NEPTUNE: A REGIONAL CABLED OBSERVATORY IN THE NORTHEAST PACIFIC

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Introduction

The NEPTUNE network of instrumented fiber-optic/power cable is likely to be the first regional cabled ocean observatory. Spatially associated with the Juan de Fuca tectonic plate in the northeast Pacific Ocean, 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. 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).

Each of NEPTUNE's nodes on the cable 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. We will be able to pose entirely new sets of questions and experiments to understand complex, interacting Earth System processes such as ocean climate change and its effect on the ocean biota at all depths; the barely known deep-sea ecosystem dynamics and biodiversity; the structure and seismic behavior of the ocean crust; and the dynamics of hot and cold fluids and gas hydrates in the upper ocean crust and overlying sediments.

The NEPTUNE Partnership

Institutions that form the NEPTUNE construction partnership are the University of Washington (UW), the University of Victoria (UVic), the Woods Hole Oceanographic Institution (WHOI), Caltech's Jet Propulsion Laboratory (JPL), and the Monterey Bay Aquarium Research Institute (MBARI). Of necessity, NEPTUNE is being built by a small number of institutions, but this observatory will serve as a community resource, somewhat analogous to a research vessel in that it is an observational platform open to a wide range of users. The principal difference is that NEPTUNE will deliver real-time data from thousands of locations 24/7/365. The NEPTUNE infrastructure may be installed as early as 2007, with shore stations in Oregon and British Columbia.

The nature of NEPTUNE's bilateral support and character is one of the program's great strengths, and Canadian funding (CAN$62.4M) from the Canada Foundation for Innovation and the British Columbia Knowledge Development Fund to the University of Victoria for the northern portion of the NEPTUNE network was announced in October 2003. This award can enable economies of scale, timing, and collaboration that would not otherwise be possible.

As of late 2003, other funded components of the NEPTUNE program include 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, the Straits of Georgia and Juan de Fuca (2004–2005), and the Monterey Accelerated Research System (MARS) in Monterey Canyon (2005). Funding sources include the National Science Foundation, the National Oceanographic Partnership Program, the Canada Foundation for Innovation, the W.M. Keck Foundation, the David and Lucile Packard Foundation, and the NEPTUNE partners.

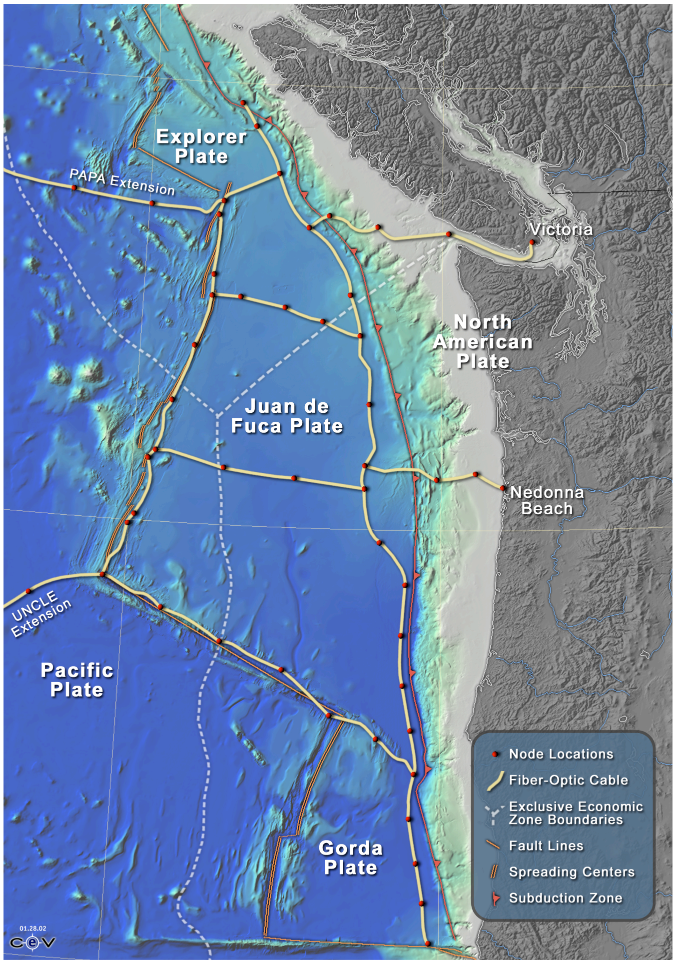

Figure 1: NEPTUNE cable system map. Extensive sensor networks and mobile platforms will extend the reach beyond each primary node into the entire three-dimensional volume of interest.

