MOOS System Functional Requirements

Revision

1.0 January. 26th 2000 Initial draft
2.0 March 22nd 2000 Use Scenarios, adaptability, temporal and spatial coverage added
3.0

Contents

1. Introduction

a) This document describes the System Functional Requirements for the MOOS (MBARI Ocean Observation System) mooring system and will form the basis for all MOOS design work

2. Science Drivers

a) The System Functional Requirements have been derived from the following:

- MOOS workshop report "Future of MBARI Ocean Observing Systems"
- identifying top level requirements through meetings with MBARI scientists
- Use Scenarios.

b) The Use Scenarios describe how the fully functional MOOS mooring system would be used to support science experiments and are attached as Appendices 1-4. Although they describe typical uses for the MOOS mooring systems, they are not exhaustive in terms of potential applications and requirements. However they have been valuable as a basis for deriving many of the top level System Functional Requirements. The Use Scenarios are outlined below.

2.1 Upper Water Column Processes

a) Coastal upwelling occurs when strong winds transport surface layer water offshore, resulting in the upwelling of nutrient rich subsurface water near the coast. Appendix 1 describes an experiment to investigate the processes associated with coastal upwelling including ecosystem population dynamics and distribution, and nutrient transportation. As these processes are episodic in nature, an adaptive sampling topology is required, such that after coastal upwelling has been detected, higher resolution sampling is needed to resolve the processes associated with the coastal upwelling.

2.2 Canyon Dynamics

a) Appendix 2 describes an experiment to investigate the physical processes that occur in the axis of the Monterey Canyon. The intention is to identify the significant processes that excavate submarine canyons, to determine the rates of these processes, to understand the role of submarine canyons as conduits for transporting materials from continents to the deep sea, and to assess the importance of submarine canyons in moving carbon to the deep-sea.

2.3 Active Mid-Ocean Ridge Processes

a) This use scenario, included as Appendix 3, outlines a multidisciplinary experiment to investigate the biogeochemical processes associated with the formation of oceanic crusts at a mid-ocean ridge, such as the Southern Cleft segment on the Juan de Fuca Ridge.

b) The major scientific theme addressed here is the temporal and spatial variability of the hydrothermal cooling and tectonic fracture that occur during the formation of oceanic crust. The hydrothermal effluent impacts the chemical composition of the overlying water column and modulates the environment for microbiol and macrofaunal species. Both surface and subsurface processes will be mapped and measured with a multidisciplinary experiment on a single ridge axis. The subsurface processes will be quantified by the deployment of an innovative suite of instruments and samplers networked via two (or three) MOOS telemetered moorings. Continuous measurement of ground motion, fluid flow, and fluid chemistry combined with field evidence of persistent diffusive flow and active extension might enable linkages to be resolved, and from these, infer the depth and progress of a brittle fracture horizon beneath a ridge hydrothermal system. By assessing the changes in the microbial community in concert with the geochemical processes it is hoped to determine the species distribution, abundance and habitat distribution for the "crustal biosphere" during various phases of the evolution of the hydrothermal system.

c) The continuous (or chronic) venting from the South Cleft hydrothermal sites rise approximately 50 to 200 m above the seafloor. The venting perturbs the lowermost water column and can be measured within the axial caldera of the ridge segment (which is two kilometers wide). The event plumes associated with either dike intrusions of major tectonic events rise up to 1000 meters above the seafloor. These turbulent events disrupt the overlying water column and move away from the vents within a few days to weeks of the event. The two megaplumes measured on the Cleft Segment, were observed displaced several kilometers from the vent sites by the time the surface ships could arrive on station.

d) Appendix 3 describes an experiment to address fundamental hypotheses on the coupling between volcanic, tectonic, hydrothermal and biological processes

2.4 Benthic Carbon Cycling Studies

a) This Use Scenario focuses on differences in carbon cycling by benthic communities in areas near or distant from the influence of organic inputs from the Monterey Canyon system.

b) Measurements will be made on the carbon availability and its utilization by benthic communities at deep-sea sites influenced by organic inputs from the Monterey Canyon and those distant from the effects of the canyon. Instruments will measure the rates of carbon input from surface waters, organic material transported down-canyon during debris flows, and rates of carbon uptake under various conditions of organic inputs. Results of these studies will broaden understanding of both the role of Monterey Canyon in the nutritional dynamics of deep-sea benthic communities and the strength of coupling between pelagic and benthic systems in the central coast.

