NEPTUNE

Real-Time, Long-Term Ocean and Earth Studies at the Scale of a Tectonic Plate

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***Abstract*-The NEPTUNE project will establish a linked array of undersea observatories on the Juan de Fuca tectonic plate. The NEPTUNE infrastructure, consisting of fiber-optic/ power cable and junction boxes, will provide significant amounts of power and an Internet communications link to sensors and sensor networks on, above, and below the seafloor. This observatory will provide a new kind of research platform for real-time, long-term, plate-scale studies in the ocean and earth sciences.**

I. INTRODUCTION

The NEPTUNE project is developing a fiber-optic/ power network of distributed sensors on, above, and below the Juan de Fuca tectonic plate in the northeast Pacific Ocean (Fig. 1a,b). Scheduled to be operational by 2006, the NEPTUNE observatory will provide a new kind of research platform for real-time, long-term, plate-scale studies in the ocean and earth sciences.

The planned 30 experimental nodes for the NEPTUNE system could be distributed over a volume extending from the air–sea interface to the bottom of the oceanic crust and will cover an area that includes the entire Juan de Fuca Plate, its margins, and beyond. These *in situ* nodal observatories will be spaced approximately 100 km apart on the network. Each will have a significant footprint of instruments bounding a volume of ocean space. These arrays will permit remote interaction with physical, chemical, and biological phenomena operating across multiple scales of space and time. Observatories in key areas of interest will be spatially extensive, covering areas up to 50 km in diameter. It will be possible to extend NEPTUNE's cable-defined footprint through the use of moored and relocatable buoys.

The electro-optical cable will provide significant power and high-bandwidth telecommunication capabilities to this array of instruments and sensors, permitting real-time data transmission and remote two-way command-control of instruments and robotic undersea vehicles. Data will flow in real time from NEPTUNE's *in situ* facility to land-based scientists, educators, decision makers, and learners of all ages (Fig. 2).

NEPTUNE offers a new means of observing and understanding our planet. It will foster a more integrated era of research and education in the ocean and earth sciences and may also serve as a unique testbed for sensor and robotic systems designed to explore other oceans in the solar system.

II. PARADIGM SHIFT IN THE OCEAN SCIENCES

Traditional expeditionary science has characterized some portion of an ocean or planet within the constraints of data collection from a ship or spacecraft. Such time-limited visits are inadequate to fully evaluate the suite of models and testable hypotheses that have grown out of this exploratory work.

Ocean scientists now stand on the threshold of a scientific revolution, a paradigm shift made possible by advances in computational sophistication, communication and power technologies, robotic systems, and sensor design. The ability to enter, sense, and interact with the total ocean environment is within our grasp. It is time to expand beyond short-term expeditions using research vessels; it is time to move toward a long-term presence on, above, and below a section of seafloor as large as a tectonic plate.