Although Canada has clearly identified and committed to funding an observatory in the northeast Pacific, discussions continue in the US regarding optimal selection of the site for the first regional cabled observatory. Several community science-planning workshops held in the US in 2003 (see below) endorsed the northeast Pacific. We hope that NEPTUNE will be the US choice, just as it is the clear choice for the Canadians.

Further US funding for NEPTUNE will be sought by competition to become the first regional cabled observatory within the National Science Foundation's Ocean Observatories Initiative (OOI). This five-year, capital-acquisition Initiative has three primary elements that will expand the capability to observe the oceans both spatially and temporally: 1) a regional cabled observatory that spans several geological and oceanographic features, 2) relocatable deep-sea observatories based around moorings, and 3) an expanded network of coastal observatories using both fiber-optic cables and moorings. The complete OOI is intended to provide cables, buoys, development platforms, moorings, and junction boxes so as to allow observation and active experiments in the near-water surface, in the water column, and below the seafloor. The observatories enabled by this initiative will be electronically linked and become a critical research-oriented component of the proposed Integrated Ocean Observing System (IOOS) now being developed and coordinated by Ocean.US through the National Oceanographic Partnership Program.

A number of countries in addition to Canada and the US are interested in pursuing regional cabled observatory efforts including Japan (ARENA), the European Union (ESONET), Korea, and possibly China. Geographical areas of interest to be covered by such observatories should be guided by science objectives and not be limited by national borders.

The Regional Cabled Observatory Concept

The regional cabled observatory concept is based on the premise that many globally significant planetary phenomena operate at or below the regional scale. Thorough 4-D examination of the full spectrum of Earth and ocean process associated with at least one regional-scale system, such as the NEPTUNE site on the Juan de Fuca plate, 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.

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.

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 many important water-column, sedimentary, and biological phenomena that occur throughout the global ocean, as well as a broad spectrum of plate-tectonic processes, including all the major types of plate boundaries. 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 US and Canada will facilitate initial cable laying, reliable shore landings, and operations and maintenance.

General 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

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 US and Canada, concluded that the Program is scientifically desirable, technically feasible, and financially reasonable. The US study was supported by the National Oceanographic Partnership Program and the NEPTUNE Partners; funding for the Canadian study was arranged by the Institute for Pacific Ocean Science and Technology).

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.

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. It will emphasize testing of all aspects of the infrastructure and will serve as a long-term test bed for instrument development.

Science Planning for the Regional Cabled Observatory

Recognizing the fundamental nature of good science planning for the first regional cabled observatory, NEPTUNE embarked upon the process in 1999 with the convening of *ad hoc* science working groups in the US and Canada for the Feasibility Studies. White papers and reports from these groups are posted at *www.neptune.washington.edu/pub/documents/documents.html.* Several follow-on workshops related to science planning for the VENUS and MARS test beds have been held. The NEPTUNE characteristics, or functional requirements (Table 1) grew out of these early workshops. One of the major issues in the development of a regional cabled observatory at this point in time is documentation of the functional requirements because they constrain and influence the engineering designs that are under way. Ideas and questions about essential requirements should be sent via email to <*penrose@ocean.washington.edu*> to be forwarded to the appropriate engineers.

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

As of late 2003, the oceanographic community is in the process of characterizing the outstanding science questions and associated experimental systems so that the design of the first regional cabled observatory can proceed with confidence. Several regional observatory science planning activities took place in 2003: the NEPTUNE Pacific Northwest Workshop (Portland, April 2003); the Workshop on Linkages Between the Ocean Observatories Initiative and the Integrated Ocean Drilling Program (Seattle, July 2003); and the Cabled Regional Observatory Workshop (CROW) (San Francisco, October 2003).

