NEPTUNE

Science Planning for the NEPTUNE Regional Cabled Observatory in the Northeast Pacific Ocean

Report of the NEPTUNE Pacific Northwest Workshop

Portland State University
Portland, Oregon
April 23–24, 2003

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Acknowledgements

The Organizing Committee would like to thank the staff at Portland State University for providing an excellent venue for the workshop. Portland State graduate students Paula Aguiar, Joost Hoek, and Antoine Pagé helped with the logistics. Funding for the workshop was provided by multiple sources: National Oceanographic Partnership Program (NOPP), University of Washington, Oregon State University, and the NEPTUNE Canada office supported by the University of Victoria.

The leaders of the five working groups contributed their time to writing the reports of their respective groups; this community service is much appreciated. Nancy Penrose, Outreach Coordinator for the NEPTUNE Program, and Brian Rasmussen, APL-UW Publications Manager, edited the report.

Navigating this Report

The *Summary and Recommendations* section provides a concise view of NEPTUNE's capabilities, syntheses of the workshop's science working group reports, and the overall recommendations that emerged from the meeting. The *Background* section expands upon the emergence and importance of regional cabled ocean observatories such as NEPTUNE, the framework for the National Science Foundation's Ocean Observatories Initiative, and the history and status of the NEPTUNE Program. The structure of the Pacific Northwest Workshop is described, followed by the full *Science Working Group Reports*: Fisheries and Marine Mammals, Ocean Dynamics, Seismology and Geodynamics, Fluid Fluxes and Geophysical Processes in the Sediments and Crust, and Ecosystems and the Carbon Cycle. Appendices include the workshop agenda, charge to participants, and participant list, including affiliations and email addresses.

Preferred Citation

Howe, B. M., A. M. Baptista, J. A. Barth, E. E. Davis, J. K. Horne, S. K. Juniper, R. M. Letelier, S. E. Moore, J. D. Parsons, D. R. Toomey, A. M. Tréhu, M. E. Torres, and N. L. Penrose, 2003: Science Planning for the NEPTUNE Regional Cabled Observatory in the Northeast Pacific Ocean: *Report of the NEPTUNE Pacific Northwest Workshop*, Portland State University, Portland, Oregon, 72 pp. *http://www.neptune.washington.edu/documents*

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SUMMARY AND RECOMMENDATIONS

The NEPTUNE network of instrumented fiber-optic/power cable is likely to be the first regional-scale cabled ocean observatory. Spatially associated with the Juan de Fuca tectonic plate, NEPTUNE will enable the in-depth study and decadal time-series observations of regional oceanography, including biogeochemical cycles, fisheries and climate forcing, ocean dynamics, life in extreme environments, and plate-tectonic processes, to name but a few topics. Networks of fiber-optic cables will deliver high-bandwidth telecommunication capabilities and considerable electrical power to hundreds of instruments and many autonomous vehicles distributed over thousands of square kilometers of seafloor and within the overlying volume of ocean. Via the Internet, sensor networks and interactive experiments will be easily accessible to researchers, educators, students, policy makers, and the public around the globe (Figure 1).

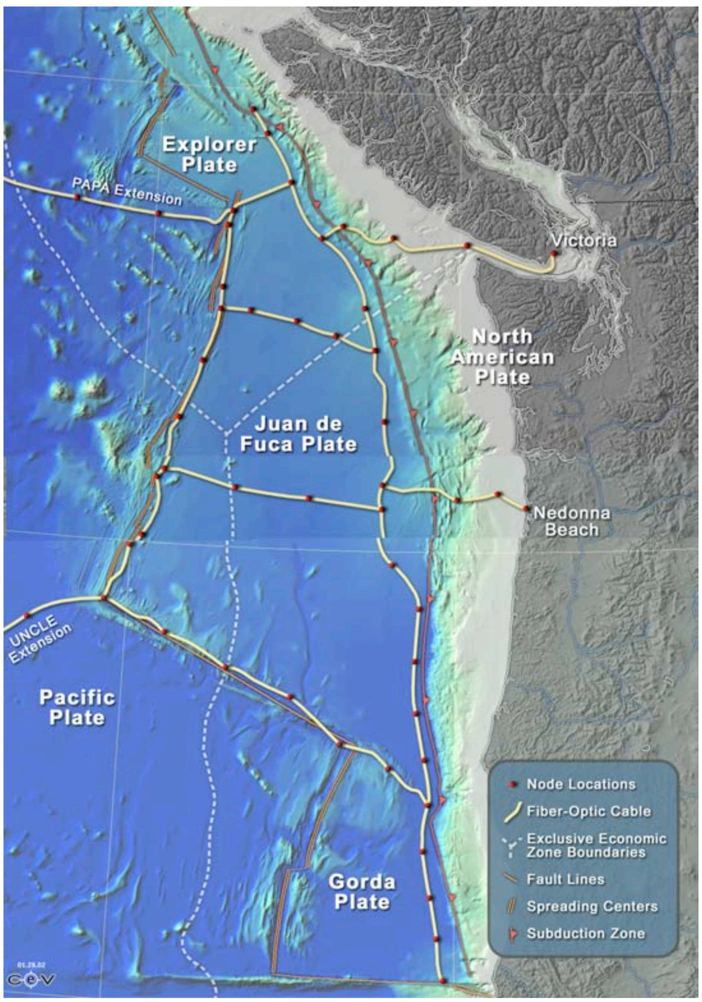

Figure 1: NEPTUNE cable system map. Extensive sensor networks and mobile platforms will extend the reach beyond each primary node into the entire three dimensional volume of interest.

The NEPTUNE infrastructure may be installed as early as 2007. As of mid 2003, several components of NEPTUNE have been funded, including development of the communications and power systems, a program office, and system engineering. Both shallow- and deep-water test-bed systems are funded and will be installed in the near future: the Victoria Network Under the Sea (VENUS) in Saanich Inlet and the straits of Georgia and Juan de Fuca (2004–2005), and the Monterey Accelerated Research System (MARS) in Monterey Canyon (2005). Canadian funding for the northern portion of the NEPTUNE network is expected to be in place by autumn 2003. U.S. funding will be sought through the National Science Foundation's Ocean Observatories Initiative (OOI). The OOI has three primary elements: 1) a global network of relocatable deep-sea buoys, 2) a regional-scale cabled observatory, and 3) an expanded network of coastal observatories. Also included are components such as project management, data dissemination and archiving, and education and public-outreach activities.

Building on these foundations and working in parallel with ongoing funding efforts, the oceanographic community is in the process of characterizing the outstanding science questions and associated experimental systems so that the design for NEPTUNE can proceed with confidence.

A workshop was convened in April 2003 in Portland, Oregon, as a step toward addressing these critical challenges and as one of a series of observatory science planning workshops in North America. Attendees at the Portland workshop represented a broad spectrum of researchers and groups and worked to define the most innovative "lead-off" community experiments and instrumentation. Their approach included reviewing earlier work done as part of the NEPTUNE U.S. and Canadian feasibility studies (NEPTUNE Phase 1 Partners, 2000; Canadian NEPTUNE Management Board, 2000). These experiments, and others under consideration by the community, will generate exceptional results in the first few years of network operation and beyond.

The research scenarios discussed at the Portland workshop will help design a NEPTUNE system that will be capable of integrating new experiments throughout the lifetime of the infrastructure. The research will also guide the generation of high-quality decadal time-series observations to answer fundamental questions of interacting Earth system processes.

The workshop had the following three primary goals:

- Inform the regional community of the remarkable opportunities provided by NEPTUNE as a part of the evolving OOI infrastructure
- Maximize the opportunities and linkages provided by NEPTUNE and its test beds as a regional *and* coastal observatory
- Entrain a broad spectrum of researchers and forge teams to plan creative research that will fully capitalize on NEPTUNE's capabilities

The workshop focused on establishing the key science experiments and technology developments that will ensure success of the system from the outset. Thematic working groups and plenary sessions developed outlines of individual and community experiments, preferred node locations, instrument packages, and paths to implementation.

Five working groups were formed around broad science themes represented by attendees:

- Fisheries and Marine Mammals
- Ocean Dynamics
- Seismology and Geodynamics
- Fluid Fluxes and Geophysical Processes in the Sediments and Crust
- Ecosystems and the Carbon Cycle

The number of participants in each group ranged from 11 to 19, with a total of 83 people attending the workshop. Reports from each group were collated, edited, and reviewed by participants to generate this comprehensive report.

Role of NEPTUNE

We expect that the expansion of the spatial and temporal observational scales made possible by NEPTUNE will result in an expansion of the conceptual framework for much of the science that we do. NEPTUNE will provide the setting for new discoveries and the development of new hypotheses and conceptual models of causal relationships in the marine environment. NEPTUNE offers considerable potential for accelerating the process by which field observations lead to concept genesis, followed by the development of new analytical and numerical models, and finally quantitative testing in the field.

NEPTUNE's capabilities will enable the scientific community to accomplish the following:

- Acquire continuous long-term, broad-bandwidth data under all weather conditions to characterize periodic (e.g., tidal), episodic (e.g., volcanic), and low-frequency (e.g., Pacific Decadal Oscillation and plate deformation) signals

- Obtain high-precision measurements coordinated in time and space, i.e., a coherent sampling array
- Provide a well-characterized environment in which process studies can be conducted
- Integrate data and information across disciplines, with multi-variate data sets to explore and test causal relationships
- Develop and verify models integrating physics, chemistry, geology, and biology
- Use power in new and creative ways (e.g., robotics and pumping)
- Use real-time communications for adaptive sampling and remote control

Science Themes

All of the working groups agreed that it is imperative to have coverage on the continental margin (i.e., shelf and slope) at multiple locations (usually in cross-margin lines) and at the same time have, at a minimum, sparse full plate coverage.

All the water-column related groups called for multiple east-west lines across the whole domain, with some additional north-south resolution (along the base of the slope and along the ridge). Some locations are tied to geographical features; some only generally so (e.g., a "picket fence"), and some specific (e.g., the Columbia River). Mobile platforms are essential to fill in between fixed sensors. Many of the geographical locations for the science themes overlapped.

High-resolution seismology and geodynamics, fluids, and some ecosystems sites are in most cases tied to specific geographical locations spread over the entire domain and require water-column observations. Many of these locations were of interest to the water column groups.

Figure 2 is a compilation of all of the groups' proposed experimental sites. This map represents one of the first steps in defining where the interesting science is to be done within NEPTUNE. Such definition will be the focus of continuing intense scrutiny as the planning process proceeds.

Fisheries and Marine Mammals

Key science issues

The dominant themes for marine-mammal studies included seasonal distribution, habitat associations, ocean dynamics, and anthropogenic influences. For fisheries, themes included spatial and temporal fluxes of biomass, resource assessment with extended temporal sampling, distribution variability in space and time, and habitat use. Using NEPTUNE to quantify and understand aquatic life cycles will be essential.

The role of NEPTUNE

This group is primarily concerned with "apex" predators located on the continental shelf (i.e., fish and mammals), with predator and prey moving independently of the water (i.e., nekton), and with the movement of organic carbon and energy, i.e., a "top down" approach. This approach complements the oceanographic view of carbon and energy moving "bottom up" from water masses and nutrients to phytoplankton, fish, and cetaceans. Combining the two perspectives will provide a synergistic and more complete picture than each separately.

Community experiments

1. Biological-physical coupling. What roles do dynamic features play in the trophic organization, dynamics, and distribution of aquatic organisms? Dynamic water motion with upwelling and sharp fronts and tied to topography occurs at many locations in the NEPTUNE domain. Sampling would be used to assess biological constituents, collect

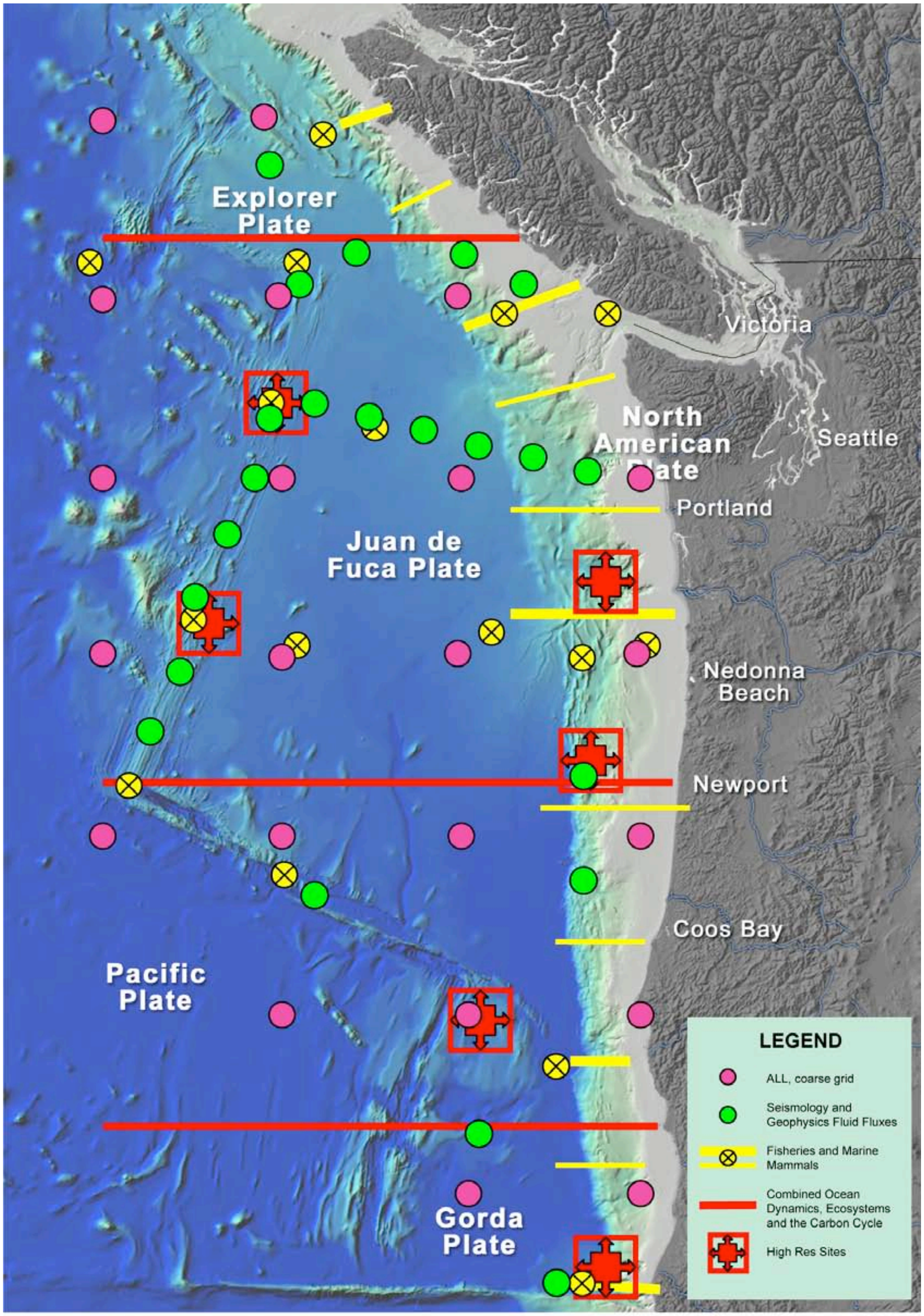

Figure 2: This figure illustrates the synergies of location among the different working groups. This composite map is conceptual and is not intended to reflect precise locations. The magenta points located on the coarse grid are intended to indicate the broad-scale coverage desired by all the groups.

samples for trophic transfer studies, and for behavioral observations including predator-prey interactions. Phased implementation could start with a cross-shelf/slope line of fixed and mobile sensors at southern Vancouver Island, with successive lines to the south at Heceta Bank and Cape Blanco.

2. *Fisheries and marine-mammal long-term observations*. What are the movements and predation of nekton within the monitored volume and their relationship to environmental conditions during those movements? Specific studies would include distribution and migration patterns in relation to environmental variability and climate change, trophic dynamics, and the effect of marine reserves on distribution and recruitment to aquatic populations. A plate-scale monitoring system is appropriate for both cetaceans and pelagic fish; it could have fixed and mobile sensing platforms.

Ocean Dynamics

Key science issues

Six major research themes were identified: flow interaction with (rough) topography, eastern boundary currents and water-mass properties, shelf/slope ecosystem dynamics, episodic and short-scale events and adaptive sampling, air-sea interactions, and tsunami generation and propagation. The group chose to expand upon the first two for their experiment scenarios.

The role of NEPTUNE

The long-term, all-weather observing capability will allow the capture of intermittent and episodic events that often are dynamically and ecologically very significant, as well as the interannual and interdecadal variability. Two-way communication and adequate power will permit adaptive sampling of small-scale features.

Community experiments

1. *Flow interaction with (rough) topography*. The small-scale interaction of flow with (rough), sloping topography is rarely resolved in numerical or observational work, yet it is likely to exert a strong influence on the conversion of energy into turbulence with global implications. Some of the scientific questions of interest are: What is the character and origin of rectified flow near the boundary? What is the relationship between barotropic and baroclinic tides and mixing? How does low-frequency flow interact with and modulate boundary-layer processes and mixing? What is the influence of mixing on mesoscale circulation and property distribution? An observational array would consist of closely spaced moorings between 200 m and 2000 m water depth. Using a phased approach a sequence of experiments with high spatial and temporal resolution observing arrays would be established every few years and left in place to accumulate data on long-term variability in each locale (e.g., slope, canyons, ridges, valleys).

2. *Eastern boundary currents and water-mass properties*. The mean currents in the NEPTUNE area transport heat, salt, nutrients, plankton, and invertebrate larvae north and south and are crucial to the ecosystem response in this region. A long-term, large-scale sustained array of instruments made possible by NEPTUNE will lead to breakthroughs in our understanding of the physical, chemical, and biological processes influenced by eastern boundary current circulation. Science questions include: What are the meridional transports of heat, salt, and biogeochemical properties and their time variability? What is the relation between meridional transport and the large-scale forcing? How does the depth of the nutricline and its concentration of macronutrients affect coastal primary productivity? What influences the time variability of the bifurcation of the North Pacific Current as it runs into the west coast? Several east-west measurement lines spanning the NEPTUNE area are required for this purpose.

Seismology and Geodynamics

Key science issues

The participants of this working group agreed with and extended extensive earlier work (NEPTUNE Science White Paper #3; NEPTUNE Feasibility Study, 2000, *www.neptune.washington.edu/pub/documents/documents.html*). Science issues (with associated questions) in this reference include the following: The seismic potential of the Cascadia subduction zone; mechanisms of plate deformation and interactions; structure and evolution of the lithosphere/asthenosphere system, and earthquakes and geological processes at plate boundaries. The group at this workshop addressed two questions: How to best synthesize the scientific motivations in the referenced white paper so that it was clear that each was a part of an integrated effort to understand the dynamics of an ocean plate? What additional science questions are raised by recent discoveries? For example, recent results suggesting hydrologic responses to remote tectonic activity provide compelling evidence for the need for long-term, plate-wide data acquisition.

Role of NEPTUNE

Understanding the life cycle of an oceanic plate will require a coherent array observing scales from ~ 1 to 1000 km over decades; NEPTUNE will provide this capability.

Community experiments

1. *A plate-wide seismic and geodetic observatory*. It is necessary to monitor the entire plate in order to detect interactions among plate boundaries and strain propagation from the boundaries to the interior of the plate. The sampling array concept in the Feasibility Study science white paper needs a substantial modeling effort and cost analysis to optimize the scientific return for the investment.

2. *Local experiments to simultaneously monitor seismic activity, crustal deformation, and hydrologic phenomena.* Instrument arrays will have apertures of a few kilometers and will be needed along each of the types of plate boundaries (e.g., ridge, transform, subduction). These multidisciplinary experiments will include biogeochemical sensors as well as geophysical sensors. Examples are discussed below and in the full report of the *Fluid Fluxes and Geophysical Processes in the Sediments and Crust* group.

Fluid Fluxes and Geophysical Processes in the Sediments and Crust

Key science issues

Hydrologic systems in the ocean crust and sediments play key roles in influencing rock alteration, mineral formation, and hydrocarbon migration. Mass, heat, and chemical exchange between the oceans and the subseafloor influence the properties of the rocks and the microbial populations we now know inhabit them. Hydrologic processes and their consequences are highly linked; to understand one process requires understanding the others. For example, earthquakes change the regional state of stress that in turn influences permeability, fluid pressure, and fluid flow, which in turn influence such things as mineralization and nutrient supply to microbes. Feedback among these processes is ubiquitous; mineralization, rock alteration, and gas hydrates generated by fluid flow change the mechanical and hydrologic properties, often to the point of seismogenic failure. Understanding these linkages is a primary goal for the next few decades. Specific questions include the following: What is the magnitude, nature, and variability of permeability and storage properties, as a function of fluid pressure and spatial and temporal scale? What are the relationships between permeability and other parameters such as fluid chemistry, microecology, and seismic properties? What is the magnitude of global fluxes, size or reservoirs, residence times, and response to transient forcing? What is the response of the biosphere to the variability of the fluid flow? What is the interrelationship of these hydrologic processes with lithospheric cycling, magmatism, seismicity, and formation of gas hydrates?

The role of NEPTUNE

The Juan de Fuca plate provides an ideal location for studying hydrologic phenomena that are both local and regional in extent, with signals coherent over spatial scales of hundreds of kilometers and temporal scales of seconds to decades. The multidisciplinary approach encouraged by coordinated experiments is exceedingly important for the study of complex bio-hydrogeologic phenomena that are inextricably linked to geodynamic, oceanographic, and seismic processes.

Community experiments

Seventeen sites were identified as specific possible locations for detailed study and grouped into five categories: sedimented and non-sedimented ridge crests, ridge flank, accretionary prism, transform faults (earthquakes on a regular basis), and intra-plate deformation. In most cases, scientific and experimental strategies are common to all locations and can be described in a generic way. A bottom-to-top approach must be employed to allow quantification of time-dependent state, properties, and fluxes in a comprehensive strategy that includes the water column, the seafloor, the transfer zone, and the reservoir. The use of boreholes [e.g., provided by the Ocean Drilling Program (ODP) and the Integrated Ocean Drilling Program (IODP)] is necessary. This generic experiment approach is refined for three cases:

1. *Ridge-flank scenario.* Monitor coupled reservoir specific processes with seafloor observations to establish the variability driven by various forcing mechanisms at various spatial and temporal scales. This will allow us to link hydrogeology, microbiology, seismic, and tracer (natural and artificial) experiments to address fundamental questions in the most extensive aquifer on Earth.

2. *Gas-hydrate provinces*. As for the ridge-flank scenario, the variability driven by different forcing must be monitored. Tomography between boreholes will image the 3D volume over time. Within boreholes, sampling will be required in the generation zone, at the base of the gas hydrate stability zone, and at high permeability horizons.

3. *Ridge axis*. In this case, the ocean above the seafloor will have to be closely monitored to determine fluxes and map plumes. Drilling in young crust will be challenging.

Ecosystems and the Carbon Cycle

Key science issues

Science questions were partitioned into two categories, Deep-Sea Ecology and Water-Column Processes. Within Deep-Sea Ecology questions were: What determines faunal diversity on the deep-sea floor? How does particulate organic matter (POM) distribution affect the fauna? How do deep-sea ecosystems respond to perturbations of different magnitude? What are the stability characteristics of hydrothermal vent and cold seep environments? How do hydrothermal systems influence neighboring environments? For Water-Column Processes (including the surface ocean and the mesopelagic zone), the questions were: What is the role of coastal upwelling systems in the control of carbon fluxes across the air/sea interface? How do carbon fluxes and elemental ratios change with ecosystem structure? What is the fate of the organic matter produced by upwelling systems? How do oceanic and climate regime changes affect ecosystem structure and elemental fluxes? What is the role of the meso-pelagic assemblage in the transport of organic matter to the benthos? And, how does meso-pelagic microbial activity vary in time and space?

