbiological samplers (e.g., McLane, osmo samplers, PPS samples), sensors for quantitative gas analyses (gas chromatographs, Raman systems), high-definition video and still cameras, current and flow sensors (including downflow), and pressure sensors. In concert, these instrument arrays will allow examination of the linkages among seismic-magmatic activity, fluid output, and microbial-macrofaunal responses to perturbations along major sections of the ridge.

Many of the necessary chemical and biological instruments have yet to be developed. This is particularly true for *in situ* microbiological sensors and samplers. As we learn more about these systems and how to quantitatively characterize various parameters remotely it will be important to induce controlled perturbations and to develop closely linked modeling efforts that can guide future experiments.

## Understanding Crustal Aging and Life: The Ridge Flank and Mid-Plate

Thermally driven fluid circulation through the oceanic lithosphere profoundly influences the physical, chemical, and biological evolution of the crust and ocean (Figure 8). Although much work over the last thirty years has focused on hot springs along mid-ocean ridges, global advective heat loss from ridge flanks (crust older than one million years) is more than three times that at the axis, and the ridge-flank mass flux is at least ten times as large. Ridge-flank circulation generates enormous solute fluxes, profoundly alters basement rocks, supports a potentially vast seafloor biosphere, and continues throughout the crust to the trench, influencing the thermal, mechanical, and chemical state of subducting plates.

Numerous recent studies have illuminated critical roles that fluid flow plays in influencing the evolution of the lithosphere and of the ocean. For example, flow within the lithosphere from ridge crests to ridge flanks contributes to major heat loss from aging plates, regional to local redistribution of heat, massive solute fluxes to and from the plate, inputs of volatiles at subduction zones, and cycling of oxygen and nutrients to considerable depth below the seafloor. Studies demonstrate that fluid regimes within the plate are highly heterogeneous and compartmentalized (physically and chemically distinct), despite evidence for transport over enormous distances (kilometers to many tens of kilometers or more). But there remains considerable uncertainty as to how much of the crust is involved in active circulation at any time—whether circulation is continuous or episodic—and how ridge-crest and ridge-flank hydrogeologic systems are related. Understanding the nature of seafloor fluid flow systems requires determining long-term histories of *in situ* temperature, pressure, fluid chemistry, and microbiology at the scale of a plate.

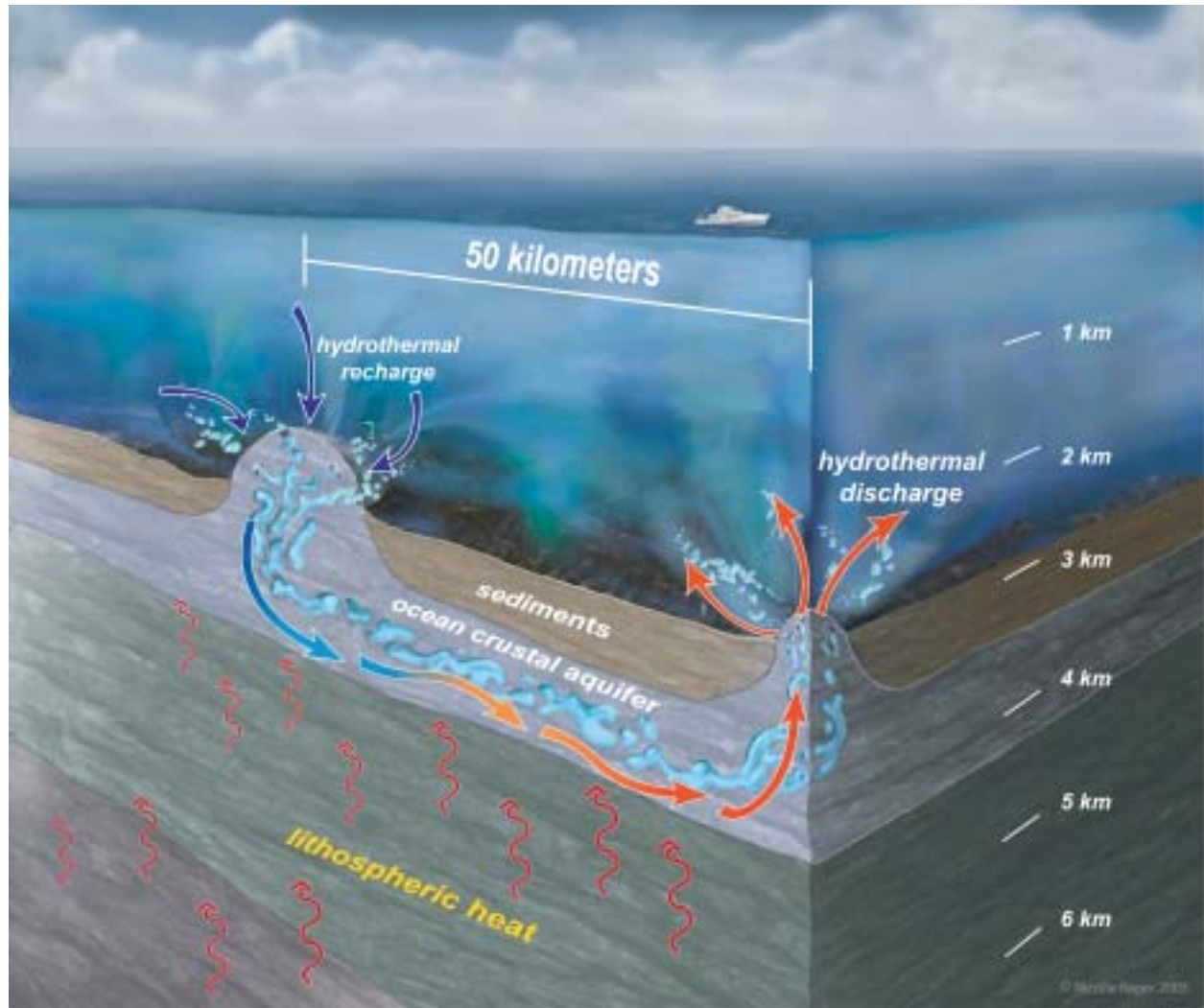


Figure 8. Fluid circulation within the seafloor through oceanic crust older than one million years transports deep heat to the overlying ocean. This process contributes to major thermal, chemical, and microbial fluxes with potential planetary significance if they are generalizable globally. On the eastern flank of the Juan de Fuca Ridge, thick impermeable sediments overlie young basaltic crust. However, old basement highs penetrate the sediment blanket creating “hydrothermal breathing holes;” these features are commonly separated by tens of kilometers. The resulting high-permeability channels become sites of either discharge or recharge, connecting deeper fluid convection cells within the high-permeability crustal aquifer to the open ocean. The resultant thermal, chemical, and microbial exchange may be much more vigorous than previously recognized and the vast areas of sediment-covered oceanic crust could represent the largest fractured aquifer system on Earth. The probability that an unexplored microbial biosphere thrives within this high permeability horizon opens the possibility that primary (microbial) productivity at the bottom of the ocean is a major source of carbon fixation within the ocean basins. ODP and IODP boreholes instrumented to study and experiment with these processes will be powerful nodes on a regional cabled observatory. In concert with instrumented basement outcrops, these drill hole arrays will allow instantaneous detection of and response to seismic and tectonic events, leading to quantification of hydrological, chemical, and microbiological processes and fluxes. Figure courtesy of Andy Fisher and Nicole Rager, University of California, Santa Cruz.

The Juan de Fuca Ridge eastern flank is presently the best place to leverage existing data sets and borehole observatories, and thus to resolve first-order questions of crustal hydrogeology and evolution. There already exists extensive site survey information, scientific drilling cores and long-term experiments, with more already scheduled. A unique opportunity exists for the IODP and the OOI to conduct integrated four-dimensional experiments by drilling arrays of holes in the selected sites, and establishing sub-seafloor observatories that complement the seafloor and water-column experiments and observations to be carried out in the region. Many of the objectives will be further served by the increased power, greater bandwidth, longer sampling times, and real-time access enabled by planned OOI facilities. For example, a multidisciplinary research program sponsored by the IODP along the flanks of the Endeavour Segment will begin in the summer of 2004. As a result of the project, three “legacy” holes will be established for hydrologic monitoring, chemical and biological fluid sampling, and microbiological incubation experiments. Other drilling projects planned for this region will involve long-term monitoring and “active” cross-hole experiments that will also benefit tremendously from a cable connection.

In addition to the hydrogeological experiments, the proposed IODP drilling, experimental, and post-drilling plan includes biological and biogeochemical study. The final stage of microbiological studies involves time-series analyses of biological communities and formation fluids, which will continue for years. Power provided by the cabled observatory will allow system monitoring and manipulation, potentially including temperature and pressure control.

## Understanding Crustal Destruction and Life: Subduction/Accretionary Complexes

Subduction megathrust earthquakes along the Cascadia margin represent a serious but poorly understood seismic hazard for the Pacific Northwest (see Earth Structure and Dynamics section). An RCO at the Cascadia convergent margin could address problems concerning the role of fluids in convergent margin processes. This focus will require combining data from spatially distributed surveys that span the entire margin with detailed process observations from a few intensive research sites. The distributed observations will provide data on temporal and spatial variability of fluxes that will be required to estimate the total budget for fluids and microbial reactants along the convergent boundary. At each distributed site there should be a few flux meters located on outcrops of varying permeabilities. Each flux meter should ideally be collocated with a shallow drive-point well that penetrates a few meters into the seafloor. Both instruments should eventually include monitors for pressure and temperature and sensors for chemical species that are important in microbial reactions.

Intensive sites will focus on understanding processes that control pore pressures, chemical and thermal fluxes, and microbial activities. Ideally there should be at least three transects for intensive studies. The main difference between plans for the intensive sites and the distributed monitoring sites is the need for boreholes. For hydrate objectives, there should be a series of closely spaced, instrumented boreholes and seafloor instruments designed to understand how upward fluid flow and subsurface microbial activity control hydrate concentrations. To investigate whether pore pressure affects the updip limit of seismogenic behavior, there should also be a transect of boreholes and seafloor instruments from seaward of the trench to the seismogenic zone. Plans for hydrologic monitoring and experiments along this transect must be closely coordinated with the geophysical

monitoring in the same area. In addition, this transect may be used to determine how subsurface microbial activities in locations without large hydrate deposits contrast with those in hydrate provinces. Eventually, a study area focused on a deeply rooted thrust fault in the forearc could be targeted to provide information on the relation of fluid pressure and flow to seismic activity in the forearc. Priority sites would include locations with hydrate deposits such as Hydrate Ridge, Barkley Canyon, and the margin of Vancouver Island. In particular, hydrate provinces such as at Hydrate Ridge off Oregon and in the northern Cascadia provide ideal natural laboratories for monitoring the time and spatial scales of hydrological forcing mechanisms, and for investigating biological processes that control formation and dissociation of hydrates. Eventually a fourth location is desirable where the imbricate thrust faults in the prism are landward verging.

Process-oriented studies will illuminate the formation properties and dynamic events that control fluid flow, providing the understanding needed to extend results to less-intensively studied and unmonitored locations. Detailed site locations must be developed but the characteristics should include transects across the presumed up dip-limit of the seismogenic zone. There should be an array of instruments in a corridor that includes measurement on and off deeply rooted active tectonic structures in the forearc with deeply sourced fluids and conduits that average out effects over substantial vertical dimensions.

### **Understanding Major Plate Discontinuities and Life: Transform Faults**

Although fracture zones are ubiquitous features of the global mid-ocean ridge spreading network, only very recently have relationships between tectonism and fluid flow within these environments been examined; the biotopes associated with these major plate boundaries are virtually unknown. Yet, they may provide some of the best opportunities to examine linkages

among earthquakes, fluid flow, and the biosphere because of their propensity for having numerous earthquakes, some of which are in large-magnitude. In addition, because of extensive faulting within such systems, deep crustal rocks are commonly exposed that are not accessible along ridge-crest environments. Thereby they provide unique opportunities to examine the affect of lithologic variability on fluid flow and biological populations in seismically active areas.

The Juan de Fuca Plate is bounded to the north by the heavily sedimented Nootka Transform Fault and to the south by the Blanco Fracture Zone, which hosts bare rock environments adjacent to small, variably sedimented, tear-apart basins. Both systems are extremely active seismically and commonly host large magnitude earthquakes. In concert, these two systems represent diverse crustal and hydrological environments.

The Nootka Transform is an optimal environment in which to examine the consequences of faulting because its hydrology is confined by sediments. This confinement promotes the attenuation of signals associated with fluid-flow forcing, crustal biogeochemical processes, crustal pressure transients, sediment destabilization, and fluid expulsion, making it an excellent target for coordinated seismological, dynamic, and hydrological observations. A limited number of instrumented observatory boreholes within the 20-km-wide fault zone, coupled with existing and planned holes along the accretionary margin, intra plate (including the array east of Endeavour Segment), and those at the hydrothermally active Middle Valley, would allow an unprecedented opportunity to assess transmission and storage properties and the nature of fluid transport within the largest fractured aquifer on Earth. It will also allow instantaneous response to seismic, tectonic, and other events to quantify hydrological, microbiological, and chemical linkages.

In contrast to the Nootka system, the Blanco Fracture Zone hosts extensive bare-rock environments with diverse crustal and geochemical characteristics and is known to be hydrothermally active. This system exhibits some similarities with fracture zone systems that are ubiquitous along slow-spreading environments such as the Mid-Atlantic Ridge. Significant crustal attenuation along the fault network has resulted in one of the very few exposures of shallow and deep crustal rocks within the Pacific. It may provide unique opportunity to examine the relationships among faulting and serpentinization of mantle rocks, associated fluid flow, and geobiological processes. Seismic events along this fault may result in episodically deep penetration of fluids into the crust or upper mantle (as well as the Nootka), producing fluids of distinct chemical signatures and growth of novel microbial communities dependent on methane and hydrogen. Although, this fault zone requires additional exploration for definition of optimal instrumentation sites, it is likely that the Juan de Fuca and Gorda Ridge transform intersection and western pull-apart basins would be important areas for placement of *in situ* instrument arrays (e.g. CO<sub>2</sub>, CH<sub>4</sub>, and H<sub>2</sub> sensors, seismometers, and microbiological samplers).

## Microbial Analyses in a Regional Cabled Observatory

The subsurface biosphere, fueled from below by geological processes, is currently unquantified and uncharacterized, but potentially it is a major biome on Earth. Do subsurface fluids and geochemicals fuel substantial microbial productivity that is independent of sunlight? Microbial populations in the subsurface certainly have the potential to capture geologically induced fluxes of energy-rich geochemicals for growth and reproduction. But what is the extent and magnitude of this postulated seafloor biosphere, and how does it figure into Earth's net primary productivity? To answer these questions, integrated approaches that couple geophysical, geochemical and microbiological parameters, fluxes, and processes are required.

Measurement of microbial communities, activities and processes *in situ*, both remotely and autonomously, is currently a challenging goal. To traverse the path from the current capabilities (sampling and shore-side laboratory measurements), to observatory-type, *in situ* remote and autonomous characterization and quantification of microbial communities, will require a phased approach. In the intermediate term, we must develop new *in situ* sensors and test them under the same range of expected conditions. Eventually this approach will allow routine remote determination of variations in microbial diversity and metabolic processes associated with crustal processes.

