ECOSYSTEM STUDIES

Preface

1. Key Priorities

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

A Regional Cabled Observatory (RCO) would provide the infrastructure to support detailed studies of benthic and pelagic ecosystems on time scales ranging from tidal, daily, and seasonal to inter annual and decadal. Assuming that reliable, robust autonomous sensors, samplers, and analyzers become available for deployment on an RCO, these studies could capture the variability and response of ecosystems to environmental factors across these nested and widely different scales. Cabled observatories would also allow deployment of instruments with high power and data bandwidth requirements, for both resolving ecosystem structure and, most excitingly, for manipulative and mensurative experiments nestled within an observing system framework. Experimental manipulations will likely require highly specialized hardware that is presently unavailable, or will be deployed in association with RCOs using traditional submersible assets (ROVs, HOVs). The ability to perform sustained, high-resolution observations of ecosystem responses to artificial and natural perturbations, continue measurements through periods of previously very low accessibility (such as seasonally rough seas), and adapt sampling strategies in real-time in response to unforeseen events are quantum changes in ocean sensing that could create opportunities to test some previously more difficult hypotheses.

While there is great promise for significant advances in our understanding of ocean ecosystem dynamics using RCOs, such progress can only be realized after a substantial increase in the capabilities, availability, and reliability of sensors, samplers, and analyzers that will comprise the real measurement tools used with the RCO. The initial installation of the RCO will provide the backbone of power and data bandwidth, with a suite of "Core" sensors that will be enhanced by "Community" and "Principal Investigator" suites of sensors. Present limitations on the types of sensors available and suitable for year-long deployments are significant, and the "Core" sensors are likely to be limited to that that will be sufficiently stable (i.e. retain adequate calibration) and reliable to deploy on an RCO to support most biological studies. This short list is limited to sensors to measure temperature, currents, optical clarity of the water column. Note that these instruments measure physical parameters and do not sense biological patterns or processes. Sampling systems ready (or nearly so) for deployment on an RCO include camera systems to store or transmit images of the water column or the seafloor, and sediment traps to capture the sinking flux of organic debris. Many other sensors have great potential for use on RCOs, but their development times are likely to be near 5 to 10 years from the present. Other desirable, but presently unavailable, sensors may require 10 years or more before they will be available. Therefore, the application of significant funds towards an instrumentation development program is essential to both encourage the enthusiasm and support of the scientific community, and to exploit the potential of the cabled network infrastructure. Without a parallel instrumentation development effort, the utility of the RCO for ecological research will be limited greatly, and the installation of complex, expensive regional cabled observatories should be subject to considerable scrutiny.

If an important element of the cabled observatory system is to enable multidisciplinary approaches to compelling questions in ocean science, then it is essential that the RCO (or other observatory system) is capable of supporting the scientific activities (i.e. making the correct measurements, collecting appropriate samples, etc.) that will result in scientific progress. For studies of ocean biology and ecology, the current status of in situ sensors, samplers, and analyzers will likely limit the value, in terms of science progress, of RCOs until significant advances in instrumentation are realized. However, the availability of the RCO is also expected to catalyze instrumentation development efforts, provided that funding is available. The RCO will provide a new perspective concerning how measurements are made concerning ocean processes. Along with this perspective, the availability of power, high data bandwidth, and real-time connectivity should fuel creative new approaches and measurements that can be supported through a parallel instrument development program. Synergy between the infrastructure of the RCO and an associated instrumentation program is likely to accelerate progress in some ocean science problems.

The dynamics of an ecosystem are a combination of the response to direct, external forces and the non-linear dynamical behavior of the ecosystem itself caused by the interactions of organisms within a fluid or sediment. The external environment changes on a variety of time-scales. However, ecosystems can also fluctuate wildly even during periods of stable environmental conditions. Although the classic examples are terrestrial (predator-prey, disease cycles, etc), they must occur within the sea and provide a large challenge for producing predictive models of ocean ecosystem dynamics. The RCO gives scientists the opportunity to observe a variety of time-space scales of environmental and ecosystem variability and infer mechanism and future behavior from the correlations and patterns in these time-series. The high power available through the RCO may allow for manipulative and mensurative experiments nestled within this context, through the use of specialized sensors and tools, to test hypotheses concerning the mechanisms and dynamics of the ecosystem itself. These can be used to both develop and refine predictive models concerning ecosystem function in relation to internal and external controls. The interaction between modeling and the understanding of underlying dynamics may be one of the more powerful synergies to arise from the creation of RCO scale science opportunities.

The Ecosystems Dynamics Group posed one overarching question for all the habitats within the RCO. Sub-questions specific to each habitat are posed under this umbrella.

How do marine ecosystems vary through time and respond to environmental and biological variation?

Marine ecosystem responses of greatest interest include changes in community structure (species diversity, abundance, and distribution, species equitability, biomass, functional roles, demographic rates of populations, and community resiliency and stability etc.), as well as rates of energy and material flow through food webs. Scales of environmental variation of greatest interest include episodic events (storms, eddies, slumps), seasonal to interannual variability and decadal variability (climate change, regime shifts, seafloor vents). For each of the distinct sub-regions within the NE Pacific, there are specific, important processes that can be uniquely or best observed in that location. The science questions then motivate choices of specific location and sensor requirements. These are described in the subsections below.