Role of NEPTUNE

The broad coverage of the NEPTUNE instrument network will permit the rapid quantitative assessment of ecosystem states and provide the power to predict future states, thus creating great potential for conceptual and numerical modeling and testing ecosystem stability and resilience.

Community experiments

1. *Upper water-column variability and its effect on the benthos.* How does the spatial and temporal variability of upper water-column processes affect deep-sea benthic community structure and function? The spatial and temporal variability of the surface production and food supply and the Lagrangian trajectory of organic matter in the water column are required. This will necessitate the observation of phytoplankton biomass from space, physical and chemical (nutrients) structure, organic matter fluxes and transformations through the water column and at the seafloor.

2. *Benthic ecosystem structure.* A prerequisite to answer the forgoing question is to first understand the spatial and temporal variability of benthic ecosystem structure over large areas subject to a broad range of environmental conditions. This will require fixed and mobile imaging as well as *in situ* sampling for ground truth. Understanding the functionality of benthic communities (e.g., respiration, reproduction, and bioturbation) is just as important; this will require intensive studies at key representative locations. Models will play a key role in understanding the coupling of the variability of the upper water column with the benthos.

Basic Sensor Suites

The working groups recommended that suites of basic sensors be included at all primary nodes to provide baseline, broad coverage of fundamental variables. To the extent possible, these instruments should possess the following characteristics: be long-lived, require little or no *in situ* calibration, measure unaliased integral quantities more representative of larger scales, and be useful for multiple disciplines. The first requirement probably calls for bottom-mounted instruments with few or no moving parts. Candidate sensors included broadband pressure, temperature, salinity (conductivity), dissolved oxygen, optical transmission and backscatter; fluorometer, broadband acoustic hydrophones and transceivers (ambient sound, inverted echosounder, acoustic profiler, fish sonar, geodesy, navigation, and communications); electrometer (for barotropic velocity), acoustic Doppler current profiler, seismometer, geophone; broadband formation pressure, seep or vent-flow monitor, continuous fluid sampler, and sediment trap. Video imagery was also requested. It was recognized that there may be different combinations of these and other sensors that may constitute a “basic suite” depending on the particular location; there are clearly many other sensors that will be used for more specific community and principal investigator (PI) experiments.

Synergies

The science working group reports list numerous possibilities for synergy with other research projects, e.g., GLOBEC and RISE for fisheries and marine mammals; ECOHAB and CORIE for ocean dynamics; EARTHSCOPE PBO and ANSS for seismology and geodynamics; IODP and RIDGE2000 for fluid fluxes and geophysical processes in the crust; and the successor program to the Joint Ocean Global Flux Study (JGOFS) for ecosystems and carbon studies.

Internal, cross-disciplinary synergies abound and indeed exemplify the full potential of a regional-scale ocean observatory. Representative synergies are as follows:

- Integrated linkages between physical, chemical, geological, and biological investigators to develop a unified understanding of ecosystems from the microbial level to the apex predator level
- Relationships between organic carbon produced in hydrothermal vents and water-column microbial assemblages
- Coordination of hydrologic experiments with the design of seismometer arrays and water-column observations
- Studies of bottom boundary-layer processes and water-column transport in association with fluid-flux groups

Education and Outreach

Innovations offered by regional observatories such as NEPTUNE will give users the ability to enter, sense, and interact with the total ocean-Earth environment. Via the Internet and other innovative media, students and the general public will be offered unparalleled opportunities to interact with scientists and their data in settings that will range from aquariums, museums, science centers, and schools to living rooms and libraries anywhere on the globe. NEPTUNE's real-time video and data streams and the products derived from them open a wide range of possibilities for education and outreach.

Although the focus of this workshop was on science planning, working groups were asked to address education and outreach opportunities in their fields. There will be possibilities to capitalize on the appeal of "charismatic megafauna" such as humpback and killer whales, and on the broad interest in migratory fish stocks such as salmon. The public's interest in hazardous earthquakes and volcanic eruptions is considerable and the potential for linking these more dramatic geologic events to hydrogeologic and biologic activity will certainly have a broad appeal. Fluid-flux processes often have short-term periodicities that lend themselves well to real-time displays.

Workshop Recommendations

Location and coverage. The regional coverage as proposed by NEPTUNE is necessary to accomplish the science outlined here and elsewhere. This regional scale is required to cover the full spectrum of plate-scale processes, including oceanographic processes from the shelf out on to the abyssal plain and beyond. The NEPTUNE array must explicitly cover the continental margin (slope and shelf) in order to study important physical and biogeochemical processes bridging the coastal and pelagic environments.

Basic sampling. Sampling of the entire volume of interest is required (e.g., from the water column to the seafloor and below). At a minimum, a widely distributed suite of basic sensors on every NEPTUNE node will consist of bottom-mounted oceanographic sensors including physical, acoustics, bio-optics, seismic and geodetic, and other sensors (e.g., video).

Funding of the base network. While we expect that the community will raise funds successfully to install instrumentation and conduct data analysis for focused, process-oriented research, the broad-based backbone of sensors needed to achieve plate-wide coverage at the broadest scales should be considered as an integral part of the core NEPTUNE facility.

Begin sensor array designs now. Begin modeling in all science areas of the NEPTUNE region immediately to assess array design and field experiment planning (e.g., perform observing system simulation experiments). A detailed analysis of instrumentation needs and the tradeoff between different possible instrument configurations is not a trivial undertaking and cannot be accomplished in a few days in a workshop setting. Rather, it will require realistic, quantitative modeling of competing scenarios. Funding must be available soon to support multiple modeling efforts to define the minimum sensor configurations required to achieve the scientific objectives and to support field surveys and pilot projects.

Construct scenario cost models. To define the proper balance between the critical elements of the NEPTUNE program, various scenarios must be considered quantitatively and priorities need to be set. Future working groups (set up to address a specific experiment) must work with more quantitative data pertaining to the technological capabilities of instruments and to their costs. Armed with such data, teams of scientists can make quantitative estimates, given cost-benefit analyses, of the minimum configuration of a plate-scale network and a schedule for its phased implementation.

Develop and implement new strategies on data management. Because of the importance data management will have in NEPTUNE, defining and supporting the data management system must be considered to be a core NEPTUNE function.

Funding situation. The National Science Foundation should clarify to the community how the Foundation intends to plan and fund regional observatory science, including the integration of workshop results, experiment design, core instrumentation, community experiments, principal-investigator experiments, and support of sensor network infrastructure beyond the base network.

BACKGROUND

The Emergence of Regional Cabled Observatories

For more than a century, oceanographers have used ship-based expeditionary studies as their primary tool for mapping, observing, and sampling the oceans. This approach has led to discovering the importance of a wide range of physical, chemical, biological, and geological processes. One of the results has been that our modern societies now recognize their increasing dependence on the oceans and the value of understanding natural processes at a variety of temporal and spatial scales. In parallel, dramatic technological advancements have occurred in sensor technologies, robotic systems, high-speed communication, nanotechnology, and rapidly escalating capabilities to computationally simulate our natural world. Societal needs, combined with technological advances, have compelled oceanographers to move beyond traditional expeditionary modes toward a new paradigm: sustained, *in situ* observations of the oceans, the seafloor, and the Earth beneath.

These next-generation facilities will use networks of fiber-optic cables to deliver high-bandwidth telecommunication capabilities and considerable electrical power to thousands of instruments and many autonomous vehicles distributed over thousands of square kilometers of seafloor and within the overlying volume of ocean. Regional cabled ocean observatories offer an example of this new paradigm, and interest in such observatories has grown worldwide within the past decade.

The regional-scale observatory concept is based on the premise that many globally significant planetary phenomena operate at or below the regional scale. The NEPTUNE regional-scale observatory will be spatially associated with the Juan de Fuca tectonic plate, which encompasses all the major types of plate boundaries. Thorough 4-D examination of the full spectrum of Earth and ocean processes associated with at least one tectonic plate/mesoscale system will generate major new insights into all such systems.

The ultimate vision of any regional cabled observatory is to enable routine, real-time interaction between an extensive community of land-based researchers and a set of diverse *in situ* instrumental sensor arrays. These arrays will be comprised of remotely operated, user-generated experiments that will detect and quantify variability over a wide range of spatial and temporal scales for a broad range of ocean and Earth processes. NEPTUNE's 3,000-km, heavily instrumented network of fiber-optic/power cable is likely to be the first of many regional-scale facilities.

The Ocean Observatories Initiative

In recent years and with support from several community-based reports (NRC, 2000, 2003; Brewer and Moore, 2001; Jahnke et al., 2002; Glenn and Dickey, 2003) momentum has built toward a focused investment in operating routinely and remotely in the ocean space. The response within the National Science Foundation's Ocean Sciences Division has been to develop the Ocean Observatories Initiative (OOI). The Dynamics of Earth and Ocean Systems (DEOS) committee, a planning effort by the academic research community and the NSF to lay the groundwork for a network of ocean observatories, has overseen many of the community activities. As of February 2003, the OOI was formally listed as a priority new start for Fiscal Year 2006 at a level of ~$208 million (over 5 years) within the Fiscal Year 2004 President's budget request to Congress (*www.nsf.gov/home/budget/start.htm*).

This Initiative will implement the following program elements: 1) a regional cabled observatory spanning multiple geological and oceanographic features and processes;

2) relocatable deep-sea buoys 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 network of coastal observatories. The OOI also includes components such as project management, data dissemination and archiving, and education and public outreach activities. Plans call for OOI sites to be managed and operated by the Ocean Research Interactive Observatory Networks (ORION) program established by the NSF. ORION activities will be consistent and synergistic with the goals of the operationally oriented National Integrated Ocean Observing System (IOOS) effort and the Global Ocean Observing System (GOOS).

A regional observatory has an important role to play in integrating the components of the OOI by seamlessly spanning the coastal to global components with a large and adaptable footprint. To achieve this integration, regional observatories must accomplish the following:

- Span coastal to global systems, thereby linking all processes
- Document variability over many scales of space and time
- Expand surface (satellite) and sparse point (mooring) coverage to an entire volume
- Archive data so as to enable modeling and data assimilation
- Maximize the scientific return from the investment in a regional facility
- Maintain optimal flexibility and expandability to operate for many decades

Any effectively operated regional cabled observatory will employ data archiving strategies that enhance modeling and data assimilation in real-time. Crucial data and metadata will be archived and accessible to enable later generations of ocean scientists to examine unprecedented comprehensive time-series information at nearly basin-scale levels of inquiry. An important criterion in selecting the location of a regional cabled observatory is the requirement to maximize the scientific return on the initial investment by placing it where the best and most diverse scientific investigations can be conducted.

Producing the first regional observatory is a substantial challenge for oceanographers in part because there is no pre-existing blueprint. The complexity and novelty of observatory implementation poses different planning, engineering, and management challenges than continued use of the more familiar open-ocean moored buoys or coastal installations, or the more traditional ship-based expeditionary approach. Regardless of the specific locality chosen for the first regional observatory, fostering the capability to implement a well-designed and tested observatory is critical to the health of the U.S. and international oceanographic community.

NEPTUNE

Several countries are interested in pursuing regional cabled observatory efforts including Japan (ARENA), the European Union (ESONET), and Canada and the United States (NEPTUNE). Geographical areas of interest to be covered by such an observatory should be guided by science objectives and not be limited by national borders. Within the U.S. and Canada, the NEPTUNE group formed a co-operative planning team in 2000 to build an observatory in the northeast Pacific. The partnership is working to create a 3,000-km network of fiber-optic/power cables that will host approximately 30 sensor network observatories at nodes along the cable. (Figure 1) To be spatially associated with the 200,000 km^2 Juan de Fuca tectonic plate, the NEPTUNE infrastructure will have a design lifetime of 25 years. The infrastructure will be designed to maintain technical and spatial flexibility and expandability for many decades. Installation is planned for 2007 with shore stations in Oregon and British Columbia.

Institutions that form the NEPTUNE construction partnership are the University of Washington (UW), the University of Victoria (UVic), the Woods Hole Oceanographic Institution

(WHOI), Canada's Institute for Pacific Ocean Science and Technology (IPOST), Caltech's Jet Propulsion Laboratory (JPL), and the Monterey Bay Aquarium Research Institute (MBARI). This consortium will design, test, and build the network on behalf of a wide community of scientists and educators; NEPTUNE will serve as a community resource, much like a research vessel is an observational platform open to a wide range of users.

Why the Northeast Pacific?

The Juan de Fuca plate in the northeast Pacific Ocean was chosen for the NEPTUNE study site to attract the broadest possible user base to this oceanographic research platform and to minimize cost. The footprint encompasses a broad spectrum of plate tectonic processes including many important water-column, sedimentary, and biological phenomena that occur throughout the global ocean. The area is small enough to be instrumented, is adjacent to a continental margin, and is close to politically stable countries committed to supporting the ocean observatory effort. The well-developed ports and other infrastructure within the U.S. and Canada will facilitate initial cable laying, reliable shore landings, and operations and maintenance.

Feasibility

Discussions of NEPTUNE-type concepts date back to the 1980s. Momentum for the present effort began to build in 1997 at the International Workshop on Scientific Use of Submarine Cables held in Okinawa, Japan, and when the DEOS effort, described earlier, was formalized.

NEPTUNE Feasibility Studies (NEPTUNE Phase 1 Partners, 2000; Canadian NEPTUNE Management Board, 2000), completed in 2000 by both the U.S. and Canada concluded that the Program is scientifically desirable, technically feasible, and financially reasonable. The U.S. study was supported by the National Oceanographic Partnership Program and the NEPTUNE Partners; funding for the Canadian study came through IPOST.

Each NEPTUNE node will host and power many scientific instruments widely distributed on the surrounding seafloor, in seafloor boreholes, and buoyed through the water column. Remotely operated and autonomous vehicles will reside at depth, recharge at observatories, and respond to shore-based users. This combination will permit complete sampling of the three dimensional volume of interest. Continuous near-real-time multidisciplinary measurement series will extend over decades. Free from the limitations of battery life, ship schedules and accommodations, bad weather and delayed access to data, scientists will monitor their deep-sea experiments in real time on the Internet, and routinely command instruments to respond to storms, plankton blooms, earthquakes, eruptions, slope slides and other events. Scientists will be able to pose entirely new sets of questions and experiments to understand complex, interacting Earth System processes such as the structure and seismic behavior of the ocean crust; dynamics of hot and cold fluids and gas hydrates in the upper ocean crust and overlying sediments; ocean climate change and its effect on the ocean biota at all depths; and the barely known deep-sea ecosystem dynamics and biodiversity.

Estimated Cost and Funding

The network and first arrays of experiments are estimated to cost approximately $250 million to design, build, and operate for the first five years. Operating costs are estimated at $10–15 million/year. By comparison, an ice-capable research vessel such as the *USCGC Healy*, which was commissioned in 1999, cost approximately $380 million to design, build, and outfit. Operating, maintenance, and support costs for the *Healy* are approximately $17 million/year.

As of mid 2003, several components of NEPTUNE have been funded, including development of the communications and power systems, a program office, system engineering, and two test beds. A desktop study of the NEPTUNE cable route was completed in 2002 *(www.neptune.washington.edu/pub/documents/documents.html).* The University of Victoria is close to finalizing the terms of a significant award (CAN$61M) from the Canada Foundation for Innovation and the British Columbia Knowledge Development Fund that will go toward constructing the portion of the network that lies in Canadian waters. NEPTUNE anticipates responding to the NSF OOI request for proposals to build the cabled infrastructure in the 2005–2006 time frame, at a level of approximately US$120M.

Test Beds

The two test beds under construction—the Monterey Bay Accelerated Research System (MARS) (*www.mbari.org/mars*) and Canada's Victoria Experimental Network Under the Sea (VENUS) (*www.venus.uvic.ca*)—are key components of the regional observatory development effort and are integral parts of the NEPTUNE program.

The main goals of these test beds are twofold: 1) mitigate engineering risk by early and realistic testing of key infrastructure components prior to deployment of the full regional cabled observatory, and 2) provide facilities for early validation of science experiments and associated sensors so that the regional cabled observatory will be used effectively for cutting-edge science once it is operational. Major additional benefits of optimizing the test-bed scenario include the opportunity to explore five elements of importance to the community: 1) interactions between facility construction personnel and the scientific user community; 2) development of prototype outreach education components; 3) refinement of the organizational and managerial functions required to produce a final major product in the form of a regional cabled observatory; 4) estimation of actual costs associated with operation of a cabled observatory; and 5) accessible test beds for new instrumentation intended for observatory development.

The VENUS system will consist of 70 km of powered, fiber-optic cable deployed in three locations in coastal southern British Columbia waters: Saanich Inlet (2004), Strait of Georgia (2005), and Strait of Juan de Fuca (2005). It will emphasize scientist-observatory interaction and local science. The MARS test bed is an advanced, deep-water cabled observatory to be installed in Monterey Bay in 2005. MARS will include an expandable science node on 62 km of submarine fiber-optic cable at 1200 m depth. In this location, it takes about 2 hr to reach the node location from the dock and deploy an ROV to the seafloor. It will emphasize testing of all aspects of the infrastructure and will serve as a long-term test bed for instrument development.

NEPTUNE Science Planning

A key finding within a report of the National Academy of Sciences, entitled *Enabling Ocean Research in the 21st Century: Implementation of a Network of Ocean Observatories* (released in July 2003) was that "Scientific planning to define the location, experiments, and instrument requirements of specific observatories varies significantly among the three OOI components, and additional planning is needed before the design of these systems can be finalized."

Recognizing the fundamental nature of good science planning, NEPTUNE embarked upon the process in 1999 with the convening of *ad hoc* science working groups in the U.S. and Canada for the feasibility studies. White papers and reports from these groups are posted at *www.neptune.washington.edu/pub/documents/documents.html.*

There have been several follow-on workshops related to science planning for the VENUS and MARS test beds. The NEPTUNE characteristics, or functional requirements, presented in Table 1 grew out of these early workshops.

A series of workshops is under way that focus on science planning for regional cabled ocean observatories (Table 2). These workshops are crucial to the development of the experimental scenarios necessary to define the NEPTUNE system architecture. Scientists who wish to be involved may submit their contact information to the NEPTUNE mailing list (*www.neptune.washington.edu/pub/forms/mailinglist.html*) and check the NEPTUNE Web site for current information on how to participate in meetings and for reports produced by workshops.

TABLE 1
NEPTUNE Characteristics

NEPTUNE will provide a real-time, long-term, interactive scientific and educational observatory for the entire Juan de Fuca tectonic plate and overlying ocean.

Power, communications, and timing capability will be supplied throughout the three-dimensional volume. This will be accomplished primarily with cabled systems, but AUVs, robotics, acoustic telemetry, and other systems will also play significant roles.

These characteristics are current design parameters. They are subject to modification from science input.

Length: thousands of kilometers of cable in a mesh topology; all nodes have multiple paths to shore

Infrastructure lifetime: 25 years with upgradeable infrastructure

Number of primary nodes: ~30

Primary node spacing: ~100–150 km

Secondary cables and nodes: allow instrument placement up to ~100 km from a primary node, including on the continental shelf and slope

System is expandable

Scientific instrument interface: standard "plug and work" interface, 400 V and 48 V, 10/100 Mb/s Ethernet, time distribution

Total power: 4 kW average and 9 kW peak at a node, with maximum total ~150 kW

Communications: up to 1 Gb s^{-1} data rate available at any single node with ~10 Gb s^{-1} maximum aggregate rate

Time signals: distributed to nodes, accurate to 1 microsecond

Reliability: a major design driver; 90% of all science connectors shall have a 95% probability of meeting all requirements in a given year

Backbone failure: cable breakage temporarily shuts down system; the system will restart, isolating the failed section, in minutes

Maintenance and servicing: use of academic assets such as UNOLS ships; scheduled system down time < 12 days per year

Data management and archiving system: stores data and metadata and enables multidisciplinary data mining

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TABLE 2
Ocean Observatory Science Planning Workshops

NEPTUNE Canada CFI Proposal Preparation Victoria, British Columbia March 3–4 2002	**NEPTUNE Pacific Northwest Workshop** Portland, Oregon April 23–24, 2003
Coastal Ocean Processes and Observatories: Advancing Coastal Research Savannah, Georgia May 7–9, 2002	**Linkages Between the Ocean Observatories Initiative and the Integrated Ocean Drilling Program** Seattle, Washington July 17–18, 2003
SCOTS: Scientific Cabled Observatories for Time Series Portsmouth, Virginia August 26–28, 2002	**Cabled Regional Observatory Workshop** San Francisco, California October 7–9, 2003
VENUS Science Workshop Victoria, British Columbia November 12, 2002	**Ocean Research Interactive Observatory Networks** San Juan, Puerto Rico January 4–8, 2004

As science planning has proceeded, questions have often arisen regarding sources of funding for instrument development and science experiments on a regional cabled observatory. The National Research Council's report on the implementation of ocean observatories (NRC, 2003) recommends the following to NSF on this topic:

- A core suite of instruments should be installed on every observatory node, and funded as part of the basic observatory infrastructure, not only to test system functionality but also to provide the essential scientific context for the observatory's effective use in basic research.
- A separate, well-funded observatory instrumentation program at NSF, and contributions from other agencies with an interest in ocean research, will be required to obtain the full suite of sensors and instruments needed to fully exploit the scientific potential of the ocean observatory structure.
- The NSF should augment its programs in instrumentation development, support and calibration for observatory-capable sensors, including increasing grant duration to ensure that instrumentation groups have the capability to support the needs of the OOI.

This Workshop

This Pacific Northwest workshop was the first formal science planning effort for NEPTUNE in the United States. We expect there to be other regional workshops like this one for NEPTUNE around the U.S., Canada, and internationally, in addition to focused thematic workshops.

This workshop had three primary goals:

- Inform the regional community of the opportunities provided by NEPTUNE
- Maximize the opportunities and linkages provided by NEPTUNE and its test beds as a regional and coastal observatory
- Entrain a broad spectrum of researchers and forge teams that will pursue creative opportunities using NEPTUNE

The workshop focused on establishing the key science experiments and technology developments that will ensure success of the system from the outset. Groups worked to develop outlines of individual and community experiments, preferred node locations, instrument packages, and paths to implementation.

As this was explicitly intended to be a regional workshop, participants were drawn primarily from the Pacific Northwest and Canada. The workshop announcement (Appendix 1) was broadcast via email to the NEPTUNE contact list in these areas, and it was open to the entire community via the Web site announcements. Working groups structured by science topic were formed; the topical themes based on a reasonable number of groups (5, see below) and previous reports, workshops, and *ad hoc* groups (NRC, 2000; Brewer and Moore, 2001; Jahnke et al., 2002; Glenn and Dickey, 2003; NEPTUNE Phase 1 Partners, 2000; Canadian NEPTUNE Management Board, 2000). The readers of this report are encouraged to refer to these earlier reports. The Science Working Group white papers prepared in connection with the NEPTUNE Feasibility Study often formed the basic foundation for the working groups at the Portland meeting. These white papers are listed below and are available at *www.neptune.washington.edu/pub/documents/documents.html.*

#1: Cross-Margin Particulate Flux Studies Associated with NEPTUNE
#2: Opportunities for Seismology and Geodynamics in NEPTUNE
#3: Seafloor Hydrogeology and Biogeochemistry: Opportunities for Long-Term Borehole Experiments
#4: Opportunities for Investigating Ridge-Crest Processes
#5: Subduction-Zone Processes: Fluid Venting and Gas Hydrates at the Cascadia Convergent Margin
#6: Deep-Sea Ecology
#7: Water-Column Processes

We will not attempt here an all-encompassing integration effort, as this is expected to be accomplished in the NSF-sponsored Cabled Regional Observatory Workshop (Co-chairs Michael Purdy and David Karl, 7–9 October 2003, San Francisco) and the ORION Workshop (Co-chairs Oscar Schofield and Meg Tivey, 4–8 January 2004, San Juan, Puerto Rico). Soon after these workshops we expect dedicated working groups/proposal teams will be established to design community experiments.