During this intermediate period, to attract microbiologists to the program, the sampling problem must be solved. We must offer opportunities to geomicrobiologists to obtain samples at will from active seafloor environments using AUVs and innovative sampling strategies. Current exploration of sample preservation techniques on the seafloor and innovative hand-off strategies using piloted or unpiloted aircraft for recovering samples in near-real-time are important directions of research.

Ultimately, at each node in an RCO, coupled geological, physical, chemical, and biological measurements need to be captured. Instruments are or will soon be available to measure currents, conductivity, temperature, water-column chemistry, seismicity, crustal fluid and chemical fluxes, and pressure that constrain and quantify geologic and hydrologic processes. For some biological processes (methane oxidation, sulfate reduction, oxygen consumption) biogeochemical sensors (microelectrodes and other chemical sensors) can be used to measure activity. Other fundamental microbial measurements (community structure and variability, primary and secondary production, specific geochemical cycling, gene expression) require sensor development before reliable *in situ* measurements can be made. *In situ* samplers and processors, and other types of biosensors are now being devel-

oped, and will be essential in the future for truly interdisciplinary studies of coupled geologic-biologic processes

One useful approach to consider for measuring *in situ* microbial processes is a simple observational strategy, with co-registered geologic, physical, geochemical, biogeochemical and biological sampling and sensing. Another approach greatly enabled in observatory settings includes experimentally induced manipulations and perturbations, with subsequent measurements of biogeochemical and biological responses. Both of these approaches are currently challenging for *in situ* use.

## A Plate-Scale Bio-Hydrology Laboratory

The Juan de Fuca Plate region provides unique potential for conducting progressively more integrated bio-hydrological experiments in all representative plate tectonic environments. Fluid migration may result from intensely focused local heat flow near ridges, more gently driven convective fluxes in the mid-plate, compaction- and compression-driven fluid expulsion at convergent margins, and earthquake-triggered transients anywhere in the plate framework. Experimenting with each of these processes in adjacent and coherent single-plate contexts will be an entire picture of fluid movement through the oceanic crust and continental margins. This image will also allow creative experimental comparisons with other localities to be well-framed. Regardless of the logistical advantages implicit in selecting the Juan de Fuca area, it is the opinion of this working group that no comparable sites anywhere offer as many scientific advantages and existing contexts for exploring the deep subseafloor biosphere and the hydrogeological systems that it feeds upon.



# Turbulent Mixing and Biophysical Interactions

Ann Gargett, Old Dominion University and Percy Donaghay, University of Rhode Island

The recent SCOTS report (Glenn and Dickey, 2003) highlighted four areas in which fundamental questions associated with the interactions between turbulent and biological fields can best be tackled through cabled time series measurements. The following is a brief description of the questions associated with these major themes, with an indication of the advantages brought by a regional-scale network.

**1. Plankton community structure.** Plankton species composition often varies dramatically from one biogeographical region to another, but the reasons for this are poorly understood. Since planktonic organisms living in the upper water column are exposed to a wide range of mechanical and buoyant forcing, it has been hypothesized that turbulence may play an important role in regulating community composition. The direct effects of turbulence on organisms include mechanical stresses, modulation of particle encounter rates, and modification of the vertical migration behavior of motile species. Other suggested means of structuring planktonic communities may appear to be independent of turbulence, but are actually closely related. For example, it has been suggested that the kind of available nutrients may influence community composition. While this is seemingly a separate question, it reflects the indirect effects of turbulence, since interplay between turbulent motions and light fields can result in modification of the nutrient menu present. Other indirect effects of turbulence occur when plankton interact with environmental factors that are determined or strongly modulated by turbulence processes, such as the development of stratification, or the input of new nutrients into the euphotic zone. If turbulence is in fact an important determinant of plankton community structure, are its effects the result of differences in average turbulence level, or of the extreme levels occurring during storms? Over what spatial and temporal scales are these differ-

ences important? Investigation of these broad issues requires an RCO that can make simultaneous time-series measurements of plankton composition and behavior, along with turbulence and other factors (both “top-down” and “bottom-up”) that have been hypothesized to control plankton community structure. Measurements must be made at several locations within two or more biogeographical provinces so that the effects of within-province variability can be separated from differences between provinces. Furthermore, data must be collected frequently enough to detect the effects of extreme events such as storms and over a long enough time frame to also evaluate the effects of climatic oscillations (e.g. ENSO, PDO, NAO) within and between provinces.

**2. Formation, dissolution, and export of marine snow.** Marine snow aggregates are believed to play a variety of important roles in marine ecosystems and the ocean carbon cycle, fulfilling multiple functions as structured habitat, concentrated food/nutrient source, and vertical transport mechanism. In doing so, marine snow may play a significant role in structuring marine ecosystems. While the existence of marine snow is rooted in the biogenic and mineral particles that form the aggregates, it is also strongly influenced by turbulence in the environment that contains them. It is generally agreed that increasing turbulence levels first enhance the formation of marine snow aggregates, by increasing collision rates of biological particles, but eventually lead to their destruction, as turbulent shears become sufficient to tear them apart. What is the formation/dissolution threshold level? The net escape of marine snow particles from the bio-active surface layer is believed to be a significant contribution to the net carbon export into the deep sea. Is the rate of net escape determined by the “fast” time scale of intermittent turbulent mix-

ing events at the base of the surface mixing layer, or by the “slower” diurnal or seasonal variation in mixed layer depth?

**3. Ecosystem effects of atmospheric variability on ENSO/decadal time scales.** Variation of marine ecosystems in synchrony with ENSO/PDO variability is well-established in a correlational sense. However, as yet, we have no understanding of the mechanistic connections involved in this co-variability. An RCO that spans a significant gyre boundary, operating over several years (ENSO) to a few decades (PDO) would allow quantitative assessment of the hypothesis that the modulation of upper ocean turbulence levels by changes in atmospheric driving forces is this missing mechanistic connection. Equally important, it would allow quantitative assessment of impacts on the composition, vertical structure and dynamics of major ecosystem components including phytoplankton, zooplankton and fishes.

**4. Benthic community structure.** The structure and variability of the turbulent bottom boundary layer (BBL) is, apart from substrate, the major factor influencing the structure of benthic communities, yet the observational knowledge of this structure is limited. How, for example, is the underlying benthos affected by changes in the structure of the turbulent BBL in the transition from continental shelves to deep ocean? Temporal variability may be an even more important issue. It is possible that the structure of benthic communities is determined less by background norms than by episodic turbulent “mega-events,” i.e., the occurrence of major eruptive events or debris flows on deep-sea benthos, or infrequent but intense interactions between surface (wind-driven) and bottom (current-and wave-driven) boundary layers on the benthos of shallow coastal regions. The net export of organic material from continental shelves is believed to be a major fraction of the organic carbon flux to long-term “storage” in the deep sea. Does the time-average cross-shelf structure of the turbulent bottom boundary layer influence this export rate, or is the

rate set instead by irregular exchanges associated with mesoscale motions? Answers to these questions require an RCO that spans the shelf/slope transition in a number of locations.

Based on these broad scientific questions, as well as fundamental questions that arose during group discussions, this working group chose observational sites (Figure 9) focused in the following three areas.

### Northern Array: Processes at Gyre Boundaries

The northern part of the Juan de Fuca Plate region is dominated by the boundary between the sub-tropical and sub-arctic gyres. The two gyres are fundamentally different physically, biologically, and biogeochemically. The sub-tropical gyre is characterized by wind-forced downwelling, and the sub-arctic by upwelling. The current separating the gyres, commonly known as the West Wind Drift, flows eastward, meets the eastern boundary, and bifurcates into northward- and southward-flowing branches. The southward branch provides the source water of the California Current, while the northward branch feeds the Alaska Current. These currents interact with flows of the shelf/slope region through upwelling and mesoscale processes.

Confluence of gyre and coastal biogeochemical provinces provides a number of ideal settings for the study of exchanges of physical and biogeochemical properties among the various provinces. For example, what are the horizontal exchanges between sub-tropical and sub-arctic gyres, and between the deep ocean and shelf? What are the vertical exchanges between the thermocline and mixed layer, and how do they vary across provinces? The Northern Array consists of seven water-column “tree” sites (we define a “tree” as an EOM riser from the bottom to a subsurface instrument node within 100-200 m of the surface, enabling the water-column access that is critical to addressing turbulence/biophysical scientific question; Figure 10).

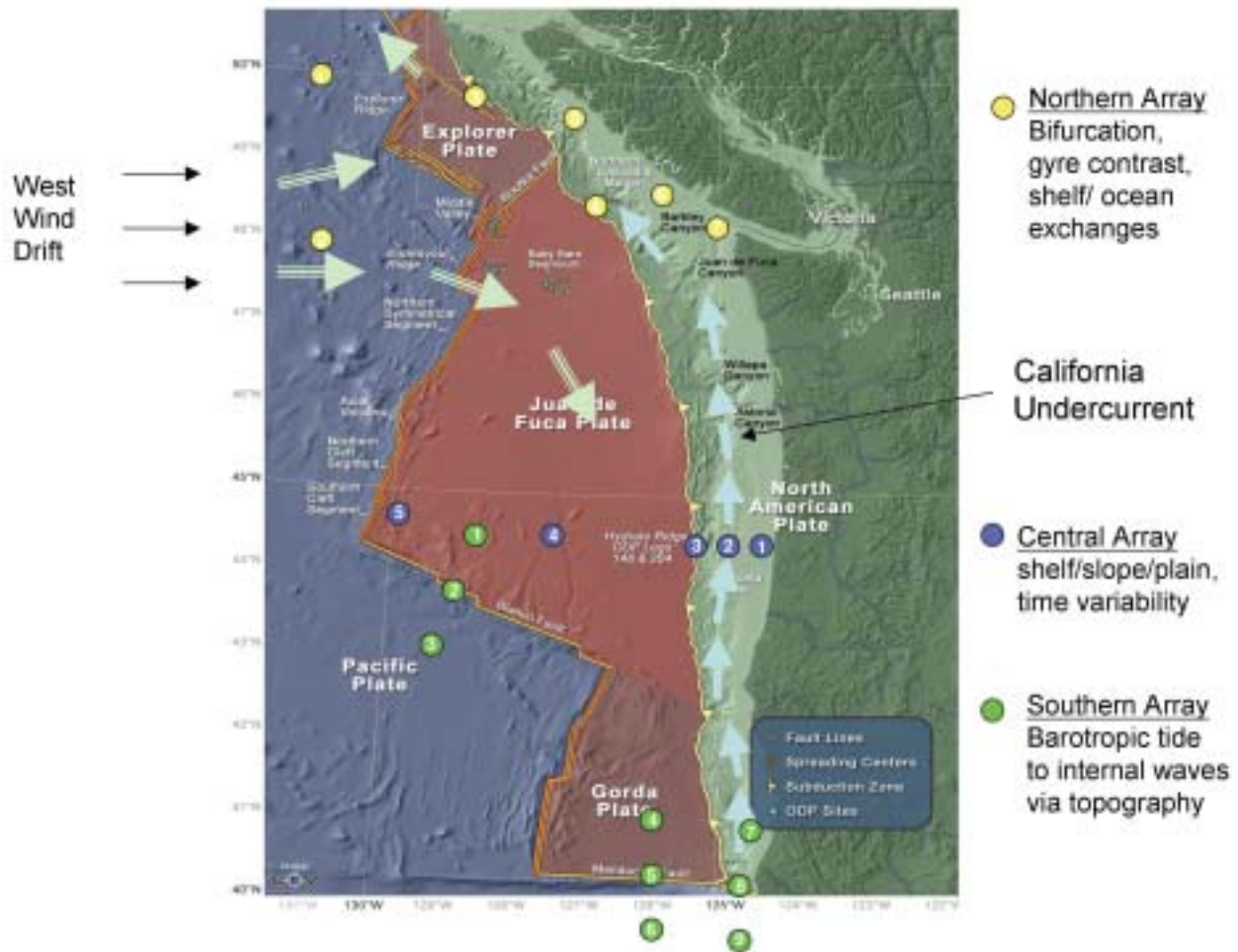


Figure 9. Primary measurement sites recommended by the Turbulent Mixing and Biophysical Interactions working group. The map shows geological provinces, major current systems and potential locations for the proposed northern, central and southern arrays. Each of the locations would have an EOM riser from the bottom to a subsurface instrument node within 100-200 m of the surface (see Figure 10), enabling the water-column access that is critical to addressing turbulence/biophysical scientific questions.

These site locations were chosen to address the widest possible range of physical and biogeochemical science questions in this region.

Sites 1 & 2 address science issues involving processes spanning the gyre boundary in the open ocean:

- Contrasting vertical turbulent fluxes and biogeochemistry
- Decadal changes in vertical structure
- Mesoscale fluxes between gyres

Sites 3 & 4 were chosen to address science questions involving the bifurcation region and the source waters of the California and Alaska Currents:

- Interannual variability of location of bifurcation, flux magnitudes
- Interaction of bifurcation with shelf/slope processes
- Variability and export of the source physical and biogeochemical properties

Sites 3-6 will allow investigation of the communication between the open ocean and shelf/slope in an area that exhibits seasonal upwelling plumes and mesoscale eddies:

- Flux of material across and along shelf/slope

Site 7 was included to investigate biological retention processes and estuarine bottom water renewal processes at the entrance to Juan de Fuca Strait.

- Ocean influence on estuarine processes
- Interannual variability of retention and California Current System

## The Central Array: Shelf to Basin

This set of sites was chosen to provide comparative time series in a variety of biophysical regimes, as required by many of the science drivers discussed earlier in this section. Addressing the breadth of these science issues requires a series of five nodes: two on the shelf, one on the slope, one at mid-plate, and one near a hydrothermally active location on the Juan de Fuca Ridge. We have chosen the latitude (44°39' N) of the cross-shelf “Newport Line” of hydrographic stations that has been maintained by Oregon State University since 1961 because it provides extensive historical information in which to view the new time-series information. This location, in a region of strong seasonal upwelling, provides contrast with the Northern Array coastal sites, and along with the Southern Array, provides an along-shelf antenna for N/S propagation of physical and biological changes driven by large-scale atmospheric variability. Although spatial resolution of this array is coarse, it will have unprecedented temporal resolution. Finally, extensive process and modeling work that has been and is being carried out in this area will help with interpretation of the time-series data.

The sites of the Central Array are designed to address seven major issues, all involving advection, turbulent mixing, organism distributions, and bio-physical interactions.