Each meeting developed overarching themes and concluded that the northeast Pacific is an ideal location for the first regional cabled observatory. Overlapping themes between the meetings were complementary, and each meeting broke ground for new approaches to different areas: the IODP/OOI workshop explored mid-plate studies in some detail; emerging themes from the Portland workshop included cetacean research and eastern boundary current studies.

The final products of all these workshops are not yet available; the report from the IODP/OOI workshop is in draft form and is under review; the CROW report is in progress and a draft is expected in early December 2003. Final reports will be made available on workshop websites (see below). For these reasons, we have chosen to provide here only brief summaries of the July and October workshops, but have included the final recommendations and summaries developed by the working groups at the Portland NEPTUNE workshop.

Cabled Regional Observatory Workshop

<www.geo-prose.com/cabled_wksp/>

The NSF-sponsored Cabled Regional Observatory Workshop addressed the regional cabled observatory component of the OOI. This workshop's main charge was to identify where the first regional cabled observatory should be located on the ocean floor. A secondary charge was to consider how, given the special characteristics of that location, the cable should be configured to best achieve the research goals across all disciplines of ocean science.

The ~80 attendees were divided into five thematic working groups:

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

Workshop on Linkages Between the OOI and IODP

<www.neptune.washington.edu/pub/workshops/IODP_OOI/>

The IODP and OOI share many common goals and challenges including needs for infrastructure investment and commitment by numerous scientists, engineers, and educators; operation through a combination of top-down, long-term planning and grass-roots scientific proposals; unprecedented opportunities for education and outreach to both scientific and nonscientific audiences; an emphasis on "active processes" within the global ocean; a sustained commitment to technological development, including design, prototyping, and testing; and a dependence of each program on the successes of the other.

The 65 attendees were divided into five thematic discussion groups, with the intent of targeting areas of primary interest to both the IODP and the OOI:

- Earthquake dynamics, Earth structure and evolution
- Lithospheric dynamics, geodetics, heat and fluid transport
- Microbiology, geochemistry, paleoceanography
- Methane (hydrates), slope stability, sediment transport
- Education and outreach

Pacific Northwest Workshop

<www.neptune.washington.edu/pub/workshops/PNW_Workshop/index.html>

For the purposes of addressing the aims of the ORION meeting, where BIG scientific questions are to be identified, relevant parts of the PNW Workshop report are reproduced here in this paper.

The 83 attendees 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 US and Canadian feasibility studies (NEPTUNE Phase 1 Partners, 2000; Canadian NEPTUNE Management Board, 2000). 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*>.

#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

The workshop focused on establishing the key science questions, possible 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

Science Themes from the Portland Workshop

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;" some specific, e.g., the Columbia River). Mobile platforms are essential to fill in between fixed sensors. Synergies regarding locations between science themes are ubiquitous.

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 overlap with water-column interest.

Figure 2 is a compilation of proposed experimental sites from all the groups. Together with earlier science workshop reports in Canada, 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 and was further refined at the CROW meeting in October 2003.