The number of participants in each group ranged from 11 to 19, with a total of 83 people attending the workshop (Appendix 2 lists participants). Each group wrote a report, and these were synthesized, edited, and reviewed by participants to form this report.

Workshop Agenda

John Delaney (University of Washington, Director of the NEPTUNE Program) and Chris Barnes (University of Victoria, Director of NEPTUNE Canada) opened the workshop with an overview of the NEPTUNE Program, providing a description of the nature, opportunities, and status of NEPTUNE and its test beds. Short invited talks describing some of the outstanding science questions in each of the five thematic areas were given by the group leaders. Breakout groups were then formed to address the innovative science that can achieve outstanding results in the first few years and beyond. The groups then elaborated on the corresponding experimental requirements, implementation plans and priorities. The groups considered the nature of the desired instrumentation (existing or to be developed) needed for the particular scientific experiments. The complete agenda is in Appendix 3.

The working groups were structured around the five interdisciplinary research themes:

- Fisheries and Marine Mammals

- Ocean Dynamics
- Seismology and Geodynamics
- Fluid Fluxes and Geochemical Processes in the Sediments and Crust
- Ecosystems and the Carbon Cycle

On the first day, within each of these themes, participants were asked to contribute to the following issues provided in the charge issued to working groups (Appendix 4):

- What scientific questions are you posing?
- What general, or preferably specific, node/site locations do you wish to instrument?
- What reliable, off-the-shelf instrumentation will ensure significant early returns?
- What longer-term developments do you envision (3–20 years after initial installation)?
- How will synoptic or co-located studies augment the value of your results/instruments?
- How will you use NEPTUNE a) interactively, and/or b) as a passive receiver?
- What questions will your former students (now as PIs) be asking in 10 years?
- How can we set the groundwork for the questions your present students will be asking in 10 years?
- On the second day, the charge was made more specific:
- Identify the science questions, building on previous work
- Develop two representative science scenarios per group (e.g., large and small scale)
- Consider basic sensors
- Recognize synergies with other programs

Summaries at the end of each day were presented in plenary sessions. All the workshop documentation, including PowerPoint presentations and this report, is available on the NEPTUNE Web site: *www.neptune.washington.edu*.

SCIENCE WORKING GROUP REPORTS

Fisheries and Marine Mammals

John Horne and Sue Moore, Leaders; Colin Finney, Scott McMullen, Dave Mellinger, Nick Peters, Earl Prentice, Dave Reitz, Gordie Swartzman, Minoru Taya, W. Waldo Wakefield

Key Science Issues

The themes that emerged during our discussion of key science issues resulted in two lists that were not exclusively limited to fish, invertebrates, or marine mammals. The dominant marine mammal themes included seasonal distribution, ocean dynamics, and anthropogenic influences. Seasonal distribution research will map and monitor the timing and spatial variability of migration routes, feeding assemblages, and aggregation areas. Ocean dynamics were characterized as the reaction of individuals and groups of animals to environmental variability at small (e.g., fronts) and large (e.g., El Niño) scales. A fixed grid fitted with sensors provides the advantage of a large region simultaneously monitored over a range of spatial scales. Anthropogenic influences include the effects of responses to noise (e.g., from vessels) and potential conflicts with shipping traffic and commercial fishing.

Dominant fisheries (i.e., fish and invertebrates) themes included spatial and temporal fluxes of biomass, resource assessment with extended temporal sampling, distribution variability in space and time, and habitat use. The flux of biomass through space over time has not been traditionally quantified over large spatial and temporal scales. Kinematic processes of migration, dispersal, and the coupling to environmental gradients have not been simultaneously assessed for an ecosystem over extended periods. Assessment surveys of pelagic (i.e., mid-water) and demersal (i.e., bottom) fish species are traditionally conducted using research vessels. Sample synopticity, resolution, and range of these Eulerian (i.e., stationary grid) surveys are limited by vessel speed, time allotted, and surface conditions during the survey. Temporal surveys from a single location or surveys conducted by a suite of sensors have not been used in the management of harvestable resources. Tracking variability in fish distributions over time facilitates demographic (e.g., births, survival) investigations at the temporal and spatial scale of a population. Habitat use by pelagic and demersal fish species is an emerging topic in resource management. Challenges associated with this theme are defining essential habitat and are quantifying the impacts of loss or damage to essential fish habitat.

Our discussions focused on long-term distribution and density observations of aquatic organisms. Many life-history characteristics (e.g., timing and path of annual migrations) are not known for fish and cetacean species. A continuous suite of sensors provides a networked platform to quantify and understand aquatic life cycles. To fully quantify and understand aquatic life cycles, a networked platform supporting suites of sensors sampling (nearly) continuously in time and space is essential.

The Role of Neptune

The fundamental difference between conventional biological sampling platforms (e.g., ships and aircraft) and observing systems such as NEPTUNE (parts of which are stationary and parts of which are mobile, e.g., AUVs), is the potential for unlimited spatial and temporal sampling from a suite of sensors in real time. This unprecedented sampling provides both opportunities and challenges to the fisheries and marine mammal science communities.

Unlike other groups currently involved in NEPTUNE planning, the fisheries and marine mammal scientific communities focus on apex predators that are located primarily on the continental shelf, and are mobile. Predator-prey interactions among organisms that move independent of water motion (i.e., nekton) transfer organic carbon (i.e., energy) from the "top down." This perspective differs from the oceanographic view of "bottom up" trophic transfer where biological-physical coupling facilitates the transfer of energy from physical structures such as upwelling that supply nutrients to phytoplankton and the subsequent consumption by zooplankton, fish, and cetaceans. Combining the two perspectives would focus on high concentrations or strong gradients as indicators of biologically or physically significant events to trigger intensive temporal and spatial sampling aimed at quantifying dominant processes that produced observed patterns.

Given that the bulk of the biomass is located on the continental shelf, the availability of nodes and spur lines on the continental slope and shelf is imperative for a successful nekton sampling program. A combination of Eulerian and Lagrangian (i.e., mobile) sampling strategies is required to adequately sample fish and marine mammals at the spatial scale of a tectonic plate. Detection ranges of most active and passive sensors limit the feasibility of relying solely on a grid sampling design. Strategic choice and placement of sensors should enable a wide variety of organisms to be continuously monitored over a wide range of spatial scales. Location of sensor arrays would be oriented by species locations and/or habitat types (e.g., Columbia River plume) that exist in the region.

Example Community Experiments

Biological-physical coupling

One potential experiment that combines elements of biological and physical coupling across many trophic levels is the entrainment by and exploitation of dynamic features (e.g., eddies, jets) by aquatic organisms. The science question is, "What roles do dynamic features play in the trophic organization, dynamics, and distribution of aquatic organisms?" There are many examples of predators attracted to or keying on concentrations of prey items at high gradient areas (e.g., fronts). The survival and recruitment of zooplankton, some invertebrates, and larval fish species are influenced by the availability of food and conditions within water masses during transport to nursery areas. Marine mammals, fish, and macro-zooplankton species exploit these patches of prey that are concentrated within or at the boundaries of physical structures.

Potential locations for sensor arrays are Cape Blanco, Heceta Bank, and southern Vancouver Island. Water motion is known or suspected to be dynamic at these locations and the sites are of interest to other scientific communities. Sensor arrays would be attached to three spur lines running from nodes up onto and across the continental shelf. Sensor arrays on the spur lines would be spaced at a resolution to detect eddy movements. Satellite detection of sea-surface temperature, ocean color, and altimetry would be used to detect the formation and track movement of eddies as they propagate. The suite of sensors would potentially include winched CTDs, video plankton recorders (VPR), fluorometers, ADCP, dissolved oxygen, and active acoustics. Passive hydrophone arrays would be used to detect the presence of vocalizing marine mammals and could be used to detect acoustically tagged mammals or fish.

As a feature approached or passed one of the spur lines, mobile samplers such as AUVs, gliders, or robotic fish would be deployed to run transects across the feature to map its boundaries, water properties, and its velocity. Sensors on these mobile platforms would include active acoustics, optics, and collection systems to sample phytoplankton (e.g., fluorometry, optical plankton counter), zooplankton (e.g., VPR), and fish (e.g., nets or biosensors). Sampling would be used to assess biological constituents, collect samples for trophic transfer studies, and behavioral observations including predator-prey interactions. Phased implementation would begin with a spur line at the mouth of the Strait of Juan de Fuca near southern Vancouver Island.

Fisheries and Marine Mammal Long-Term Observations

Monitoring the distributions and movements of cetaceans and some fish would greatly improve the biological and ecological understanding of many species. The basic question is, "What are the movements and predation of nekton within the monitored volume and their relationship to environmental conditions during those movements?" This question addresses biological processes of migration, predation, and interaction with the environment. If constituents can be identified, then species-specific census counts can be used for population monitoring and stock assessment of commercially important resources. Specific studies that could be conducted during this monitoring include: distribution and migration patterns in relation to environmental variability and climate change, trophic dynamics, and the effects of marine reserves on distribution and recruitment to aquatic populations.

A plate-scale monitoring system is particularly appropriate for vocalizing cetaceans. Cetaceans produce calls ranging from low to high (~10 Hz – ~100 kHz) frequencies, which is the widest range of any class of organisms (Figure 3). Unlike humans, sound production and reception is the probably the most important sense to these animals. Autonomous passive hydrophone arrays have been deployed in the Gulf of Alaska and Bering Sea. These recording systems are limited in power and data storage, and the deployed instrument packages must be retrieved before any data can be downloaded. Real-time access to the data is not possible.

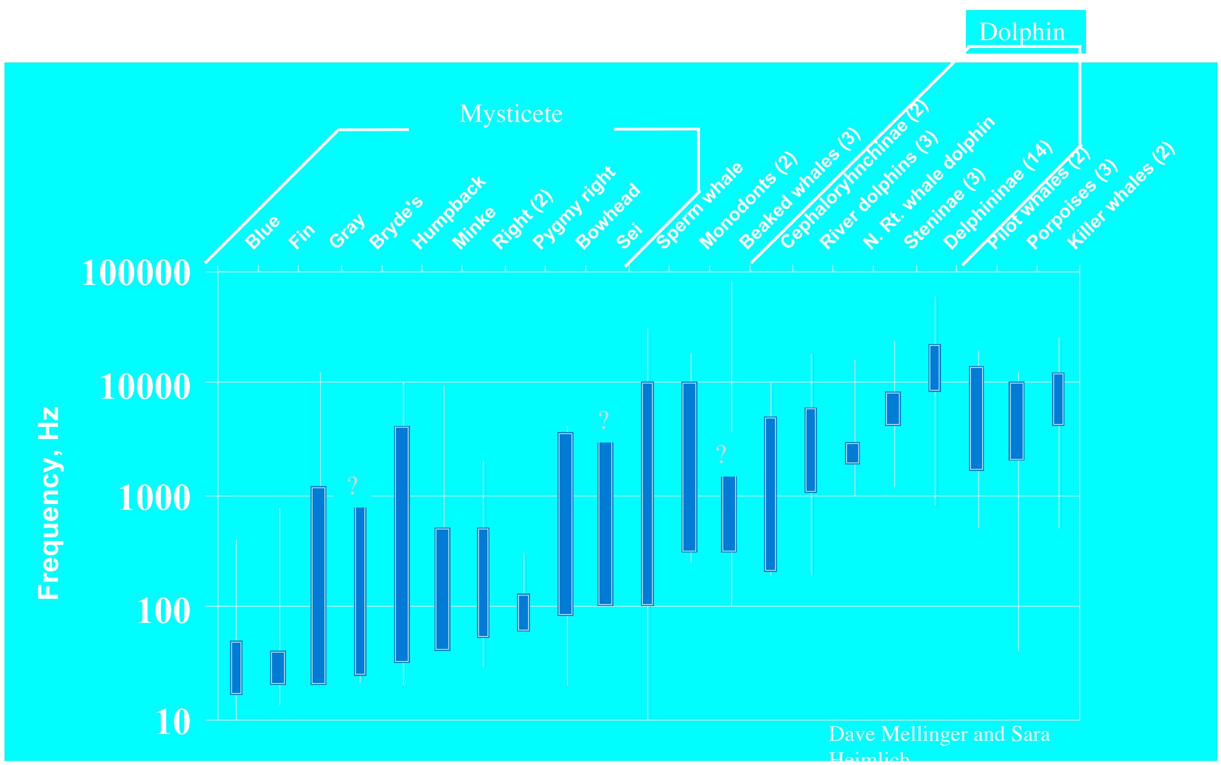

Figure 3. Frequency range of cetacean vocalizations (image compiled by Dave Mellinger and Sara Heimlich).

Many strategies could be used to locate sensor arrays. For cetaceans, an ideal design would place vertical and horizontal hydrophone arrays at every node and on spur lines extending onto the continental shelf (Figure 4). The regional coverage would ensure detection of all vocalizing animals because there are offshore (e.g., blue, fin, sperm whales) and nearshore (e.g., gray, humpback whales) forage areas and migration routes used by different species. A more restricted approach would place individual hydrophones along an offshore and a nearshore corridor (Figure 5). Satellite tags on individual animals could be used to augment tracking the movements of groups or populations of whales.

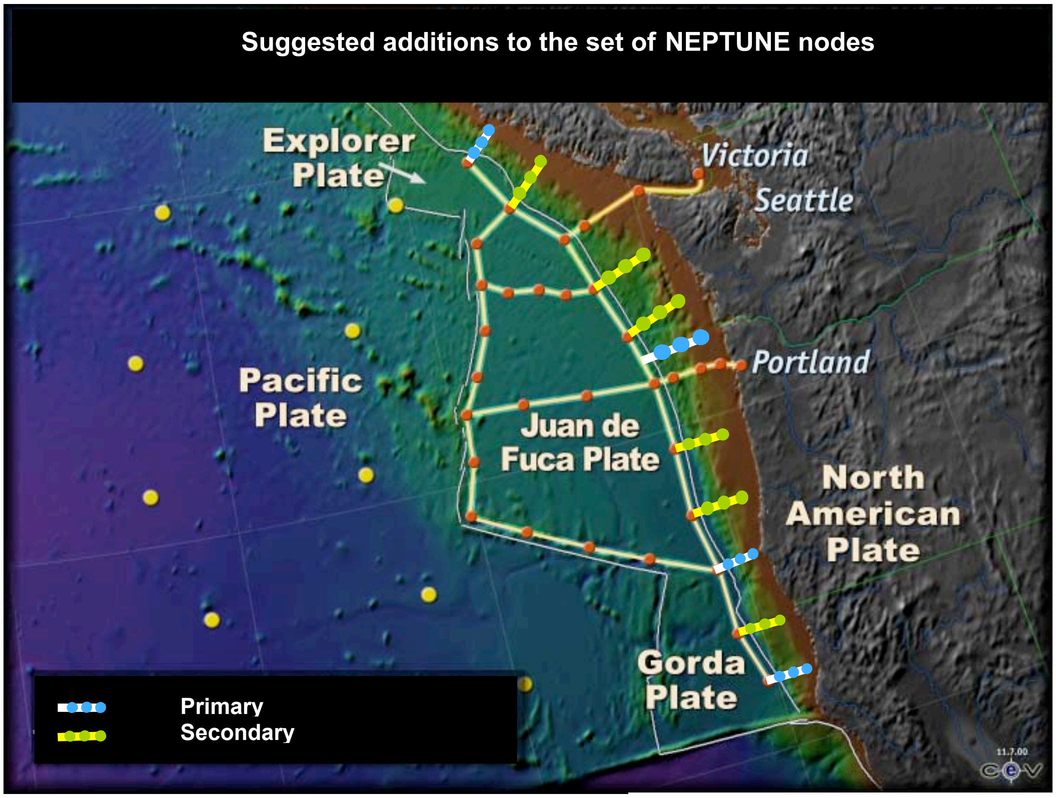

Figure 4. Proposed continental shelf hydrophone array locations.

A variety of sensors is required to detect cetaceans and fish species that can be divided into large pelagics (e.g., tunas), middle pelagics (e.g., Pacific hake), and small pelagics (e.g., herring). Vocalizing cetaceans are best detected using arrays of 20 to 40 hydrophones that permit beamforming (providing bearing angle), which greatly increases the range at which we can detect and track cetaceans. An array of hydrophones placed vertically, spanning most of the water column, would enable matched field processing to estimate both range and depth of vocalizers. Restricting the number of hydrophones would place one hydrophone at each node, buoyed up to the sound channel axis or higher. A 3D array of four hydrophones would allow determination of the direction from which cetacean calls arrive. Two of these hydrophones in the vertical would allow the study of diving behavior of vocalizing animals.

There are two frequency ranges for hydrophones that would receive sound from a variety of cetacean and porpoise species. Dolphin and porpoise whistles contain harmonics as high as 100 kHz. The harmonics may be used in species identification and received signals should be sampled at 200 kHz. These hydrophones should be located near the surface, as high frequency sounds attenuate quickly through water. Hydrophones used to receive vocalizations from large whales do not need comparable bandwidth due to the low-frequencies of their calls. Hydrophones that capture sounds up to 24 kHz with signal sampling at 48 kHz are sufficient. The latter sampling rate is suggested as it matches the sampling rate of commercial DAT recorders.

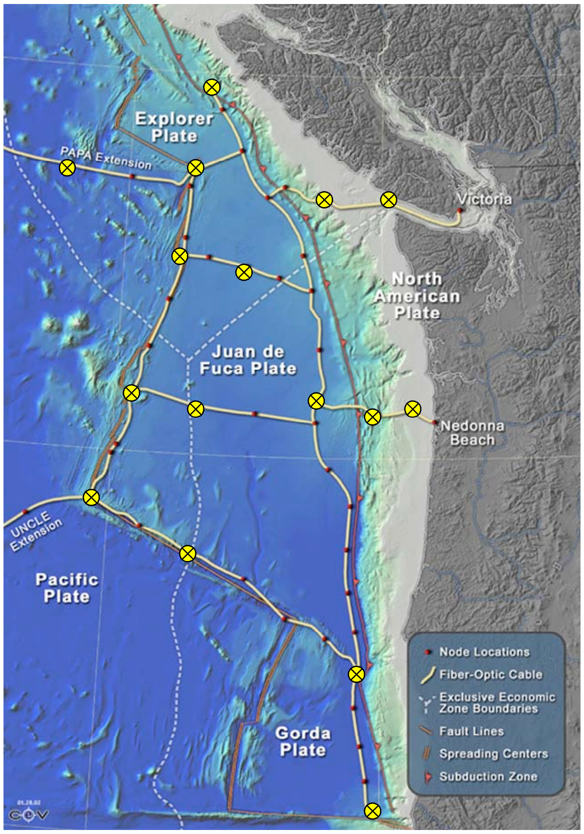

Figure 5. Example hydrophone array placement to enable cetacean tracking through the NEPTUNE grid (image compiled by Kate Stafford).

It is germane to ask how a NEPTUNE cetacean monitoring system would differ from the current SOSUS array. The location of all sensors would be optimized to receive sound from many species of cetaceans and not necessarily from submarines or other anthropogenic sources. Spatially distributed hydrophones would allow the horizontal and vertical tracking of animals in three spatial dimensions over time. The receiving frequency range of the hydrophones would be targeted to encompass the vocalization range of whales and porpoises in the region. Horizontal and vertical arrays will allow the vertical location of an animal in the water column to be identified and to monitor diving behavior of a tracked individual. Finally, all other physical and biological data collected from the NEPTUNE network could be used as correlates to the cetacean vocalization and location data.

Access to plate-scale monitoring is also appropriate for some pelagic fish species. Oceanic distributions and movements of salmon are not well known. Arrays of hydrophones have been proposed in a picket fence design to detect acoustically tagged fish as they migrate from the Aleutian Islands in the Gulf of Alaska along the continental shelf to southern Washington state (Figure 6). Acoustically tagged fish would be detected as they passed within the range of any hydrophone in a fence array. Migration rates and the return to natal rivers and streams can be documented for different species and populations. Annual migrations of large to small pelagic fish species could be tracked in at least two ways. Active acoustic systems could be used to examine seasonal fluxes of biomass along the continental shelf (e.g., annual Pacific hake migration) and diel movements within the water column. The sonar systems could be mounted at nodes or in mobile platforms that conduct survey transects along fixed paths from a single node or between a series of nodes. At this time, acoustically identifying targets to species is not possible based on acoustic signals alone. Tagged fish within large schools could be detected with hydrophones while the population is monitored using active acoustics. Since similar fish tend to travel together, the combination of acoustics and optics could be used to detect known populations of fish.

In contrast to these Eulerian sampling strategies, Lagrangian methods could be used to monitor specific fish populations. Satellite nodes could be used to extend the effective monitoring range of the NEPTUNE grid. Mobile platforms such as AUVs could track populations by focusing on a single tagged individual during the migration. When an AUV was close to a satellite node, it would dock to recharge batteries and download data. A second AUV could takeover tracking or once the original AUV was recharged, it would resume its tracking of the population. A variety of sensors could be installed on the mobile platform depending on the fish species being tracked, and ancillary data needs. Recent developments in material science and robot kinematics potentially make the tracking platform less obtrusive to fish within a school.

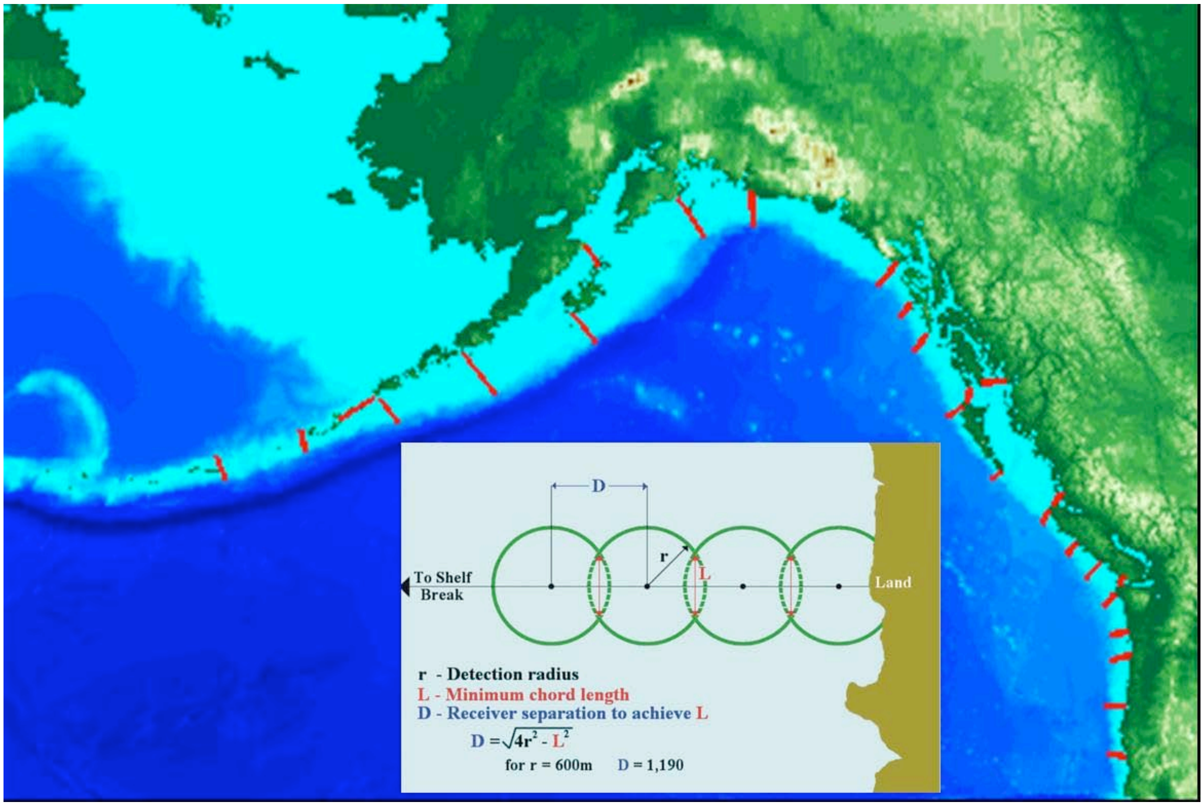

Figure 6. Proposed hydrophone array locations of the Pacific Ocean Salmon Tracking Project (POST). Additional information can be found at *www.coml.org/descrip/post.htm.*

However, there are a number of challenges to Lagrangian tracking by mobile platforms. These challenges include, in part, the ability to navigate and accurately log position while underwater and extending AUV mission life from hours to days.