- What is the long-term variability in upwelling? How far offshore do the effects of variations in upwelling extend?
- What is the spatial variation (onshore to deep waters) in turbulence in the photic zone, the nutricline and the benthic boundary layer? How does

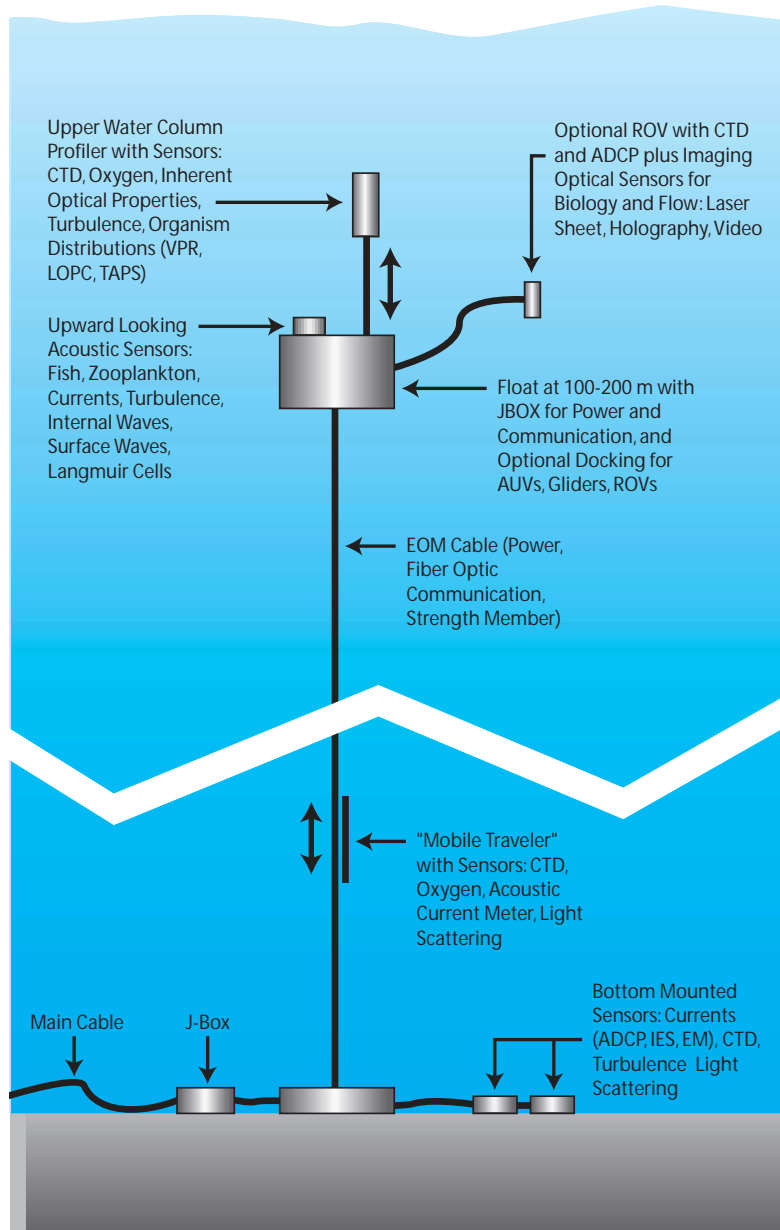
that variation affect the distribution of plankton and fishes through behavioral responses? How does it affect plankton population dynamics through recruitment, mortality, and lateral transport?

- What is the spatial variation (onshore to deep waters and south to north) in turbulence and ecosystem response to the PDO and ENSO?
- How do changes in the location and intensity of the West Wind Drift affect oceanic ecosystems off the western United States (e.g., the effects of sub-arctic waters that periodically head south)?
- What is the long-term variability in the intensity and offshore extent of cross shelf transport of plankton, biogenic material, and sediments?
- Is variability in the intensity, depth and offshore extent of the seasonal chlorophyll-A maximum related to variability of upwelling or changes in the intensity of transport by the California Current?
- How does long-term variability in near-bottom flows and turbulence affect the physical dispersion, lateral transport and subsequent settlement of benthic organisms that inhabit the shelf, slope, central plate and Juan de Fuca Ridge?

## Southern Array: Tidally Driven Mixing

One of the most important issues in determining the large-scale ocean circulation is how the great bulk of the ocean is mixed. Utility of present circulation models is limited by their ability to parameterize both the turbulence that mixes the ocean and the instabilities that lead to turbulence. Results from isolated field experiments covering specialized geographical areas and cruise time scales (< 1 month) suggest that modification of the barotropic tide by its interaction with topography is a significant generator of high-wavenumber internal gravity waves and turbulence. The power and bandwidth of an RCO offers unique capability to assess the modulation of these tidal and flow interactions with topography over long time periods.

Figure 10. Potential design for proposed “EOM trees” for long-term observation of turbulence and biophysical interactions in the water column. The core components of the EOM tree are the upper water column node located on a subsurface float, a taut electro-optical-mechanical (EOM) cable that connects the water column node to the bottom anchor and main observatory cable, an upper water column profiler deployed from the subsurface float, and a crawler profiler for sampling the water column below the subsurface float. The subsurface float is a fully functional observatory node equipped with a junction box (J-Box) that provides power and real-time, high-bandwidth communications to sensors mounted on the float and on an upper-water column profiler. The subsurface float is equipped with standard upward looking acoustic sensors for remote measurement of currents (ADCP) and fish (fish sonar) plus more experimental acoustic sensors for remote measurement of zooplankton, fish swimming, turbulence, waves, and small-scale flows. The upper water column profiler is equipped with standard sensors for CTD, oxygen and inherent optical properties (IOP) plus more experimental sensors for measuring turbulence and the distribution and composition of the biota (biota sensors listed are the Laser Optical Plankton Counter - LOPC, Video Plankton Recorder -VPR, and Tracor Acoustic Profiling System - TAPS). The figure also illustrates how the capabilities of the EOM trees could be expanded by equipping the subsurface float with docking stations for AUVs and ROVs that could be used to periodically survey the surrounding waters and assist in the maintenance of other components of the system.



Within the region of the proposed Northeast Pacific cabled observatory, there are two areas that are of prime comparative value for such studies. Each represents a fundamentally distinct bottom topography and wave generator. The Mendocino Escarpment (sites 4-6) is a single sharp and long edge with a deep drop off to the south. The sharp edge is oriented perpendicular to the barotropic tide, an orientation that maximizes tidal flow/topography interactions. Further offshore, sites 1-3 across the Blanco Fault

span topography that in contrast consists of multiple, smaller-amplitude ridges, still roughly normal to the barotropic tide. At both sites, deep turbulence observations would involve three sites—one north of, one south of, and one atop the ridge—equipped with water column “trees” to support a variety of flow and turbulence sensors.

Although not required for the fundamental comparative studies of deep sea turbulence generation by tide/topography interactions, the addition of a set of sites (7-9) across the Mendocino Fault along the continental shelf would allow exploration of the effects of abrupt N/S depth variation coupled with abrupt transition of shelf width on a variety of physical and biological processes. For example, how does the California Undercurrent negotiate this transition zone? What is the fate of biological material moved offshore by the persistent mesoscale eddy that sits off Cape Mendocino? How do the answers to such questions change over annual/ ENSO/decadal time scales?

## Sensors

This working group agreed that RCO nodes identified in Figure 11 as necessary for the study of turbulence and biophysical interactions should be provided with “EOM trees” (as defined earlier) to provide essential access to the water column and the near-surface zone. As depicted in Figure 10, the group envisions these trees equipped with “canopy nodes,” supported on a subsurface float at depths of 100-200 m from the ocean surface and providing the same power, communication, and junction-box (J-box) capabilities as the bottom nodes, thus allowing them to support a “canopy” of sensors in the upper water column. These EOM trees need to be equipped with sensors that can simultaneously measure the vertical distribution of the biota (phytoplankton, zooplankton, fish), physical structure (temperature, salinity, density), and physical processes (current velocity, turbulence, internal waves, surface waves, Langmuir cells). These EOM tree-based measurements will be particularly important near the surface (upper 200 m) where effects of turbulence and biophysical interactions are very large, but undetectable by bottom-mounted sensors. Trees will support three types of core sensor packages: (1) sensors mounted on the subsurface float at about 100-200 m depth, (2) a profiler that can collect data from the subsurface float to the surface, and (3) a mobile “traveler” that can make repeated profiles between

seafloor and canopy nodes. The canopy node should have a base instrument suite that includes a CTD (pressure, conductivity, temperature) and oxygen sensor for collecting time series data at the depth of the node and upward-looking ADCP for measuring vertical profiles of horizontal currents. This canopy node should also include acoustic sensors for remotely measuring the vertical distribution of biota and physical processes in the upper water column. The upper-water column profiler should include a base suite of instruments including a CTD, an oxygen sensor, and a standard optical package for measuring inherent optical properties (IOPs), as well as more experimental instrumentation designed to measure turbulence levels, organism distributions, and biophysical interactions. The mobile traveler that makes profiles repeatedly between seafloor and canopy nodes should have a base instrument suite that includes a CTD, an acoustic current meter (ACM), an oxygen sensor, and a compact optical package for measuring suspended particulate load. It should also be complemented by a bottom-mounted package that includes a CTD, an optical backscatter sensor (suspended particle load), an ADCP, an inverted echo sounder (heat content/baroclinic currents), a horizontal electrometer (barotropic currents), and acoustic Doppler velocimeters (turbulence). The working group felt that a fully implemented RCO should have this bottom-mounted package duplicated at all bottom nodes.

# Ecosystem Dynamics

Tony Michaels, University of Southern California and Jim Barry, Monterey Bay Aquarium Research Institute

The Ecosystems Dynamics working group posed one overarching question for the habitats encompassed the Northeast Pacific RCO: **How do marine ecosystems vary through time and respond to environmental and biological variation?**

Marine ecosystem responses of greatest interest to the Ecosystems Dynamics working group include changes in community structure (e.g., species diversity, abundance, and distribution, species equitability, biomass, functional roles, demographic rates of popu-

lations, and community resiliency and stability), as well as rates of energy and material flow through food webs. Temporal scales of environmental variation of greatest interest include episodic events (slumps, storms, eddies), seasonal to interannual variability, and decadal variability (climate change, regime shifts, seafloor vent processes). Biological variability, such as anomalous plankton blooms (e.g., coccolithophores in the Bering Sea during the 1997 ENSO event) or rapid shifts in the survival and abundance of megafaunal fishes or invertebrates (e.g., the Amperima

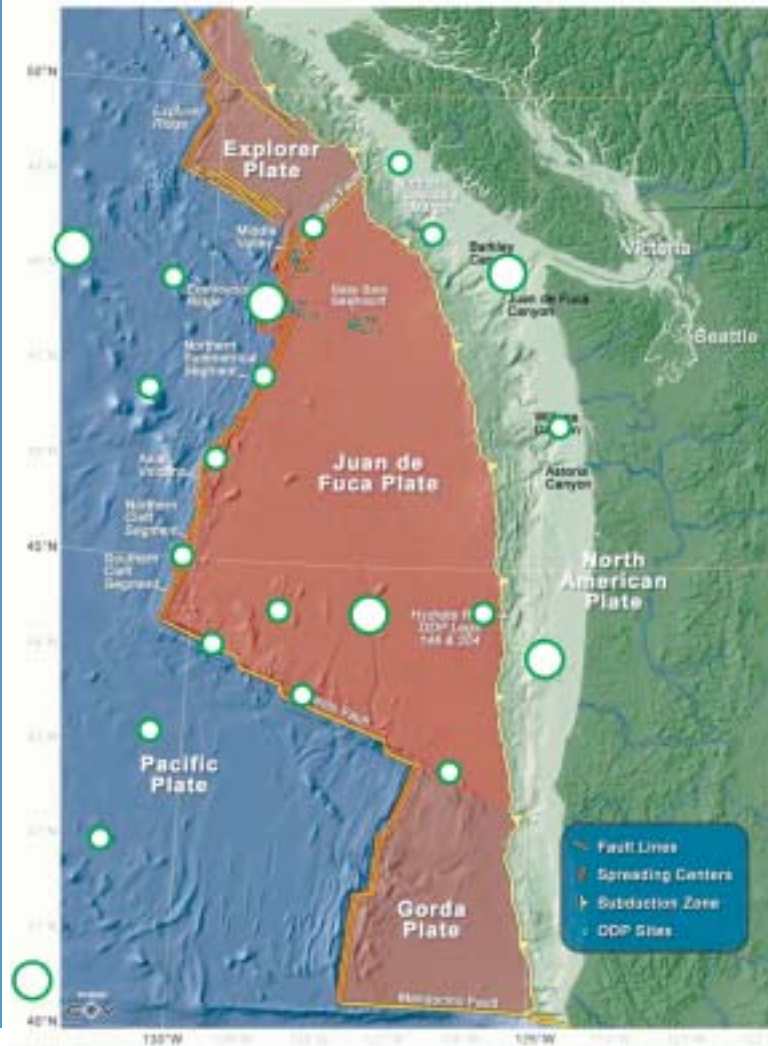


Figure 11. Primary measurement sites initially recommended by the Ecosystems Dynamics working group. Large circles indicate “super sites,” which would include enhanced instrumentation as compared with other priority sites. Subsequent discussions with two other working groups modified the location of several of these circles (see Initial Deployment section).

event in the abyssal Atlantic or shifts in continental shelf rockfish abundance in the Northeast Pacific) can have large, cascading influences within the ecosystem through trophic interactions, regardless of the degree of coupling with environmental variability. By deploying a suite of physical and biological sensors and instruments on the RCO, it may be possible to dissect the relative roles of environmental versus top-down, biologically mediated regulation of ecosystem structure and function.

The spatial scales of the major bathymetric features and ocean circulation patterns were used by the working group to define distinct sub-regions, or ecosystems, accessible by the Northeast Pacific RCO, including the continental shelf, slope, abyssal plain, seamounts, and pelagic (epi-, meso-, and bathy-pelagic) realms. Methane seeps and hydrothermal vent habitats that support chemosynthetic biological communities were also considered. For each of the distinct sub-regions within the Northeast Pacific, there are specific, important processes that can be uniquely or best observed in that location. The science questions then motivate choices of specific location and sensor requirements (Figure 11). These are described in more detail below and in the full working group report (see [http://www.geo-prose.com/cabled\\_wksp](http://www.geo-prose.com/cabled_wksp)).

The major emphases considered by the Ecosystems Dynamics group for RCO studies were benthic seafloor and benthic-pelagic processes, due largely to the biases of the investigators present, the greater perceived difficulties of RCO support for water column studies, and partial overlap with the Turbulent Mixing and Biophysical Interactions group. This benthic processes bias should not, however, diminish the importance of pelagic and nektonic studies by the RCO, which should be considered in greater detail by a broader working group.

## Seafloor Ecosystem Studies

Benthic habitats within the Juan de Fuca RCO region span a variety of depths, habitats, and oceanographic conditions within a temperate eastern ocean boundary biome. Features include the continental shelf, continental slope and rise, bathyal and abyssal basins, seamounts, deep-sea ridge crests, hydrothermal vents, and hydrate-rich sediments along tectonically compressed accretionary sediments. These environments are inhabited by highly diverse communities of benthic and benthic-pelagic species assemblages, which depend nutritionally on either allochthonous inputs of organic debris through vertical sinking and laterally advection, or on chemosynthetic biological productivity at hydrothermal vent environments and sites of methane/sulfide release from the seafloor. In many cases, understanding of factors that regulate or influence community structure in terms of the diversity, distribution, and abundance of species, and community dynamics in terms of variation in the population demography (birth and death rates of species) and community productivity, is relatively limited.

The Juan de Fuca RCO would enable detailed studies of the structure and natural variability of seafloor communities as well as their response to environmental variability on many spatial and temporal scales. In addition to seasonal and interannual scales of variability, the long expected lifetime of the cabled system would overlap many other scales of oceanographic variability, including ENSO and Pacific Decadal Oscillation, as well as a significant period of expected secular climate warming, with large expected oceanographic consequences.