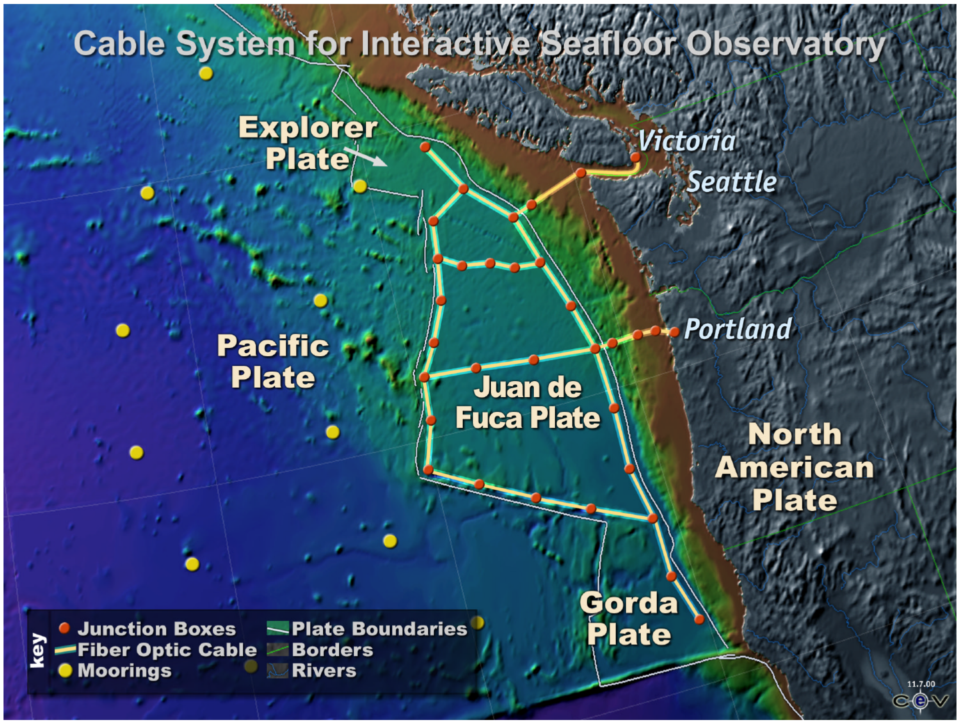
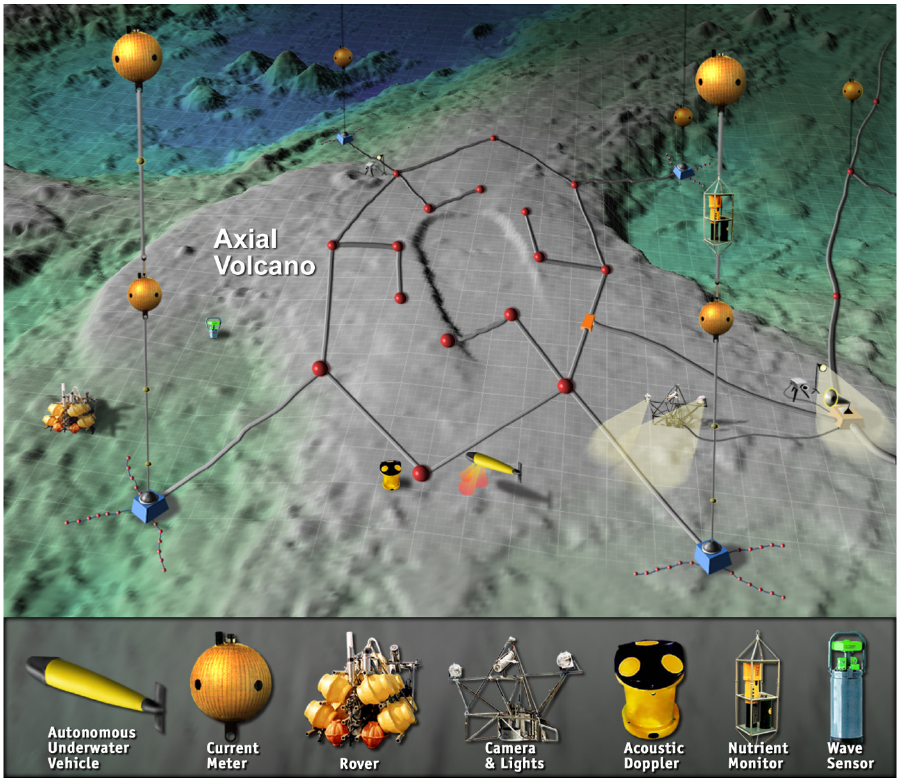


Fig. 1 (a) NEPTUNE cable system map. NEPTUNE will provide power and communications bandwidth via fiber-optic/power cable to junction boxes (nodes) on the Juan de Fuca Plate and surrounding areas. By connecting sensor networks to the nodes, with extensions onshore and offshore into the interior, scientists will for the first time have the capability to study a host of interrelated processes with high spatial and temporal resolution over long periods of time. (b) A generic NEPTUNE observatory network, draped over Axial Volcano and based on the NOAA/PMEL New Millenium Observatory.