Regional sub questions, experiments and data:

The bathymetry and physical oceanographic patterns in the northeastern Pacific in the region of the Juan de Fuca plate define a diverse set of pelagic and benthic marine ecosystems. The continental shelf environment is relatively narrow, yet extensive, and includes submarine canyons, sites with strong land / ocean interactions such as the Columbia River, and important coastal upwelling sites (Vancouver Island, Cape Blanco). The continental slope in the region is incised with numerous submarine canyons where shelf / slope transport processes are focused. The bathyal basin of the Juan de Fuca plate is largely surrounded by the Juan de Fuca ridge crest and Blanco Transform Fault. Seaward of the plate boundaries the seafloor slopes to abyssal depths, but is peppered with seamounts, particularly to the northwest. Such bathymetric complexity provides opportunities to investigate the generality of physical and biological processes that regulate the distribution and population dynamics of species, and the organization and productivity of communities.

Oceanographic variability in this region is considerable and includes several spatial and temporal scales. The large scale pattern includes the West Wind Drift, the major

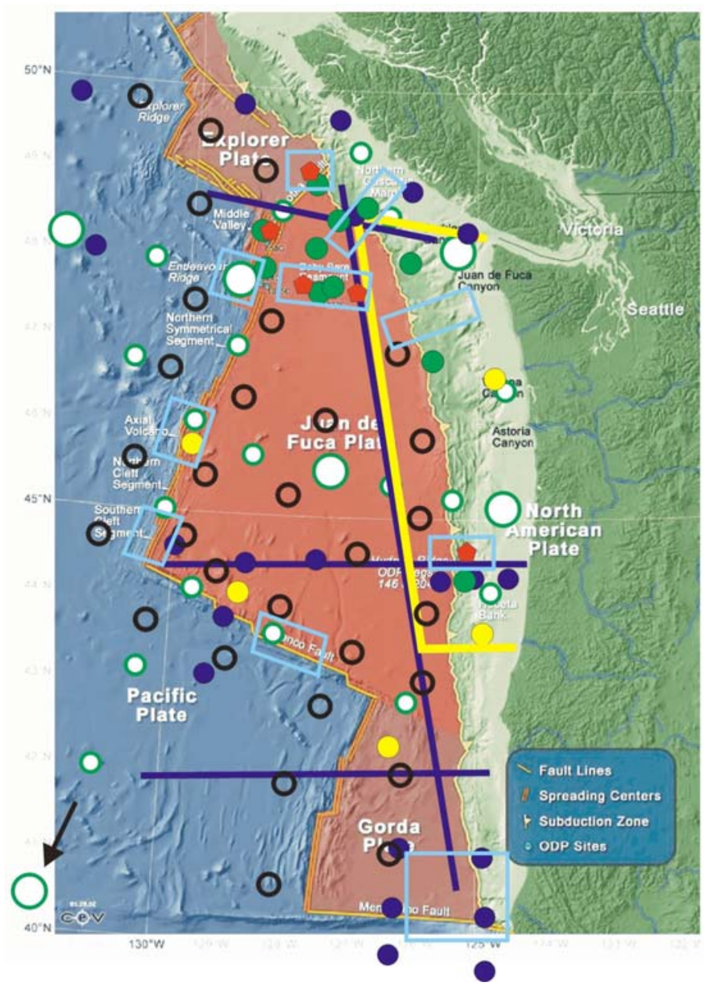

Figure 1. Map of Juan de Fuca area showing locations for RCO nodes proposed by CROW working groups. Black circles – solid Earth cycle OBS site, Blue rectangles – solid Earth cycle intensive study site, red circles – geodynamics boreholes, green circles – fluid flow studies ODP IODP sites, dark blue circles – ocean turbulence study sites, yellow dots – biogeochemical studies sites, blue & yellow lines – biogeochemical studies transects to include numerous nodes, white dots – ecosystem studies sites (small = standard, large = "super-site".

eastward flowing, wind-driven current that forms the boundary between the central north Pacific (CNP) and sub-Arctic gyres, diverges within the study area to produce the Alaska Current and California Current. The position and intensity of the WWD shifts over interannual to decadal scales, leading to variation in the volume of transport for its daughter currents. Variation in these large-scale features is known to influence strongly the patterns of productivity in the California Current and Alaska Current, including very large shifts in community structure throughout the trophic web. Smaller scales of variation in ocean physics also characterize the region, such as mesoscale circulation, turbulence induced by interactions of large flow patterns with bathymetric features (e.g. JDF Ridge), shifts in the position and depth of the California undercurrent, upwelling events, ENSO, and seasonally intense inputs of river runoff.