3. Geographical Coverage

3.1 Installation Locations

a) MOOS placement locations include:

- Monterey Bay area and immediately adjacent waters extending out 1000 kilometers (3500m)
- Equatorial pacific
- Northern area of the East Pacific Rise southwest of Mexico's Baja Peninsula
- Ocean station "P" at 50N, 145W in the North Pacific (4150m)
- Axial Seamount (1600m)
- Juan De Fuca ridge complex (2500m)
- Gorda ridge (3900m)
- Loihi Seamount, 35 kilometers south east of Hawaii
- Locations in the western Pacific (5500m)
- Central pacific gyre area off Monterey Bay (4500m)

3.2 MOOS Deployment Water Depths

a) The majority (80%) of sites of interest have maximum deployment depths that are less than 4000 meters. All of the sites in the Use Scenarios fall within this 4000m depth range. Areas deeper than 4000 meters could not use MBARI ROV's for deployment of a benthic instrumentation portion of the MOOS mooring system.

b) The shallowest deployment sites for the MOOS mooring are in coastal areas including inshore Monterey Bay where the depth is 30 meters.

4. Duration of Deployment

a) The MOOS mooring will be deployed the periods up to a maximum of 3 years providing time series or durations consistent with the timescales of episodic events of interest.

b) The minimum deployment duration is likely to be determined by logistic and cost/benefit considerations.

5. Episodic Event Response (Adaptability)

a) The Use Scenarios identified many situations where the MOOS system will be deployed to detect episodic events and then to respond adaptively to the detection of an event, including:

- Onset of a coastal upwelling event (see sections 6.2.1.1; 6.2.1.4; 6.2.1.5)
- Investigating geomorphic changes caused by sedimentary mass transportation along the axis of a canyon after detection of a mass wasting event (see section 6.2.2)

- Measuring the formation and dissipation of an hydrothermal megaplume or event plume following a volcanic event on an active mid ocean ridge segment (see section 6.2.3.2 (b)(c) and 6.2.3.3)

b) The spatial and temporal measurements and the associated sensors needed to detect and respond to an event are described in more detail throughout section 6

c) Event Detection. Detection of the event by the mooring may be through:

- direct communication from shore informing the mooring processors that an episodic event has started. In this situation the event is detected by systems external to the MOOS system
- measurements recorded by sensors on the MOOS mooring. This information will then be processed by the MOOS mooring and a response initiated (see (d) below)

d) Response When Mooring Sensors Detect Onset of Event. In the situation where the event was detected by sensors on the MOOS mooring, the system would respond in the following manner:

- communicate the event detection to shore
- start a pre-determined response by initiating a mission profile, taking more data with its suite of sensors, implementing new sampling strategies, launching AUV's etc.

e) Response When Onset of Event Communicated to MOOS Mooring. In the situation where the onset of the episodic event were communicated to the MOOS system from shore, the system would respond in the following manner:

- follow a set of mission commands communicated from shore, or
- start a pre-programmed response by initiating a mission profile, which could include taking more data with its suite of sensors, implementing new sampling strategies, launching AUV's etc.

6. Measurements and Instrumentation

6.1 Supported Instrumentation

a) Appendix 5 contains a detailed list of measurements and the associated instruments currently used to take these measurements. The MOOS mooring will not be able to support all of these instrument simultaneously, so the Use Scenarios have been used to provide a basis for determining:

- the need for simultaneous measurements to support a science program.
- the required temporal and spatial coverage of measurements around the MOOS mooring
- sampling topologies prior to and after episodic event detection

b) From these requirement will be derived the MOOS mooring system power, communication and instrument port configuration requirements.

c) Due to the large number of different instruments that the MOOS mooring needs to be capable of supporting there is a need to be able to efficiently change the mooring instrumentation configuration by incorporating a standard instrument interface. In addition the MOOS mooring system must be capable of readily interfacing to, and supporting, new instruments with the minimum of support effort.