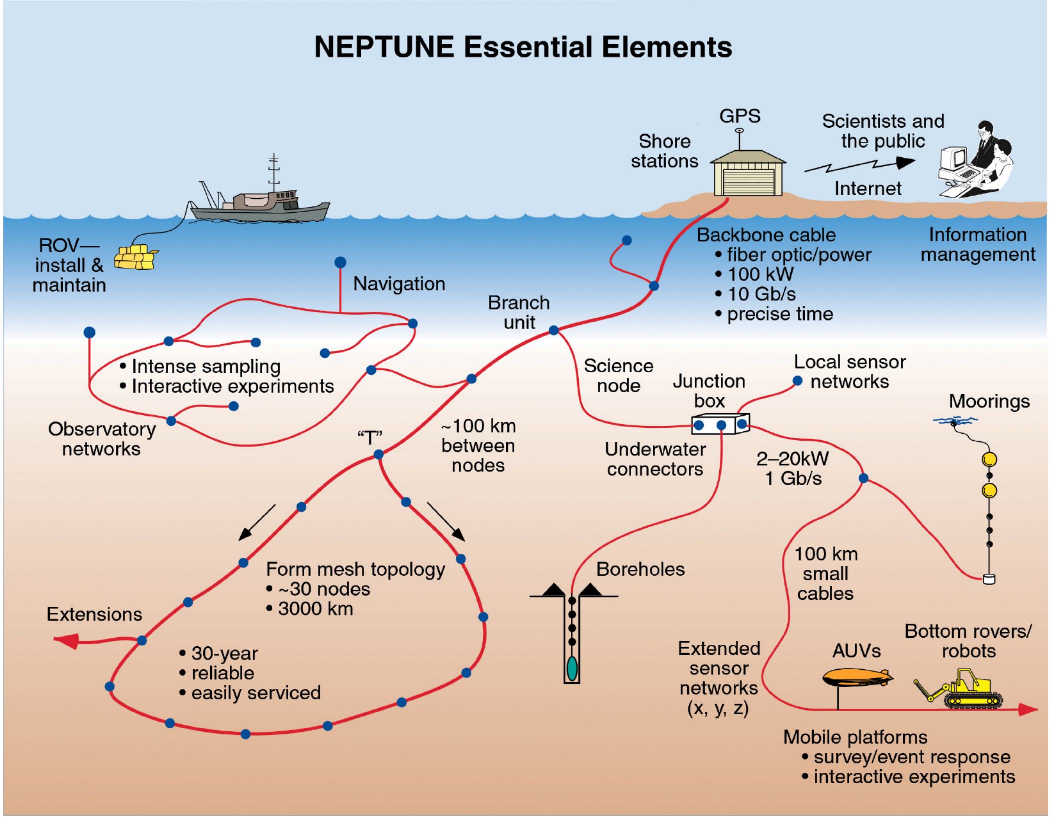


Fig. 2. Land-based scientists and the public are linked in real time and interactively with sensors, sensor networks, and various mobile sensor platforms in, on, and above the seafloor. NEPTUNE's fiber-optic/power cable and associated technology provide the enabling network infrastructure.

NEPTUNE's plate-scale observatory concept is based on the following premises:

- Many globally significant planetary phenomena, involving both oceanographic and solid earth processes, operate at or below the scale of a tectonic plate.
- Thorough four-dimensional examination of at least one plate/mesoscale system will generate major new insights into all such systems.
- Understanding the interactions among the myriad processes operative at such scales will require decadal commitment to the studies.

A recent U.S. National Research Council report [1] concluded that "Seafloor observatories present a promising, and in some cases essential, new approach for advancing basic research in the oceans." Partly based on this report's recommendations, the National Science Foundation has proceeded with a new program to support long-term research observations and interactive experiments from the sea surface to the seafloor and beneath. NEPTUNE anticipates competing as the regional, tectonic-plate-scale component of this Ocean Observatories Initiative.

Observatories such as NEPTUNE will create opportunities to address such compelling intellectual and societal themes as the search for life within and beyond earth, anticipation of crippling natural hazards, improved management of marine resources, anthropogenic influences on ocean and climate systems, and a deeper understanding of habitat complexity.