Synergies

There are several biological-physical research programs currently under way along the west coast of North America. Some of these programs are finishing while others are just being initiated. Current programs include: GLOBEC, COAST, RISE, EcoHab, and Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO). Interaction with these programs will provide guidance in the selection of spur line locations, historical documentation of physical features and biological responses, and additional detection and tracking of features by other sensing programs.

The potential for synergistic research exists within and external to the NEPTUNE community. Biologists are interested in how animals respond to and interact with their environment. The continued evolution of "ecosystem management" among government agencies will encourage additional and ongoing linkages between physically and biologically oriented investigators. The Sloan Foundation's Census of Marine Life has initiated a demonstration phase of the salmon monitoring project, the Pacific Ocean Tracking and Evaluation NeTwork (POTENT).

Education and Outreach Opportunities

'Charismatic megafauna' is a phrase commonly used to describe marine mammals. It is not hard to attract public interest when providing information on pinnipeds or cetaceans. Public interest in the killer whales, such as Keiko, of Hollywood fame, and Springer, the local Puget Sound killer whale, are two recent examples. The growth of the whale watching industry as part of eco-tourism has been rapid and worldwide. Several opportunities exist for education and public outreach. Current examples include Web sites that track the migration of satellite tagged humpback whales in the Atlantic.

The northeastern Pacific has some of the largest fish and invertebrate commercial fisheries in the world. In recent years, populations of commercially important species have dramatically increased or decreased. Information on the basic biology of many species including life cycles could be tied into the feeding (Community Experiment 1) and tracking annual migrations (Community Experiment 2) along the continental shelf of the northeastern Pacific. Salmon is synonymous with the Pacific Northwest. Web-based resource material could be constructed for any student group, commercial fishing associations, or recreational fishing group.

Recommendations

Sensors

Because of the rapid and continued development of commercially available passive and active acoustic instruments, specific equipment will not be identified until the NEPTUNE grid is in place. In general, however, the group agreed that there must be sensors on the continental shelf, that biocide will be required on sensor faces, and that periodic calibration of all sensors will be required. Active sonars could be upward looking, but there is not a long history of their quantitative use. Awareness must be maintained of potential conflicts between active sonar use and marine mammal harassment guidelines.

Ideal sensors for marine mammal studies would consist of horizontal arrays of 20 to 40 hydrophones (10 Hz–100 kHz) spread throughout the grid (e.g., Figure 4) with additional vertical hydrophone arrays (with beamforming capability) of 20 to 40 hydrophones to track animals. A minimum suite of sensors would consist of four bottom-mounted and two buoyed hydrophones at as many nodes as possible.

Ideal sensors for studies of fish would include an active acoustic system (~100 kHz, wide-beam angle) at all nodes on the continental shelf and acoustic fish tags that can be interrogated or detected by sonars. A minimum sensor suite would consist of an active sonar system (~100 kHz) placed on as many continental shelf nodes as possible.

Equipment development: a marine mammal and fish detector

A monostatic sonar system could be developed using a broadband sonar as a passive receiver and as an active sonar. A frequency range of 10 Hz–100 kHz would meet the interests of both marine mammal and fisheries groups. This monostatic sonar could cycle between active pinging and passive listening.

A bistatic sonar system, developed by combining distributed passive hydrophones with a transmitter, would use the hydrophones to collect cetacean vocalizations and reflected sound from the fish. Data would then be processed separately.

Ocean Dynamics

Antonio Baptista, Jack Barth, Jeff Parsons, Leaders; Tim Boyd, John Garrett, Yoon Sang Kim, Mike Kosro, Murray Levine, Doug Luther, Parker MacCready, Jerry Mullison, Jan Newton, Jeffrey Nystuen, Thomas Sanford, Scott Springer, Fritz Stahr, Terry Thompson, Kevin Williams, Sarah Wilson.

Major recommendations

- Extend the NEPTUNE array up onto continental margin (slope to mid-shelf) in order to study important circulation and ecosystem processes in those regions
- Include a basic bottom-mounted physical/acoustics/bio-optical oceanographic sensor suite on every NEPTUNE node
- Immediately begin circulation and ecosystem modeling of the NEPTUNE region to assess array design and field experiment planning

Background

The Northeast Pacific ocean circulation is influenced by a variety of processes that include the large-scale North Pacific gyre, wind and buoyancy forcing, and flow-topography interaction including bottom boundary-layer processes. These processes span a huge range of time and space scales, from interdecadal to seconds and from gyre scale (≥1000 km) to turbulent mixing scales (1 cm). This range of time and space scales presents a wealth of ocean dynamics and cross-margin processes that can be addressed by a regional ocean observing system. We outline in this report a few examples of these processes on which significant scientific progress could be made through a long-term, sustained ocean observing system effort. We did not attempt to include all possible experiments, but rather chose to focus on one large-scale and one small-scale experiment. Previous NEPTUNE white papers on *Water-Column Processes* and *Cross-Margin Particulate Flux Studies associated with NEPTUNE* were written by *ad hoc* science working groups meeting in 1999 during the preparation of the NEPTUNE feasibility study; these white papers are available from the NEPTUNE Web site at *www.neptune.washington.edu*.

Oceanographic processes of interest in the NEPTUNE region include the following: both the mean and time variability of boundary currents and barotropic velocity; mesoscale variability as manifested by eddies, filaments and jets; coastal trapped waves and open-ocean Rossby waves; barotropic and baroclinic tides; tsunamis; wind and buoyancy driven shelf flows; cross-shelf transport of temperature, salinity, sediment, plankton, and pollutants; and mixing processes in the surface and bottom boundary layers and as associated with topographic irregularities and hydrothermal vents.

Figure 7 provides an overview of regional circulation in the northeast Pacific. In Appendix 5 we summarize ocean circulation in the northeast Pacific and provide a short description of boundary-layer processes.

Role of NEPTUNE

The group considered the impact of the unique capabilities of a regional ocean observatory on our science. One of the foremost capabilities is the ability to collect long-term time series that capture multiple geophysical events on a variety of time scales, in particular, the episodic events that are so important to ocean circulation and ecosystem dynamics (e.g., storms, sediment re-suspension events, blooms, and interannual variability). Long time scales are also critical for discerning interannual and interdecadal variability. The basic NEPTUNE array provides synoptic, high spatial resolution measurements of many oceanographic processes (e.g., boundary currents) and even more dense arrays of instruments can be hung off the basic nodes

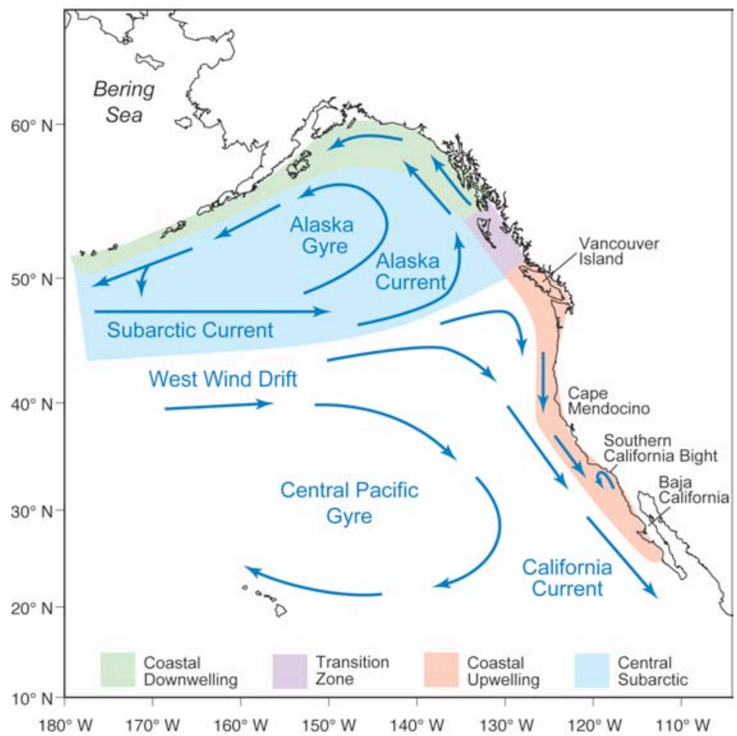

Figure 7. Regional circulation in the northeast Pacific.

in targeted process studies. The real-time, two-way communications will open new ways of measuring and studying ocean processes. This two-way communication and the blend of sensor platforms envisioned for NEPTUNE will allow adaptive sampling using instrument arrays, remote platforms and targeted research cruises (e.g., in response to an episodic event such as a harmful algal bloom or undersea eruption). The adaptive aspects allow for optimized sampling of oceanographic processes of interest.

Another extremely valuable enabling aspect of the regional observatory is its "all-weather" capabilities. We are presently limited all too frequently by difficult operating conditions at sea. The unique access to real-time data from the sea will also lend itself to outreach and education activities. Our working group recognized that the regional observing system will have both paradigm- and culture-shifting impacts through data immersion and cross-discipline sensors and scientific interactions. Lastly, access to power will enable long-term mooring operations and the use of remotely operated and autonomous underwater vehicles.

Modeling

Modeling of the northeast Pacific is occurring at a number of scales and at several institutions. The coastal modeling group at Oregon State University is modeling the regional ocean circulation (Oke et al., 2002) as forced by spatially uniform winds measured from a single, centrally located meteorological buoy or by spatially variable winds derived from an atmospheric circulation model (Bielli et al., 2002). Studies of circulation in the Columbia River estuary and on the adjacent shelf are being carried out by researchers in the Columbia River Estuary (CORIE) project at Oregon Graduate Institute/Oregon Health and Sciences University (OGI/OHSU). On a larger scale, researchers at NOAA's Pacific Marine Environmental Laboratory (PMEL) are modeling the Pacific Northwest circulation by embedding it within a larger north Pacific model as part of an effort funded by the Global Ocean Ecosystem Dynamics (GLOBEC) effort. Scientists at University of California-Los Angeles (UCLA) are modeling the entire west coast using a high-resolution (5 km) version of the Regional Ocean Modeling System (ROMS). Many of these efforts also include ecosystem components (Spitz et al., 2003). Modeling of the entire west coast is also being done at the Naval Research Laboratory (NRL). These models are mature enough to be used to assess the proposed NEPTUNE array design for studying circulation features of interest as described below.

Modeling of the barotropic tide is ongoing in the northeast Pacific, again on both large (Egbert et al., 1994; Foreman et al., 1998) and small scales (Foreman et al., 1993; Kurapov et al., 2003) both with and without assimilating ocean-surface height or radar-derived surface currents.

Some of the circulation models are assimilating data; the regional Oregon coastal ocean work of Oke et al. (2002) that assimilates radar-derived surface currents is one example. Other large-scale north Pacific models can assimilate ocean-surface height data or sea-surface temperature.

While much progress has been made on circulation modeling in the northeast Pacific, much remains to be done. The modeling systems need to be designed and their operational capabilities evaluated. The observing system, *in situ* sensors and remote sensing plus models, must be improved through better and more consistent quality control of the sensors and their data. This needs to be done such that analysis of long time-scale phenomenon can be carried out and trends detected in the region. Models should be capable of running for multiple years without drifting away from climatology so that any trends detected by the observing system are real and not a product of model error. By considering the error covariance central to any data assimilation technique, the way in which (limited) data get projected into corrections of the flow field over the entire model domain can be assessed. This leads to efficient array design and an understanding optimal placement of observational resources. Another approach to evaluating array design is through the use of observing system simulation experiments (OSSEs; Malanotte-Rizzoli, 1996). Knowledge of where to best place observational resources will be important when considering the survey design for targeted sampling by autonomous vehicles within the regional observing system footprint. Data assimilation can also be used for hypothesis forming and testing. Lastly, work needs to be done on using models, particularly ocean-atmosphere models, to explore decadal and longer time-scale processes and time variability.

Basic Oceanographic Sensor Suite Recommendation

Our working group was uniformly in agreement about the need to include a basic physical/acoustics/bio-optical oceanographic sensor suite on every NEPTUNE node. The sensor package would be bottom mounted and include sensors for pressure, conductivity, temperature, and optical backscatter (a measure of suspended particle load). A broadband acoustic transducer array (transmit and receive) should also be included for monitoring ambient sound (wind, rain, marine mammals, shipping, and seismic waves) and as a navigation aid and potential communications channel for AUVs or other untethered sensors. There should be several instruments that measure properties in the water column either acoustically (inverted echo sounder for heat content/dynamic height, and ADCP for currents and backscatter) or electrically (horizontal electrometer for barotropic velocity). Further measurements in the water column are desirable, e.g., temperature, salinity, chlorophyll fluorescence, but no consensus was reached on details of these sensors. It is likely that water-column sensor packages will be associated with targeted research efforts as described here. The utility of a video camera for bottom-type identification and for education and outreach was identified.

Major Research Areas

We identified several major research categories during our discussions. Given the expertise represented in our working group, the emphasis was on physical oceanographic processes. For more discussion of cross-shelf sediment transport processes, see the 1999 NEPTUNE Feasibility Study white paper *Cross-Margin Particulate Flux Studies associated with NEPTUNE*, available at *www.neptune.washington.edu*.

The processes covered by this Pacific Northwest Workshop working group were as follows:

- Flow interaction with (rough) topography
- Eastern boundary currents and water mass properties
- Shelf/slope ecosystem dynamics

- Episodic and short-scale events and adaptive sampling
- Air-sea interactions
- Tsunami generation and propagation

There was insufficient time to address each of these categories, so we chose to focus on the first two to provide examples of a large and small spatial scale experiment. The ecosystem dynamics category has obvious overlap with the *Ecosystems and the Carbon Cycle* working group because knowledge of the circulation, mixing, and air-sea exchange are important to the ecosystem response.

Experiments

Flow interaction with (rough) topography

Flow-topography interaction can take many forms including adjustment of flow along mesoscale (tens of kilometers; dynamics occurring on the Rossby radius of deformation scale) variations in bottom topography or coastline. For the purposes of outlining a specific scientific research question, we concentrated on flow-topography interaction involving a stratified fluid over sloping bottom topography either with or without small-scale (tens of meters to a few kilometers) irregularities. This small-scale topography is rarely resolved in numerical or observational work, yet it is likely to exert a strong influence on the conversion of energy into turbulence. Our knowledge is particularly lacking for rough sloping topography, and the experiment outlined here could have great value for understanding slope flows around the world. The types of processes in question are captured in Figure 8.

These processes include mixing, bottom boundary layer dynamics, internal waves, sediment resuspension, and tidally rectified flow. Locations for flow-topography interactions are on continental shelves and slopes, ridges, and in submarine canyons. The scientific questions of interest are as follows:

- What is the character and origin of rectified flow near the boundary?
- What is the relationship between barotropic and baroclinic tides and mixing?
- What are the dynamics of internal wave reflection and mixing?
- How is bottom boundary layer stress dependent on the overlying fluid properties (currents, stratification) and what are its effects on mixing?
- How does low-frequency flow interact and modulate boundary-layer processes and mixing?
- What is the balance between form drag and skin friction?
- What is the influence of mixing on mesoscale circulation and property distributions?
- What is the impact of mesoscale motions and mixing on the transport and distribution of benthic material?

A possible high-spatial resolution array to study flow-topography interactions is sketched in Figure 9. The dense mooring array would hang off the seafloor cable, either from a convenient node or a spur line extending up the topographic feature.

With five or six appropriately spaced (in the vertical) velocity and density measurements, fluxes of energy in the tidal and near-inertial internal wave bands may be calculated (Kunze et al., 2002). Using an array of moorings, the divergence of the energy flux, a measure of energy generation/dissipation, may be calculated.

Within the northeast Pacific Ocean, a number of potential sites that fall within the basic NEPTUNE array were identified for studying flow-topography interaction and are indicated in Figure 10. These include the following:

- The continental shelf and slope with different characteristics including regions with a

- gentle slope, near the shelf break, on a slope with corrugations (e.g., the corrugated,
- slope-perpendicular terrain of the Trinity, northern California margin; the slope-parallel
- mini-basins of the Oregon margin), in association with canyons, and as influenced by the
- undercurrent with and without mean vertical shear
- Mid-plate seafloor, both planar and with corrugations
- A submarine ridge including a strong scarp (e.g., Mendocino), a seamount (e.g., Axial), a fault valley (e.g., Main Endeavor), and the ridge valley

At any particular site, the observing array would be built up over time, increasing spatial and temporal resolution as the relevant scales of interest are identified until a degree of oversampling is obtained. Fine tuning of the array can then be done to optimize it for decades-long observations. Other flow-topography interaction arrays could be deployed in other regions at the same time (or sequentially using a phased approach) and left in place for decades. Each experiment would add immensely to our understanding of flow-topography interaction and its importance for mixing and for influencing the regional circulation and water-property distributions.

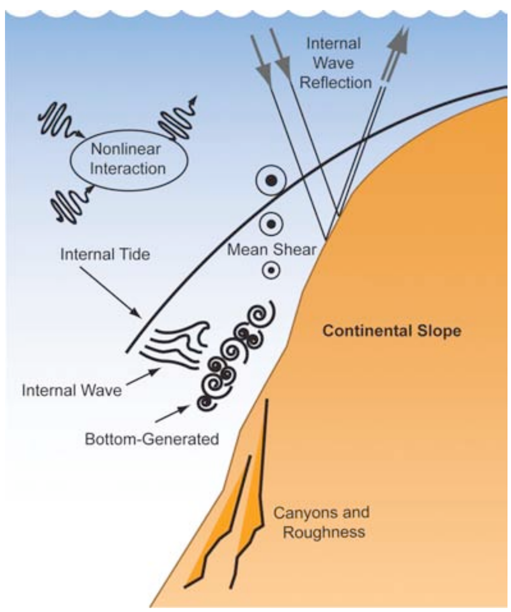

Figure 8. Cartoon of mixing processes over the continental slope. Courtesy of Murray Levine, Oregon State University.

Eastern boundary currents and water-mass properties

As described above (and in Appendix 5), the regional circulation off the Pacific Northwest coast is strongly influenced by the presence of various eastern boundary currents including the North Pacific Current (aka, the West Wind Drift), the California Current, the California Undercurrent and the Davidson Current. Except for the east-west North Pacific Current entering from the west just north of the proposed NEPTUNE region, each of these currents is a strong north-south flow located over or adjacent to the continental margin. The California Current is a surface-intensified, equatorward current that can reach speeds of 0.5–1.0 m s^{-1} and extends into the water column down to 500–1000 m. The California Undercurrent is

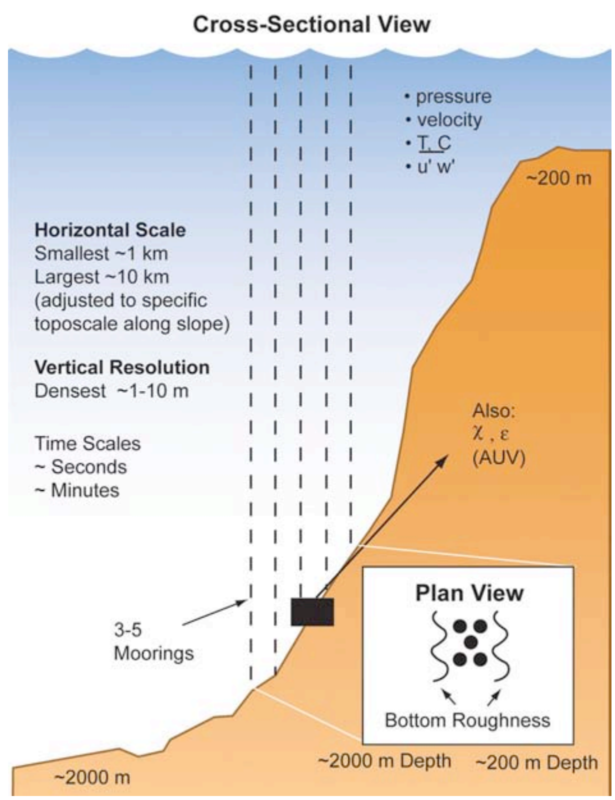

Figure 9. Elements of an observational array for a flow interaction with (rough) topography experiment. Vertical lines in the section view represent moorings; effort is concentrated on the continental slope.

a subsurface poleward current with a core at 200 m. It has an average speed of 0.15 m s^{-1}, but individual realizations of it can reach twice that speed. The California Undercurrent provides an important connection between the proposed NEPTUNE study region and processes occurring farther south, including as far as the equator. The Davidson Current is a strong (speed up to 1 m s^{-1}) poleward surface-intensified flow found over the continental shelf and slope in winter. These currents transport heat, salt, nutrients, plankton, and invertebrate larvae north and south and are crucial to the ecosystem response in this region. The eastern boundary currents exhibit variability on a variety of time scales from the 2–5-day event time scale, through the seasonal time scale to interannual (El Niño/La Niña) and interdecadal [Pacific Decadal Oscillation (PDO)] variability. A long-term, large-scale sustained array of instruments made possible by a regional observatory will lead to breakthroughs in our understanding of the physical, chemical and biological processes influenced by the eastern boundary current circulation.

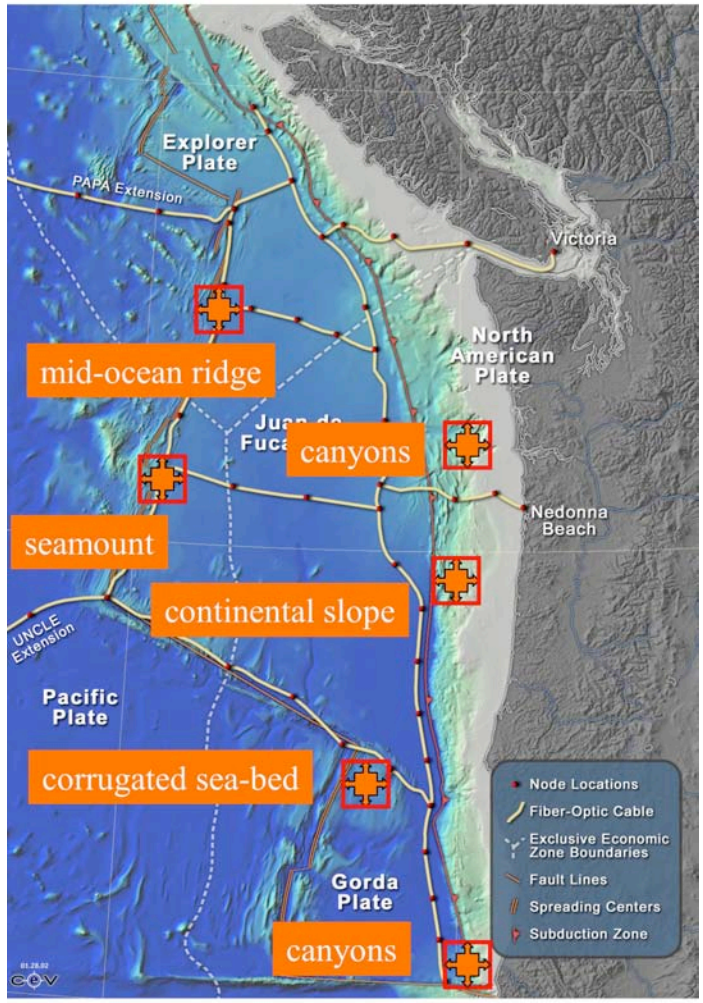

Figure 10. Potential sites for studying flow interactions with (rough) topography.