Key experiments in deep-sea benthic ecology that are high priorities for the RCO will be to measure the degree of variation in benthic community rate processes, particularly carbon uptake and remineralization, in response to variation on a variety of spatial and temporal scales. Novel methods to measure com-



munity oxygen consumption and elemental fluxes in and out of the sediment are becoming available and may be used at a series of sites (shelf, slope, bathyal and abyssal plains) to measure changes in energy flow. Simultaneous studies of changes in community patterns (i.e., species' distribution and abundance) using camera systems to determine megafaunal diversity, abundance, and activity will be coupled to high-frequency measurements of carbon input and a suite of standard oceanographic parameters. Recent advances in optical and acoustic imaging (multi-frequency acoustic arrays) and tracking (acoustic tags) techniques could be applied near RCO nodes to broaden our understanding of the abundance, movements, and behavior of major benthic-pelagic fishes (e.g., macrourids). Replication of these measurements at several sites over time scales that capture important cyclic features and episodic events will provide an unprecedented view of the generality of benthic ecosystem responses to variation in ocean processes.

## Continental Shelf and Slope

Productivity over continental shelves is typically high compared to open ocean regions, and it is in these regions that both ecosystem response to environmental variability and biological controls may be strongest. Most expeditionary studies lack the temporal resolution to document even the patterns of abundance of key trophic groups, let alone track the degree of coupling between oceanographic variability and community structure of function. A network of RCO-based studies on the continental shelf and slope could track key physical processes (e.g., upwelling plumes) and monitor plankton community succession and biologically-driven changes (zooplankton grazing/nekton predation) throughout not only a single event, but overall several years, providing an unprecedented perspective of these systems. In addition, deeper instruments could track the export flux of organic debris toward the seafloor, and enable a broader understanding of coupling of seafloor processes to upper water column events.

Much of the continental shelf and slope is covered in sediments that support spatially heterogeneous communities of invertebrates. Shelf benthos are typically thought to be influenced much more strongly by physical processes than are those in slope and abyssal environments, and also by disturbances associated with human activities (e.g., fishing, pollution). The influence of biological interactions on the structure and energy flow in shelf, slope, and other deep-sea communities is very poorly known. Nearly all shelf and slope communities, however, share a common dependence on water-column production to provide most or all of the primary production that drives benthic food webs. In each system, episodic physical and biological events have potential to play key regulatory roles in the spatial and temporal patterns in community structure, but capacity to quantify the contributions of these events has been limited historically by limited access to the seafloor—particularly on a repeated basis. An RCO in the Northeast Pacific offers an ideal platform to test the regulatory roles of these episodic events in benthic shelf and slope habitats, and to revisit regions of the seafloor at different times and in response to episodic events.

## Shelf Environments

Shelf environments are affected by physical disturbances generated during storm events, but are also linked strongly to the water column through the temporal coupling of the input flux of phytoplankton production to the seabed with cycles of upper ocean productivity. In the North Pacific, the productivity of the upper water column, as well as the delivery of organic material to the seabed, is strongly seasonal, creating variability in the quantity and quality of food resources in both systems. Thus, a combination of physical disturbances and linkages with upper-ocean productivity can influence development and stability of shelf communities. In addition, however, the life histories of species may lead to large variation in the relative importance of various factors that may influ-

ence their population dynamics. For example, many benthic invertebrates and benthic-pelagic fishes have planktonic larval stages that experience high mortality prior to settlement to the benthos. The RCO will enable more detailed studies of these systems than previously possible, allowing scientists to address a wide range of questions concerning ecosystem patterns and functions.

Benthic organisms may also have feedbacks on water-column processes; this linkage may be relatively strong and coupled closely in time and space in shelf systems, whereas in deep-sea systems this linkage is more likely to occur only on longer time scales (i.e., temporal mixing scales between bottom and surface waters) and with wider horizontal separation. For example, benthic communities play key roles in decomposition of organic material and regeneration of nutrients into the water column, but only recently have these roles been identified with key benthic species.

Benthic organisms also influence the mobility and stability of sediments. Microbes and sedentary macrofauna, for example, can stabilize sediments whereas deposit-feeding macrofauna bioturbate and can thereby increase sediment mobility. Problems to address include: determining the extent to which sediment transport change seasonally, and the role of sedimentary fauna in this process; and whether bioturbators contribute to harmful algal blooms by mobilizing cysts, or remobilizing pollutants that might otherwise be buried in sediments.

## Slope Environments

Slope environments are coupled less directly to upper water column disturbances than on shelf environments, but there is nonetheless the potential for strong spatial and temporal dependence. By deploying suites of physical sensors (CTDs, current meters, fluorometers, turbidity sensors) and biological instru-

ments (cameras, benthic rovers capable of various rate measurements, optical and acoustic arrays) on a subsea cabled network, many important questions concerning the slope ecosystem dynamics that can be addressed.

Many of the key issues that would be studied in shelf environments are relevant to slope environments as well, but the issue of diversity maintenance in slope environments is particularly compelling because of suggestions that slope environments are species rich despite the absence of macroscopic habitat heterogeneity. It has been hypothesized that small-scale patches, generated through episodic events (e.g., phytodetrital pulses, predation disturbance) may be especially important in creating a patch mosaic in slope environments that is critical to diversity maintenance.

The RCO infrastructure provides unprecedented opportunity to test the regulation of biodiversity patterns in sedimentary fauna and the role that sediment fauna play in the cycling of nutrients, stabilizing of sediments, and mobilizing of pollutants and pathogens. Through continuous measurement of particle flux to the benthos, frequency and intensity of episodic disturbance (e.g., sediment resuspension events), larval supply and settlement to different environments, it will be possible to advance significantly the understanding of pattern and diversity maintenance in shelf and deep-sea sediments. Through measurement of sediment nutrient efflux, and bioturbation and pollutant mobilization rates, it will be possible to determine the role of specific taxa and faunal diversity in regulating these key processes.

The shelf break and upper slope are increasingly identified as key areas for the potential injection of iron-rich sediments from the seafloor to the upper ocean, thereby stimulating phytoplankton productivity, and also for high benthic biomass. These sites might be considered as high priorities for full instrumentation

concerning physical and biological processes from the seafloor to the surface for studies of bio-physical coupling for both pelagic and benthic communities.

## Abyssal Basins

Until recently, bathyal and abyssal seafloor ecosystems were thought to be coupled only weakly to the input of organic debris from surface waters, owing to the expected damping of variation in surface productivity by remineralization and slow sinking of organic carbon exported from the surface. We know now that organic debris can reach the seafloor at depths of >5000 m quickly, leading to a rapid response by the benthos. This advance has prompted many additional questions concerning the dynamics of abyssal communities and linkages to various scales of upper-ocean variability.

Deep-sea communities may respond to variation in the flux of organic carbon by a corresponding change in the uptake and productivity of all biotic components of the community or through a less-equitable partitioning of energy flow among community components. Although Smith et al. showed that the metabolic rates of the sediment community were relatively invariant to decreased input of organic material, it is not known whether changes in food availability are “absorbed” largely by microbial populations and less so by metazoans, or vice versa. Observatory studies in abyssal basins will allow observations of various faunal components (benthic, benthic-pelagic fishes and invertebrates) and organic carbon inputs, as well as the local to regional physical oceanographic conditions that may also influence benthic and benthic-pelagic community patterns and processes.

Several measurements and observational methods will be important. They include core measurements of benthic and benthic-pelagic oceanographic parameters (currents, temperature, pressure, oxygen, suspended sediment) and energy flux (organic carbon

input). Biological parameters will range from periodic imaging of benthic and benthic-pelagic megafaunal communities from moored and mobile camera systems to rate measurements (e.g., sediment community oxygen consumption, carbon remineralization and nutrient fluxes) to more advanced determination of changes in microbial and meiofaunal population abundance and condition (DNA/PCR processors, sediment sampling and preservation tools). In addition, nektonic animals inhabiting the abyssal benthic-pelagic zones (and shallower) may be studied using acoustic arrays, perhaps mounted on vertical profilers capable of excursions to hundreds of meters above the seabed, acoustic tagging techniques, and novel methods yet to be developed.

## Seamounts

Seamounts are widely distributed and very abundant in the world ocean and have recently received attention as a priority for ocean exploration (NOAA). Although seamount communities are known to be highly diverse, factors that influence their community structure and dynamics are not well understood. These “island” habitats have high degrees of endemism, as expected from their isolation. Current speed, depth, distance from the euphotic zone, and productivity of the overlying water column are known to influence seamount community patterns, but the relative importance of these structuring features and the underlying mechanisms connecting them to observed community structure are not understood. Cabled undersea networks have enormous potential in advancing understanding of questions concerning the biology and ecology of seamount communities.

Trawling activities on seamounts have devastated benthic communities on many seamounts through the virtual removal of entire communities of sessile, hard substratum species. Factors influencing the colonization, recruitment, growth, and productivity of

major seamount faunas are almost entirely unknown. Observations using camera systems, oceanographic instrumentation (currents, other), and advanced methods, including experimental manipulations, promise significant advances in this area.

Seamounts can also have significant effects on the midwater and near-bottom plankton and nekton, depending on their depth beneath the surface and position relative to the deep-scattering layer. Previous studies have documented the effects of seamount predators (mainly scorpaenid rockfishes) on vertically migrating midwater species that encounter the seamount summit during their morning descent to deeper waters. This very effective biological pump enhances seamount productivity, yet remains poorly understood. Clearly, RCOs hold great promise for understanding the complex coupling between physical and biological processes on seamounts.

## Deep-Sea CO<sub>2</sub> Sequestration Issues

Consideration of deep-sea carbon sequestration, coupled with the continued acidification of the world ocean suggests that the future ocean will be lower in pH, with presently unknown impacts on the structure and dynamics of shallow and deep-sea communities. Use of the RCO to investigate effects of elevated CO<sub>2</sub> / reduced pH on benthic and benthopelagic populations and communities may be possible using experimental manipulations similar to the Free-Air CO<sub>2</sub> Enrichment (FACE) studies presently under study in a variety of terrestrial systems.

## Vents and Seeps

Seafloor volcanic spreading ridges host hydrothermal activity that provides energy for unique biological communities fueled by chemosynthesis. Vent biomass along these hydrothermal fields rivals that of the most productive marine ecosystems. Hydrothermal vent communities are known to be highly dynamic, subject

to drastic changes in composition and biomass at time scales of weeks to months. Such changes are presumably brought about by seismic, magmatic, hydrothermal, and oceanographic processes that shape the vent environment, although such interactions are difficult to observe without continuous monitoring. The Endeavour Segment is proposed as a site for studies of vent ecosystem dynamics. Endeavour Segment is known for its widespread and abundant high-temperature venting through large and numerous sulfide mineral edifices. Vent communities colonize actively venting sulfide edifices as well as seafloor vents where fluids discharge through basaltic rock.

Tectonic compression along the convergent boundary of the Juan de Fuca and North American Plates is thought to drive seepage of methane-rich pore fluids from hemipelagic sediments, which, like hydrothermal vents, support chemosynthetic communities. These communities are particularly abundant in areas such as Hydrate Ridge (Figure 2), where methane hydrate is abundant beneath the seafloor. An RCO at Hydrate Ridge would provide opportunities for interdisciplinary studies of tectonic compression, fluid expulsion, hydrate formation and degassing, microbial mediation of biogeochemically important fluxes (e.g., AMO), and chemosynthetic metazoan community patterns and processes. Synergy among the relevant disciplines, coupled with long-term observations of physical and biological patterns and processes, and focused manipulative experimental studies, promises rapid advances in understanding these systems.

## Epipelagic Realm

The epipelagic realm encompasses the euphotic zone and the waters immediately below it to a depth of approximately 200 m. It is the zone of solar-stimulated primary production, and is influenced by dynamics at the surface of the ocean (heat flux, wind stress, freshwater inputs, atmospheric deposition), and at the base of the surface mixed layer (diapycnal mixing, sedimentation of organic material). Organic

carbon fixed in the epipelagic zone forms the major food source for nearly all organisms inhabiting depths below the euphotic zone.

Planktonic community structure and dynamics in the epipelagic are tightly coupled to physical forcing, and exhibit scales of variability from micrometers to hundreds of meters vertically, and micrometers to thousands of kilometers horizontally. A dominant horizontal scale of variability is given by the baroclinic Rossby radius of deformation (a scale determined by the physical environment), which typically ranges from 5-30 km, depending on the water depth, vertical stratification, and latitude. The RCO node spacing, with sub-nodes deployed by extension cables, will support instrument spacing that can be commensurate with these oceanographic scales. Docked AUVs with physical oceanographic sensors could increase greatly the spatial resolution of these measurements.

This Northeast Pacific region is the site of significant gradients in pelagic biomes. The West Wind Drift bifurcates in the northern part of the study region, forming the Alaskan Coastal Current to the north, and the California Current System to the south. Waters of the Central North Pacific Gyre to the southwest of the study region are oligotrophic (nutrient-poor), and the West Wind Drift is one of the major High Nutrient, Low Chlorophyll (HNLC) regions of the planet. These strong gradients shift seasonally, and are predicted to shift in response to long-term climate change. Thus long-term observations spanning this region have the potential of providing unprecedented insights into planktonic community response to environmental change over scales from hours to decades.

The epipelagic ecosystem will be explored using long-term, high-temporal-resolution observations, combined with ship-based observation programs, and manipulation experiments (such as long-term iron fertilization at specific sites). It is possible now to deploy a suite of sensors to monitor physical processes

in the epipelagic zone, and new sensor development will enable high-resolution measurements of epipelagic fauna. For example, the environmental sample processor (ESP), developed by MBARI, is capable of rapid and automated quantification of the abundance of many species of phytoplankton. Thus, deployment of ESP-like instruments on the RCO, coupled with acoustic arrays, cameras, and novel sensor to monitor higher trophic levels, could allow detailed measurements of upper ocean ecosystem dynamics.

Observations would be assimilated into models of the physical and biological dynamics to gain enhanced understanding of the underlying dynamics. To optimize costs vs. benefits, we propose a nested regional observing system. The backbone system would consist of “standard” sites arranged to define cross-shelf and along-shelf transects, and a set arranged to define the boundaries of a volume targeted for data assimilative models. “Super sites” would consist of smaller, well-defined regions that would be more densely instrumented. The purpose of this arrangement of standard and super sites is to obtain large-scale (> mesoscale) continuous observations at the boundaries of a volume to constrain the fluxes through that volume, while the super sites would allow resolution of sub-mesoscale gradients. This nested approach will provide strong constraints to physical-ecosystem models, allowing a teasing apart of the physical and biological dynamics controlling the observed fields.

Studies will require observations across the shelf and shelf break, in deep waters of the Central North Pacific Gyre, and across the WWD. The significant changes in benthic topography within the region allow observation of the effects of, for example, shelf breaks, spreading ridges, and benthic plains on the physical and biological dynamics of the epipelagic. Strong wind forcing will create significant physical variability on the shelf and slope, underscoring the need for enhanced spatial resolution in these areas.

Research on pelagic community structure represents one of the largest instrumentation and intellectual challenges for an RCO. This type of research will require instruments that can be used to identify the organisms that are present on a variety of scales and some elements of their dynamics (growth, physiology, ecology). Molecular approaches have been identified that may be able to allow some of these measurements, but it will be a real challenge to make those instruments operational on the time scale of the RCO. Acoustic techniques may be the most promising for measurements of fish and megainvertebrates. Imaging instruments have great potential, and some are near operational capability. Sample collection and storage for later analysis is also possible. Intellectually, the fact that the water moves past a fixed site presents a host of challenges for relating the observations at a site to the spatially variable processes that produce those patterns. It is clear that to move forward in this area will require a coupling between the activities on the RCO and the more traditional science conducted from ships. As RCO technologies mature, gliders, AUVs, and other mobile vehicles may extend the capabilities of the remote system to cover some of the ship-based needs.