A. *Inner Space/Outer Space*

The spectrum of scientific studies currently envisioned for the NEPTUNE facility covers a broad range. One major opportunity arises from recent evidence that submarine volcanoes support a substantial, unexplored high-temperature microbial biosphere sustained by volatile fluxes from the earth's interior. This insight implies that seafloor hydrothermal vent fields may be the "tips of icebergs" in total biomass supported by active submarine hydrothermal systems. A significant microbial biosphere apparently thrives within the brittle outer shell of the volcanically active submarine portions of earth.

Similar submarine volcanic systems may exist on other solar bodies, such as Europa, the second moon of Jupiter. The new field of microbial volcanic ecology is, therefore, doubly powerful. By designing innovative strategies to explore the relationships between volcanoes and the life they support here on earth, we gain not only essential knowledge about newly discovered processes and life forms on our own planet, but also critical new insights into how we might explore for signs of life on other solar bodies. NEPTUNE will allow intimate real-time access to the vigorous geophysical and geochemical processes that sustain this sub-seafloor volcanic biosphere.

NEPTUNE may also serve as a unique testbed for sensor and robotic systems designed to explore other oceans in the solar system. Indeed, we can regard NEPTUNE as an inward-looking Hubble telescope, vastly enhancing the potential for discovery by allowing unprecedented four-dimensional imagery of planetary processes not entirely restricted to earth: by looking inward, focusing on integrated, scientific experimentation in remote or hostile environments on our own planet, we will also be looking outward.

B. *The Neptune Study Area*

To attract the broadest possible user base to this full-service oceanographic research platform and to minimize cost, we sought a study area that had a small footprint but encompassed myriad important earth and ocean processes. The Juan de Fuca plate was chosen for its representative spectrum of globally occurring earth-ocean processes and because it is in an ideal location close to major ports in British Columbia, Washington, and Oregon. The Plate is small and entirely submarine, and we propose treating the entire system as an ocean-earth laboratory [2].

C. *The Feasibility Study*

One of NEPTUNE's important early efforts was completion of a feasibility study in June 2000 [3]. The study was funded by the National Oceanographic Partnership Program and by the four NEPTUNE Phase 1 partners (University of Washington, Woods Hole Oceanographic Institution, the California Institute of Technology's Jet Propulsion Laboratory, and NOAA's Pacific Marine Environmental Laboratory**).** Many other institutions and individuals contributed generous time and effort to the feasibility study. Since completion of the study, two more partners have joined the project: Canada's Institute for Pacific Ocean Science and Technology (IPOST) and the Monterey Bay Aquarium Research Institute (MBARI).

The feasibility study, which is posted on the NEPTUNE web site (*www.neptune.washington.edu),* concluded that 1) there are strong intellectual and societal drivers for implementing NEPTUNE, 2) NEPTUNE is feasible from a technological point of view, and 3) within the context of what NEPTUNE brings to the earth, ocean, and planetary sciences, the system cost is reasonable.

III. SCIENTIFIC OPPORTUNITIES/ SOCIETAL BENEFITS

We will be able to address a host of scientific opportunities and societal challenges with the capabilities envisioned for NEPTUNE. Indeed, the ultimate measure of success of any scientific facility is the innovative character and quality of the scientific research and public education that are enabled.

The *ad hoc* science working groups listed below were convened to hold brainstorming sessions to identify research opportunities that NEPTUNE could enable and to develop preliminary examples of science experiments.

- Cross-margin particulate fluxes
- Seismology and geodynamics
- Seafloor hydrogeology and biogeochemistry
- Ridge-crest processes, subduction zone processes (fluid venting and gas hydrates),
- Deep-sea ecology
- Water-column processes, and
- Fisheries and marine mammals.

The working groups addressed the scientific viability of large, long-term group or community studies and of shorter-term individual investigator experiments and observations. The white papers produced by these working groups are posted on the NEPTUNE web site. Listed below are some of the scientific opportunities and societal benefits that will be engendered by NEPTUNE.