Processes of interest are as follows:

- Interannual and interdecadal variability
- The California Undercurrent and its connection to processes occurring farther south
- The depth, concentration, and alongshore transport of nutrients in the nutricline
- Mesoscale, 20–100 km, eddies and meanders
- Cross-margin transport
- Alongshore transport by the vertically sheared north-south currents
- Various large-scale wave phenomena (e.g., coastal trapped waves, tides)

Science questions of interest are as follows:

- What is the meridional transport of heat, salt, water, and biogeochemical properties and
- what is the time variability (from the 2–10-day weather band to interannual and
- interdecadal) of that transport?
- What is the relationship of meridional transport and large-scale forcing by the wind
- and/or alongshore pressure gradients?
- How does the depth of the nutricline and its concentration of macronutrients affect
- coastal primary productivity?

- Alternatively, how does alongshore transport of nutrients affect coastal primary
- productivity?
- What is the partition between shelf, slope, and deep-ocean meridional transport?
- What influences the time variability of the bifurcation of the North Pacific Current
- (aka, West Wind Drift)?

Although the proposed NEPTUNE array is not ideal for addressing the final question, some analysis is possible with the existing design and would be enhanced significantly if the ocean weather station (OWS) PAPA extension line is completed.

Locations of potential east-west lines for studying eastern boundary current processes are drawn on the NEPTUNE array, Figure 11. The array to study eastern boundary currents and water mass properties (an example of which is provided in Figure 12) should extend alongshore from a northern line off Vancouver Island, include a central line off Oregon (the Newport Hydrographic Line at 44.65°N is preferred given its history, accessibility, and proximity to Hydrate Ridge), down to a southern line at Crescent City. Alternative, but less desirable, line locations are the Nedonna Beach cable landing and a line at Coos Bay, Oregon. The lines should extend from about the 50 m isobath to well out beyond the continental margin because the eastern boundary currents easily extend several hundred kilometers offshore.

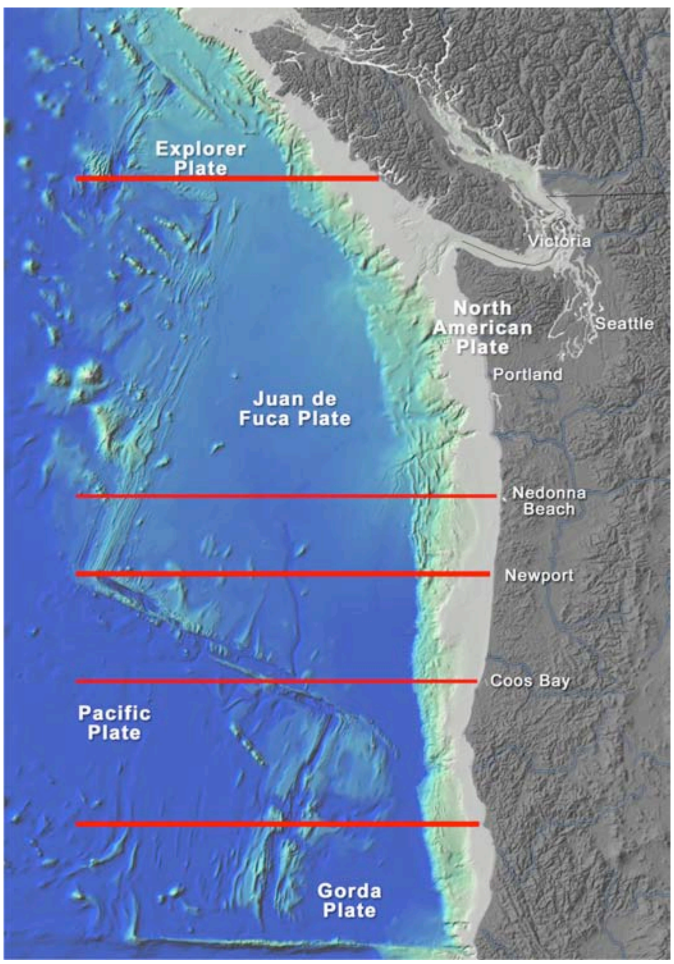

Figure 11. High-priority (thick) NEPTUNE lines that could be used to address questions about eastern boundary currents and water mass properties. (Thin lines are alternative locations.)

Each east-west line would consist of either a margin-crossing cable-landing line or a spur line up the continental margin. The spur line might require a new node located on the continental margin if the distance from the coast to the closest full-ocean depth node exceeds the nominal node spacing of 50–100 km. An “extension cord” would continue for another 30 km or so to the 50-m isobath. To capture the eastern boundary currents’ physical, bio-optical, and chemical properties, moorings should extend into the water column from the seafloor cable at about the 50, 100, 150, 800, 1200 and 3000-m isobaths. Additional water-column moorings would extend from existing nodes closest to the margin and farthest to the west near the plate boundary. The between-mooring spacing for the inner 7 moorings would range from about 15 to 30 km. All moorings should be capable of making measurements to the sea surface. This may best be accomplished through vertical profiling systems, but some of the moorings should have surface expressions in order to accommodate meteorological instruments (e.g., wind, radiation). The moorings should be equipped with velocity profilers, and temperature, salinity, nitrate, dissolved oxygen, light transmission, and chlorophyll fluorescence sensors.

The eastern boundary current study array could be done in a phased implementation, starting with a single east-west central line, preferably the Newport Hydrographic Line but the Nedonna Beach cable landing line would work if it is the only one available. That single line could be populated with instruments at given east-west and vertical spacings. Then this array could be evaluated with an eye toward optimizing the instrument spacing. Next, the array could be expanded (i.e., replicated) to the north and to the south to explore the meridional variation of the eastern boundary currents.

This experiment offers some excellent synergies with existing and proposed continental margin observational programs, for example the recently funded NSF Coastal Ocean Processes (CoOP), the River Influences on Shelf Ecosystems (RISE) program off the Columbia River, the NSF-funded Ecology of Harmful Algal Blooms (ECOHAB) project, the proposed NSF OOI coastal observatory component and the proposed Ocean.US Integrated Ocean Observing System (IOOS).

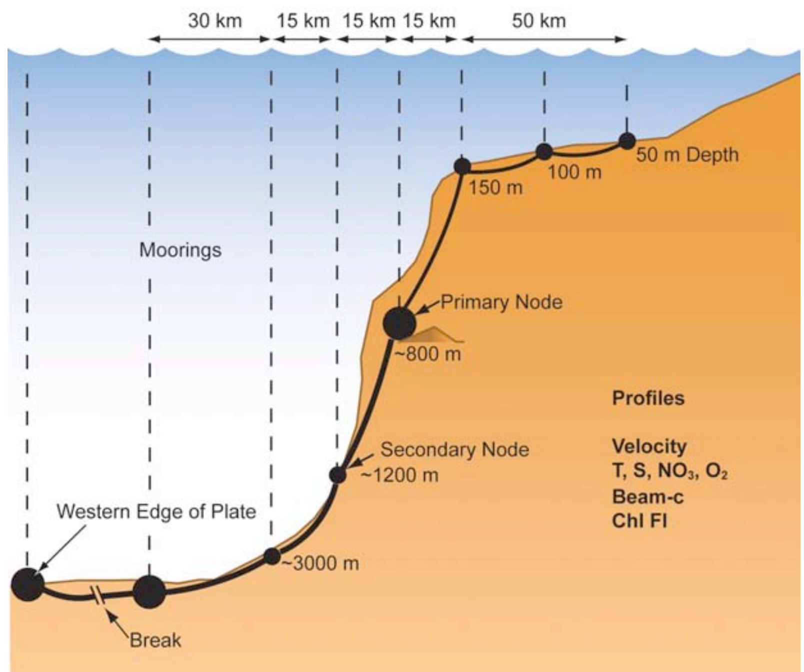

Figure 12. Elements of an observational array for an eastern boundary current and water mass properties experiment. Vertical dashed lines represent moorings at the indicated spacing across the continental margin. Note the break in horizontal scale just inshore of the "edge of plate" node. Moorings would likely have profilers with "sampling rates" of hours.

Other Oceanographic Processes of Interest

Although there was insufficient time to detail an experiment on continental shelf and slope ecosystem dynamics and noting that subject area was being covered by the *Ecosystems and Carbon Cycle* working group, we did note a few of the relevant processes of interest.

Arguments for the value of continental margin studies include the fact that much of the north-south transport of heat, salt, nutrients, plankton, and any potential pollutants occurs over the continental margin. Flow-topography interaction, including both energy dissipation and the generation of mesoscale variability, occurs at the margin near the coast. A large portion (25–50%) of primary productivity, and potential uptake of atmospheric CO_2, occurs over the margin. Strong air-sea interactions (e.g., fog formation and strong wintertime barrier jets) are found over the margin.

The continental margin is also where many migrating and resident marine mammals and seabirds are found. Finally, much of the ship traffic occurs in the coastal ocean, so any improvements such as aids to navigation, search and rescue, and pollutant-transport predictions are important societal benefits.

Much discussion and background on continental margin processes has been set forth by the Global Ocean Ecosystem Dynamics (GLOBEC) project and by the CoOP and ECOHAB programs.

Important scientific issues revolve around the following:

- Cross- and along-margin transport of water and the biogeochemically important
- materials it contains
- The ecology of harmful algal blooms
- Food-web dynamics and their differences/evolution between different flow regimes
- Large river plumes (e.g., Columbia River, freshwater out of the Strait of Juan de Fuca)
- and their nutrient and iron content and importance for salmon habitat
- The concentration and depth of nutrients available at depth as influenced by the
- poleward California Undercurrent and the depth of the nutricline

Another type of oceanographic process of high interest, but for which there was insufficient time to detail, is the study of episodic or short time-scale events. These episodic events are often missed by conventional ship-based, campaign-oriented studies. The availability of a sustained presence afforded by the NEPTUNE array would increase our chances of capturing these episodic events. Examples include the following:

- Sediment-resuspension events
- Turbidity currents
- Efflux of material from vents
- Ridge-plume response to seismic activity
- 2–10-day wind events (storms)
- Phytoplankton blooms, both productive and harmful; and
- Spring internal tides and mixing events.

The two-way communication and potential for directing autonomous vehicles to the region of an episodic event will provide an extraordinary new look at these critical events.

The phenomena of tsunami generation and propagation is also of high scientific and societal interest in the Pacific Northwest. If the NEPTUNE nodes are equipped with bottom-pressure sensors as recommended, this will provide an unprecedented array for tsunami research. There are synergisms with the *Seismology and Geodynamics* working group's efforts and also with the Tsunami Research Center at Oregon State University.

Air-sea interactions are important for setting the surface properties of the northeast Pacific Ocean and are at the heart of weather modification in this region (e.g., fog formation, strength of land falling storms, etc.). Significant progress could be made on these issues by using the NEPTUNE array to measure wind and rain directly, with surface buoys attached directly to the array, or acoustically. These direct estimates would be invaluable for providing ground truth for satellite remotely sensed estimates of these fields. Radiative fluxes would need to be measured directly from surface buoys, and again would be invaluable as ground truth and as input to numerical atmospheric and evolving atmosphere-ocean models. There is expected synergism with the new NOAA Cooperative Institute for Oceanographic Satellite Studies (CIOSS) at Oregon State University.

Synergies with other projects

- Shelf/slope ecosystem research through NSF CoOP (e.g., COAST, RISE) and ECOHAB (Figure 13)
- Comparison of flow-topography interaction with that being studied around mid-ocean submarine ridges (Hawaii Ocean Mixing Experiment)

- Bottom boundary-layer processes and water-column transport in association with fluid flux groups (e.g., methane hydrates on the slope, strata formation on margins)
- Salmon studies by NMFS and BPA
- Estuary studies (CORIE: Columbia River Estuary, PRISM: Puget Sound Regional Synthesis Model)
- VENUS coastal/estuarine cabled observatories in Saanich Inlet, straits of Georgia and Juan de Fuca
- IOOS regional coastal observatory in the Pacific Northwest
- Ridge 2000 Integrated Study Site–Endeavour Segment, Juan de Fuca Ridge

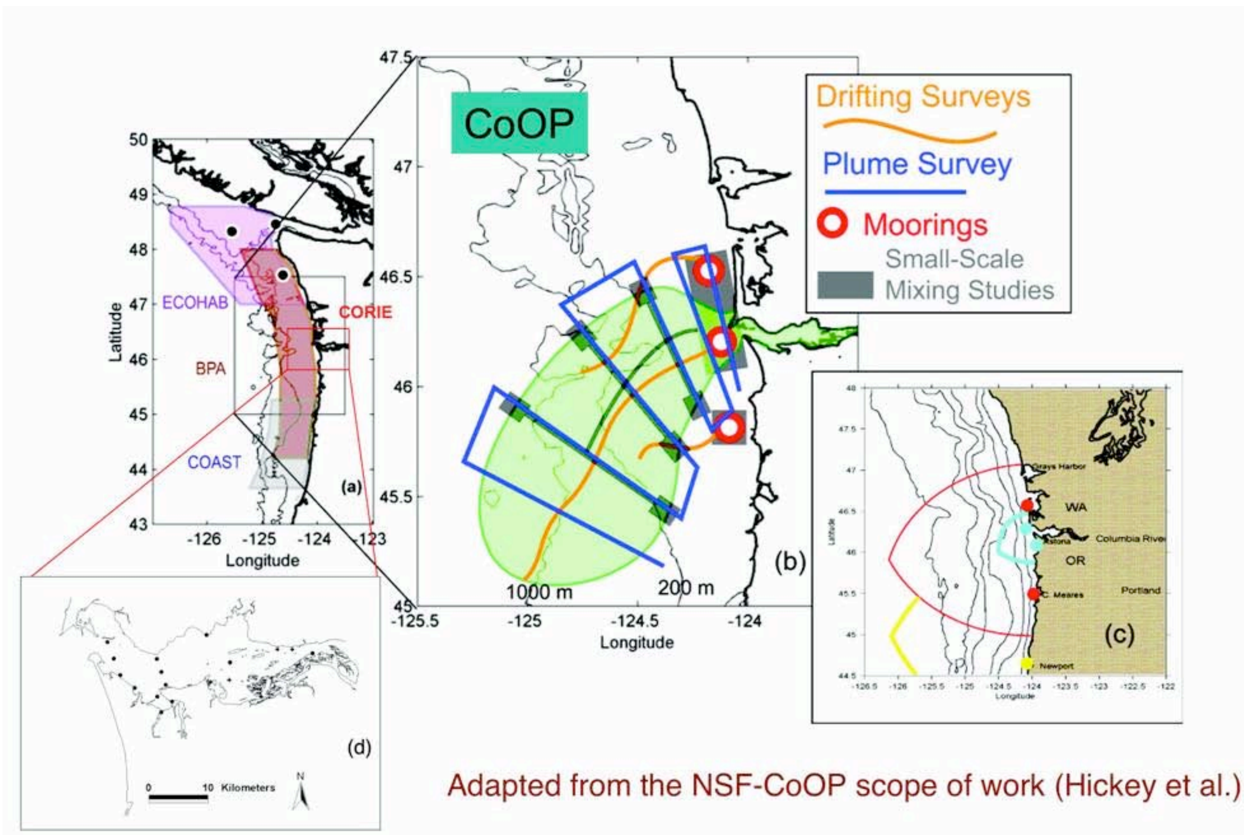

Figure 13. (a) Some major Oregon-Washington oceanographic field programs: ECOHAB, Bonneville Power Administration (BPA) studies, and the CoOP project Coastal Advances in Shelf Transport (COAST). (b) and (c) Elements of the CoOP project, River Influences on Shelf Ecosystems (RISE) (adapted from RISE, Hickey et al., *http://oceanweb.ocean.washington.edu/rise/overview.htm);* and
(d) A schematic of the Columbia River Estuary (CORIE) observation network.

Seismology and Geodynamics

Doug Toomey, Anne Tréhu, Leaders; Andrew Barclay, Bill Chadwick, David Christie, Bob Dziak, Roy Hyndman, Jim Jackson, Randall Keller, Kristi Morgansen, Tom Pratt, David Rodgers, Keith Shepherd, Michael Slater, Debra Stakes, Minoru Taya, Eleanor Willoughby, Harry Yeh

Introduction

The seismological and geodetic components of NEPTUNE will provide a unique opportunity for long-term monitoring and investigation of the inter-related processes that control the formation, evolution, and destruction of an oceanic plate and of the interactions of that oceanic plate with the leading edge of a continental margin. Understanding the life cycle of an oceanic plate and its interactions with an adjacent continental plate will require a series of experiments that address processes at a variety of scales, ranging from plate-scale monitoring (using arrays with apertures of about 1000 km) to more local experiments with apertures on the order of a few kilometers. Figure 14 shows one type of plate deformation model with implications for seismic hazards that can be tested using data from NEPTUNE. A particularly exciting advantage of a NEPTUNE-like facility is its ability to monitor and investigate multi-scale phenomena over an extended period of time.

In June 1999, an *ad hoc* working group met as part of the NEPTUNE Feasibility Study to discuss the important seismologic and geodynamic questions that a NEPTUNE facility could address. A comprehensive report was produced, and we refer the reader to the NEPTUNE Science White Paper #2, *Opportunities for Seismology and Geodynamics (http://gore.ocean.washington.edu/reportsmeetings/neptune_seismology),* referred to here as S&G-WP1. The outstanding scientific issues discussed in Section 3 of S&G-WP1 include:

3.1 The seismic potential of the Cascadia subduction zone
3.2 Mechanisms of plate deformation and interactions
3.3 Structure and evolution of the lithosphere / asthenosphere system
4. Earthquakes and geological processes at plate boundaries

Each of these broad scientific issues encompass several specific scientific questions that the *ad hoc* working group discussed in some detail.

The previous *ad hoc* working group also made general recommendations for the characteristics of the proposed seismic and seafloor geodesy networks, and we refer the reader to sections 4 and 5 of that report:

4. Seismic network
4.1 Network design and priorities
4.2 Sensor choices and installation
4.3 Network operations
5. Seafloor Geodesy

Given the extensive nature of the previous report (S&G-WP1), we focus in this document on some important phenomena that have been recognized since publication and then make recommendations to help achieve the NEPTUNE vision in a timely and effective way. We note that the participants of the Portland meeting agreed with the contents of S&G-WP1. Consequently, what appears in the remainder of this document can be viewed as additions to the previous report.

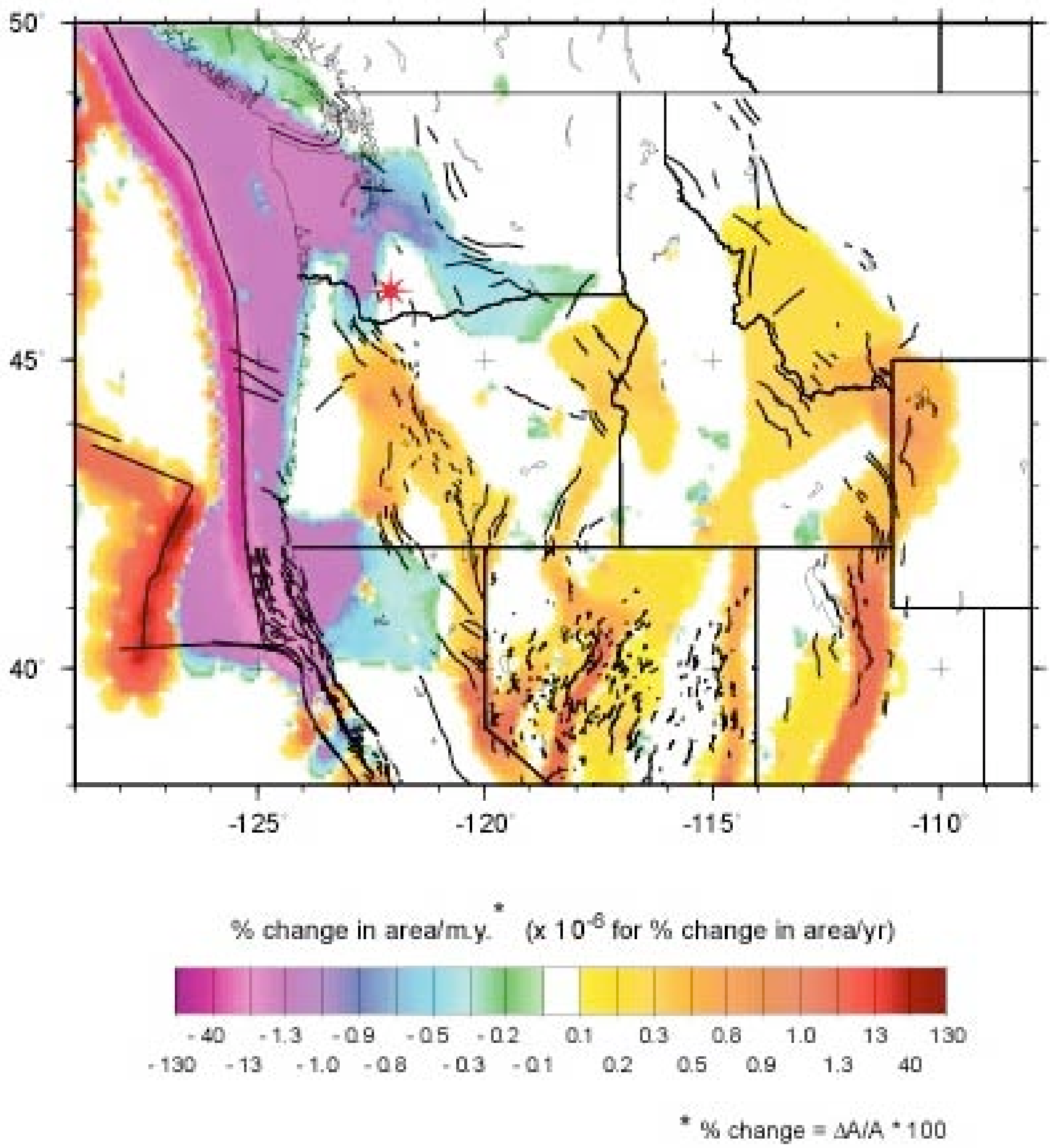

Figure 14: Isotropic strain map for the preferred model for Region 3, Pacific Northwest. Warm colors (red) indicate a gain in area (dilatation). Cool colors (purple) represent a loss of area (contraction). Strain values are log scaled. Largest values are along the Cascadia subduction zone, Gorda ridge, Klamath Mtns. And Olympic Mtns. Red star is the preferred Euler vector location for the Coast Range rotation (Hemphill-Haley, 1999).

Scientific Rationale

The working group generally agreed that the scientific issues discussed in S&G-WP1 were fundamental and comprehensive. However, there was considerable discussion of two general questions inspired by the report. The first question was how best to synthesize the scientific motivations presented in S&G-WP1 so that it was clear that each was part of an integrated effort to understand the dynamics of an oceanic plate system. The second question was whether there were additional scientific objectives inspired by recent discoveries that were not included in the previous report. We will address each of these topics in turn.