The CROW Steering committee members involved in biogeochemical cycles, turbulence, and ecosystem studies defined a large number (~80) of potential sites for benthic and water column studies that would exploit the diverse set of oceanographic and bathymetric variability that typifies the region. The Earth sciences groups proposed a similar number of sites that spanned the important sites for geophysical studies. Recognizing the large infrastructural costs for this first regional cabled subsea observatory, a set of "high priority" sites was designated, which focus on capturing various scales of oceanographic and bathymetric variability, and which require benthic

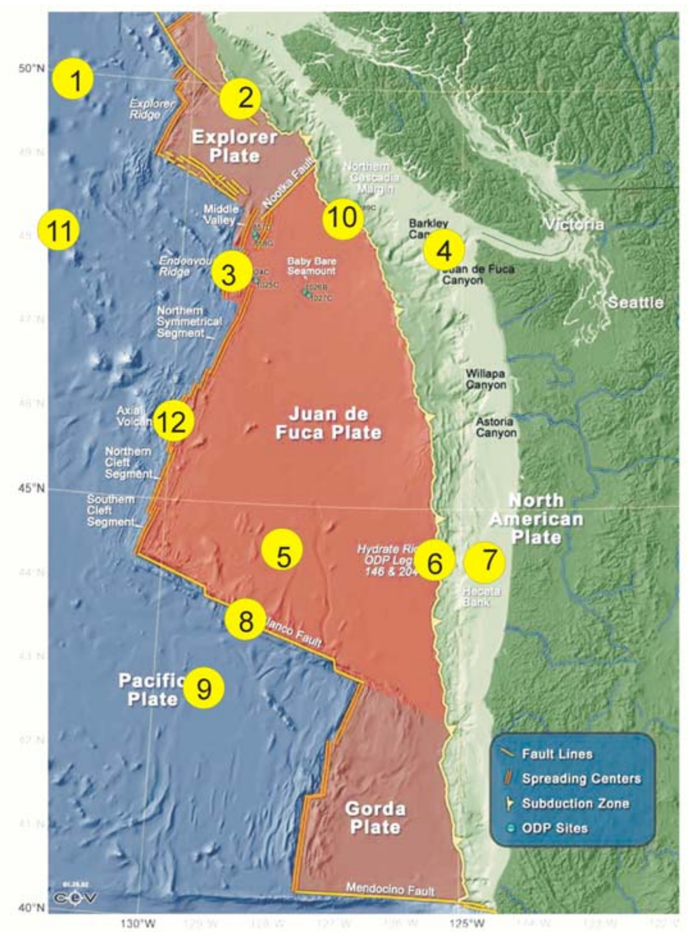

Figure 2. Map of RCO region showing high priority study sites (Yellow dots).

nodes and water column risers to within 200 m of the ocean surface. Connectivity and power to the cabled network will be required at the bottom and surface of these node locations. These sites are illustrated in Figure 2.

Numerous ecosystem studies are supportable using the RCO station layout shown in Figure 2. Sites are located on all major bathymetric features (Continental Shelf – 2, continental slope – 3, bathyal basin – 1, abyssal basin – 3, mid-ocean ridge – 2, and mid-ocean transform fault – 1). Comparisons of data collected from these sites will allow detailed studies of similar processes in very different habitats, broadening our understanding of linkages between environmental variation and ecosystem pattern and function. The high priority stations also encompass gradients in ocean physics. Physical sensors located along the N/S set of stations will allow detection of the position and intensity o the West Wind Drift. In addition, current and ocean physics measurements at stations 1, 2 and 5 to 9 will allow determination of the divergence of the WWD and inception of the Alaska and California Currents. Shelf slope interaction studies will be served best by comparisons among stations 6&7 and 4&10. Hydrothermal Vent communities are common at the Endeavour Ridge, beneath station 3, and at Axial Volcano, near station 12. Hydrate Ridge, a site of intense interest for methane hydrate and chemosynthetic communities, is located near station 6. Seamounts are well developed and common near station 11. The station positions also take advantage of the long time series of observations along the "Newport Line" (Stations 5 – 7). Finally, the distribution of high priority stations spans several gradients in ocean productivity (Figure 3), ranging from gradients in the intensity of coastal upwelling, north-south gradients in productivity (related partially to the WWD), and major onshore / offshore gradients in ocean temperature and upper ocean productivity.

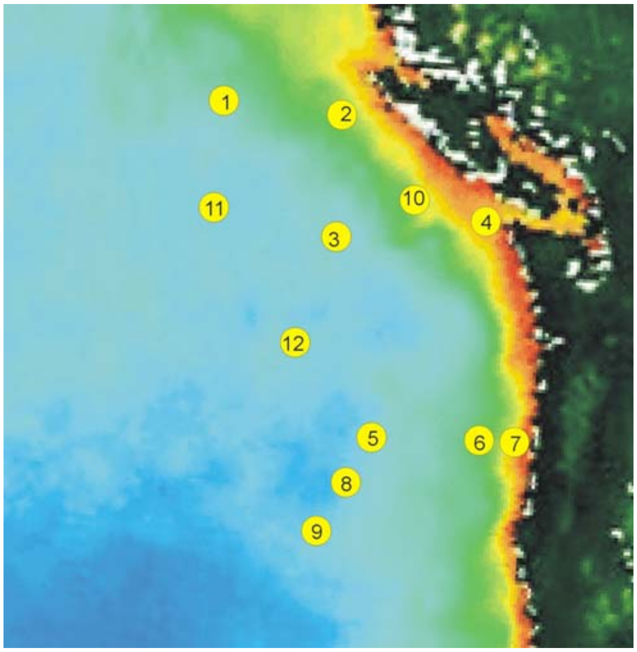

Figure 3. Ocean color (summer average ocean color) with station locations for regional cabled observatory.