For the first time, using NEPTUNE, **earthquake and deformation patterns** associated with the creation, aging, and destruction of oceanic plates can be examined in a continuous, integrated fashion for decades. The NEPTUNE study area includes all major types of oceanic plate boundaries, including the Cascadia subduction zone [4,5]. A seafloor seismic network will capture the earliest signals from great subduction zone earthquakes and can contribute critical information to tsunami and ground-shaking warning systems. NEPTUNE is very complementary to U.S. and Canadian initiatives to enhance land-based observations.

• **Ridge-crest volcanism** is intimately related to the formation of metal deposits, modulation of seawater compositions, local heating of the overlying ocean, and support of a microbial biosphere. NEPTUNE's capabilities will help establish the specific nature of links and variations between geological, physical, chemical, and biological processes at active mid-ocean ridges [6]. A recent grant from the W.M. Keck Foundation to NEPTUNE will support the development and operation of sensors to document fluid transfer from deforming ocean crust to the overlying ocean at two sites within the NEPTUNE study area.

A crucial use of NEPTUNE will be rapid response to eruptions of submarine volcanoes to sample the exotic microbiological materials released there. Enzymes extracted from diverse microbial communities supported by extreme conditions within the ocean and underlying crust are and will be sources of bioactive materials for powerful industrial applications. The ability to track and sample otherwise undetected eruptive events will give us new access to such compounds.

- Despite the vigor of ridge-crest activity, it constitutes less than 10% of the total global flux of heat and chemicals from the earth's interior. Ridge flanks and mid-plate portions of our planet represent the **zones of major heat and chemical transfer** from the earth's interior to the hydrosphere and biosphere. Instrumented boreholes within the oceanic crust can serve as laboratories for studying the interdependence of tectonics, fluid and thermal flows, and biological activity [7]. Early evidence indicates that these relationships are at least partially forced by tides, but the ramifications are not clear. Intriguing new data suggest that plate activities may be more interconnected than previously suspected.
- Studies of the volatile fluxes expelled along a subduction zone will allow cross-correlation with major and minor earthquake activity, thus giving crucial information about potentially major, non-steady-state carbon movements. The **role of subduction gases and methane hydrates** in the dynamics of the continental slope is virtually unknown. The classic study site for fluid venting and gas-hydrate formation and breakdown is located within the NEPTUNE study area [8]. Global interest in hydrates reflects their role as a vast potential energy resource and a significant source of greenhouse gases. Documentation of the formation and accumulation rates of gas hydrates, as well as metal deposits, will provide new insights into the search for scarce resources.
- **Migration of fish stocks and marine mammals** along and across the continental shelf can be quantitatively tracked using innovative acoustic techniques [9]. Tying this to small- and large-scale oceanography and the regional carbon budget will be a worthy challenge.
- A **fully instrumented suite of water-column moorings** will allow continuous four-dimensional real-time assessment of the physical, chemical, and biological interactions in a zone of divergence and in nearshore upwelling processes. Collecting model-guided, continuous, long-term data series will improve current models of the oceanic processes that occur in the NEPTUNE study area and could fundamentally re-orient biological approaches to ocean science [e.g., 10, 11]. NEPTUNE will also provide the capability to conduct unique quantitative assessments of certain portions of the carbon cycle.
- Sediment transport along and across the continental shelf and into the deep ocean can be quantified as a function of the processes that drive such systems**. Large fluxes of sediment** laden with carbon and anthropogenic chemicals cross the northeast Pacific continental shelf to the adjacent deep-sea floor in a highly episodic fashion during major storms [12]. The mechanisms, however, are largely unknown. NEPTUNE's capabilities will permit measuring, sampling, and experimentation during these episodic events. A more complete understanding of water-column physics, chemistry, and biology will permit addressing the links between primary productivity, fisheries, marine mammal migration, and deep-sea ecology.
- The deep sea represents two-thirds of our planet yet is virtually unexplored in terms of biocomplexity. The NEPTUNE network will provide the capability to develop a functional understanding of the **ecology of deep-sea biota**, only a small percentage of which have been sampled or identified [13].