6.2 Instrumentation Temporal and Spatial Coverage

a) Temporal and spatial sensor measurements are listed below for each of the main MOOS Use Scenarios.

6.2.1 Use Scenario 1: Upper Water Column Processes

a) The Use Scenario to investigate upper water column processes sets out to address the following questions concerning the biological and chemical response to the physical phenomena:

6.2.1.1 Are nutrients resuspended during coastal upwelling?

a) Using dominant physical indicators like temperature and current, the MOOS system will need to detect the onset of an upwelling event within twelve hours of the start of the event. A high-resolution (6 hours) time series at a single stationary location within the mean area of historical upwelling is sufficient for event detection. The periodic sampling of the same area along the 10-km trajectory of a mobile platform is also sufficient. Nutrients of interest include micro-nutrients (iron and aluminum) and macro-nutrients (nitrate, silicate, phosphate, and particles). Measuring these nutrients upon event detection is sufficient to answer the above question. Necessary sensors include iron, CTD, ADCP, fluorometer, and transmissometer or OBS.

6.2.1.2 How far are nutrients transported offshore during upwelling?

a) During upwelling, nutrients are transported perhaps as far as 100km along shore and 200km offshore over a period of several weeks. Investigating such transport mechanisms requires a combination of water-mass tracking, synoptic maps, vertical sections, and time series. Event detection is also required detect the large-scale jets that affect the transport question out to 200km. Water-mass tracking involves making periodic high-resolution measurements (4 hours, 1km) for the purpose of maintaining the position of a mobile observing platform within the water mass. Synoptic maps with a temporal resolution of less than 24 hours are required. These maps must adapt their scale from 20-200km and resolution from 1-10km as the water mass spreads from the upwelling source to the outer regions. Vertical sections to 200m with resolutions of 2m (0-30m depth) and 10-25m (30-200m depth) are also required. Finally, a 2- to 4-week time series at a single location within the trajectory of the upwelling plume with a resolution of 2-4 days is required. Necessary sensors include iron, CTD, ADCP, fluorometer, CO_2, nitrate, and transmissometer or OBS.

6.2.1.3 What processes force along-front flow, cross-front exchange and enhanced vertical flow at fronts, and what are the consequences of these processes?

a) Convergence at fronts enhances horizontal and vertical flows and concentrates marine life. Instabilities that develop along the fronts enhance cross-frontal exchange and vertical flow. These dynamical variations influence cycling of nutrients and particles, and hence biological processes at fronts. Resolution of frontal flow patterns can be achieved at a basic level by synoptic 10-km vertical sections of the upper 100m across the front at a horizontal resolution of less than ½ km and a vertical resolution of less than 5m. Because of the rapid evolution of frontal structure and processes, synoptic in this case would mean performing sampling pattern in less than six hours. Understanding the processes and their integrated effects, however, requires the synoptic resolution of a volume. Furthermore, the sampling effort must also resolve propagating processes. Volume resolution can be achieved through a series of parallel cross-frontal sections. The required along-front horizontal spacing of transects is 1 km or less over an along-front horizontal scale of 10 km, and the required synopticity is less than one day. To define evolution of a propagating frontal process, volume-resolving sampling must be repeated at least twice at a temporal resolution of a few days. Required sensors include CTD, ADCP, fluorometer, OBS, CO2, iron, and nitrate.

6.2.1.4 What is the biological response to upwelling?

a) In this discussion, an algal bloom will be used as an example of scale. The requirement for event detection is the same as that in Section 6.2.1.1; however, the locations of the different types of events (e.g., algal blooms, upwelling events) do not necessarily coincide. Water-mass tracking on a scale of 5-10km with a spatio-temporal resolution of 1km and four hours is also necessary. As in Section 6.2.1.2, daily 10km×10km synoptic maps with a resolution of ½ km are required over a period of several weeks. Required sensors include iron, CTD, ADCP, fluorometer, nitrate, transmissometer or OBS, and Genosensor. Water samples and meteorological measurements are also required.

6.2.1.5 What and where are the major sources and sinks of nutrients, primary productivity, and zooplankton?

a) This question can be addressed in a manner similar to those in Sections 6.2.1.2 and 6.2.1.3.