Seafloor Ecosystem Studies

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

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

The responses of benthic communities, inhabiting major seafloor ecosystems within the region, to environmental variability are expected to differ, though the importance of various factors are not yet understood. For example, atmospheric and climatic variability will undoubtedly exert strong influence on upper ocean productivity and the export flux of carbon, but the degree of coupling between upper ocean and benthic systems may vary depending upon depth, the magnitude of variation in carbon flux, other sources of carbon input (e.g. lateral flux), or other factors.

Important questions in benthic ocean science include:

- How tightly coupled are benthic community patterns and processes to variation in upper ocean physical and biological productivity?
- Do components of benthic communities (i.e. microbial, protozoa, meiofauna, macrofauna, and megafauna) differ in their response to various scales of upper ocean variability?
- What are the key factors influencing the colonization, community development, successional patterns, and stability of deep-sea communities?
- Do biological interactions (predation, competition) or physical processes exert the greatest influence on the structure and organization of deep-sea benthic communities?
- What is the role of extrinsic factors influencing the survival and distribution of marine larvae versus intrinsic processes (post-settlement survival) on the population dynamics and community structure of deep-sea benthic communities?
- How do rates of energy flow among benthic community components vary in response to periodic or episodic changes in carbon input from the upper ocean?

And while these themes underlie much of the science proposed for specific seafloor ecosystems, the integration of these studies among relatively disparate systems will provide an unprecedented advance in our understanding of the generality of ecosystem linkages and processes.

Key experiments in deep-sea benthic ecology that are high priorities for the RCO system will be to measure the degree of variation in benthic community rate processes, particularly carbon uptake and remineralization, in response to variation on a variety of spatial and temporal scales associated with oceanographic variation. Novel methods to measure community oxygen consumption and elemental fluxes in and out of the sediment are becoming available and may be used at a series of sites (shelf, slope, bathyal and abyssal plains) to measure changes in energy flow. Simultaneous studies of changes in community patterns using camera systems to determine megafaunal diversity, abundance, and activity will be coupled to high-frequency measurements of carbon input and a suite of standard oceanographic parameters. Replication of these measurements at several sites over time scales that capture important cyclic features and episodic events will provide an unprecedented view of the generality of benthic ecosystem responses to variation in ocean processes.

Continental Shelf and Slope

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

Shelf environments

Shelf environments are affected by physical disturbances generated during storm events, but are also linked strongly to the water column through the temporal coupling of the input flux of phytoplankton production to the seabed with cycles of upper ocean productivity. In the north Pacific, delivery of organic material to the seabed is strongly seasonal, creating variability in the quantity and quality of food resources. Thus, a combination of physical disturbances and linkages with upper ocean productivity can influence the development and stability of shelf communities. In addition, however, the life histories of species may lead to large variation in the relative importance of various factors that may influence their population dynamics. For example, many invertebrates inhabiting sedimentary environments have a planktonic larval stage that experiences high mortality prior to settlement to the benthos. The RCO will enable more detailed studies of these systems than previously possible, allowing scientists to address a wide range of questions concerning ecosystem patterns and function, such as:

- To what extend does timing of larval release relative to phytoplankton production influence survivorship?
- Does delivery of phytodetritus to the seabed and its composition influence patterns of larval settlement, and subsequent patterns in adult communities?
- Do larvae actively respond to these patches or is delivery primarily passive?
- To what extend do storm events influence patterns of recruitment, by opening up habitat through disturbance and mortality of adults?
- Does spatial patchiness in food resources contribute to the patchy nature of these communities and help to regulate patterns of diversity of macrofauna, meiofauna and even microbial diversity, or is much of this pattern driven by internal controls such as predation or competition?
- Do human activities such as trawling that disturb the seabed alter these patterns?
- Do human activities that increase frequency and intensity of phytoplankton blooms alter sedimentary faunal composition?
- What is the response of microbial, macrofauna, and megafaunal communities to variation in organic carbon input from the euphotic zone caused by climate variability?

Benthic organisms may also have a feedback effect on water column processes; this linkage may be relatively strong and coupled closely in time and space in shelf systems, whereas in deep-sea systems this linkage is more likely to occur only on longer time scales (i.e. temporal mixing scales between bottom and surface waters). For example, benthic organisms play a key role in the decomposition of organic material and regeneration of nutrients into the water column. But have only recently begun to understand the roles of different organisms in this process.

- To what extent does benthic biodiversity influence efflux of nutrients from sediments, or is this flux strictly dependent on the presence of key taxa (e.g. microbes) or functional groups.
- Does loss of specific groups of organisms (e.g. microbes) compromise the capacity of sediments to regenerate nutrients?
- Are there indirect regulators of this process, such as oxygenation of sediments, and does the specific makeup of bioturbators play a role?

Benthic organisms also influence the mobility and stability of sediments. Microbes and sedentary macrofaunal, for example, can stabilize sediments whereas deposit-feeding macrofauna bioturbate and therefore increase sediment mobility. Specific questions include:

- To what extent does sediment transport change seasonally, and what role do sedimentary fauna play in this process?
- Can bioturbators contribute to harmful algal blooms by mobilizing cysts, or remobilize pollutants that might otherwise be buried in sediments?