NEPTUNE provides the scientific community its first chance to study plate-wide processes. To understand this (or any other) oceanic plate system, we must accomplish the following:

- Delineate the physical characteristics of the plate and underlying mantle
- Understand the formation of oceanic crust and lithosphere at the ridge
- Understand how the oceanic crust and mantle evolve with age (including sedimentation on the plate)
- Understand the destruction of the plate at the subduction zone
- Understand the interaction of the ridge, intraplate, and subduction zone processes and the time scale of this interaction

The need for a plate-wide observatory

The working group put particular emphasis on the last objective. Achieving this objective requires that we study the plate-scale system as a whole, in contrast to studying a series of disparate and (conceptually) unrelated processes. The working group agrees that practically every topic discussed during the meeting or presented in the S&G-WP1 fits into one of the above categories, and thus contributes to an overall goal of understanding an oceanic plate. The links, however, are not always explicitly defined. We recommend that future NEPTUNE planning documents emphasize this aspect of NEPTUNE.

Interactions between plate boundaries

Since preparation of S&G-WP1, interactions between tectonic, magmatic, hydrogeologic, and biological processes along the ridge axis and near ridge-transform intersections have been discovered (e.g, Delaney et al, 1998; Johnson et al., 2000; Dziak et al., 2003, Lilley et al., 2003). Seismic and/or magmatic activity can trigger active fluid flow, resulting in the release of warm, bacteria-laden fluids into the ocean. Tidal influence on mid-ocean ridge seismicity (Wilcock, 2001; Tolstoy et al., 2001) and vent activity has also been recognized. Similarly, forcing of fluid flow by tides has been documented at accretionary complexes (Torres et al., 2002), and forcing of flow by regional and local earthquake activity is suspected but has not yet been clearly documented.

While studies in the marine environment have been restricted to correlations between magmatic, tectonic and hydrologic processes on a local scale—because of the local nature of the available marine data sets—studies of hydrothermal systems on land, which have access to a variety of continent-wide data networks, suggest that distant earthquakes affect local hydrology and seismicity (Brodsky et al., 2000; Gomberg and Davis, 1996). The mechanism for these long-distance tectonic/seismic/hydrogeologic interactions remains elusive. Acquisition of synoptic plate-wide observations of seismic activity, strain, and hydrological properties from a small oceanic plate has the potential to reveal the mechanisms responsible for these plate-scale processes. A better understanding of such long-distance stress propagation, in turn, has the potential to lead to major advances in understanding what triggers major natural hazards such as subduction zone earthquakes and tsunamis caused by earthquakes and/or submarine landslides, and eventually developing effective warning systems.

It is also likely that there are multiple feedbacks between tectonic activity and fluid flow. For example, fluid flow alters the chemistry of rocks, thus altering their physical properties and their response to tectonic stress. In sediments, fluid flow leads to mineral deposition, resulting in clogged plumbing systems, stress accumulation, and renewed earthquake activity. The time scale of these feedbacks is probably too long to be captured in short-term focused experiments of the sort possible with self-contained autonomous arrays. Identifying and understanding these feedbacks requires NEPTUNE's capabilities. Long time series with real-time data access are needed to detect changes as they occur and to reconfigure instrumentation and sampling rates to optimize data return.

Early warning systems for earthquakes and tsunamis

Real-time data access also has the promise of enhancing earthquake and tsunami early-warning systems. Earthquake early-warning systems are currently in effect in Japan, Mexico, and Taiwan, and a new algorithm has recently been proposed tailored to Southern California (Allen and Kanamori, 2003). These systems require real-time, networked access to data from sensors near the earthquake source. NEPTUNE will enable deployment of seismometers and pressure sensors in an array along the deformation front of the Cascadia subduction zone. These sensors can be used to quantify offshore ground motions as they happen, thus providing near-source data on offshore earthquakes and slope instabilities. This is of great importance to the Pacific Northwest because very large earthquakes and tsunamis originating offshore on the plate boundary between the Juan de Fuca and North American plates have occurred in the past and are bound to happen again. Recent experience in Japan with offshore cabled stations, which recorded seafloor ground-motion data from the recent Tokachi-Oki earthquake, have demonstrated both the scientific value and survivability of such stations.

Two sample community experiments

A plate-wide seismic and geodetic observatory

Distribution of seismic and geodetic instruments around the entire plate is essential to achieve the objective of monitoring the entire plate at once and thus detecting interactions between deformation along plate boundaries and in the interior of the plate. A first attempt to define an array for resolving mantle flow patterns associated with plate motion and propagation of strain pulses through a plate is discussed in S&G-WP1. However, the report does not rigorously define the minimum and optimum station distributions needed to successfully achieve these objectives. Moreover, it is likely that funding constraints will result in a phased implementation of the NEPTUNE facility, an issue that the working group discussed without coming to a clear resolution. A detailed analysis of instrumentation capabilities and costs and of the tradeoffs between different possible instrument configurations is necessary before either a complete array design or a phased implementation plan can be recommended. Modeling studies are not trivial undertakings that can be accomplished in a few days in a workshop setting. Rather, it will require realistic, quantitative analyses of competing scenarios. NEPTUNE, or its supporting program, should allocate funds to support several modeling efforts to define the minimum sensor configurations required to achieve the scientific objectives and use these design studies to establish a plan to phase in array installation. Any such plan should be constructed so as to maximize the scientific return at each stage of implementation. Suggestions that the National Science Foundation will support such studies through peer-reviewed proposals are not realistic. A second issue, discussed further below and not yet well resolved, is that the data management needs for a plate-wide seismic and geodetic array will be similar to those that have been developed for IRIS and UNAVCO.

A local experiment to monitor simultaneously seismic activity, crustal deformation, and hydrogeologic phenomena

Networks with these objectives will have apertures of a few kilometers and will be needed along each of the types of plate boundary studied (ridge, transform, subduction zone). A detailed, comprehensive outline of such an array can be found in the section in this report entitled *Fluid Fluxes and Geophysical Processes in the Sediments and Crust*. Acoustic, seismic, and geodetic sensors are an essential part of such an array (see Table 3 in *Fluid Fluxes* section of this report). Also essential are high-resolution bathymetric, sidescan, and 3D seismic surveys to define seafloor morphology and subsurface structures. Repeated surveys will be needed to detect temporal changes. Because of the wide range of data types, the variable degree to which pre-processing is needed to make the data useful in integrated studies, and the need to search for correlations between data types that have previously been interpreted independently, considerable pre-experiment planning will be needed to define database format and the nature and structure of metadata that should be preserved.

Synergies

The synergy between the seismological and geodynamic component of NEPTUNE and other initiatives such as EarthScope [USArray and PlateBoundary Observatory (PBO)], and the Advanced National Seismic System (ANSS) are considerable. These related initiatives have been discussed in the *Linkages Outside NEPTUNE* section of S&G-WP1. Most importantly, timely implementation of NEPTUNE is particularly crucial because these other initiatives are well under way. Proposals for science related to Earthscope were due at NSF in July 2003. Installation of seismic and geodetic instrumentation for the USArray and PBO, respectively, is expected to begin in 2005, with major efforts in 2006 and 2007. NEPTUNE data acquisition should overlap in time with these initiatives to capture interactions between offshore and onshore plate boundaries.

Education and Outreach

Seismology and geodynamics lend themselves to a wide range of outreach efforts. The public's interest in hazardous earthquakes and volcanic eruptions is considerable and the potential for linking these more dramatic geologic events to hydrogeologic and biologic activity will certainly have a broad appeal. Examples of how seismology is being used in E&O activities can be found at the IRIS Web site.

Recommendations

Questions and recommendations resulting from the Portland workshop are summarized below.

1. What is the role of a data management and distribution center in NEPTUNE? A mechanism for efficient and comprehensive distribution of data to the community will be a critical component of NEPTUNE, and more attention needs to be directed to defining how this will be done. Addressing the *Seismology and Geodynamics* (S&G) group's objective of understanding links between tectonic activity and fluid flow will require merging and comparing multiple complex datasets, thus requiring community-wide efforts to define the data and metadata needed to achieve the science objectives. This difficult work must be done before installation of sensors. The S&G working group recommends that defining and supporting the data management system be considered to be a core NEPTUNE function.
2. What is the optimum distribution of sensors needed? The answer to this question is different for different scientific objectives and for different sensors. To date, most discussion of this issue has been qualitative and superficial, driven to some degree by the proposed NEPTUNE node spacing and unbounded optimism (i.e., detachment from likely costs). A detailed analysis of instrumentation needs and of the tradeoff between different possible instrument configurations is not a trivial undertaking and cannot be accomplished in a few days in a workshop setting. Rather, it will require realistic, quantitative modeling of competing scenarios. NEPTUNE should allocate funds to support several modeling efforts to define the minimum sensor configurations required to achieve the scientific objectives.
3. What is the most effective way of "populating" the NEPTUNE backbone? At present, the NEPTUNE plan encompasses only the communications backbone. While we expect that the community will be successful at raising funds both to install instrumentation and

conduct data analysis for focused, process-oriented research, we are concerned that the broad-based backbone of sensors needed to achieve plate-wide coverage will be difficult to fund through science grants to individual investigators or small groups of investigators. This base network (the scope of which is still to be defined) should be part of the core NEPTUNE facility.

4. A corollary of recommendations 1–3 is that various scenarios must be considered quantitatively and priorities need to be set to define the proper balance between the multiple critical elements of the NEPTUNE program. To do so, future working groups must be supplied with more quantitative data pertaining to the technological capabilities of instruments and to their costs. Armed with such data, teams of scientists can make more realistic and better estimates, given cost-benefit analyses, of the minimum configuration of a plate-scale network and a schedule for its phased implementation. These include the following: vertical hydrophone arrays; seafloor, buried, and borehole broadband seismometers; and geodetic instruments of various types as well as instruments required by the other working groups.

As the scientific rationale for the seismology and geodynamics group is well established and documented in S&G-WP1, the *Seismology and Geodynamics* working group believes that it is now time to make significant headway on these important issues related to implementation.

Fluid Fluxes and Geophysical Processes in the Sediments and Crust

Earl Davis and Marta Torres, Leaders; Ross Chapman, Carol Chin, Bob Embley, Martin Fisk, Fabrice Fontaine, Gary Klinkhammer, Kyohiko Mitsuzawa, Mark Nielsen, Clare Reimers, Roy Hyndman

Unique Utility of NEPTUNE

The Juan de Fuca plate provides an ideal location for studying interrelated hydrologic phenomena (e.g., stress, strain, and hydrologic transmission) that are both local and regional in extent (i.e., displaying coherent signals over scales of several hundred kilometers). The flexibility in experiment scale inherent in the NEPTUNE network configuration is ideal for studying the wide range of processes affecting fluid transport in sediments and crust. At the smaller, single-node scale (hundreds of meters to kilometers), local hydrologic processes can be studied in unprecedented detail. At the broader scale, the node distribution would facilitate simultaneous interdisciplinary observations made over the entire plate and would allow for interrelationships among hydrologic variations and their causes to be studied along the plate boundaries and in the plate interior. Relationships between processes occurring at plate boundaries and within plates are currently unknown, because traditional experiments done at each of these environments have been carried out independently by diverse teams of investigators. A node-based system will facilitate and encourage simultaneous observations of disparate nature that often tend to be uncoordinated but that if done together can be highly complementary.

The proposed NEPTUNE infrastructure provides the means to carry out long-term continuous observations that are difficult or impossible with traditional autonomous instrument deployments. Using NEPTUNE we can meet the following objectives:

- Acquire continuous, long-term, broad bandwidth data to characterize periodic (e.g., tidal) behavior accurately and to capture discrete episodic (e.g., tectonic and magmatic) events
- Obtain high-precision measurements coordinated in time and space
- Integrate information of hydrologic phenomena with other relevant data (e.g., oceanographic and seismic)
- Make use of power to permit occasional active pumping, heating, and/or biological experiments
- Develop a potential for AUV or moored water-column surveying and sampling

General Goals that can be Addressed by NEPTUNE

Hydrologic systems in the ocean crust and sediments at ridge crests, ridge flanks, and accretionary margins at subduction zones play key roles in influencing rock alteration, mineral formation, and hydrocarbon migration. Interstitial water, often present at elevated temperature and pressure, promotes major mass, heat, and chemical exchange between the oceans and the subseafloor, influences the mechanical properties of the rock that hosts it, and provides nutrients for seafloor and sub-seafloor microbial populations.

Hydrologic processes and their consequences are highly linked; to understand any single one requires an integrated knowledge of the others. For example, earthquakes are known to change the regional state of stress, and this, in turn, influences permeability, fluid pressure, fluid flow, and thus the transport of energy and mass. The inverse of this is also true. Rock alteration, mineral precipitation, and the formation of gas hydrate caused by fluid flow change the mechanical and hydrologic properties of the formation, probably to the point that seismogenic failure may ultimately be found to be inextricably linked to variations in the hydrologic state.

One of the primary goals over the next few decades will be to understand these linkages. We need to clarify the nature and quantify the magnitude of the episodic processes that may dominate hydrologic regimes near tectonically and magmatically active plate boundaries relative to the chronic state established by thermal buoyancy in hydrothermal systems and long-term strain in accretionary prisms.

Fundamental topics to be addressed by NEPTUNE observatories include the following:

- Magnitude and nature of permeability, variations with fluid pressure, and the spatial scales for the variations in permeability and storage capacity
- Magnitude and nature of storage properties, variations with fluid pressure, scaling (temporal, spatial)
- Relationships between permeability and other parameters (lithology, structure, lithostratigraphy, fluid chemistry, microecology, seismic properties)
- Magnitude of the global fluxes, size of reservoirs, residence times, response to transient processes (tides, seismic events)
- Response of the biosphere to composition, episodicity, and magnitude of fluid flow, and feedback between biological and geological processes
- Interrelationship of these hydrogeologic processes with lithospheric cycling, magmatism, seismicity, and formation of gas hydrates

Community/Interdisciplinary Experiments

Location criteria

Experiments spanning a broad range of scales are required to address the nature of chronic, periodic, and episodic hydrologic systems. At the node scale (hundreds of meters), sites must be well chosen with respect to structures that focus flow through the seafloor and allow seafloor and water-column monitoring instrumentation to characterize local budgets for energy and mass flow on a continuous basis. With few exceptions the sites must also provide good targets for drilling in order to allow the hydrologic state and properties of sub-seafloor formations to be observed (see discussion of *Generic Experimental Approach*, below).

A suite of such coordinated nodes is required at the plate scale. These would include sites at the plate boundaries to characterize the near-field response to episodic events and the intrinsic nature of important “type” examples of active hydrologic systems. In addition, nodes within the plate interior will address similar objectives but, in addition to the local objectives, will include the far-field plate-wide response to episodic events.

Exact locations must be established on the basis of high-quality site characterization; in many cases these should be considered in parallel with the process of establishing IODP drilling sites. Potential sites, some currently more “mature” in terms of site characterization and experimental objectives than others, are listed here, grouped in five general categories; Figure 15 shows the locations of the sites listed below.

Ridge crests: sedimented and non-sedimented

Endeavour Ridge and Axial Volcano – arguably the best understood axial systems where detailed mapping and many short-term monitoring experiments have been carried out. Both are hydrothermally and tectonically or magmatically active. Both will be the focus of considerable attention through the RIDGE2000 and NeMO programs in the future; NEPTUNE will become a necessary component of those research activities.

Middle Valley – a well-characterized sedimented rift that is hydrothermally and tectonically active. Borehole monitoring experiments at ODP Sites 857 and 858 provide an excellent starting point for a broader program for NEPTUNE monitoring here.

Cobb Segment – at present poorly characterized, but a likely candidate for future tectonic, magmatic, and hydrothermal activity and bound to be important in how it both responds and contributes to the regional strain field and related hydrothermalism.

Cleft Segment – segment analogous to the Cobb segment, not well characterized, but probably a key node in the segmented Juan de Fuca system. The Cleft segment may be highly coupled tectonically and hydrologically to episodic slip activity along the Blanco fracture zone.

Explorer Ridge – a site of recent hydrothermal investigations and known hydrothermal activity.

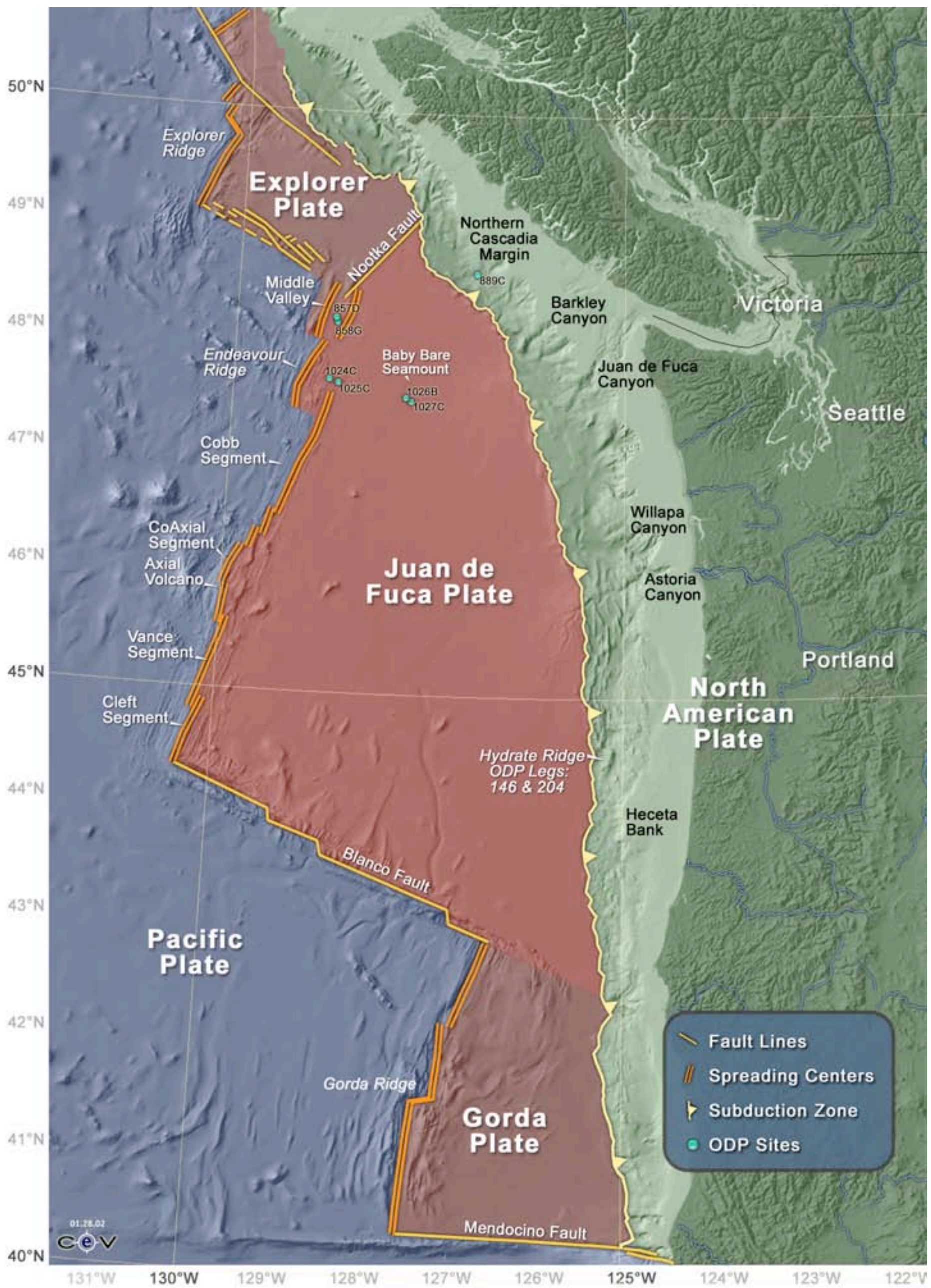

Figure 15. Locator map for features identified as experimental sites for fluid flux and geophysical processes studies.

Ridge flank

Eastern Flank of Juan de Fuca Ridge. – ODP sites 1024–1027 and other new sites to be proposed constitute a transect from the vicinity of the Endeavour Ridge axis to regions near the continental margin. This setting provides an opportunity to study hydrologic conditions in sediment-sealed igneous crust over the full width of the Juan de Fuca plate. It spans a range in lithospheric age from roughly 1 to 7 Ma and covers a range of crustal temperature from roughly 15°C to over 200°C.

Mid-plate basement outcrops (e.g., Baby Bare) - these sites serve as natural hydrologic windows into the otherwise completely sediment-sealed regional igneous crust.

Accretionary prism

Hydrate Ridge – offshore Oregon, is capped by gas hydrate, with massive near-seafloor deposits at its summit. This area includes focused aqueous and gas transport, as well as distributed flow. It has been well characterized by high resolution seismic and seafloor reflectivity surveys, as well as by several submersible programs to the area. Site of drilling during ODP Legs 146 and 204.

Northern Cascadia – ODP Site 889, offshore Vancouver Island gas hydrate study area that is relatively free of structural controls on flow; distributed flow is target of new IODP drilling proposal.

Shallow sites (above the gas hydrate stability zone) – potential linkage to shelf transfer studies, climate change, and fisheries, e.g., Heceta Bank.

Canyons – where these features might expose fluid migration patterns, resulting in fluid venting and in some cases gas hydrate formation at the seafloor, e.g., Barkley Canyon.

Subducting plate deformation studies – to study offshore strain associated with slow slip events just below the locked portion of the Cascadia megathrust interface, and other strain-related hydrologic processes deep within the accretionary prism.

Transform faults: earthquakes on a regular basis

Nootka fault – a sediment-covered highly active fault that intersects the accretionary prism, where seismic ground motion, hydrogeology, and mechanical properties can be studied.

Blanco fault – a classic transform, including extensional basins where hydrothermal venting may be focused.

Mendocino fault – high seismicity, overthrusting, and hydrologic activity at ocean/continent intersection indicated by presence of gas hydrates.

Intra-plate tectonic deformation

Gorda plate – thinly sedimented, episodic broadly distributed seismicity.

Explorer plate – thickly sedimented, continuous seismic activity.

Generic experimental approach

Many hydrologic characteristics, scientific objectives, and experimental strategies are common to all locations described above, and therefore they can be discussed in a generic way. The hydrologic structure and processes usually involve a deep hydrologic "reservoir", a "transfer zone," and seafloor manifestations of flow that are linked vertically and horizontally to one another, and respond to forcing functions that may be induced locally or regionally. Where this is true, a bottom-to-top approach must be employed to allow quantification of time-dependent state, properties, and fluxes in a comprehensive strategy that includes the water column, the seafloor, the transfer zone, and the reservoir (Figure 16). Sensors will differ among the sites, although the generic "blueprint" has broad application with suitable tailoring. A generic suite of sensors could include the following: broadband seismometer, broadband seafloor pressure, broadband formation pressure (possibly at multiple levels in a borehole), seep or vent-flow monitor, and continuous fluid sampler (where there is detectable flow; the latter to be done even if it needs servicing every couple of years).