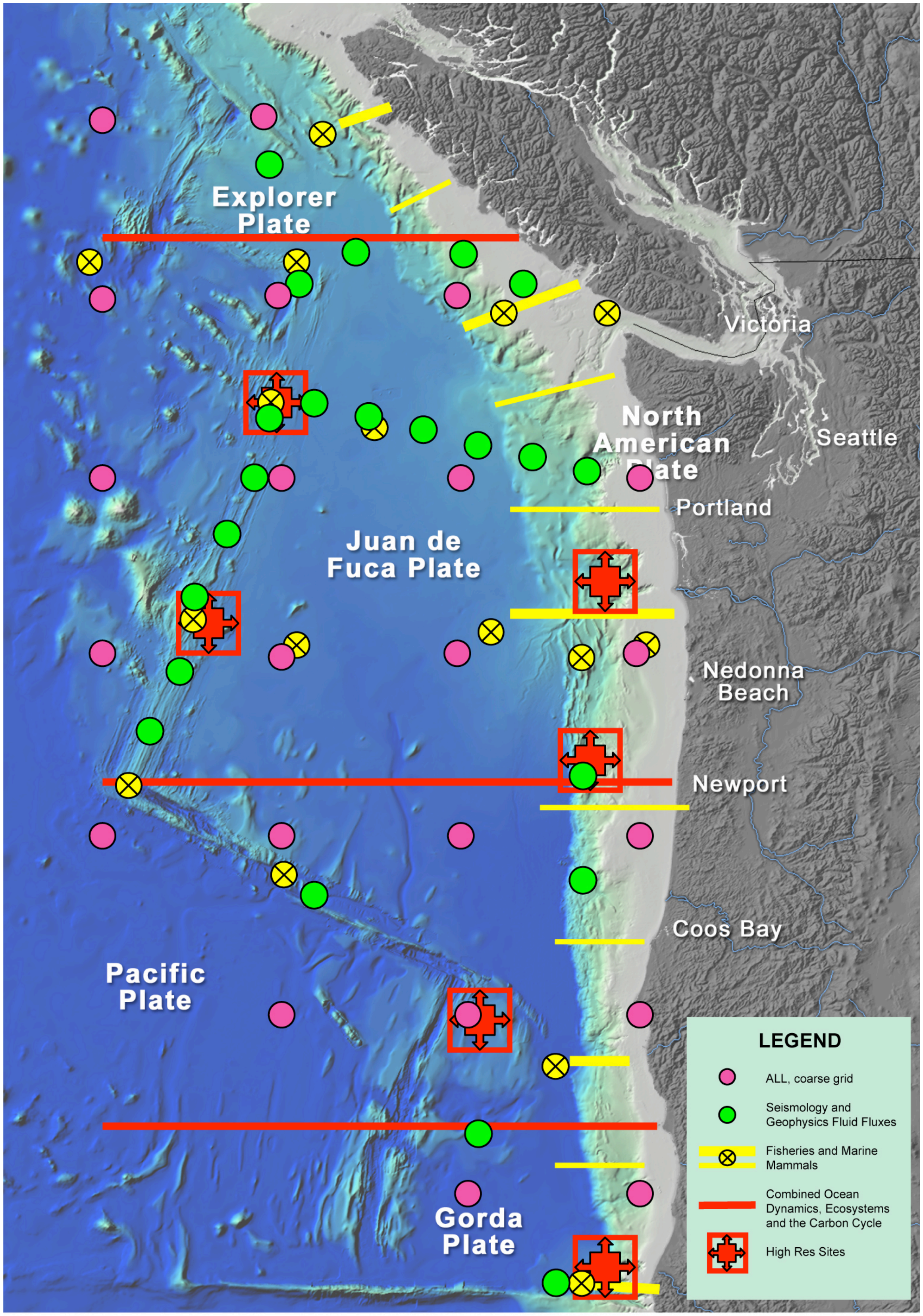

Figure 2: This figure illustrates the synergies of location among the different working groups. This composite map is conceptual and is not intended to reflect precise locations. The magenta points located on the coarse grid are intended to indicate the broad-scale coverage desired by all the groups.

• *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 samples for trophic transfer studies, and 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 Point 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 spatial-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 small-array experiments 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? And, 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 the 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? And, 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 kms 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 and costing effort 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 *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, 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? And, 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 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 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 called for. 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 experiments.

General 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

General 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.

Portland 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 consisting 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 be successful at raising funds both 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.

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 US and international oceanographic community.

References and Websites

All references in this paper may be found in the reference list from "Science Planning for the NEPTUNE Regional Cabled Observatory in the Northeast Pacific Ocean: Report of the NEPTUNE Pacific Northwest Workshop," which is posted at
<www.neptune.washington.edu/pub/workshops/PNW_Workshop/ws_reports_documents.html>

There are three files: small pdf, large pdf, and the original MSWord document, which includes digital images that may be downloaded. PowerPoint presentations from the Workshop are posted below the links to the Report.