Slope environments

Slope environments are coupled less directly to upper water column disturbances than shelf environments, but there is nonetheless the potential for strong spatial and temporal dependence. There are many important questions concerning the slope ecosystem dynamics that can be addressed from a subsea cabled network, such as;

- To what extent does horizontal and vertical flux of materials influence spatial and temporal patterns of delivery of organic material to sediments?
- Does this patchiness influence patterns in benthos?
- Do episodic storm events that do penetrate to upper slope depths influence benthic patterns through disturbance, or are storm effects indirect, through increased export of organic material in the form of phytodetritus or carcasses of whole organisms (e.g. salps, jellyfish)?
- To what extent do these processes influence patterns of diversity?
- Do regime shifts in the upper water column translate into faunal differences in deep-sea sediments?
- Are these differences a manifestation of different types of material flux or changes in survival of larval stages of benthos that may spend part of their planktonic period in the upper water column?
- How do the structure and dynamics of slope communities vary between canyon and non-canyon habitats?
- How variable is carbon transport to the deep-sea between canyon and non-canyon habitats?

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

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

Abyssal Basins

Until recently, bathyal and abyssal seafloor ecosystems were thought to be coupled only weakly to the input of organic debris from surface waters, owing to the expected damping of variation in surface productivity by the remineralization and slow sinking of organic carbon exported from the surface. We know now that organic debris can reach the seafloor in >5000 m quickly, leading to a rapid response by the benthos. This advance has prompted many additional questions concerning the dynamics of abyssal communities and linkages to various scales of upper ocean variability. These include, but are not limited to;

- Is the productivity and community dynamics of benthic abyssal communities carbon limited?
- How are changes in upper ocean productivity manifested in deep-sea benthic communities?
- Do abyssal faunal assemblages (i.e. microbial, meiofaunal, macrofaunal, megafaunal groups) respond similarly to variation in organic fluxes?
- How are deep-sea communities affected by different scales of oceanographic variability (e.g. seasonal to decadal, and periodic to episodic)?
- How are the population dynamics (i.e. rates of reproduction and survival) affected of deep-sea benthos affected by extrinsic factors (i.e. variation in carbon input) and intrinsic factors (e.g. biological interactions)?

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

Several measurements and observational methods will be important. These include core measurements of benthic and bentho-pelagic oceanographic parameters (currents, temperature, pressure, oxygen, suspended sediment) and energy flux (organic carbon input). Biological parameters will range from regular images of benthic megafaunal communities from moored and mobile camera systems to rates measurements (e.g. sediment community oxygen consumption, carbon remineralization & nutrient fluxes) to more advanced determination of changes in microbial and meiofaunal population abundance and condition (DNA / PCR processors, Sediment sampling and preservation tools).

Seamounts

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

- What factors regulate the structure and productivity of seamount communities?
- What are the time scales for community development on seamounts?
- What is the relationship between upper ocean productivity, depth of the seamount peak, and seamount community structure and productivity?

Trawling activities on seamounts have devastated benthic communities on many seamounts through the virtual removal of entire communities of sessile, hard substratum species. Factors influencing the colonization, recruitment, growth, and productivity of major seamount faunas are almost entirely unknown. Observations using camera systems, oceanographic instrumentation (currents, other), and advanced methods, including experimental manipulations, promise significant advances in this area.

Deep-Sea CO_2 Sequestration Issues Consideration of deep-sea carbon sequestration, coupled with the continued acidification of the world ocean suggests that the future ocean will be lower in pH, with presently unknown impacts on the structure and dynamics of shallow and deep-sea marine communities. Use of the cabled network observatory to investigate the effects of elevated CO_2 / reduced pH on benthic and bentho-pelagic populations and communities may be possible using experimental manipulations similar to the Free-Air CO_2 Enrichment (FACE) studies presently under study in a variety of terrestrial systems.

Vents and Seeps:

Seafloor volcanic spreading ridges host hydrothermal activity that provides energy for unique biological communities fueled by chemosynthesis. Hydrothermal vent fields are among the most geologically active areas on Earth and vent biomass rivals that of the most productive marine ecosystems. Hydrothermal vent communities are known to be highly dynamic, subject to drastic changes in composition and biomass at time scales of weeks to months. Such changes are presumably brought about by the seismic, magmatic, hydrothermal, and oceanographic processes that shape the vent environment, although such interactions are difficult to observe without continuous monitoring. The Endeavour Segment of the Juan de Fuca Ridge is proposed as a site for studies of vent ecosystem dynamics. Endeavour Segment is known for its widespread and abundant high temperature venting, through large and numerous sulphide mineral edifices. Vent communities colonize actively venting sulphide edifices as well as seafloor vents where fluids discharge through basaltic rock. Proposed studies include:

- Ecosystem dynamics (growth, recruitment, succession) in relation to fluid flow variations, mineral accretion and edifice growth
- The influence of local to ridge segment scale water mass dynamics in the dispersal and transport of vent organism larvae, and the export of hydrothermal productivity to the adjacent deep-sea ecosystem
- Seismicity as a source of perturbation for ecosystem processes.

Tectonic compression along the convergent boundary of the Juan de Fuca and North American plates is thought to drive seepage of methane-rich pore fluids from hemipelagic sediments, which, like hydrothermal vents, support chemosynthetic communities. These communities are particularly abundant in areas such as Hydrate Ridge (Figure 2, Site 6), where methane hydrate is abundant beneath the seafloor. Important questions concerning the biological consequences of methane seepage include:

- What is the relationship between rates of fluid release and seep community structure and productivity.
- Is the productivity of seep communities limited by rates of fluid release or by other factors, such as sulfate penetration into the sediment, rates of anaerobic methane oxidation (AMO), or oxygen availability?
- What factors regulate the colonization and community structure of seep communities?