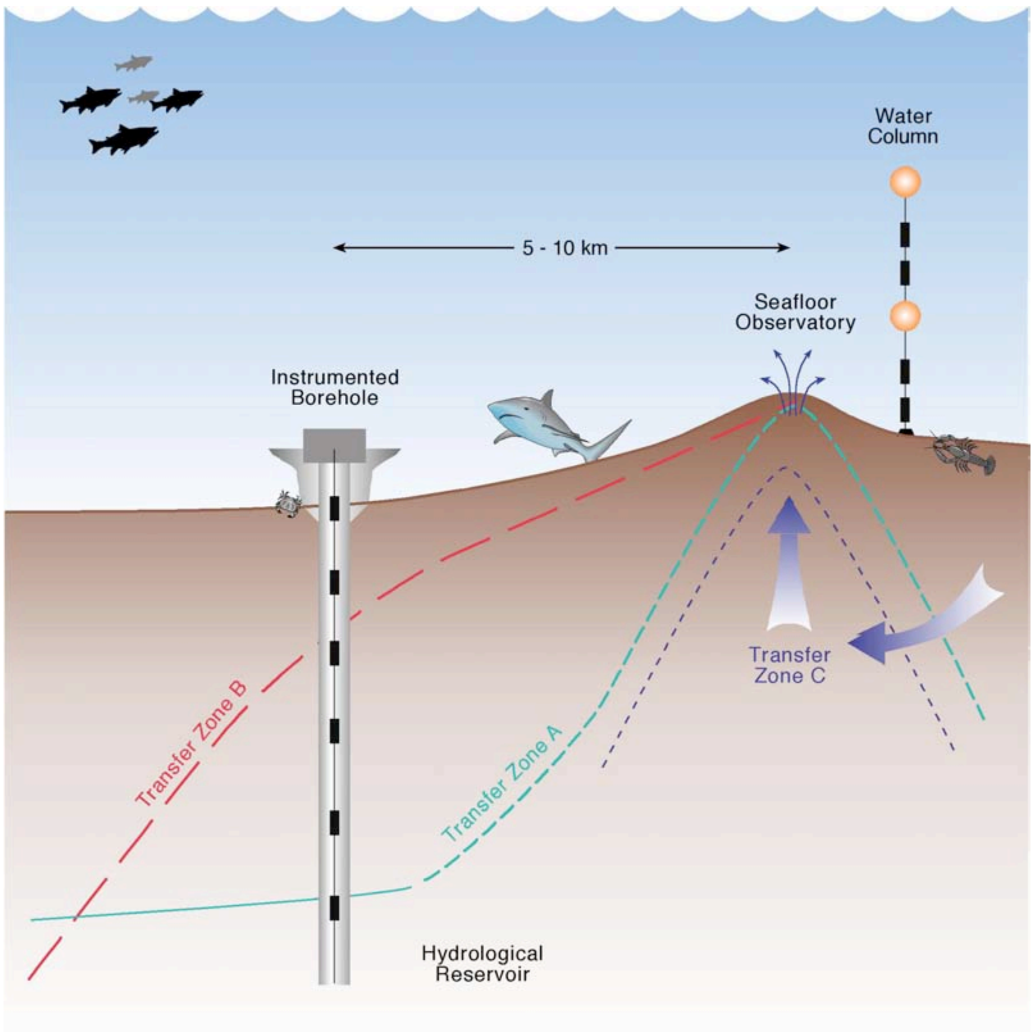

Figure 16. Schematic representation of a coupled "bottom-to-top" observatory at the node scale designed for quantifying fluid fluxes and geochemical processes in the sediments and crust. The general system involves: a deep hydrologic reservoir, which must be monitored by an instrumented borehole, a transfer zone, and seafloor manifestations. In this cartoon the reservoir represents either igneous crust beneath the sediments at ridge flank, or sections within the accretionary complex beneath the BSR. The transfer zone in ridge flanks is represented by hydrated sediments and crustal outcrops at the ridge flank (transfer zone A). On gas hydrate provinces, hydrocarbons migrate through structurally or lithostratigraphically controlled horizons (transfer zone B). At the ridge axis fluids migrate through a permeable crust (transfer zone C). Seafloor observatories at sites of fluid venting include axial vents, off-axis springs, and cold seeps. The water column serves as an integrated recorder of large axial vent plumes, small flank spring plumes, and gas-bearing margin seeps. The instrumentation for the boreholes, seafloor, and water column monitoring is detailed in Table 3.

Most sites should ideally incorporate borehole experiments, with the possible exception of unsedimented ridge-axis sites, only because they do not lend themselves to drilling with present technologies. Details for the approach proposed for ridge flanks, gas-hydrate bearing settings, and ridge axes are summarized below, and specific sensors and instrumentation packages are listed in Table 3. In all cases, we envision the horizontal extent of these borehole observatories to be on the order of 5 to10 km.

We foresee that the largest power need will be that required by occasional active pumping and hydrate decomposition experiments, but these needs are as yet ill defined. In addition, to determine integrated fluxes and plume characterization we envision significant occasional power requirements to support a variety of instruments for a comprehensive response to events at a ridge axis. However, in the majority of the cases, the autonomous sensors that have been up to now powered by batteries will be adapted to the cabled network, and these by definition have small power requirements.

NEPTUNE's many advances will enable a quantum step forward in fluid flux and geophysical processes studies. The increase in bandwidth for signal detection will be very large. Instruments will be able to run without disruptions and associated calibration uncertainties, data gaps, etc. for long periods of time, thus pushing confident hydrologic signal detection into annual to decadal periods. Power, data flow, and accurate time will easily push signal detection into seismic periods. We know that there are linkages and feedbacks between hydrology and seismology, geodynamics, oceanography, and the deep biosphere. However, studying such linkages with current technologies is painfully inefficient. Cabled, autonomous observatories will render these studies dramatically easier.

Ridge-flank scenario

Pre-site characterization. A good understanding of heat budgets, locatable springs, and an instrumentable boundary at the seafloor is required.

Approach. Monitor coupled reservoir-specific processes with seafloor observations to establish variability in various spatial and temporal scales (meters to kilometers, minutes to years) tied to various forcing mechanisms. Borehole observations should be conducted in sediment covered crust and at an outcrop, instrumented with an array that is of the proper scale to monitor reservoir characteristics, and should include monitoring of pressure, temperature, and resistivity, fluid sampling, incubation experiments, and active hydrologic experiments via pumping and tracer analyses (Table 3). These coordinated active and passive hydrologic, biologic, and seismic experiments will address fundamental questions about the most extensive hydrogeologic formation on Earth: the oceanic crust.

Gas hydrate provinces

Site characterization. Ideal sites for establishing seafloor observatories should have surface manifestations of fluid venting and hydrate deposits. These should be linked to borehole experiment sites where the presence and/or absence of structural controls for fluid flow (e.g., faults, high permeability horizons, anticlines, and seismic "wash-outs") have been adequately mapped by geophysical surveys and/or deep sea drilling.

Approach. Monitor coupled reservoir-specific process with seafloor observations to establish the variability at the various scales associated with various forcing mechanisms (Table 3). Because the response occurs in a three-dimensional space, a suitably instrumented borehole array in gas hydrate provinces would provide a tomographic image to monitor the hydrological system over time. At least some of these boreholes should be drilled and cased to ~1000 meters for monitoring changes in the chronic long-term strain of the deeper parts of the accretionary prism, and to quantify the response to the changes in properties of the formation above the bottom simulating reflector (BSR). The casing should include windows to systematically characterize the formation as well as to allow for sampling at specific horizons, which include the following:

- Generation zone – for repeated hydrocarbon and biology monitoring (either by sample collection or *in situ* sensors), at *in situ* pressure and temperature
- Base of gas hydrate stability zone – where the spacing and density of sampling windows should be determined by hydrate distribution and formation properties
- High-permeability horizons – where stratigraphy (e.g., high permeability sands) or structure (e.g., faults) might dictate location and response of fluid flow to changes of formation state

Ridge axis

Site characterization. The site must be well mapped, and should preferentially be hydrothermally and tectonically or magmatically active.

Approach. The observatory design for ridge-axis settings has been well developed in the NEPTUNE Feasibility Study (Science White Paper #3: Seafloor Hydrogeology and Biogeochemistry). It includes a variety of seafloor monitoring instrumentation, coordinated with an oceanographic net to establish fluxes and map plumes (Table 3). At present, technology for drilling in very young crust is still developmental and high-temperature and corrosive fluids pose a challenge for borehole seals. Once the necessary technology matures, however, use of boreholes for hydrologic monitoring and experiments will be a central part of ridge axis observatory studies.

Synergies

The program described here has significant internal and external synergies. Within NEPTUNE the understanding of fluid fluxes and geochemical processes in the sediments and crust requires extensive coordination of hydrologic experiments with the design of seismometer arrays and water-column observations planned by other groups. Interactions are thus foreseen with geodynamics, ocean chemistry, microbiology/ecology, and sediment-transport groups. There is also a variety of external synergies, the most clear of which is coordination with IODP for deep-sea drilling and borehole installation and instrumentation. In addition, cooperation with the Polaris/Earthscope/US Array, and Ridge2000 programs will be very valuable.

Education and Outreach

Short-term hydrologic signals generated by tidal, barometric, and oceanographic (e.g., mesoscale eddies) forcing may lend themselves to real-time display.

Table 3. Characteristics of Water Column, Seafloor, and Borehole Observatories for Quantifying Fluids Fluxes and Geochemical Processes in the Sediments and Crust

Type locations	Ridge flanks	Gas hydrate provinces	Ridge axis
Water column: to monitor integrated response of the system over a fluid discharge area			
Mooring: designed to collect samples, and data with *in situ* chemical sensors, current meters, transmissometers, CTD and high sensitivity pressure sensors	Would only be appropriate if flow at the seafloor is large enough that the mooring instruments can capture variations in chemical or heat flux.	Include devices for monitoring and quantifying gas flow when appropriate.	Oceanographic net to establish fluxes and map plumes (see white paper)
AUV response	Not needed	Could be wireline deployed	Sampling on regular schedule as well as vent response
Acoustics	Not needed	Tomography and passive acoustics	Active sonar
Up-looking ADCP	yes	yes	yes
Seafloor: to quantify relationship of forcing function and seafloor response on a wide dynamic range			
Array of fluid flow measurements to characterize temporal and spatial variability of out and inflow. These might include mechanical, osmotic (non-real time), thermal, Cl-conductivity meters	yes	yes	yes
Seismometer local area network: (broadband, strong motion and hydrophone- to be coordinated with seismology group).	yes	yes	yes
Time series of temperature, pressure, electrical conductivity, self potential	yes	yes	yes
Macrobiology (bio-cameras and interactive experiments)	yes	yes	yes, also real time video at both high and low temperature vents
Microbiology, activities, enzymes and cultures. Interactive experiments	yes	yes	yes
Oceanographic parameters (e.g., currents, tides)	yes	yes	yes
Fluid composition by sampling and sensors	yes	yes	yes
Seafloor compliance	yes	yes	yes
Quantification of gas discharge by a variety of tools, which might include: backscatter imaging of gas plume, cameras, methane sensors, optical sensors.	not needed	yes	not needed
Sampling of sediments and pore fluids at pressure	not needed	yes	yes
Rovers to sample a seafloor footprint in response to episodic events	yes	yes	yes
Shallow drill holes provide access to levels below seafloor hydrologic complications and can be useful for geochemical and microbiological processes	yes, use outcrop as a producing well to maximum potential.	yes	yes
Horizontal and vertical strain	yes	yes	yes
Borehole:			
Pressure	yes	yes	Challenges: **1.** Temperature and corrosive environments on borehole seals; **2.** Establishing holes in highjly fractured rock; **3.** High potential for perturbation. Need to carefully evaluate experience at TAG to determine whether bare-rock holes would be useful for monitoring purposes.
Temperature	yes	yes	
Flow meters with limited moving parts, opportunities for addressing biofouling issues (heat pulse, Doppler)	yes	yes, particularly important in areas of rapid gas hydrate formation	
Indirect fluid flow (via tracers and temperature perturbation proxies)	yes	yes	
Fluid composition via 1) sampling (e.g., osmotic samplers) and analyses of major and minor elements, organics, and 2) sensors: e.g., CO_2, sulfide and other reducing species, radon, organics.	yes	yes	
Microbial response (enzyme activity, in situ cultures)	yes	yes	
Particle density	yes	yes	
Interactive hydrologic experiments, including pumping and tracers	yes	yes	
Real-time access to data, preliminary analyses, to adjust testing and sampling parameters	yes	yes	
Tests from borehole to seafloor	yes	yes	

Ecosystems and the Carbon Cycle

Kim Juniper and Ricardo Letelier, Leaders; Paula Aguiar, Sandra Brooke, Bill Fornes, Brian Hall, Joost Hoek, David Martin, Monica Orellana, Antoine Pagé, Timothy Petersen, Kenneth Stedman, Ger van den Engh, Jan Newton, Robert Collier

This working group had expertise in phytoplankton ecology, deep-sea microbial ecology, optical oceanography, chemical oceanography and carbon fluxes, coastal and estuarine ecology, benthic macrofauna, especially larval dispersal and reproductive cycles. It lacked representation in the areas of zooplankton, nekton, and mezopelagic systems.

The primary goals addressed by this workgroup were: 1) how NEPTUNE could help improve our understanding of the pelagic and benthic ecosystem and 2) the identification of critical scientific questions that could be addressed by researchers using the NEPTUNE infrastructure.

Key Scientific Questions

There are some clear areas in marine ecology and biogeochemistry in which basic knowledge has been hampered by the lack of information. The following is a description of some of the most compelling questions that could be addressed by the NEPTUNE observatory. Because of the intrinsic characteristics of the systems and methodologies used to study them, we have divided our discussion into deep-sea and water-column domains.

Deep-sea ecology

1. *What determines faunal diversity on the deep-sea floor*? Observed high faunal diversity in what appears to be a relatively uniform environment on the floor of the deep ocean has puzzled ecologists for decades. One school of thought proposes that this diversity is the result of spatial patchiness, created by small-scale disturbances. Thus the deep seafloor consists of a mosaic of patches at different stages of development and recovery from disturbance, permitting the existence of an abundance of species with different and even similar niche requirements. Considerable progress in understanding this question could come from the extensive use of AUVs proposed for NEPTUNE node stations. Repeated, high resolution mapping of the seafloor would provide data to both confirm the existence of faunal patchiness among the visible megafauna and document their temporal evolution. In addition, systems could be developed for passive and active collection and preservation of specimens. As well, shipboard sampling will be required to confirm visual identification of megafaunal species and to verify corresponding patchiness among associated sediment infaunal species.

2. *How does particulate organic matter (POM) distribution affect the fauna*? The availability of POM is of fundamental importance to the deep-sea fauna. Observed seasonal cycles in benthic fauna appear to be driven by the cycle of energy fluxes to the benthos. Continuous time series studies and repeated high-resolution surveys will potentially make major contributions to our understanding of how the movement, life histories, and recruitment patterns of the seafloor fauna are affected by the spatial and temporal distribution of fresh organic matter.

3. *How do deep-sea ecosystems respond to perturbations of different magnitude?* The key role proposed for perturbations in deep-sea benthic ecology will be an important focus of NEPTUNE research. Both continuous time series studies and repeated high resolution surveys will allow scientists to document the frequency and scale of perturbations such as benthic storms, organic matter sedimentation events, and anthropogenic disturbances, and study the biological responses to these perturbations, from the specific to the ecosystem level.

4. *What are the stability characteristics of hydrothermal vent and cold seep environments?*

Hydrothermal vents and cold seeps are located in areas of intense geological activity but their response to rapid or catastrophic environmental change is poorly understood. Continuous local and site-scale monitoring of vent and seep habitats by NEPTUNE will allow exploration of questions such as the relative stability of vent versus seep communities, and characterize patterns of community succession.

5. *How do hydrothermal systems influence neighboring environments*? The movement of organic carbon produced in hydrothermal vents is probably a source of energy for neighboring communities and water-column microbial assemblages. The quantification of this transport and its relative contribution to the total organic matter required to support heterotrophic activity on the Juan de Fuca plate is an important ecological and biogeochemical question that can be addressed using the NEPTUNE infrastructure.

Water-column processes

NEPTUNE will permit continuous, three-dimensional monitoring of water column processes at the scale of the Juan de Fuca plate. This creates considerable potential for advancing our understanding of ecological and biogeochemical processes at the scale of an oceanographic region. The group identified potential areas of impact on research in both the surface ocean and the meso-pelagic zone.

1. *What is the role of coastal upwelling systems in the control of carbon fluxes across the air/sea interface?* While continental margins occupy <10% of the ocean surface area, organic carbon production in these regions represents up to 30% of total ocean production. Tsunogai et al. (1999) delineate several mechanisms that may act to pump CO_2 from continental shelf regions into intermediate and deep oceanic waters and estimate that this "continental shelf pump" could be responsible for as much as a 1 Pg C sink annually on a global basis. One of their proposed mechanisms is consistent with the recent observations of a large offshore transport of dissolved organic carbon (DOC) from the Mid-Atlantic Bight (Valho et al., 2002). But the generality of margins being autotrophic is uncertain (Smith and Hollibaugh, 1993). Additionally, numerous other biogeochemical processes focused at continental margins could significantly alter global distributions and fluxes of carbon and other bioactive elements. These processes include such phenomena as 1) coastal upwelling, off-shore transport in advective filaments, 2) accelerated cross isopycnal mixing due to turbulence associated with bottom friction, 3) accelerated vertical particulate flux and 4) interactions with bottom sediments and pore waters that may alter macronutrient and micronutrient abundances. The offshore length scale of these phenomena is generally several hundred kilometers. Therefore, while the continental margin system includes the continental shelf, it generally extends over the continental slope and rise regions as well. A comprehensive study of the magnitude of organic production and its fate in coastal environments requires the design of sampling and experimental strategies that may be addressed only within an ocean observatory such as NEPTUNE.

2. *How do carbon fluxes and elemental ratios change with ecosystem structure?* The structure of oceanic food webs influences the quality and amount of carbon export from particular ecosystems, as well as the elemental ratios of its biota and the inorganic nutrient pools in the water. Food web structures vary in space and in time over seasonal, annual, decadal and geologic time scales. Elemental stoichiometries, the ratios of one element to another in either the particulate or dissolved phase, are often key elements of geochemical models. They are emergent properties of marine ecosystems, dictated by the differential partitioning of elements as they flow through the food web. We do not fully understand what constrains these ratios, but do know that output of geochemical models can be very sensitive to assumptions about these stoichiometries. In order to understand how ecosystem structure

affects the flow and distribution of bioelements in the marine environment, we need to monitor and study elemental fluxes over a large range of pelagic ecosystem types. The geographic study region of the NEPTUNE network will cover ecosystem structures ranging from coastal eutrophic, to open ocean oligotrophic.

3. *What is the fate of the organic matter produced by upwelling systems?* The transfer of organic carbon from the surface ocean to the deep sea is one of the primary factors regulating the CO_2 content of the atmosphere. Roughly 90% of the organic carbon exported from the surface ocean is respired in the mesopelagic zone (approximately 100 to 1000 m), corresponding to the thermocline in much of the world's ocean. The thermocline is ventilated on time scales of decades, roughly an order of magnitude faster than the ventilation of the deep sea. Consequently, carbon regenerated in the deep sea remains isolated from contact with the atmosphere much longer than does carbon regenerated in the mesopelagic zone. Moreover, in coastal environments organic carbon remineralized in the shelf may be released back into the atmosphere as a result of winter mixing, or transported across the shelf into the deep ocean through advection. In this context, the NEPTUNE laboratory will provide the basic infrastructure to continuously track the fate of organic matter leaving the euphotic zone in oceanic regimes ranging from coastal upwelling to oceanic oligotrophic, and to examine the influence of varying climatic and oceanographic conditions on this process.

4. *How do oceanic and climatic regime changes affect ecosystem structure and elemental fluxes?* Changes in environmental climate may involve changes in the baseline conditions (i.e., increased sea surface temperature and water column stratification or shift in the timing of the spring transition), changes in the intensity of mesoscale perturbations (i.e., increase in storm intensity or upwelling events), or changes in the rate of perturbation events (i.e., increase frequency in El Niño Southern Oscillation events). Each one of these perturbations may generate significant changes in the ecosystem structure and associated biogeochemical cycles.

5. *What is the role of the mesopelagic assemblage in the transport of organic matter to the benthos?* The depth scale for remineralization of particulate organic carbon within the mesopelagic zone is regulated by the interplay between the sinking rate of particulate matter and the factors that control its conversion to a suspended or dissolved phase. Aggregation, disaggregation, dissolution, and remineralization are all factors that influence the size, composition, density, and sinking rate of organic and inorganic particles. Organisms play an active role in these processes.

6. *How does mesopelagic microbial activity vary in time and space?* Excluding hydrothermal inputs, the rate at which organic matter reaches the benthic environment is a function of the amount of organic matter being exported from the euphotic zone, and the rate of remineralization within the water-column. Empirical power-law fits to a composite of shallow floating sediment trap data (e.g., Martin et al., 1987) are often used to describe remineralization length-scales and export to the deep ocean. However, the parameters used to fit these empirical relationships are found to vary from site to site, indicating that these parameters are sensitive to changes in local conditions. Predictive models must be mechanistic in nature and account for factors that influence the power-law relationship, such as climatic change, episodic bloom events, mineral ballasting, food web structure, etc.

Role of NEPTUNE

Ecological and biogeochemical modeling represent ultimate scientific end-uses of NEPTUNE-based research.

Numerical Models. NEPTUNE will produce unique data sets in several areas that will permit major advances in the development of numerical models of ecological and biogeochemical processes in the ocean. These include the following:

- Reactive spatial and temporal coverage. NEPTUNE infrastructure will permit sampling over a large range of spatial and temporal scales. In addition, sampling resolution may be changed in response to the detection of events in order to document rapid change
- High-quality, multi-variable data sets to explore and test causal relationships
- A well-characterized ocean environment within which process studies can be developed
- Broad spatial coverage by the NEPTUNE instrument network will permit the rapid quantitative assessment of ecosystem states, and provide the power to predict future states
- Great potential for numerical experimentation and the testing of system stability and resilience. For example, NEPTUNE instruments could permit researchers to track the propagation of perturbations through the physical and biological components of the marine ecosystem

Conceptual Models. We expect that the expansion of observational scales made possible by NEPTUNE will result in an expansion of our conceptual framework. As a result, NEPTUNE will enable new discoveries and the development of new hypotheses about causal relationships in the marine environment, leading to new conceptual models of ecosystem function. NEPTUNE offers considerable potential for accelerating the process by which field observations lead to concept genesis, followed by the development of new numerical models and finally quantitative testing in the field.

Example Community Experiments

Upper water-column variability and production export

How does the spatial and temporal variability of upper water-column processes affect food export to the benthos? Answering this question will require addressing all areas of research described in the previous section, and cannot be undertaken without an infrastructure of the kind proposed for the NEPTUNE observatory. It requires, among others issues, characterization of the spatial and temporal variability in surface production and export, and documentation and modeling of the Lagrangian trajectory of organic matter in the water-column. In order to accomplish this goal we will need to characterize, measure, and quantify the following:

- Chlorophyll as a proxy for phytoplankton biomass from space; validate using mooring measurements
- Physical and chemical (nutrients) water-column structure, including light (from moorings)
- •Export organic matter fluxes derived from surface production data and models and measured in the seafloor using sediment traps
- Transformations of organic matter through the water-column

Benthic ecosystem response

To detect the response of deep-sea benthic ecosystems to changes in organic matter flux, we must first understand the nature of spatial and temporal variability of benthic ecosystem structure over a large geographic area encompassing a broad range of environmental conditions. This will require the use of the following:

- An array of fixed time-series cameras and AUV imaging (visible species and faunal traces)
- Sampling surveys to ground truth the imaging characterization of benthic diversity

We will also need to understand benthic community functionality. This might be best achieved through intensive studies at key representative locations focusing on processes such as benthic respiration, larval supply and colonization, and bioturbation using benthic chambers, and characterizing chemical, microbial, and meiofaunal gradients in the sediments, and that of microbes and meiofauna. The development of new conceptual and numerical models may be required to couple the spatial and temporal variability observed in surface waters with that observed in the benthic environment. We will also need to constrain the range of water column physical variables affecting biological processes in the studied area.

Recommendations

Site selection

The NEPTUNE infrastructure will allow the development of the nested observational collection strategy required to address the scientific questions outlined above. The selection of observatory sites should cover a broad range of conditions determined by the large-scale hydrographic patterns, general circulation, biogeochemical variability, and topography of the region. Remote sensing data will provide invaluable complementary information regarding the large-scale distribution of sea surface characteristics.