6.2.1.6 What is the impact of climate variability on the above questions?

a) The following four system components are necessary to respond to the above question:

- a short-term, high-resolution system response to episodic events,
- a stationary observing topology for long-term time series,
- a remote sensing capability to augment the first two components,
- a modeling capability to interpolate between the above three components

b) Investigating the impact of climate variability on episodic processes requires first a high-resolution investigation of the processes themselves, which has been addressed in Sections 6.2.1.1 – 6.2.1.5. Tying together high-resolution episodic investigations with a spatially sparse time series requires the additional spatial and temporal information provided by remote sensing. Although limited in the number of measured properties, remote sensing can provide large-scale daily synoptic maps that include those events not investigated by the observing system. Furthermore, remote sensing provides high-resolution information on both boundary conditions and forcing functions for model studies. Finally, to the extent that modeling provides a theoretically based interpolation of the remaining "dimensional holes" in the larger long-term picture, model studies can augment the interpretation of the processes and aid in characterizing their long-term variation.

6.2.2 Use Scenario: Canyon Processes

a) This Use Scenario, to establish the significant processes that excavate submarine canyons, includes three independent measurements systems:

- Instrumenting the canyon floor to establish a time series to better define the processes associated with sediment transport along the canyon axis and the rates and frequency at which episodic sediment transport events occur.
- Sediment sampling with an ROV to establish the stratigraphy of the most recently deposited channel floor materials
- Repeat mapping of the channel floor at the highest resolution possible to determine the changes that occur in topography of the channel floor.

b) The first of these measurement systems would exploit the capabilities of the MOOS system. Five near bottom instrument packages would be sited at varying water depths along the axis of Monterey Canyon, in addition to a control instrument package outside the canyon. The five monitoring stations will be approximately equally spaced along the canyon floor between ~250 and ~2250 m water depths. Collectively these instruments would form an array to measure the passage of energy and material along the canyon axis with synchronous time series data on the current structure and suspended sediment content in the lower 100 meters of the water column above the canyon floor. Each station in the array will be designed to capture the current structure and sediment suspended load from the seafloor upwards to 80m off the ocean floor.

c) A MOOS mooring would be deployed with a multi port benthic node capable of interfacing to 6 remote instrumentation units that are located at a distance of up to 10km from the benthic node. Each station will be instrumented with:

- a near bottom mounted upward looking ADCP that will outline the current structure through most of the benthic boundary layer. The ADCP generates toughly 750 bytes of data and requires approximately 1.2 watt-hours per measurements. Ideally, measurements would be taken every 20 seconds. The selected unit can be self power and log data internally for 30 days under these conditions.

- a near bottom transmissometer to quantify near bottom sediment loading. This device will generate roughly 10 bytes of data and require 0.03 watt-hours per measurement. Ideally measurements will be taken every 20 seconds which is approximately a 50% duty cycle. This instrument does not have built in power or data logging capabilities
- a near bottom conductivity and temperature sensor to track hydrographic changes in the benthic boundary layer. These sensors can be combined with
- a near bottom current meter to assure a current measurement below the first bin of the ADCP. The combined CT and current meter generates roughly 20 bytes and requires 5mW-hours per measurement with measurements desired every 20 seconds. Measurements every 20 seconds is essentially continuous for this instrument and this device can self power and log data internally for approximately 9 weeks with the standard internal lithium battery pack under these conditions.

6.2.3. Use Scenario 3: Active Mid-Ocean Ridge Processes

a) This scenario is an example of how the MOOS system could be used on an active mid ocean ridge such as the South Cleft of the Juan de Fuca ridge.

b) The South Cleft hydrothermal sites can be effectively monitored by two or three MOOS moorings with benthic hubs and an AUV docking station. The on-axis instrumentation (six seismometers, two hydrothermal packages, one AUV station) will cover an area of five kilometers (maximum) by two kilometers). This will be supplemented by an additional six seismometers that will be deployed up to 10 km east and west of the axis site. These latter instruments could be deployed to collect data autonomously, be serviced by an AUV acting as a data courier or be networked to the same (or a second) benthic hub. A current meter will be added to two of the geophysical packages that are placed on either side of the axis to assist with tracking plume dissipation.

c) Telemetry. Only the telemetry capability of the MOOS Mooring will be required at the surface node. Store and forward data telemetry is acceptable for this experiment (with a reasonable latency on the order of 1 day).

d) Time Synchronization. This will be required and can be accomplished with a GPS time receiver on the surface node.