## Meso- and Bathypelagic Realms

The flux of particulate and dissolved organic carbon from the surface layer of the ocean to the deep sea via the biological pump is a primary mechanism by which carbon dioxide is removed from the surface ocean. Imbalances between the downward flux of carbon and its return to the surface are a major mechanism through which the oceans regulate the concentration of carbon dioxide in the atmosphere. Although about 90% of the particulate flux sedimenting from the surface layer disappears in the mesopelagic zone (100-1000 m) as a result of consumption or remineralization, the species composition and food-web interactions of this important community remain poorly known. Biological interactions, owing to the

mild physical variability of the upper ocean, are likely to play a large role in organizing deep-sea pelagic communities, yet we have a very limited understanding of even the trophic interactions characterizing these environments, let alone their role in structuring deep-sea ecosystems. An RCO provides unprecedented opportunity to observe the meso and bathy pelagic zones to gain a view of the basic patterns in this system to guide future hypotheses and experimentation.

## Sensors

A significant instrument development program that parallels the planning and installation of any RCO is essential to address most biological themes planned for RCO studies. Temperature sensors, acoustic systems such as acoustic Doppler current meters, optical backscatter sensors, and transmissometers to measure water clarity are available today that are suitable for RCO deployments. Active acoustic systems are available to detect, classify, and monitor biological targets and physical characteristics throughout the water column ranging in size from phytoplankton to marine mammals. It is critical to note, however, that many other sensors, samplers, and *in situ* analyzers that are deployed for short periods (i.e., weeks to months) on moorings or operated from ships, are not yet suitable for RCO deployment. More complex systems, including various submersible autonomous platforms (AUVs, Benthic Rovers, *in situ* manipulator boom), *in situ* samplers (sediment sampler, water samplers, plankton samplers), analyzers (Environmental Sample Processor [ESP], elemental analyzer), and other specialized instruments (sample recovery systems) will not be available for deployment on the RCO for a considerable period, perhaps exceeding the lifetime of the RCO.

Ultimately, the ability to conduct controlled experiments, both mensurative and manipulative, will be a key part of any exploration of ecosystem dynamics. Progress in ocean ecosystem studies may be more efficient and successful using traditional expedition-

ary approaches until sensor development advances to a point that a suitable suite of biologically relevant sensors are available and reliable for RCO deployment. However, expeditionary and cable observatory studies should, nevertheless, be used together to test hypotheses about mechanisms and the robustness of models. Strong tests require the ability to perturb or manipulate an aspect of the biological system and move through the system to document the response. These tests require standard sensors on mobile platforms. In other cases, novel manipulative devices may be required to control a volume of water or sediment, manipulate it such as through the addition of a substrate, contaminant or physical change and then measure a unique response. The scale of these devices varies from small incubators to the manipulation of entire landscapes such as through trawl scars or drilling of new hydrothermal vent outflows.

# Ocean, Climate, and Biogeochemical Cycling

Ken Denman, Canadian Centre for Climate Modeling and Analysis, and Nate Mantua, University of Washington

An RCO offers new opportunities to detect oceanic variability from subtidal to interdecadal time scales, and to observe both long-term changes and establish a “mean” picture of the regional role in the ocean carbon cycle. In particular, the sampling from a regional cabled observatory can:

- span “event scales” to climatic trends, with spatial delineation of environmental forcing and biogeochemical signals. “Events” include both episodes and regime shifts.
- resolve mesoscale eddy spatial scales and episodic event scales in environmental forcing and biogeochemical signals.
- capture time scales of climatic variation and change.
- span shelf to deep-sea environments to determine synchronicity and exchange associated with large-scale events and trends.

The Northeast Pacific region provides several distinct bathymetry roughness environments for observation and determination of the role of ocean margins in vertical mixing and exchange of heat and other properties over ocean basins. An RCO also offers great potential for real-time adaptive sampling, an emerging methodology.

To exploit these opportunities in a scientifically exciting and productive manner, the working group developed the following priority themes to guide detailed planning:

1. Observe the regional oceanic response to external forcing from subtidal to interdecadal time scales: Determine the regional climate change fingerprint.
2. Quantify the contribution of the region to the global carbon cycle: Are oceanic boundary current upwelling systems a source or sink of atmospheric carbon?

3. Determine the role of regional features and processes in physical transports and biogeochemical cycles.

## Key Issues

Common with the other two “water-column” working groups, we felt that mooring platforms extending basic power/communications capability into the water column must be part of the basic/core infrastructure from the start.

It also became clear that for an RCO to realize its full potential, there is a need to measure exchanges across the upper and lower boundaries. Most importantly, there must be a related, coordinated activity for ongoing development of sensors.

## Science Questions

Theme 1. Regional response to external forcing (climate, tectonics, terrestrial inputs)

- How does ENSO variability affect the physical and biogeochemical structure of the thermo- and nutrient structure?
- How does methane hydrate flux (stability?) respond to climate and seismic forcing?
- How does ocean productivity respond to variations in the hydrological (rivers, precipitation) cycle?
- How does the regional exchange of carbon (CO<sub>2</sub>, CH<sub>4</sub>) with the atmosphere and the seafloor change with these external forcings?
- What physical mechanisms determine the structure of the regional current system?
- How do these physical mechanisms change as a result of the external forcings?
- How do these physical processes affect biogeochemical cycles?



Theme 2. Role of regional features and processes in physical transports and biogeochemical cycles

- How do specific topographical features (e.g., smooth slope, rough slope, ridges and slope features, canyons), affect diapycnal mixing along the ocean margins and the transport of mixed waters from the boundaries to the ocean interior? (Howe et al., 2003) The (bottom) boundary mixing of the ocean likely plays a key role in the maintenance of the abyssal stratification, so this line of research is of global importance.
- What is the relative contributions of various meso-scale processes (e.g., upwelling filaments, instabilities in the boundary current) on nutrient flux and ecosystem dynamics?
- What is the spatial and temporal variability of remineralization? And what controls it?

Theme 3. Determine the contribution of the region to the global biogeochemical (e.g., carbon, iron) cycles

- How are nutrients and carbon exchanged between the coastal margin and the oceanic interior?
- What is the contribution of eastern boundary current regions to the global carbon cycle?

Figure 12 illustrates schematically most of the processes operating in the water column along the boundary between the continental shelf and the ocean interior.

## Experiments and Data

The proposed experiments that could be conducted with an RCO fall into three main types:

### 1. Regional-scale sustained observations for climate.

The sampling array must span the whole region, with matching sensor suites in key environments such as offshore pelagic, shelf-edge, slope, mid-shelf. Key objectives are to:

- Determine the mean and varying budgets of heat, salt and biogeochemical variables in a 3D volume encompassing the continental shelf and extending to deep waters beyond the continental slope.
- Provide a data set highly resolved in time and space over long enough time scales for constraining and evaluating coupled models.

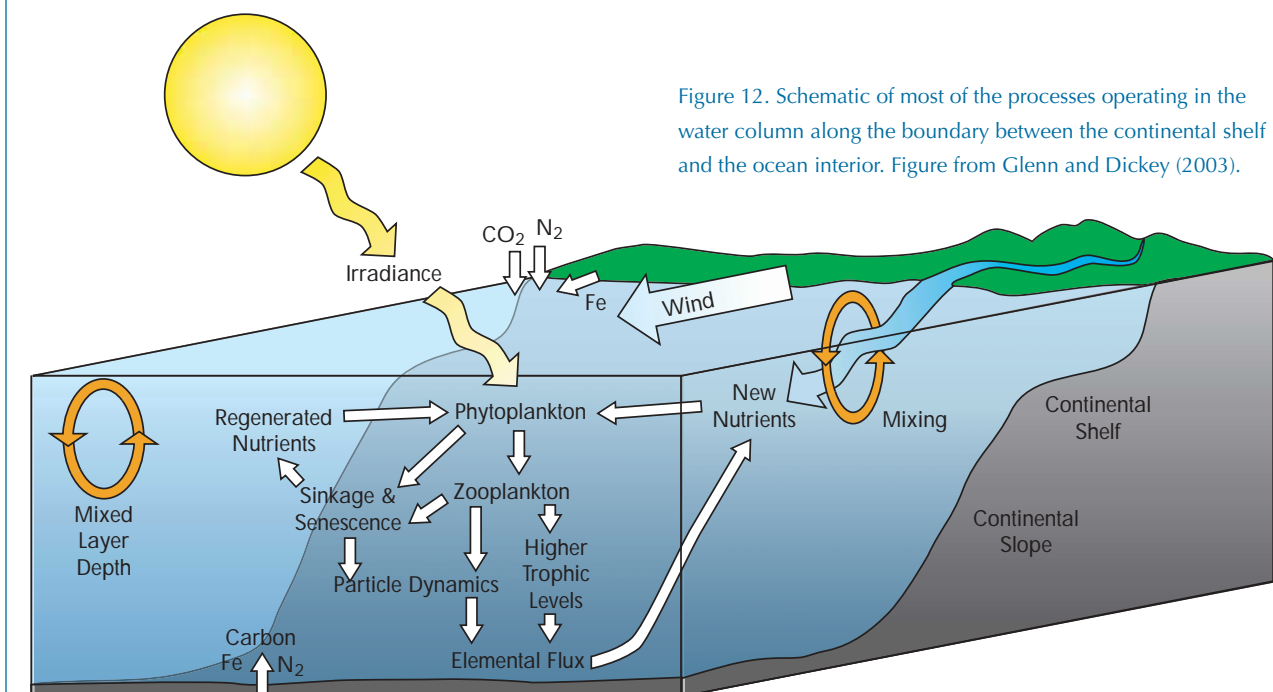


Figure 12. Schematic of most of the processes operating in the water column along the boundary between the continental shelf and the ocean interior. Figure from Glenn and Dickey (2003).

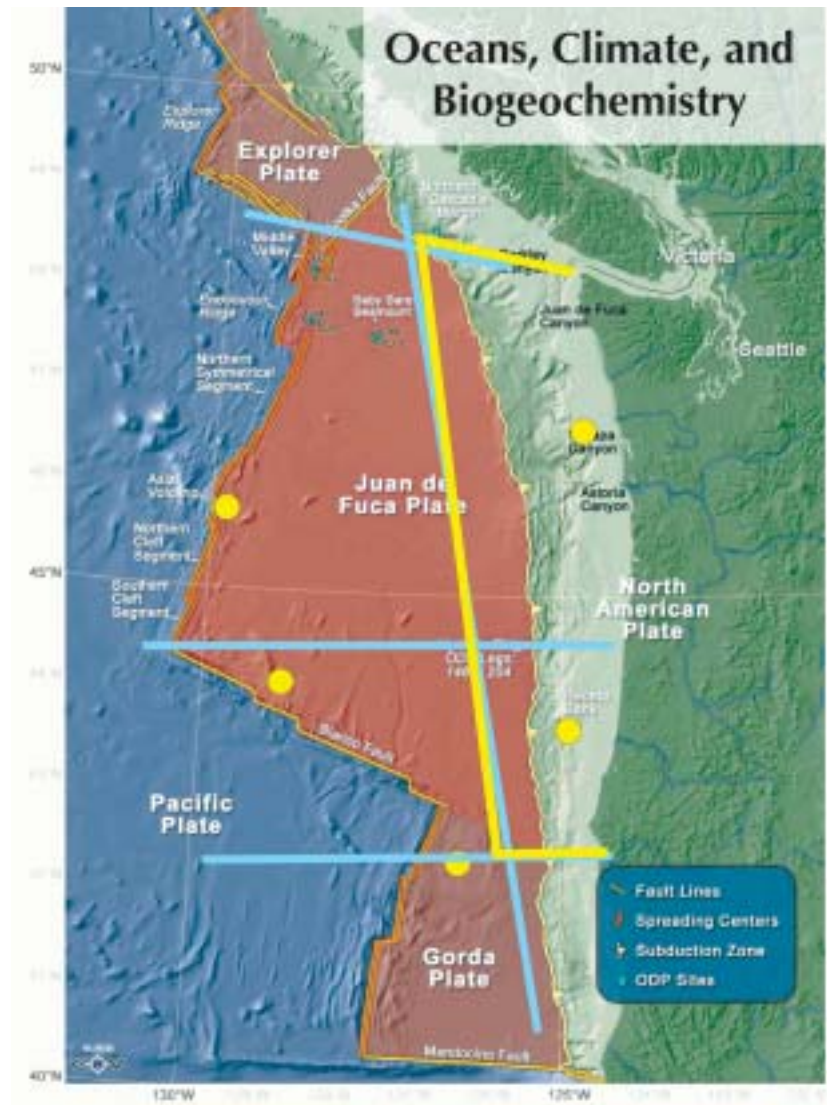
**2. High-resolution study of ocean mixing.** The proposed study area encompasses a wide range of energetic environments. Potential exists for topography/mixing experiments at five specific sites (yellow dots in Figure 13)—on a ridge crest, a transform fault, a steep continental slope, in a canyon and over severely rough topography on Gorda Plate—to estimate the contribution of each type of site to small-scale mixing along oceanic margins.

**3. Carbon budget control volume.** In physical oceanography, inverse techniques have been developed to determine flows into and out of a “control

volume”—a region of the ocean enclosed by a combination of connected sampling lines (extending from ocean bottom to sea surface) and the bottom. The proposed RCO in the Northeast Pacific offers the opportunity to extend this analysis to the flows of carbon and related biogeochemical elements and tracers. To undertake such an analysis, the following sampling strategy would be required:

- Three east-west lines (blue lines in Figure 13) of water-column moorings (attached to the bottom nodes) from the shelf to the ridge, number of moorings (~5/line) TBD, The northern line follows the inner station positions along Line P. The middle

Figure 13. Primary measurement sites recommended by the Oceans, Climate, and Biogeochemistry working group. The map shows locations for carbon budget and flow/topography sites. Yellow dots indicate the locations of topography/mixing experiments. Blue lines indicate the placement of lines of moorings. The north-south blue line shows the location of a line of moorings near the base of the continental slope. The yellow line is the control volume which, together with the coastline of Washington and Oregon, completely encloses a region or volume of the ocean.



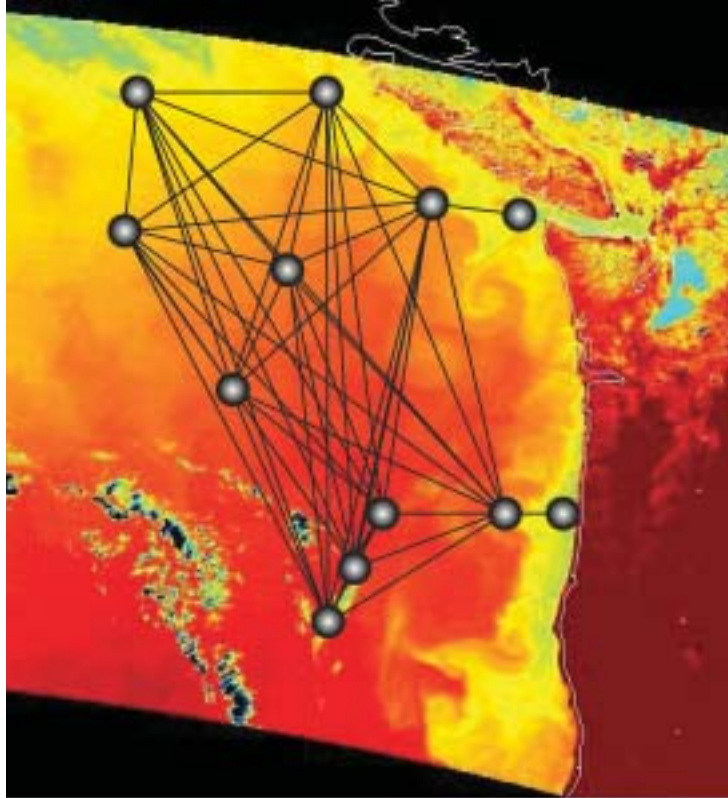


Figure 14. Configuration of a possible tomographic array in the Northeast Pacific RCO to (i) study the bifurcation of the West Wind Drift, (ii) study the source region of the California and Alaska Currents, and (iii) provide the biologists (and all disciplines) with the temperature and current fields needed to help determine the role that physical forcing plays in the ecosystems in the region. The number of paths providing temperature, absolute velocity, and vorticity data grows quadratically with the number of moorings/transceivers.

line repeats the Oregon State University Newport Line along  $44^{\circ}39' N$ . The southern line is designed to cut through the flow separation south of Cape Blanco that carries shelf waters SW into deep water.