IV. ENGINEERING OVERVIEW AND INFRASTRUCTURE

A. *Moored Buoys vs. Cable*

There are two distinct approaches to providing power and communications to a distributed set of seafloor science nodes: 1) a distributed set of buoys, each linked to a seafloor science node, and 2) a seafloor fiber-optic telecommunications cable connecting a distributed set of science nodes to one or more shore stations. In the first case, the moored surface buoys supply power to the seafloor instruments and provide a satellite data link to land. In the second case, the seafloor fiber-optic telecommunications cable links the science nodes to one or more shore stations. Selecting the most appropriate approach depends on the amount of power needed for seafloor nodes and science instruments, on the maximum anticipated data rate over the lifetime of NEPTUNE, and on cost.

Power and data-rate issues argue strongly against the use of buoy technology for the core portions of the NEPTUNE array. The use of buoys would place significant limitations on NEPTUNE experiments because the power requirement for NEPTUNE exceeds the several hundred watts that could be provided by buoys. Similarly, the required data rate capacity for a NEPTUNE science node exceeds that which a satellite link can service by several orders of magnitude. In addition, the required technological developments and commercial uncertainty surrounding available satellite systems further weakens the case for their use.

Underwater fiber-optic telecommunications cable technology, however, is highly advanced and commercially available. It is capable of handling the higher data rates needed for NEPTUNE and providing the needed levels of power to the seafloor. Using a non-standard approach for power delivery, it is feasible to send many tens of kilowatts to the seafloor. For these reasons, we have selected the cable approach for NEPTUNE.

B. *Observatory requirements*

NEPTUNE's infra-structure must meet the following requirements of the scientific program:

- Bandwidth capable of supporting HDTV and acoustic tomographic studies at many nodes
- Power to operate autonomous underwater vehicles (AUVs) and bottom rovers
- Very accurate timing signals to support dense seismometer arrays
- Real-time information on the status of instruments
- Real-time ability to change measurement parameters and download data
- Reliable time series measurements, and
- User-friendly information management system.

To meet these requirements, NEPTUNE is planning at least two **shore stations**: one in Victoria, Canada, which will include a major visitors' center, and one in the U.S., most likely in Nedonna Beach, Oregon. Shore stations will provide power and communications to the cable, as well as controlling and managing the overall system. The main **cable**, which will be standard, commercial-off-the-shelf cable from the submarine telecommunications industry, will be buried out to a water depth of about 2000m to protect it from fishing trawls and will carry power and communications to the seafloor nodes, to which instruments will be interfaced.

We have selected a mesh network topology for the **power and communications systems** to meet capacity requirements and to maximize reliability and flexibility [14]. The basic trade-offs in the **power system** design can be made easily and mean using a DC "parallel" approach with self-regulating power supplies, which is unlike conventional submarine telecommunications systems [15]. Our power system designs indicate that much as 100 kW overall can be delivered for the entire 30-node scenario. The basic power needs can be met with 2 – 10 kW per node. Major power consumers include instruments that require motion (AUVs, pumps), heat transfer (freezers to preserve specimens, heaters for polymerase chain reactions used in DNA work, heaters for clathrate studies), light (video), and "hotel" electronics. The major consumers of communications bandwidth are video and high-frequency acoustics; significant fractions of a gigabit per second are required at a node, with order 10 Gb/s required overall.

Gigabit Ethernet, the high-speed version of a widely used data networking technology, has been selected as the backbone **communications** technology that will meet NEPTUNE's requirements. This dependable and affordable system is based on data networking technology widely used to connect the Internet to laboratories, classrooms, and homes around the world. The primary development effort will be in the engineering integration of available, commercial-off-the-shelf components. Innovations will optimize nonstandard approaches to power and communications to meet NEPTUNE's special needs.

The Canadian National Research Council's Herzberg Institute of Astrophysics is leading the NEPTUNE **data management and archiving** effort. This Institute, located in Victoria, British Columbia, is responsible for the Hubble Space Telescope archive in Canada and is one of the key institutions in the Gemini project. The NEPTUNE data management and archive facility will be designed to allow users efficient and seamless access to NEPTUNE data. The approach is based on distributed archiving of selected data combined with robust and reliable data access and mining tools. The facility will provide the scientific community, educators, and the general public with on-line access to all NEPTUNE scientific data to ensure maximum use of those data and to guarantee that data sets are preserved for use by future generations.