Regional cabled observatory studies at Hydrate Ridge provide opportunities for interdisciplinary studies of tectonic compression, fluid expulsion, hydrate formation and degassing, microbial mediation of biogeochemically important fluxes (e.g. AMO), and chemosynthetic metazoan community patterns and processes. Synergy among the relevant disciplines, coupled with long-term observations of physical and biological patterns and processes, and focused manipulative experimental studies, promises rapid advances in understanding these systems.

Epipelagic

The epipelagic realm encompasses the euphotic zone and the waters immediately below it. It is the zone of solar-stimulated primary production, and is influenced by dynamics at the surface of the ocean (heat flux, wind stress, freshwater inputs, atmospheric deposition), and at the base of the surface mixed layer (diapycnal mixing, sedimentation of organic material). Organic carbon fixed in the epipelagic zone forms the major food source for most benthic organisms.

Planktonic community structure and dynamics in the epipelagic are tightly coupled to the physical forcing, and exhibit scales of variability from centimeters to hundreds of meters vertically, and meters to thousands of kilometers horizontally. A dominant horizontal scale of variability is given by the baroclinic Rossby radius of deformation (a scale determined by the physical environment), which ranges from 5-30 km, depending on the water depth and vertical stratification.

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

Important questions concerning the ecosystem dynamics of the epipelagic are:

- What are the physical and biological controls on production?
- What is the importance of episodic events (storms, blooms) relative to the “mean” state in determining production and fluxes through the epipelagic?
- How are planktonic community structure and dynamics affected by perturbations such as changes in circulation (e.g., upwelling), atmospheric deposition (e.g. Fe), or long-term changes such as ENSO or the PDO?
- What is the relationship between biological community structure and particle export from the upper ocean?
- What is the relationship between the mesoscale eddy structure and upwelling plumes and the dynamics of the biological system?
- What are the time-space scale dynamics of blooms of organisms from primary producers to larger herbivores and carnivores and what can we understand to help predict the timing and impacts of these blooms.
- What is the spatial and temporal variability of cross-shelf transport? Is it dominated by episodic events at specific locations, or is it more widely distributed in space and time? How do these patterns affect the ecosystem dynamics?

We propose to explore these questions using long-term, high temporal resolution observations of the epipelagic ecosystem, combined with ship-based observation programs, and manipulation experiments (such as long-term iron fertilization at specific sites). Observations would be assimilated into models of the physical and biological dynamics to gain enhanced understanding of the underlying dynamics. To optimize costs vs. benefits, we propose a nested regional observing system. The backbone system would consist of "standard" sites arranged to define cross-shelf and along-shelf transects, and a set arranged to define the boundaries of a volume targeted for data assimilative models. "Super" sites (Figure 2, sites 3, 5, 7, 9, 11 check these) would consist of smaller, well-defined regions that would be more densely instrumented. The purpose of this arrangement of standard and super sites is to obtain large-scale (>mesoscale) continuous observations at the boundaries of a volume to constrain the fluxes through that volume, while the super sites would allow resolution of sub-mesoscale gradients. This nested approach will provide strong constraints to physical-ecosystem models, allowing a teasing apart of the physical and biological dynamics controlling the observed fields.

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

Research on pelagic community structure represents one of the largest instrumentation and intellectual challenges for an RCO. This type of research will require instruments that can be used to identify the organisms that are present on a variety of scales and some elements of their dynamics (growth, physiology, ecology). Molecular approaches have been identified that may be able to allow some of these measurements, but it will be a real challenge to make those instruments operational on the time-scale of the RCO. Imaging instruments have great potential and some may be near operational capability more quickly. Sample collection and storage for later analysis is also possible. Intellectually, the fact that the water moves past a fixed site presents a host of challenges for relating the observations at a site to the spatially variable processes that produce those patterns. It is clear that to move forward in this area will require a coupling between the activities on the RCO and the more traditional science conducted from ships. As RCO technologies mature, gliders, AUVs and other mobile vehicles may extend the capabilities of the remote system to cover some, but not all, of the ship-based needs.

Meso and bathy pelagic

The flux of particulate and dissolved organic carbon from the surface layer of the ocean to the deep sea via the biological pump is a primary mechanism by which carbon dioxide is removed from the surface ocean. Imbalances between the downward flux of carbon and its return tot he surface are a major mechanism through which the oceans regulate the concentration of carbon dioxide in the atmosphere. Although about 90% of the particulate flux sedimenting from the surface layer disappears in the mesopelagic zone (100-1000m) as a result of consumption or remineralization, the species composition and food web interactions of this important community remain poorly known. An RCO provides an unprecedented opportunity to observe the meso and bathy pelagic zones to gain a view of the basic patterns in this system to guide future hypotheses and experimentation.