- One north-south line of moorings offshore near the base of the continental slope, to close the control volume (yellow line in Figure 13).

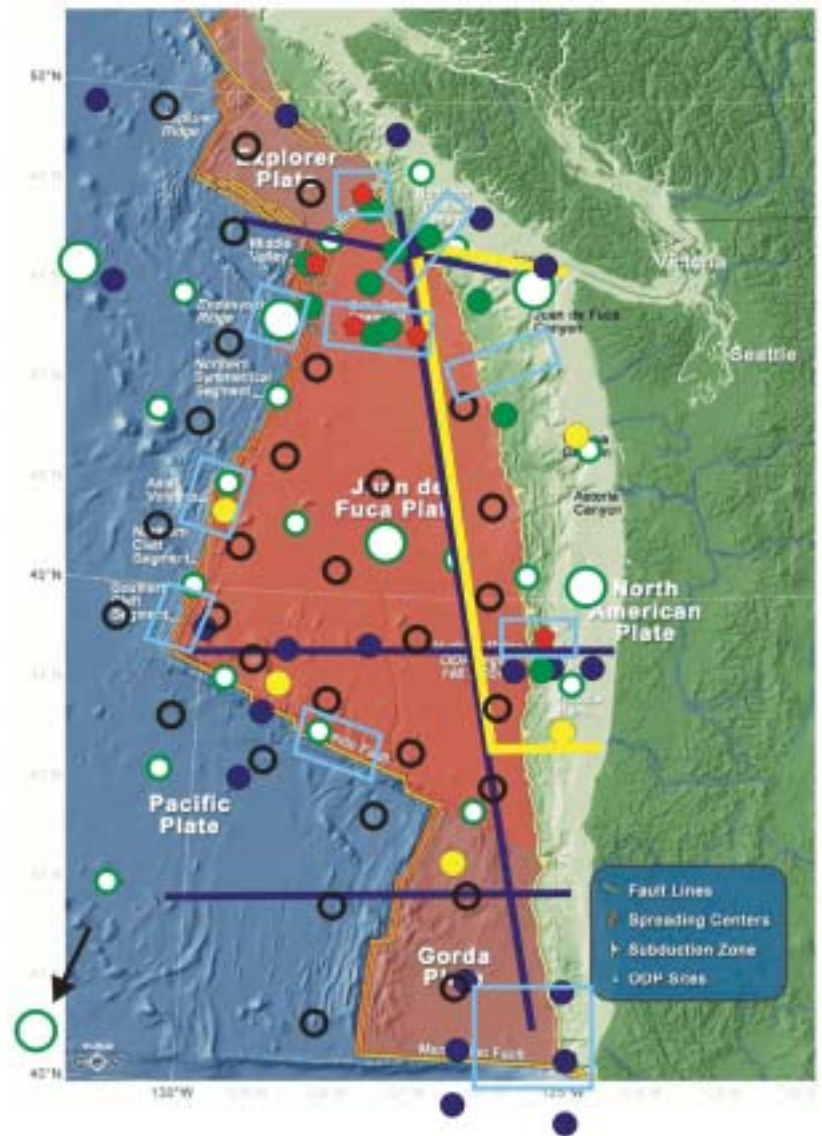
All three of the above experiments call for the synoptic measurement of temperature and velocity fields over the regional domain with varying degrees of resolution. Ocean acoustic tomography can contribute to this requirement (Figure 14).

# INTEGRATION

At the end of 2.5 days of working-group deliberations and presentations, workshop chairs and team leaders met for an additional 1.5 days to synthesize the output from thematic working groups and determine an optimal integrated deployment plan that would most effectively address all the primary science priorities. Figure 15 plots all of the RCO nodes recommended by the five scientific working groups, which total over 100. A fully implemented RCO in the Northeast Pacific Ocean would encompass all the circles and rectangles shown in the figure.

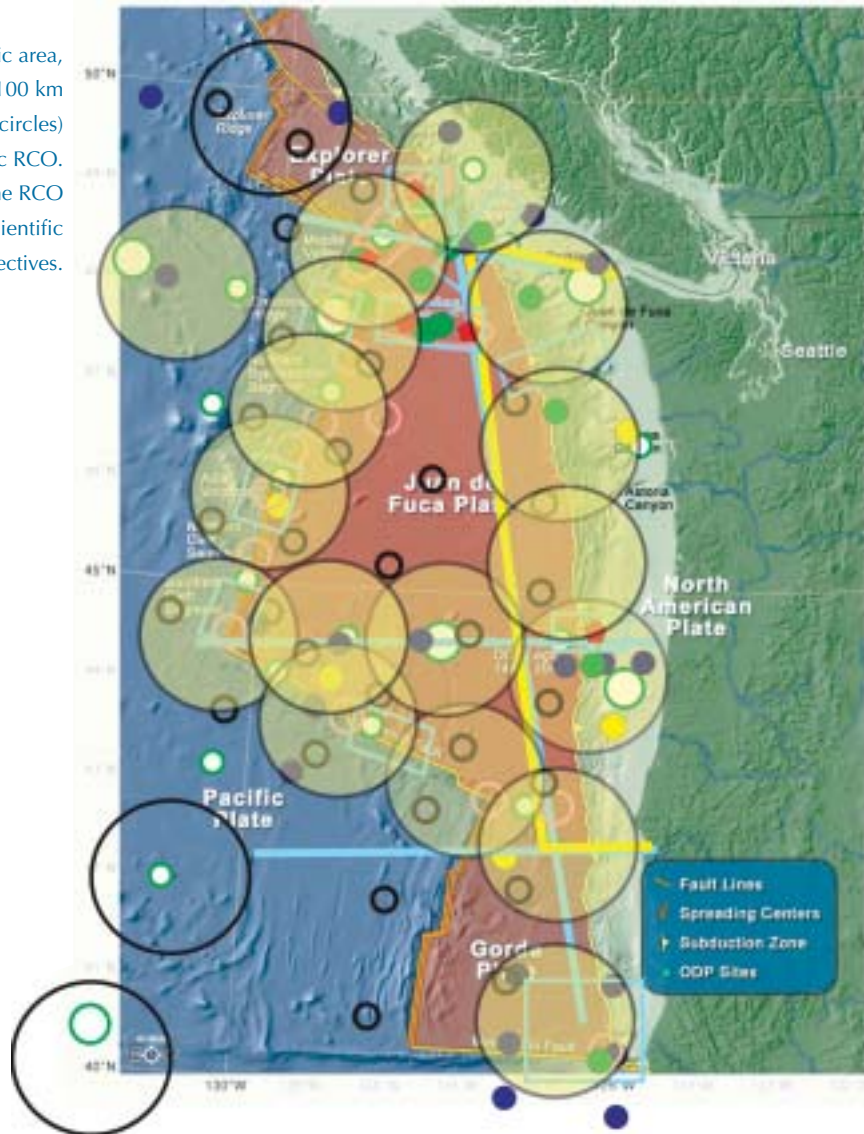
The workshop premise was that after full deployment, there would be about 20-30 nodes for a system with ~3500 km of cable (number of nodes and node spacing dictated by technical considerations). Cable extensions could be as much as 100 km. To determine how many high-priority sites could be captured during initial deployment, circles were drawn with a radius of approximately 100 km along the proposed cable route (Figure 16). These circles capture most of the high-priority instrumentation sites recommended by all the scientific working groups.

Figure 15. Map of Northeast Pacific area showing locations for Regional Cabled Observatory nodes proposed by the five scientific working groups. Black circles – solid Earth cycle OBS site, Blue rectangles – solid Earth cycle intensive study site, red circles – geodynamics boreholes, green circles – fluid flow studies ODP/IODP sites, dark blue circles – ocean turbulence study sites, yellow dots – biogeochemical studies sites, blue & yellow lines – biogeochemical studies transects to include numerous nodes, white dots – ecosystem studies sites (small = standard, large = “super-site”).



In addition to this all-important “integration task,” the workshop leadership was challenged to begin to introduce constraints of fiscal reality into the deliberative process by identifying the key elements of an “Initial Deployment” in the Northeast Pacific. It was recognized that resources would inevitably restrict the nature and number of sensors that could be deployed immediately upon completion of cable-laying. Therefore, the working group leaders were challenged to identify their highest-priority requirements. The next chapter of this report describes what an initial RCO deployment in the Northeast Pacific might look like.

Figure 16. Map of the Northeast Pacific area, as in Figure 15, with cable extensions ~100 km radius from each central node (yellow circles) spread throughout the Northeast Pacific RCO. By frequent use of cable extensions the RCO can capture the largest number of scientific objectives.



# INITIAL DEPLOYMENT

At the outset of the workshop, participants agreed that during the RCO's initial deployment, sufficient measurements must be made to permit important results to be generated that address at least some aspect of all the working groups' needs. Participants concluded that it was practical, within fiscal and logistical constraints, to instrument a modest number of locations.

## Plate-Scale Geodynamics Observatory

Establishing a complete plate-scale geodynamic observatory will take several years. The highest-priority community instrumentation for installation with the observatory infrastructure is outlined below. This instrumentation would provide 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 Ridge leading to a better understanding of the coupling among 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 a plate-scale geodynamic observatory (~ 10 sites)
- Endeavour ridge-crest observatory instrumentation (~ 12 seismometers, geodetic, magnetotelluric, 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)

## Initial Sites for Water-Column Observations

Three of the working groups (Oceans, Climate, and Biogeochemical Cycles; Turbulence and Biophysical Interactions; and Ecosystems Dynamics) succeeded in identifying 12 priority sites for initial implementation of observations throughout the full water column (Figure 17). These locations were selected to provide immediate returns to a broad cross-section of the interested scientific community, and to initiate the sustained measurements necessary for investigating issues of climate variability and anthropogenic climate change. Sustained measurements of the physical environment (e.g., temperature and salinity profiles) at all locations will support efforts to establish a global climate monitoring system. As described below, instrumented "trees" at many of the 12 sites shown in Figure 16 would fulfill multiple functions within the priority science identified by the three working groups. In addition, many of these sites are in locations of common interest to the other two groups.

1. The subset of sites [1,11,12,9] enables comparison of substantially different oceanic biogeochemical provinces, ranging from the southern fringe of the

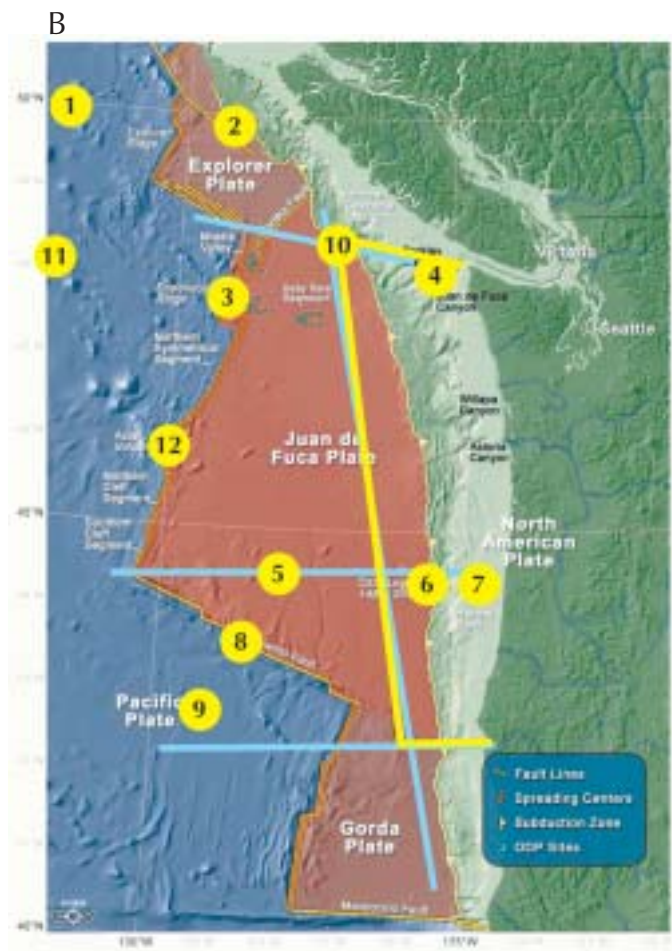
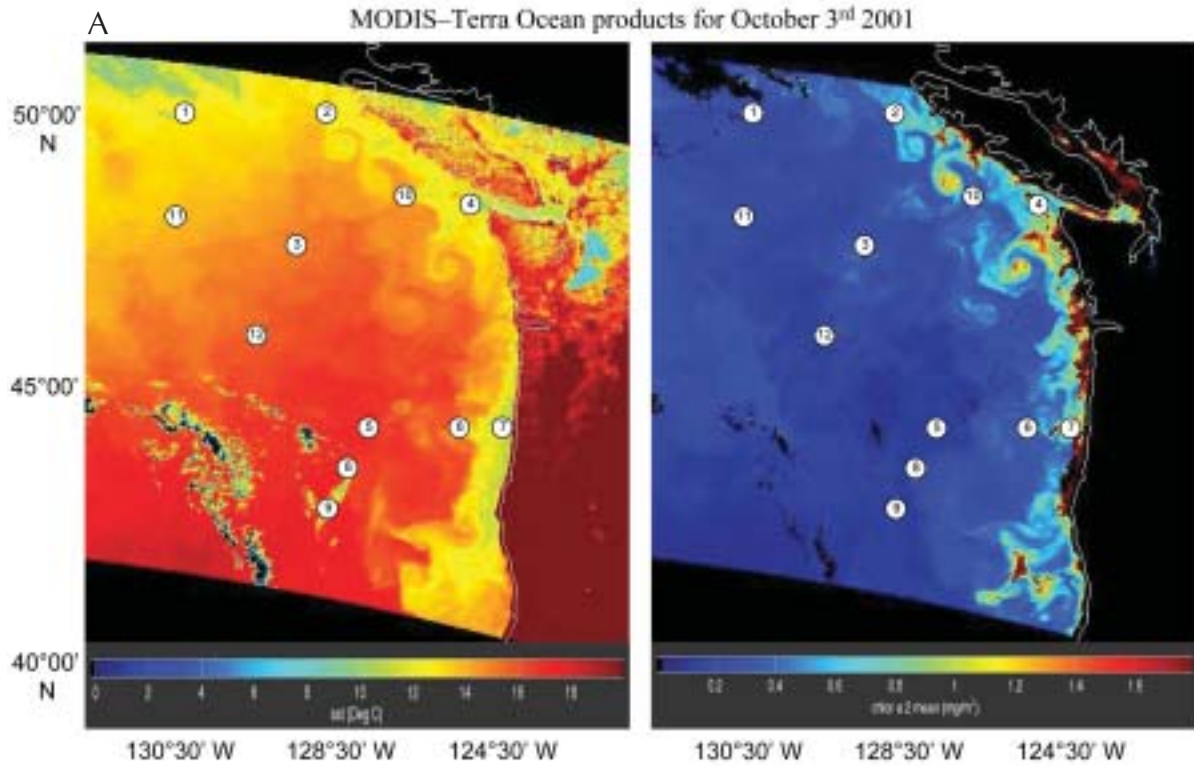


Figure 17. Approximate geographical distribution of high-priority stations displayed against the spatial distribution of (A, left) Sea Surface Temperature (SST), (A, right) chlorophyll (chl), and (B) bathymetry in the planned observatory region. The proposed sites, recommended by three working groups, are located on all major bathymetric features (continental shelf, continental slope, bathyal basin, abyssal basin, mid-ocean ridge, transform fault) and will allow a N/S sub-arctic/sub-tropical comparison, the resolution of N/S fluctuations in the West Wind Drift (WWD) and its bifurcation (Sites 1,11,12, and 9), studies of offshore-onshore transports (Sites 1-2, 3-4, and 5-7) and shelf-slope interactions (Sites 6-7 and 4-10), studies of tidal flows and topography interactions (Sites 5,8, and 9), and comparisons of N/S along-shelf flows (Sites 4 and 7). The location of several sites (3, 6, 7,8, 12) coincide with high-priority sites identified for plate dynamics and fluids studies. Sites are also located in the proximity of hydrothermal vent communities (3 and 12) and methane hydrate-rich environments (6). Sites 5-7 take advantage of the long-time-series observations along the “Newport Line”. Finally, the distribution of high-priority stations spans several gradients in ocean productivity, ranging from gradients in the intensity of coastal upwelling, north-south gradients in productivity (related partially to the WWD), and major onshore/offshore gradients in ocean temperature and upper ocean productivity.