Although significant research and development are required in the realm of robust, versatile chemical and biological sensors, a suite of existing oceanographic and geophysical **instruments** is available today for straightforward adaptation to the NEPTUNE infrastructure. For these reasons, excellent scientific opportunities and outreach capabilities can be realized as soon as the system is in place. With time, growing sophistication of new sensors and evolving experimental strategies will strengthen NEPTUNE's contributions to oceanography.

Two proof-of-concept test beds, one in California and one in Canada, are planned and will allow complete assessment of key design parameters prior to deployment of the full NEPTUNE facility at plate scale.

V. EDUCATION AND OUTREACH

NEPTUNE's Internet technology offers great educational potential. It can provide a wide range of new opportunities to explore and investigate the dynamics of the marine world using real-time data flow to classrooms and living rooms coupled with cutting-edge visualization techniques.

Two workshops have been held on NEPTUNE's potential in education and outreach. Participants have included science teachers, curricula developers, educators at science centers and aquariums, scientists and engineers. Reports from these workshops are posted at *www.neptune.washington.edu*.

VI. INTERNATIONAL PARTICIPATION

NEPTUNE is an international program. The study area spans the territory and exclusive economic zones of the U.S. and Canada. The Canadians intend to be major contributors to NEPTUNE and hope to raise 30% of the funding for construction, reflecting the proportion of the Juan de Fuca Plate that lies within Canadian waters. In addition to our NEPTUNE Canada partner, scientists at GEOMAR Research Center for Marine Geosciences in Kiel, Germany are undertaking a long-term, extensive study of the gas hydrates found in the Hydrate Ridge area off the coast of Oregon and will be active participants in the NEPTUNE scientific program. We are also in the process of defining the level of participation of a consortium of Japanese institutions.

VII. IMPLEMENTATION AND COST ESTIMATES

Phase 2, Development, was formally launched in September 2000 and is loosely defined as all activities between completion of the Feasibility Study and the initiation of activities for Phase 3, Installation. A major Phase 2 effort is the establishment of science working groups. Their task will be to conceptualize the design and develop the prototypes of the community experiments.

Activities during Phase 3, Installation, are procurement and deployment of the NEPTUNE backbone infrastructure with the initial suites of sensors for community experiments. Phase 4, Operations, will revolve around four functions: network operations, data management, sensor network maintenance, and node and cable maintenance.

The total cost to develop, install, and operate the observatory for its first five years is estimated at $250 million; $100 million for construction; $75 million for sensor and experiment development; and $15 million per year for ongoing science and operating costs. (All costs are in year-2000 U.S. dollars.)

VIII. SUMMARY

The history of science shows that new technologies such as telescopes and microscopes commonly result in discoveries that are difficult to predict. By providing continuous access to the time domain in a well-defined spatial context, NEPTUNE will enable quantum leaps in our understanding of processes in the ocean and underlying lithosphere. These leaps in turn will translate into a greatly improved ability to model and predict the behaviors of these dynamic parts of our environment and their impact on our social and economic well being. For the first time, the supply of substantial amounts of continuous power and two-way communications to a diverse set of sensors and interactive experiments will allow science at sea to become as rich and unfettered as science on land.

NEPTUNE will drive improvements in deep-submergence technology and could provide unparalleled test beds for robotic exploration of extreme habitats, dynamic earth systems, and complex oceanographic processes. Internet access to instrument arrays and robotic systems will allow novel types of involvement by scientists, learners of all ages, and the general public.

The level of excitement that NEPTUNE and its capabilities has engendered among members of the broad marine science community leaves no doubt that the time to move ahead is now. NEPTUNE's series of cabled seafloor instrument sites will provide a national and international focus for innovative earth, ocean, and planetary science investigations, engaging the imaginations of researchers and public alike.

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