Subquestions:

- What are the quantitative and qualitative characteristics (i.e., source, chemical composition) of the particulate flux?
- What is the spatial and temporal variation in the mean flux of particulate matter versus episodic fluxes (i.e., large deviations from the mean)?
- What are the rates of microbial remineralization with depth over time and how do these vary in response to different scales of climate variability and carbon flux?
- What is the vertical variation in species composition, abundance, and distribution of mesopelagic organisms over time (diel, seasonal, interannual, decadal)?
- How do vertically migrating zooplankton and fish influence particulate and dissolved elemental flux through the mesopelagic zone?

Sensors:

A very significant instrument development program that parallels the planning and installation of any regional scale cabled observatory is essential to address most biological scientific themes planned for RCO studies. The status of biological sensors and instruments is presently unsuited to the long deployment times expected between service periods for individual nodes on the RCO. Few sensors presently available can retain their calibration and stability over several months, let alone yearlong periods. Temperature sensors, acoustic systems such as acoustic doppler current meters, optical backscatter sensors and transmissometers to measure water clarity are available today that are suitable for cabled observatory deployments. It is critical to note, however, than many other sensors, samplers, and in situ analyzers that are deployed for short periods (i.e. weeks to months) on moorings or operated from ships, are not yet suitable for RCO deployment. More complex systems, including various submersible autonomous platforms (AUVs, Benthic Rovers, In situ manipulator boom), in situ samplers (sediment sampler, water samplers, plankton samplers), analyzers (Environmental Sample Processor [ESP], elemental analyzer), and other specialized instruments (sample recovery systems) will not be available for deployment on the RCO for a considerable period, perhaps exceeding the lifetime of the RCO.

Considering the current limitations of sensor availability for a variety of disciplinary studies, it is important to consider the value of RCO development until the suite of available sensors is sufficient to support high priority science objectives in most disciplines expected to be served by the RCO. Lacking the appropriate sensor-suite, the likelihood of significant scientific advances in pelagic and benthic biological studies, may be low relative to the costs of installation and maintenance of the RCO. Nevertheless, significant advances in instrumentation and sensor capabilities, which will require creative new approaches or enhancements of existing instruments, is likely to be catalyzed by the availability of the RCO. Thus, parallel RCO and instrument development efforts may be highly productive.

The above caution concerning the present status of sensor development notwithstanding, we can consider the types of sensors required to support studies of ecosystem dynamics. The sensor and sampling platform choices for investigating ecosystem dynamics are a combination of direct measurements of time-dependent, biological systems, measurements of the environmental context and the ability to conduct manipulative experimentation within this context. Further, the design of the experiments requires some explicit sampling of a variety of spatial scales and thus creates important demands for a more expansive infrastructure than the simple cable and node backbone common to the entire system.

Most of the sensors required for ecosystem research are dictated by the science questions themselves and are logically community or PI-owned rather than part of the limited Core suite. However, the backbone itself will require substantial additional components as minimum criteria for conducting any of this research and these platforms and extensions should be part of the core design and implementation of the Cabled Observatory. All of this research requires that space be resolved or explored, either continuously or sequentially, on scales of meters to 100s of kilometers. This mandates that adequate extension cables be generally available to connect a distributed set of instruments to a node, particularly in the super-site areas. The water column measurements requires that a vertical profiling capability be present, sometimes as a mooring, sometimes as a moored array, more frequently as s profiling platform or array of platforms. Beyond this, many of the experiments also envision the ability to move around the region with ROVs, AUVs, gliders, boom systems or rovers. These mobile systems should be a multiple-user component of the fundamental infrastructure, sufficiently well designed and managed so that individual science groups can acquire partial use of the platforms when needed.

The direct time-series measurement of biological and environmental parameters includes a mix of COTS instruments, sampling tools under development and some technologies that are still on the drawing board. A variety of sensors exist to characterize the physical, chemical and bulk-biological system (see Table 1). The best developed of these measure hydrography, flow, optics, use acoustics to measure zooplankton or sediment traps to measure fluxes. Chemical sensors are starting to be available for some nutrients, chemical species, bulk plant pigments and particles. The real challenges come in trying to characterize biological community structure. In these cases there are a few imaging systems like HDTV cameras, Video-Plankton Recorders, Optical Particle Counters that exist, but have not been made so widely available as to ensure adequate quality and supply.

The most promising technologies are either in development or merely ideas at this stage and will require substantial investments. The developmental periods for many of these sensors may exceed the lifetime of the first RCO. The use of genetic and immunological approaches, in situ flow cytometers, elemental analyzers and other next-generation identification systems will be an absolute requirement for realizing the value of the

Cabled Regional Observatory for Ecosystem science. Further advances in visualization technologies, automated image processing, optical and acoustic technologies must also be encouraged. However, for some measurements, in situ approaches are probably always going to be inadequate and the ability to capture, preserve and return a physical sample will be necessary. The development of all of these technologies must be a high priority, very early in the development of the system so that they are ready for use synoptic with the availability of the Observatory.

Rate measurements are a special subset of the desired measurement suite. We can gain great information about the ecosystem by comparing the time-dependent abundance of the organisms that are present to the changes in the physical environment. However, understanding the mechanisms that determine these dynamics is important for using models to test mechanistic explanations of the patterns and predict future behavior of the system. Measuring growth rates, fluxes, metabolism and even reproduction could be critical tools for improving our understanding of mechanisms. Some tools exist, COTS such as sediment traps. Some have been fairly well developed for use in benthic landers, such as benthic respiration chambers, micro-profilers for calculating sediment gradients and estimating fluxes and even respirometry chambers. An interesting world of more biological approaches to rates and metabolism, rooted in genomic, proteomic and metabolomic ideas should also be explored to fill out the possibilities for measuring biological rate processes.