- highly productive micro-nutrient-limited HNLC sub-arctic gyre to a region with the lower productivity associated with macro-nutrient limitation in the sub-tropical gyre. In addition, this coarse spatial array will allow monitoring of major variability in the N/S position of the West Wind Drift.
2. The site pairs [1-2], [3-4], and [5-7] will allow comparison of onshore-offshore processes and fluxes at locations characterized by different upwelling and mean current regimes.
  3. The site pair [1,11] monitors variability in biophysical fields being advected towards the coast in the West Wind Drift, while the pair [2,10] should delineate associated variability in the N/S divergence of fluxes of mass and biogenic material feeding into either the Alaskan Stream or the California Current. Sites [2 and 10] are located in a highly dynamic and ecologically diverse region of the Northeast Pacific that should provide insights into climate-scale (seasonal-to-interannual and interdecadal time scale) impacts on regional physics and ecology. This area includes exceptional food-web productivity and diversity due to the combined influences of sub-arctic inflows [Sites 1-4, 10 and 11], inland seas outflows [Site 4] and seasonally intermittent coastal upwelling. Measurements obtained from these array sites will support a variety of research objectives as well as the management of valuable marine resources (e.g., U.S. NOAA Fisheries and Canada's DFO management decisions involving commercially valuable fish stocks, harmful algal blooms and marine mammals). Knowledge of fluxes into the eastern sub-tropical gyre at its northern boundary also provides an essential upstream condition for biophysical conditions within the entire California Current system.
  4. Sites [4,7] provide an estimate of along-shelf variability in biophysical fields. Despite the coarse spatial scale, co-variability (or lack thereof) between extended time series observations in these two locations would provide improved tests of various hypotheses relating ocean productivity to the success of commercially important fisheries.
  5. Sites [3,12] are located at major venting locations along the Juan de Fuca Ridge, locations that will be intensively occupied by the geophysical part of the observatory community. The water column observation sites would be located along the flanks of the ridge at these locations, concentrating on variability in the along-ridge flows and their ability to transport larvae of vent animals between venting sites, as well as fortuitous measurements of the biophysical signatures of mega-plumes.
  6. Near-bottom current and microstructure measurements over the rough topography of the shelf break (Sites 2, 10, 6), at the ridge (Site 12), and across the transform fault (Sites 5, 8, and 9) will provide data necessary to better understand and model boundary mixing that may be key to understanding the maintenance of the observed abyssal stratification. Diapycnal mixing near the seafloor is also a source of mechanical stirring that helps transport mixed water, nutrients, etc. from the coastal margins into the interior ocean. Continuous, high-frequency (subtidal time scale) and spatially distributed sampling across the complex bottom topography of the shelf-break, ridge and transform fault will provide information necessary to quantify the statistics of bottom-water mixing that vary on a broad spectrum of time scales (from shorter than tidal to seasonal and interannual). The small spatial scales associated with these mixing processes are rarely resolved in numerical or observational work, despite their global implications for the maintenance of abyssal stratification. In addition, Site 5 is a part of the comparative suite of locations (see 2. above), which will characterize shelf-to-basin variation in turbulence and biophysical processes.



7. Arrays of water-column sensors at Sites [5-9] will enable sampling of biophysical processes from the exceptionally productive upwelling zone (over the shelf) to the nutrient-poor, sub-tropical waters west of the shelf break. Sustained observations of the upper water column (mixed layer/euphotic zone) will provide insights into climate-scale (seasonal-to-interannual and interdecadal time scale) impacts on regional physics and ecology. Measurements obtained from these arrays will support a variety of research objectives as well as the management of valuable marine resources (e.g., NOAA Fisheries management decisions involving commercially valuable fish stocks, harmful algal blooms and marine mammals). Sustained measurements over multiple years will allow researchers to quantify and better understand the relationships between event-scale biophysical processes and more slowly varying parts of the climate system like the seasonal cycle, (interannual) ENSO variations, and the PDO. Near-bottom current and microstructure measurements over the rough topography of the shelf break and the transform fault separating the Pacific Plate from the Juan de Fuca Plate will provide data necessary to better understand and model boundary mixing processes that may be key to understanding the maintenance of the observed abyssal stratification.

7. Site 4 is of major interest as a site of larval retention, harmful algal bloom development, and a source of deepwater renewal for large areas of the inner coastal waters of southern British Columbia and northern Washington.

8. Site 11 will be located near major seamounts that are characteristic of the region, allowing access to this unique deep-sea environment.

It is realized that time-series measurements at sparsely distributed points will be spatially aliased in regions of strong lateral variability. Each nominal point-sampling time-series site should be supple-

mented by spatially distributed point measurements that can resolve smaller-scale features (e.g., AUVs and gliders) and/or with integrating measurements that yield unaliased observations by averaging out the smaller scales (e.g., electric field/barotropic velocity and acoustic tomography). In the design stages, it will be necessary to estimate the degree of spatial aliasing using existing data, numerical models, and observing system simulation experiments (OSSEs). The possibility of spatial aliasing should not keep us from establishing water-column time series at the earliest stage of observatory deployment, any more than the possibility of temporal aliasing has kept us from making shipborne measurements.

# TOWARD A GLOBAL NETWORK OF RCOs

All workshop attendees recognized the clear reality that a single RCO located in the Northeast Pacific (or anywhere else for that matter) would not adequately address the broad range of dynamic Earth and ocean processes about which so little is understood. Therefore, each of the working groups was asked to consider locations for additional RCOs, planning for which should be initiated as part of the overall OOI. Table 2 lists the additional sites considered by the scientific working groups and provides a priority rating for each location. Below is a summary of the discussions from each working group.

## Earth Structure and Dynamics of the Oceanic Lithosphere

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 multidisciplinary observatory data in other tectono-volcanic, oceanographic, and biogeographic settings. Several additional sites for RCOs of particular interest for studies of Earth structure and geodynamics are discussed below, some of which are priority areas for other major U.S. geoscience programs (e.g., R2K, MARGINS, IODP, OMD, EarthScope).

**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 RCOs 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 backarc 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 Northeast New Zealand in the south; and the fastest global rates

**Table 2. Potential Additional Sites**

Location	Earth Dynamics	Fluids	Turbulence	Ecosystem Dynamics	Biogeochemical Cycling
Tonga / Kermadac	High	High	Medium	High	Medium
Western US	High		Low	Medium	Medium
Mid-Atlantic Ridge	High	High			
Polar Arctic	High	High	Low	High	Low
Costa Rica	Medium	High			
Nankai	Medium	High	Medium	Medium	
U.S. East Coast	Low	Medium	High	High	High
Sub-arctic N. Atlantic (GIN Seas)	Low	Low	Low	Medium	High
Antarctic / Drake / Scotia Arc	Medium	High	High	High	High
Indonesia				High	
PAPA / UNCLE			High	High	High

Table showing qualitative “expressions of interest” by the respective team leaders in each of the regions proposed for consideration as additional RCO sites. Blanks mean that insufficient information was available for an assignment to be made.

of subduction and transform faulting (240 mm/yr). The Mariana arc has the additional characteristic of forearc serpentinite mud volcanism.

**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 RCO will cover the plate boundaries north of Cape Mendocino.

A California Borderlands RCO 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 occur-

ring 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 RCO would include seismic monitoring, plate boundary structural investigations, submarine landslide studies, and tsunami detection. This would constitute the oceanic complement to the EarthScope Plate Boundary Observatory. The Gulf of California–Salton Sea is one the MARGINS focus sites for continental rifting and initial sea floor spreading.

**Slow and Ultraslow Spreading Centers** (Mid-Atlantic, 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 Mid-Atlantic Ridge (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 MAR 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 tectono-magmatic cycle may be instrumented further north on the slow-spreading Reykjanes Ridge where there is currently no 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 time-series transect 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.

## Fluids and Life in the Oceanic Crust

There is little doubt that the greatest advantage of the Juan de Fuca Plate for the study of hydrologic processes, particularly those which are coupled with biologic, tectonic, geodynamic, and seismic processes, is the regionally continuous blanket of low-permeability sediments that hydrologically isolates the crust from the overlying ocean. This confinement allows quantitative observations to be made and uncontaminated samples to be taken that are truly representative of *in situ* conditions from ridge crest to subduction zone. The site also provides a geographic “compression” that is unquestionably unique. The Juan de Fuca system covers much of spectrum of parameters that are important to bio/seismo/hydrologic processes, but it is certainly not complete, and this leads to the recommendation that other, complementary sites be considered for future observatory deployments. Three notable examples include:

**Lau Basin.** As a future RCO, the Lau Basin offers an important opportunity to investigate linkages among geobiological, hydrological, and geophysical processes associated with a supra-subduction zone environment. The 11-km-deep Tonga Trench is the locus of the fastest subduction on Earth and the associated slab seismicity is powerful and of high frequency. The spreading system along this back-arc is characterized by a wide range of crustal compositions from tholeiitic to rhyodacite; variable spreading rates; and ridge morphology that include extensive regions underlain by a steady-state magma lens, a wide range in hydrothermal fluid compositions and venting styles, and macrofaunal communities that may be the most globally different of the deep-sea hydrothermal vent sites in terms of community structure. The wide diversity of hydrothermal chemistry, which includes solutions significantly affected by input from magmatic fluids, provides an opportunity to explore effects of geochemical differences on microbial growth and distribution. Because of these attributes it is a RIDGE Integrated Study Site and was a focus of the Ocean Drilling Program (Site 836), which drilled into an active hydrothermal area. Redeployment of a cable that is already in this area, which includes an existing land station, makes this an excellent and efficient choice as a future RCO.

**Costa Rica.** It has been known for nearly three decades that the Cocos Plate subducting beneath the Central America is anomalously cool. The plate is reasonably well sedimented, but owing possibly to extreme permeability and occasional outcropping seamounts, the upper crust of the plate is very well ventilated (heat flow approaching the subduction zone is more than ten times lower than that approaching the Cascadia margin, and pressures are indistinguishable from hydrostatic). The cool and hydrologically well-drained thermal and hydrologic structure of the plate are in marked contrast to the situation at the Juan de Fuca Ridge. This contrast would allow biological, geochemical, hydrologic, and seismotectonic studies to be carried out in a part of the pressure-tempera-

ture “domain” that is not present at the Juan de Fuca site. Another advantage to studies here is that the Costa Rica margin is much more active than Cascadia; typical intervals between large (magnitude > 7) earthquakes are of the order of 50 years.

**Nankai Trough.** The Nankai accretionary complex off southwestern Japan has been the focus of intense geophysical study over the past two decades; exciting work will continue over the next decades as the program to drill into the subduction thrust seismogenic zone gets underway. This and coordinated ancillary studies will create unprecedented opportunities for developing long-term seafloor and deep borehole observatories for studies of mid-plate and subduction processes. An opportunity exists to coordinate with Japanese scientists, who are planning an RCO called ARENA. There is no question that the geophysical studies and others will benefit greatly from an RCO.

## Turbulent Mixing and Biophysical Interactions

**Convergent boundary of distinct biogeochemical (BGC) provinces.** Additional RCOs are needed where very different communities exist in close proximity because of convergent gyre flows. In particular, an appropriately sited observatory on the east coast of the United States would also incorporate features that are not present in the Northeast Pacific, specifically: (1) western boundary current /shelf interactions and (2) the contrast of reducing (wide) shelves vs the oxidized (narrow) shelves.

**Arctic/Greenland, Iceland, Norwegian (GIN) Seas.** This is an area of deep water formation, driven by surface buoyancy losses. Although the GIN Seas are more accessible than other deep- and bottom-water formation areas (in ice-covered Antarctic regions), it is a hostile observational environment during the wintertime formation period. Because this is perhaps the most important region for determining global climate on all time scales, from interannual through

decadal to millennial (ice age), the ability to make extended measurements of turbulence is of great interest.

**Southern Ocean.** This region is the most extreme turbulent environment in the world ocean. The enormous air-sea fluxes of buoyancy and momentum that occur in the open ocean here are assumed to drive high levels of small-scale turbulence and water-mass modification, however, no direct turbulence measurements have yet been made in this region. Mesoscale fluctuations driven by instabilities of the Antarctic Circumpolar Current produce large horizontal transfers of water properties and biological material. An RCO in the Antarctic, Drake Passage/Scotian Arc region would provide improved observing capabilities in this extreme environment.

## Ecosystem Dynamics

The Ecosystems Dynamics working group considered several alternative locations for RCO installation, concluding that many locations would be suitable, owing to the large expected gain in understanding of ecosystem processes for many, if not most, sites discussed. Features that were considered to be desirable for any location were a large degree of oceanographic and bathymetric diversity, or strong oceanographic boundaries or gradients. The Northeast Pacific is highly suitable owing to its distinct seafloor provinces (shelf, slope, bathyal basin, mid-ocean ridge), and sharp upper ocean gradients. Several alternative locations with nearly equal priority are listed below.

**Western Boundary Current.** An RCO positioned to exploit oceanographic variability that contrasts greatly with the Northeast Pacific would be a strong candidate for a second, or alternate, ecosystem studies RCO. The advantages of the Northeast Pacific region for RCO studies, including its diverse oceanographic and bathymetric variability, is also available elsewhere. For example, a western boundary current location along the eastern United States would

provide a strong, contrasting comparison with the Northeast Pacific, owing to its wide continental shelf, western boundary current, and strong oceanographic gradients.