Coastal circulation in the east boundary of the North Pacific is intense, and our working group recommended that a large-scale benthic and water column observation infrastructure incorporate the following:

- *High east-west spatial resolution, including shelf stations.* East-west sampling lines should extend, when possible, from the continental shelf off the west coast of North America to the Juan de Fuca Ridge. Each line should contain a series of nodes for monitoring long-term changes in benthic and water column ecology and biogeochemistry on the shelf, the slope, the abyssal plane and the ridge.
- *Sparse north-south resolution.* In order to monitor the long-term ecosystem variability resulting from shifts in large scale circulation and the strength of eastern boundary currents, a latitudinal gradient sampling scheme should extend north and south of the North Pacific Current, with at least one east-west sampling line north of the center of this current, and two lines south of it.
- *Avoid stations directly influenced by vents and seeps.* Although our working group recognized the importance of studying the effects of vents and seeps on the deep-water column and benthos, we concluded that this aspect will be better addressed by other projects using the NEPTUNE infrastructure. Including vent and seep sites into a large scale sampling net will introduce a level of complexity difficult to address without increasing significantly the number of sampling sites.

The overall plan should also consider a set of small-scale study sites. These sites would be a subset of the large scale sites and would be equipped to address mesoscale spatial variability, allowing an in-depth characterization of benthic community structure and functionality. We expect that selected study sites will bracket the full range of upper water column primary production rates and water column depths. However, in order to understand how the flow of energy and organic matter from the euphotic zone is coupled to the benthic environment, we need to understand currents within the studied region. When possible, these small scale sampling sites should have replication. Some replication could occur through the comparison of selected small-scale study sites in consecutive latitudinal transects.

Instrumentation

Basic instrumentation for large-scale observatory sites should include the following:

- Benthos: CTD, and O_2 sensors, current meters/ADCP, fluorometer, scatterometer, transmissometer/nephelometer, acoustic transducers for navigation and communication, inverted echosounder, and ambient sound, camera (video and still)

- Water column: profiler equipped with CTD, fluorometer, radiometers, transmissometers, nutrient sensors, and current meters

The mesopelagic environment is a critical region of the water column that remains undersampled. Biological activity within this region is largely responsible for the decrease in fluxes of particulate organic matter between the base of the euphotic zone and the benthic environment. Hence, it plays a key role in the coupling of benthic biological activity to the upper water column. To date, most the research into organic matter remineralization in the water column below the euphotic zone has used deep-sea sediment traps. The inclusion of such measurements close to the seafloor but removed from the region where resuspension of particles may contaminate the signal is recommended. When alternative approaches that monitor microbial activity in the water column below the euphotic zone become available, they should be integrated within the NEPTUNE core sampling program in order to better characterize the vertical distribution of biological activity and elemental fluxes.

In addition to the equipment listed above for large-scale benthic sampling, small scale stations should include, when possible, autonomous underwater vehicle (AUV) technology in order to repeatedly survey mesoscale benthic variability around and/or between selected nodes. This will allow characterization and monitoring of benthic community structure. Ground truth validation from ship based sampling surveys will be needed as an integral part of this effort. In addition, and in order to characterize and monitor benthic community functionality, these stations should include the following measurements:

- Benthic respiration (O_2, CO_2, and other elemental fluxes across the water column–sediment interface)
- O_2 sediment profiles (sediment probes)
- Bioturbation rates and redox gradients in the sediments(using sub bottom cameras)
- Larval supply
- Fecundity (possibly using ROV technology to collect samples)
- Microbial and meiofaunal diversity and abundance (requires sediment sampling)

Although coastal environments are relevant to the study of the transfer of matter between land and marine environments or when assessing anthropogenic perturbations of the marine environment, our workgroup chose not to consider the coastal benthos because of a lack of expertise and the perceived high benthic spatial variability observed in this environment, which would require a complex sampling strategy just to determine general patterns (see the *Ocean Dynamics* section in this report for some discussion of coastal ecosystems).

Finally, it is expected that NEPTUNE will exploit, as well as foster the new technologies required to characterize and monitor biological diversity and activity in remote regions of the ocean. We anticipate that the sampling strategies proposed by our workgroup will evolve as a result of these new technologies and in response to an increased understanding of the study region.

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Appendix 1. Workshop Announcement

2nd Announcement
NEPTUNE Pacific Northwest Workshop
23 – 24 April 2003
Smith Memorial Center, Portland State University, Oregon

www.neptune.washington.edu www.neptunecanada.ca

NEPTUNE is planned to be the world's first regional, plate-scale cabled observatory. It will "wire" the Juan de Fuca Plate in the northeast Pacific Ocean, enabling the in-depth study and decadal time series observations of the regional oceanography, including biogeochemical cycles, fisheries and climate forcing, ocean dynamics, life in extreme environments, and plate tectonic processes, to name but a few topics. This "cabled observatory" will be based on a multi-node, submarine, fiber-optic/power cable network deployed around the plate and beyond. It will provide power for instrumentation (including ROVs and AUVs) as well as make seafloor sensors and interactive experiments easily accessible via the Internet to researchers, educators, policy makers, and the public around the globe.

We are working towards installing the NEPTUNE infrastructure beginning as early as 2007. Both shallow (VENUS) and deep (MARS) test bed systems are now funded, and will be installed in Saanich Inlet, the Straits of Georgia and Juan de Fuca (www.venus.uvic.ca, 2003–2005) and in Monterey Bay canyon (www.mbari.org/mars, 2005). Canadian funding for a portion of NEPTUNE-proper is almost in place. Building on these foundations and working in parallel with ongoing funding efforts, we must define the outstanding science questions and their required experimental systems, so that we can move into the technical design phase for NEPTUNE.

To address these critical challenges, NEPTUNE is conducting this workshop in the Pacific Northwest, one of a number around North America. Participation by a broad spectrum of researchers and groups is required to *define* the most innovative "lead-off" science (e.g., community experiments and instrumentation) that will generate exceptional results in the first few years of operation. We also need to *design* the NEPTUNE system to integrate new experiments through its lifetime and to generate high quality decadal time series observations to answer fundamental questions of the interacting Earth systems.

GOALS:
- **Inform the regional community of the remarkable opportunities provided by NEPTUNE.**
- **Maximize the opportunities and linkages provided by NEPTUNE and its test beds as a regional and coastal observatory.**
- **Entrain a broad spectrum of researchers and forge teams that will pursue creative opportunities using NEPTUNE.**

FOCUS: **Help establish the key science experiments and technology developments that will ensure success of the system from the outset.**

RESULT: **Outlines of individual and community experiments, preferred node locations, instrument packages and paths to implementation.**

The results from this workshop and other regional and thematic workshops will be used to refine the research agenda, priorities for instrumentation, and multidisciplinary community teams, feeding into a major workshop on Observational and Interactive Oceanography, planned for early 2004 (www.coreocean.org/deos). Soon thereafter, we expect to have established dedicated working groups/proposal teams designing community experiments prior to the installation of the main NEPTUNE infrastructure in 2007. Your participation and input NOW is ESSENTIAL to help shape the future of observatory science.

Format of the Workshop. An overview talk will lead off with a description of the nature, opportunities, and status of NEPTUNE and its test-beds. Short invited talks will describe some of the outstanding science questions that can be addressed by NEPTUNE. Breakout groups will then be formed to address the innovative science that can achieve outstanding results in the first few years and beyond. Groups will then elaborate the corresponding experimental requirements, implementation plans and priorities. The groups will need to consider the nature of the desired instrumentation (existing or to be developed) needed for the particular scientific experiments.

Working groups will initially divide around five interdisciplinary research themes:

- Ecosystem Dynamics and the Carbon Cycle
- Fisheries and Marine Mammals
- Ocean Dynamics and Cross-shelf Processes
- Geophysics and Seismology
- Fluid Fluxes and Geochemical Processes in the Sediments and Crust.

Within each of these themes, participants should contribute to the following issues:

- What scientific questions are you posing?
- What general, or preferably specific, node/site locations do you wish to instrument?
- What reliable, off-the-shelf instrumentation will ensure significant early returns?
- What longer-term developments do you envision (3-20 years after initial installation)?
- How will synoptic or co-located studies augment the value of your results/instruments?
- How will you use NEPTUNE a) interactively, and/or b) as a passive receiver?
- What questions will your former students (now as PIs) be asking in 10 years?
- How can we set the groundwork for the questions your present students sill be asking in 10 years?

PLEASE RESPOND with a short statement of interest describing your particular area of expertise and how you (and co-workers) anticipate contributing to NEPTUNE and its goals, tentative identification of research focus area, and answers to the questions above Any and all ideas and suggestions are welcome, as are volunteers to help during the workshop.

Register on the workshop web page:
http://www.neptune.washington.edu/pub/PNW_Workshop/index.html.
Address queries to Liesje Bertoldi at bertoldi@u.washington.edu.
Space is limited to 150 people: first come, first serve. To keep costs to a minimum there will be NO registration fee. Travel costs to this regional workshop are the attendees' responsibility; continental breakfast, snacks and lunch will be provided. A third and final workshop announcement will be issued in early April that will communicate any final details or changes in the program. The workshop details (maps, hotels, travel, etc) are listed and updated on the workshop web page (above).

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Appendix 3. Workshop Agenda

AGENDA
NEPTUNE PACIFIC NORTHWEST WORKSHOP
Portland State University, Portland, Oregon
23–24 April 2003

Wednesday, April 23

Plenary Session
Room 327-328 at the Smith Union Memorial Center

0730 – 0830	Continental Breakfast
0830 – 0840	Welcome, introductions, logistics – Colin Finney
0840 – 0900	Keynote Speaker – John Delaney Introduction "Interacting with the Oceans for Research and Education: The NSF Ocean Observatories Initiative"
0900 – 0920	Keynote Speaker – Chris Barnes Science vision and direction; charge to the working groups
0920 – 0935	Potentials for *Ecosystem Dynamics and Carbon Cycling* – Ricardo Letelier
0935 – 0950	Potentials for *Fisheries and Marine Mammals* – John Horne
0950 – 1005	Potentials for *Ocean Dynamics and Cross-Shelf Processes* – Jack Barth
1005 – 1020	Potentials for *Geophysics and Seismology* – Anne Tréhu
1020 – 1035	Potentials for *Fluid fluxes* – Earl Davis
1035 – 1050	Form Working Groups – Break-out rooms will be assigned at this time
1050 – 11:15	Break – Refreshments in meeting room

Working Groups to Meet
Rooms to be assigned based on group size

1115 – 1230	Working Groups Meet
1230 – 1330	Lunch – Main Meeting Room 327-328
1330 – 1500	Working Groups Meet
1500 – 1530	Break – Main Meeting Room 327-328
1530 – 1630	Working Groups Meet

Plenary Session
Room 327-328 at the Smith Union Memorial Center

1630 – 1730	Review of Progress Questions answered

Public Lecture
Ballroom Room (355) at the Smith Union Memorial Center

1930 – 2030	John Delaney "Oceans on Earth and Elsewhere: Exploring the Marine Environment in the 21st Century"

Thursday, April 24

Plenary Session
Room 327-328 at the Smith Union Memorial Center

0730 – 0830	Continental Breakfast
0830 – 0900	Welcome back, Goals for the day, Revisit Charge to the Working Groups – Bruce Howe
0900 – 0930	Review presented by each group leader – 5 minutes each

Working Group Meetings
Meetings in Break-out Rooms

0930 – 1045	Working Groups Meet
1045 – 1115	Break – Main Meeting Room 327-328
1115 – 1215	Working Groups Meet
1215 – 1315	Lunch – Main Meeting Room 327-328
1315 – 1445	Working Groups Meet
1445 – 1500	Break – Main Meeting Room 327-328

Plenary Session
Room 327-328 at the Smith Union/Memorial Center

1500 – 1550	Review presented by each group leader – 10 minutes each
1550 – 1600	Next steps, wrap-up
1600	Meeting Adjourned

Appendix 4. Charge to the Working Groups

NEPTUNE Pacific Northwest Workshop
23–24 April 2003
Smith Memorial Center,
Portland State University
Portland, Oregon

Charge to Participants

Introduction

NEPTUNE is driven by the major challenges and questions in ocean science. The unique design of the project, with interactive laboratories and remotely operated vehicles (ROVs) supplied with communication and power, spread over a vast plate-scale area, will enable researchers to study processes previously beyond of the capabilities of traditional oceanography. We recognize that the ultimate measure of the program's success will be the innovation and quality of the scientific research it enables. This workshop is therefore an opportunity for you to create the experiments that will take the greatest advantage of this observatory.

Charge to the Participants

1. Define the role of NEPTUNE
   - What can this observatory provide that other methodologies cannot.
2. Develop key science issues that can be addressed by NEPTUNE
   - What are the specific scientific hypotheses?
   - What are the specific processes we are trying to capture
3. Identify community experiments
   - Node location
   - Concrete scenarios
   - Identify sensor and sensor networks
   - Establish the Functional Requirements needed for the experiment
   - Phased implementation
   - Data management needs
4. Identify synergies
   - With other community experiments
   - With other programs (e.g. IODP, IOOS, Global DEOS)
5. Identify education and outreach opportunities

Final Result

During the workshop the various working groups will prepare outlines of whitepapers. The group leaders, with the help of the organizing committee, will then use the outlines to produce draft papers that will be distributed to the participants for input and review. The finished white papers will be made available to other groups meeting around the country and presented at the DEOS sponsored observatory science workshop planned for 5–9 January 2004.

Appendix 5. Northeast Pacific Circulation and Boundary Layer Processes

The North Pacific Current (aka, the West Wind Drift) approaches the North American continent from the central Pacific and bifurcates into the poleward Alaskan Current and the equatorward California Current (CC) (Hickey, 1979) (Figure 10). The latitude of this separation occurs at about the latitude of central Vancouver Island, or about 50ºN.

During spring and summer, time-averaged surface velocities over the continental shelf and slope in the northern CC off the Pacific northwest are equatorward (Huyer et al., 1978). Velocities are strongest in the core of an equatorward upwelling jet with its axis located over the mid-shelf at ~80–100 m depth and located approximately ~15 km offshore of central Oregon (Huyer et al., 1978). Summertime average near-surface velocities obtained from moored observations are up to 0.35 m s^{-1} in the core of the upwelling jet while surface currents driven by individual wind events can reach in excess of 0.8 m s^{-1}. The alongshore flow is correlated for long distances (~100 km or more) along the coast (Kundu and Allen, 1976). Nearshore reversals, i.e., poleward flow, can occur in response to wind relaxations or periods of northward wind (Kundu and Allen, 1976; Send et al., 1987).

Mean surface flow offshore of the continental slope in the northern CC is equatorward and weak (<0.1 m s^{-1}) (Hickey, 1979). Mesoscale meanders and eddies are associated with the relatively strong mean equatorward upwelling jet over the continental shelf and slope are embedded in the weaker equatorward surface flow in the adjacent deep ocean. Meanders result from hydrodynamic instability and flow-topography interaction and have horizontal wavelengths of 20 to several hundred kilometers (Barth, 1989; 1994). Eddies in the northern CC are usually found offshore of the equatorward upwelling jet and can be either cyclonic (Barth and Smith, 1998) or anticyclonic (Huyer et al., 1998) and range in diameter from ~50–90 km.

Strub and James (2000) describe the seasonal evolution of the CC system using altimeter and satellite SST imagery. The equatorward, surface intensified CC flows relatively close to the coast and is relatively straight in the spring when winds turn upwelling favorable. By late summer and fall, the flow consists of meandering jets and eddies formed via baroclinic instability and flow-topography interaction. In winter, flow near the coast is poleward in the Davidson Current and eddies formed earlier in the year continue to persist offshore.

A poleward undercurrent flows continuously from at least 33ºN–51ºN at an average depth of 200 m and speeds of 0.15 m s^{-1} (Pierce et al., 2000). The undercurrent is located over the continental slope and poleward flow is sometimes found at depth on the outer shelf (Figure A1).

During the winter, flow over the shelf and slope is poleward in the Davidson Current with surface flows sometimes reaching 1 m s^{-1} (Hickey, 1979; Austin and Barth, 2002). Together with the undercurrent, flow throughout the upper water column (<1000 m) over the shelf and slope is poleward.

Spring and summer upwelling of cold, nutrient-rich subsurface water into the euphotic zone over the continental shelf leads to strong phytoplankton growth and production of organic carbon which is then either transported offshore, consumed by higher trophic levels, or exported to the sea floor.

The Columbia River and Strait of Juan de Fuca contribute significant amounts of freshwater to the northeast Pacific region. In the summer, the signature of the Columbia River input can be traced far to the south—to at least to the Oregon-California border and even beyond to central California—carried there by the equatorward California Current. In the winter, the buoyant inflow turns northward, essentially extending the region of continuous counter-clockwise coastal flow from the Oregon-Washington border up through the Alaska Coastal Current.

Within the seasons, the currents and sea level respond to wind forcing on a 2–10-day time scale, the so-called "weather band." These wind events drive upwelling and downwelling on the shelf and result in significant alongshore flows.

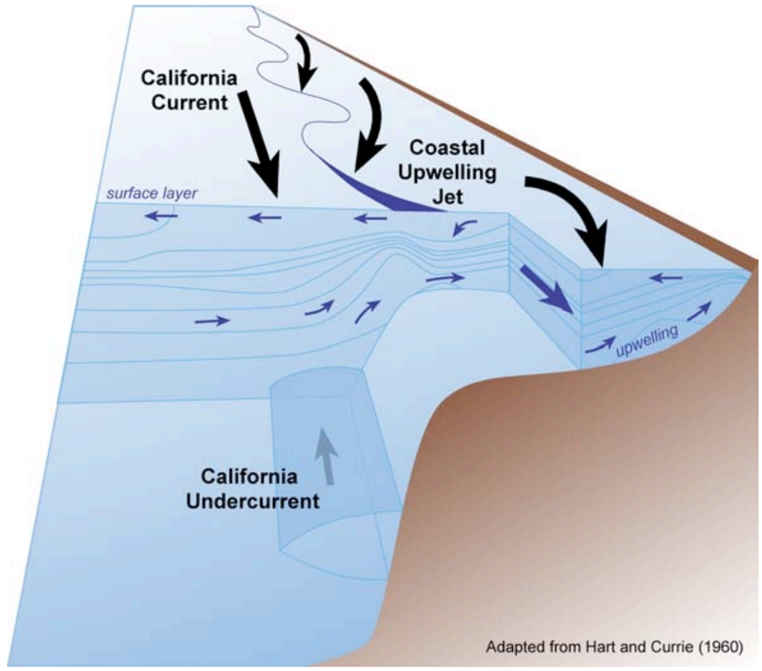

Figure A1. Eastern boundary current system of equatorward and poleward flows off the Pacific Northwest coast.

As the strong wind-driven boundary current flows gain strength, they interact with alongshore variations in the bottom and coastline topography. This causes shelf and slope flows to separate from the margin, carrying with them nutrients and shelf-type biological communities (e.g., Barth et al., 2000). Significant flow-topography interaction takes place at coastal promontories and at submarine banks and canyons, mid-ocean ridges and fracture zones. All of these features are present in the NEPTUNE study area. Another type of flow topography interaction is the creation of strong baroclinic tides by barotropic tidal flow over varying topography as found near the continental shelf break. The baroclinic tide can have important consequences for ocean mixing, creating convergence and divergence zones capable of concentrating prey, and in causing onshore transport of material (e.g., planktonic larvae).

The hydrographic, velocity, nutrient, phytoplankton, and zooplankton fields all vary interannually in response to the El Niño/La Niña cycle (see the 2002 *Progress in Oceanography* Volume 54 for a collection of articles on the 1997–1998 El Niño and its consequences along the U.S. west coast). On interdecadal time scales, these fields are strongly influenced by the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997).

Boundary layer processes are important to both the sea surface and the seafloor. Wind-driven mixing near the sea surface has a strong influence on the physics and ecosystem response in the oceanic surface layer. In turn, understanding the dynamics of heat and mass transfer at the sea surface plays a crucial role in the interpretation and modeling of short-term meteorological and long-term climatic data (Csanady, 2001). On-offshore surface Ekman layer transport is the prime driver of upwelling and downwelling circulation over the margin. The surface Ekman layer is also fundamentally important to the transport of freshwater and terrigenous nutrients from large river plumes (e.g., the Columbia River plume).

Near the seafloor currents remobilize and distribute sediments and organic material. These processes are crucial for both water-column and benthic ecosystems. In turn, the shape of the ocean bottom affects the intensity and spatial distribution of near-bed mixing. Internal wave reflection and scattering and may interact with the bottom, ultimately regulating long-term dynamics of the margin (Cacchione et al., 2002). Aside from quasi-continuous processes like tidally generated breaking internal waves, rare events, such as turbidity currents or extreme storms, play an important role in the evolution of the seabed (Puig et al., 2003), abyssal water masses (Kampf et al., 1999), and the removal and transport of water-column contaminants and nutrients (Thomsen et al., 2001). As mentioned in the main body of the report, these events are difficult and expensive to capture with traditional ship-based sampling strategies.

Through interaction of internal tides and sloping bottom topography, intensified mixing may occur along the continental slope or mid-ocean ridge slopes. This can take the form of internal wave induced instabilities or nonlinear breaking of the internal waves. The internal tide generated at a critical slope may also contribute increased vertical shear and create regions of mixing. An example of this was documented near Monterey Canyon by Lien and Gregg (2001) who found elevated turbulence kinetic energy dissipation along the M2 internal tide ray paths. The form and level of this boundary mixing is critical to the mixing of fluid properties (heat, salt, nutrients) in the world's oceans.

Appendix 6: List of Acronyms

ADCP: Acoustic Doppler Current Profiler

BPA; Bonneville Power Administration

CFI: Canada Foundation for Innovation

CIOSS: Cooperative Institute for Oceanographic Satellite Studies

COAST: Coastal Advances in Shelf Transport

CoOP: Coastal Ocean Processes

CORIE: Columbia River Estuary

CTD: Conductivity, temperature, depth

ECOHAB: Ecology of Harmful Algal Blooms

GLOBEC: Global Ocean Ecosystem Dynamics

GOOS: Global Ocean Observing System

IES: Inverted Echo Sounder

IODP: Integrated Ocean Drilling Program

IOOS: International Ocean Observing System

IRIS: Incorporated Research Institutions for Seismology

NMFS: National Marine Fisheries Service

NSF: National Science Foundation (U.S.)

NeMO: Mew Millennium Observatory

NEPTUNE: Northeast Pacific Time-integrated Undersea Networked Experiments

NOAA: National Oceanic and Atmospheric Administration

NOPP: National Oceanographic Partnership Program

NRC: National Research Council

NRL: Naval Research Laboratory

ODP: Ocean Drilling Program

OGI: Oregon Graduate Institute

OHSU: Oregon Health and Sciences University

OOI: Ocean Observatories Initiative

ORION: Ocean Research Interactive Observatory Networks

OSSE: Observing System Simulation Experiments

OSU: Oregon State University

OWS: Ocean Weather Station

PDO: Pacific Decadal Oscillation

PISCO: Partnership for Interdisciplinary Studies of Coastal Oceans

PMEL: Pacific Marine Environmental Laboratory

POM: Particulate Organic Matter

POST: Pacific Ocean Salmon Tracking

POTENT: Pacific Ocean Tracking and Evaluation NeTwork

PRISM: Puget Sound Regional Synthesis Model

RISE: River Influences on Shelf Ecosystems

ROMS: Regional Ocean Modeling System

SOSUS: SOund Surveillance System

UCLA: University of California-Los Angeles

VENUS: Victoria Network Under the Sea

VPR: Video Plankton Record