Ultimately, the ability to conduct controlled experiments, both mensurative and manipulative will be a key part of any exploration of ecosystem dynamics. Progress in ocean ecosystem studies may be more efficient and successful using traditional expeditionary approaches until sensor development advances to a point that a suitable suite of biologically relevant sensors are available and reliable for RCO deployment. However, expeditionary and cable observatory studies should, nevertheless, be used together to test hypotheses about mechanisms and the robustness of models. Some of these require the ability to perturb or manipulate an aspect of the biological system and move through the system to document the response. These require standard sensors on mobile platforms. In other cases, novel manipulation devices may be required to control a volume of water or sediment, manipulate it such as through the addition of a substrate, contaminant or physical change and then measure a unique response. The scale of these devices varies from small incubators to the manipulation of entire landscapes such as through trawl scars or drilling new hydrothermal vent plumes.

Table 1. Sensor Lists (see text for links to the science questions) CORE instrumentation is labeled as such, Community Instruments are labeled with an asterisk*, all others are seen as PI-owned.

SENSORS	Suitable for ~1 year Deployment?	Upper Ocean	Pelagic	Shelf	Slope	Basin	Ridge	Sea-mount	Vent / Seep	Core	Com-munity	PI
Imaging System, digital still camera	Available	X	X	X	X	X	X	X	X	X		
Imaging System, video camera	Available	X	X	X	X	X	X	X	X		X	
Profiler, vertical, benthic boundary layer	Available	X	X	X	X	X	X	X	X		X	
Profiler, vertical, upper ocean	Available	X		X	X	X	X	X				X
Sampler, sediment trap	Available	X	X	X	X	X	X	X				X
Sensor, Current Meter, ADCP	Available	X	X	X	X	X	X	X	X	X	X	
Sensor, Currents, surface, CODAR	Available	X									X	
sensor, optical backscatter	Available	X	X	X	X	X	X	X	X		X	
Sensor, pressure	Available			X	X	X	X		X	X	X	
Sensor, Temperature	Available	X	X	X	X	X	X	X	X	X		
Sensor, Transmissometer	Available	X	X	X	X	X	X	X	X		X	
Analyzer, nutrients (ISUS)	Future	X							X		X	
Analyzer, sulfide ISUS	Future								X			X
Flux Chamber (O2, Nutrients, metals)	Future			X	X	X	X		X			X
Imaging system, bioluminescence camera (active / passive)	Future	X	X									X
Imaging system, Video plankton recorder	Future	X	X	X	X	X	X	X	X		X	
Manipulation tool, flow flume	Future			X	X	X	X	X	X			X
Manipulator, food input system (e.g. carbon injection)	Future			X	X	X	X	X	X			X
Manipulator, sediment stirrer	Future			X	X	X	X	X	X			X
Manipulator, temperature	Future								X			X
Platform, AUV	Future	X	X	X	X	X	X	X	X		X	
Platform, Benthic ROVER	Future			X	X	X						X
Profiler, sediment microprofiler	Future			X	X	X		X	X			X
Respirometer, chamber, in situ	Future	X		X	X	X	X	X				X
Sample injector	Future			X	X	X	X	X	X			X
Sampler, high temperature fluids	Future	X							X			X
Sampler, larval	Future	X	X	X	X	X	X	X	X			X

Sampler, particle pump	**Future**	X		X	X	X	X	X			X
Sampler, sediment w/ preservation	**Future**			X	X	X			X		X
Sampler, water	**Future**	X	X	X	X	X	X	X	X		
Sampler, zooplankton	**Future**	X									X
Sensor, Acoustic arrays (passive and active)	**Future**	X	X	X	X	X	X	X			X
Sensor, CO2	**Future**	X							X	X	
Sensor, DOM, multispectral	**Future**	X			X	X					X
Sensor, methane	**Future**								X		X
Sensor, optical fluorescence	**Future**	X	X	X	X	X	X	X	X	X	
Sensor, oxygen	**Future**	X	X	X	X	X	X	X	X	X	
Sensor, Salinity	**Future**										
Sensor, sulfide (ISUS)	**Future**								X		X
Sensor, temperature, acoustic array	**Future**								X		X
Analyser, Environmental Sample Processor (ESP)	**Distant Future**	X	X	X	X	X	X	X	X		X
Analyzer, elemental, in situ	**Distant Future**	X	X	X	X	X	X	X	X		X
Analyzer, HPLC, in situ	**Distant Future**	X	X	X	X	X	X	X	X		X
Manipulation tool, bulldozer for ROVER	**Distant Future**			X	X	X					X
Manipulator, boom array for vent studies	**Distant Future**								X	X	
Manipulator, faunal abundance	**Distant Future**			X	X	X	X	X	X		X
Sample recovery system	**Distant Future**			X	X	X	X	X	X		X
Sampler, Drilling tool	**Distant Future**								X		X
Sampler, plankton, microbial, meiofaunal	**Distant Future**	X	X	X	X	X	X	X	X		X