**Tropical System – Tonga / Kermadec.** This location provides another contrasting set of upper ocean conditions, and includes important hydrothermal vent systems. Comparison of ecosystem patterns and dynamics among various oceanographic settings could reveal important generalities concerning ecosystem function throughout the world ocean.

**Polar Oceans.** RCO installation in the Arctic and Antarctic is desirable, considering the very different polar settings. For example, RCO installation in the GIN Seas provide access to an enclosed polar basin in a region expected to experience an amplified climate warming signal. In contrast, the Drake Passage/Scotia Arc is an open Antarctic Basin with considerably different upper ocean dynamics.

**Other considerations.** A cost-effective means of learning ecosystem science is likely to be from placement of ecosystem observatories in the centers of provinces that have been reasonably well explored and where some processes are reasonably well understood. Such placement affords the power of *a priori* prediction and the rapid learning that results from iteration of observation around ever-refined prediction. Prime candidates would include pelagic subtropical gyre ecosystems sampled in HOT and BATS, the deep-sea benthos of Rockall Trough and the surrounding North Atlantic studied in a succession of European Union explorations and experiments, and the pelagic and benthic ecosystems of the Peruvian upwelling studied over many decades of oceanography (e.g., CUEA ENSO). Each province has its own themes and hypotheses developed from prior studies, but many surround the issues of time variation of nutrient quantity and quality at ranges of trophic levels.

## Ocean, Climate, and Biogeochemical Cycling

### Extensions

*Northeast Pacific.* There was broad interest in extending cables farther out into the Northeast Pacific to be able to compare and contrast observations in the sub-tropical and sub-arctic domains. It may be that moored observatories are the most cost-effective way to reach these sites, but there is an existing communications cable with a junction in the vicinity of Ocean Station P (50°N, 145°W). Certainly, the group thought that there was a great opportunity to link events and changes in the Northeast Pacific RCO region with larger-scale oceanic changes. Specifically, the group wants to monitor the physical gyres (sub-polar and sub-tropical) and their distinct biological domains, including PAPA and ALOHA to capture main environments affected by the Pacific Decadal Oscillation.

### New Sites

*Polar Regions.* Because climate change is expected to be felt first in polar regions, the working group felt that there are interesting challenges and opportunities in both the Southern Ocean and Arctic—from pole to deep convection areas (e.g., Greenland Sea).

*Northwest Atlantic.* The Northwest Atlantic offers opportunities to study several dynamic environments and also a strong contrast with the Northeast Pacific Eastern Boundary Current regime:

- Compare and contrast Eastern Boundary Current region (Northeast Pacific) with a Western Boundary Current region (Gulf Stream)
- Narrow (Northeast Pacific) versus broad shelves
- Newfoundland basin a possibility—comparable geographic features—mixing/topography

# RECOMMENDATIONS

The workshop premise was that funding would be available to support the emplacement of 20 to 30 primary nodes along ~3500 km of seafloor electro-optic cable. The following recommendations are made within this context.

## Plan for a Globally Distributed Network of RCOs

The complexity of the dynamics of ocean and ocean floor processes, that operate at the broadest range of temporal and spatial scales, requires that a network of RCOs be established around the globe during the next several decades. Planning for this network should begin, entraining all interested nations even as the first prototype RCO is being designed and installed.

## Locate the First RCO in the Northeast Pacific

The first RCO should be located in the Northeast Pacific, and should be designed optimally to tackle the broadest range of important, process-oriented research themes that span all ocean science disciplines.

Recommendations concerning sensor types and sites are included in figures shown in the report. Consideration must be given to the wide use of “extension cables” that, when judiciously located away from the primary nodes of the main cable, permit great flexibility to locate sensors over very large areas of the ocean floor. Resource limitations inevitably require the identification of a set of highest-priority sensors and observation sites that should be populated as part of the “first deployment” plan to insure timely production of exciting and important results. This “first deployment” plan, described in the report, includes five

sites and transects to tackle crustal and lithospheric problems and twelve “super sites” to address water column physical, chemical, and biological processes.

## Observe the Full Water Column

Although the earliest genesis of ideas for a cabled observatory on or near the Juan de Fuca Ridge emphasized primarily seafloor measurements, workshop attendees recommend equipping at least 12 primary sites with full water-column moorings connected to the main cable so as to distinguish them from other moorings that may be deployed elsewhere in the global ocean. These moorings would permit multidisciplinary observations from within a few tens of meters of the sea surface down to the ocean floor.

## Use this Unique Infrastructure to Support Only High-Quality Research and Education

It is critical to insure that the resources and capabilities of the new infrastructure are applied to the best and highest priority research and education projects. Workshop attendees recommend that, although the cable system itself will require base-level “facilities funding,” the experiments and the research and education that the infrastructure is used to support should be selected through the traditional competitive proposal process.

## Develop New Sensor Technologies

Workshop attendees recognized that the single most profound challenge to the success of this program lies in the limited availability of proven sensors capable of making the needed measurements on multi-year time scales. This is an issue not only of availability of fund-



ing, but is a problem with the culture of modern-day ocean sciences. Workshop attendees recommend that community leaders and funding agencies consider practical mechanisms to build a new “technology culture” in oceanography that will appropriately facilitate timely progress in this area.

### **Build Linkages Between Observations and Other Key Research Approaches**

Observational strategies must not be implemented in isolation from other complementary research approaches. The modeling community must be entrained from the outset to consider how to optimally locate measurement sites. Similarly, there is a need for multiple ship-based measurements, not only for preliminary site characterization to guide cable and node placement (for both engineering and research purposes), but also to supplement long-term observations with repeat spatial surveys around observation nodes.

### **Maintain a Quality Infrastructure**

The peer review system can be used to maintain quality in the research programs that are supported, but alternate methods will have to be devised to insure the long-term quality of the infrastructure services themselves. From the outset tough oversight and review procedures must be in place to insure that 20 years in the future this infrastructure has evolved in the most productive ways and is providing high-quality and reliable service to its research users in an efficient and economical way.

# SUGGESTED READING

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- NEPTUNE Science White Papers, various authors, <http://www.neptune.washington.edu/pub/documents/documents.html#Anchor-Science-49575>
- New Seafloor Observatory Networks in Support of Ocean Science Research. [www.coreocean.org/deos/Dev2Go.web?id=232087&rnd=491](http://www.coreocean.org/deos/Dev2Go.web?id=232087&rnd=491)
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# APPENDIX 2:

## ENGINEERING OVERVIEW

Alan Chave, Woods Hole Oceanographic Institution and  
Gene Massion, Monterey Bay Aquarium Research Institute

NSF has funded several prototype, single-node cabled observatories (e.g., H2O, MARS). It has also initiated research and development projects to address some of the high-risk elements for an RCO, including power distribution, data communications, precision time distribution, and system engineering.

RCO design must be driven by science requirements, which are derived from use scenarios and interaction with the science community. The science requirements are comprised of a combination of the set of system functions that meet user requirements and a set of bounds on how well these functions must be carried out. The science requirements lead to a set of design specifications and options that must be evaluated to understand how functionality balances with cost and risk. In addition, there are several key technical constraints, including minimizing life-cycle cost (the sum of capital and integrated operations and maintenance costs), providing a sufficiently reliable system to support science within reasonable maintenance cost bounds, supporting an expandable system so that additional nodes can be added within the power and data design limits, and providing for system upgrades as technology and science needs evolve. The whole process is highly interactive and iterative, and is ongoing rather than complete.

The main physical components of an RCO include shore stations to provide power to the seafloor plant and a communications link to the Internet, a fiber optic/power cable connecting the shore stations and wet plant, and a set of seafloor nodes housing data

communications and power electronics as well as the interfaces to sensors and sensor networks. The current design goal is for 20 to 30 seafloor nodes distributed at up to 170 km intervals along ~3500 km of submarine cable. The final node location and topology will be determined by science community input, including that provided by this workshop. Reliability considerations dictate the use of standard submarine telecommunications components where this is feasible and cost-effective. This consideration applies especially to the fiber optic/power cable (including installation practices) and high-voltage terminations.

Key functional components of an RCO include:

1. A power system that delivers high voltage (up to the 10 kV limit of standard submarine telecommunications cable) to a series of seafloor nodes where it is transformed to standard voltages for science use. The performance goal is 100 kW delivered by each of two shore stations, which results in 9 kW peak and 4 kW average science (i.e., in addition to the hotel load for the node) power per node on a 26-node system. Standard user voltages of 48 and 400 V will supply low- and high-power users.
2. A backbone data communications network to link the seafloor nodes to each other and to the shore stations. The performance goal is for an aggregate data rate of 8 Gbits/s on the backbone. Minimum latency to enable tele-operations both from shore and between or within a single node is a key requirement.

3. Dual time distribution systems to provide synchronized time across the observatory. The IP-standard network time protocol (NTP) can provide order 10 milliseconds accuracy time which will meet the needs of most users. An additional 1 microsecond accuracy time signal will also be provided on a system separate from the backbone data network.
4. A science instrument interface that provides standard 10/100BaseT Ethernet, 48/400 VDC power, and precision time at 10 wet-mateable connectors on each science node. An additional node port will support 1000BaseF Ethernet and high voltage power to facilitate extension cables as described below. The node SII system also provides for ground fault and over current monitoring as well as individual port control. SII modules (SIIMs) will be provided which incorporate power conversion (e.g., 5 or 12 VDC), data conversion (e.g., serial to Ethernet), and electrical to optical interfaces or the reverse. The SII and SIIM interfaces with shore systems to provide a “plug and work” environment, support metadata insertion, and other functions as required.
5. A data management and archiving (DMAS) system that provides a set of standard software services for instruments or users to interface to the system. DMAS also provides for data archival with appropriate access controls and storage of metadata with data and to interface users to observatory control functions. The goal is to standardize DMAS services so that the interface to any observatory is seamless.
6. Provision for up to 100 km extension cables with a range of capabilities and costs. These will facilitate taking many of the capabilities of a node directly to the points where science needs are strongest by providing a secondary node. The full range of feasible extension cables is under evaluation. However, it should be noted that extension cables and secondary nodes will inevitably be less reliable than

the main RCO system. This potential limitation will have to be factored into operations and maintenance planning.

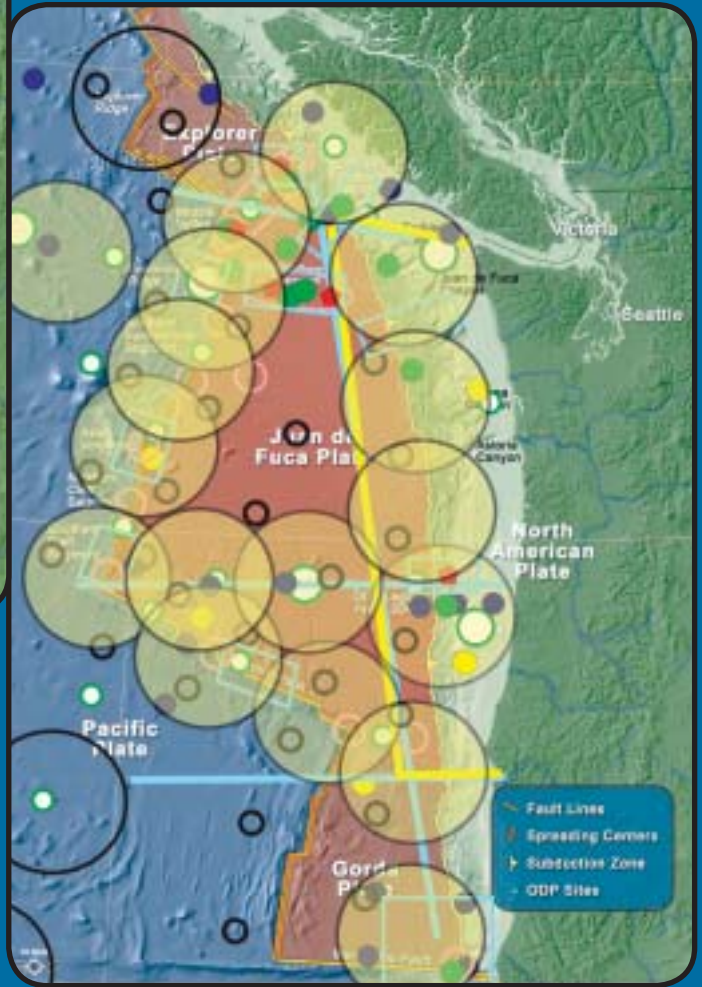
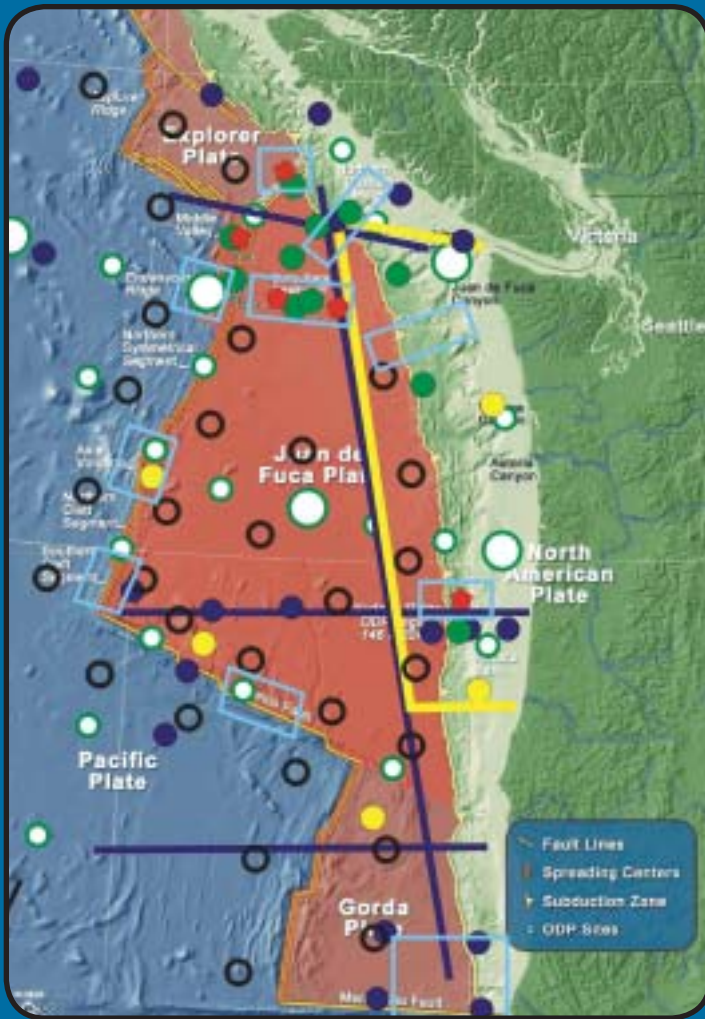
At this time, very capable power and data communication subsystems are at the preliminary design stage where high-risk issues have been addressed and prototyping can be initiated. A complete instrument-to-user system design has been conceptualized. Most of the rest of the subsystems are at the concept stage. The MARS testbed is scheduled for installation in mid-2005 to test the key components of an RCO.

There is a real need for community review of the design to refine the requirements. This is probably best carried out through more extensive use scenarios and interaction of observatory engineers with the science community.

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