6.2.3.1. Benthic Instrumentation: Geophysical Instrumentation Package

a) The long term instrument deployments will include 12 geophysical packages deployed in an array around the south Cleft vent sites. The geophysical packages will include short-period seismometers, short baseline tiltmeters, and high resolution pressure gauges. These packages will be used to monitor local and regional ground motion.

b) All 12 of these packages will have one short period seismometer and one high resolution pressure gauge. Two of the 12 packages will also have a short baseline core hole tilt meter that will be drilled into a rock face. The data rate for the seismo/pressure package is 66 Mbytes per day and less than 70 Mbytes per day with a tilt meter. The units draw 6 watts per day and can be self powered for 12 months. It should be noted that these numbers are based on the sensor connected to the current generation of the MBARI LP1 datalogger. The hoped for upgrade of the logger Onset cpu to a StrongArm may modify the power consumption. However, the Strongarm will also permit more advanced compression and data characterization schemes for selective data telemetry as well as provide an ethernet port for more rapid data transfer to an AUV.

c) Seismometers. A two-scale experiment has been designed, with two internal arrays arranged to detect, locate, and characterize small near-surface microearthquakes along the axis, and an external array designed to distinguish earthquakes over a broad region. The internal array of six packages will be located around the two most hydrothermally active localities in the southern Cleft area. This small array can be used to distinguish between near surface events and deeper events associated with a cracking front located in the middle crust (depth ~3km.). The external array of six instruments is designed to discriminate between events located along axis (and thus associated with diking events, the hydrothermal system, or axial tectonic events), and those tectonic events located off-axis). The array will also detect and locate events along the axis but outside the main field area. These packages will be deployed up to 10 kilometers off axis.

d) Tilt Meters. Two short-baseline corehole tiltmeters will be deployed at two sites on opposite sides of the Cleft wall to monitor volcanic inflation or tectonic rotation. The sensor has a resolution of 0.1 microradian and a range of 1.0 degree from sensor null on each of two channels. High resolution Paroscientific pressure gauges will be deployed in concert with the tilt sensors and the seismometers to provide simultaneous measurements of absolute depth as well as to provide pressure data for studies of ocean tides, and pressure and tilt data for measurement of solid earth tidal deformations.

e) Current Meter. An S4 current meter or ADCP will be added to two of the packages to measure current direction near the seafloor to assist with the tracking of plume movement.

6.2.3.2 Benthic Instrumentation: Hydrothermal Vent Instrumentation

a) Two hydrothermal vents will be instrumented to include chemical samplers and sensors, bacterial samplers, and temperature recorders.

b) Hydrothermal and Geochemical Samplers. The two most active vent sites as south Cleft (Vent 1 and Vent 3) will be instrumented with a suite of samplers and in situ analyzers to constrain the temporal variability of fluid flow and chemistry. OsmoSamplers will be deployed to provide continuous, although small volume samples. An additional external osmotic pump will be employed to add acid to the sample stream, thus keeping redox sensitive chemical species (e.g., Fe, Mn) in solution. Osmotic Analyzers use the same type of pump system, but analyze for specific ions in situ using standard colorimetric reagents. OsmoAnalyzers for iron are under development at MBARI. Continuous monitoring of the Fe and particulates (via transmissivity) in vent and buoyant plume fluids will become a useful indicator of venting activity. The ISUS system will be deployed to monitor bromide as a monitor of the fluid salinity, as well as sulfide, nitrate, and organic carbon. As other sensors become available (i.e. nutrients, methane, oxygen, silica, microbial and larval assays) these will be added to the vent instrumentation.

c) Water Sampler. A remote large volume water is required to collect weekly samples for a period of one year. To take advantage of in situ event detection capabilities the sampler would be networked with the MOOS benthic hub that also monitors temperature, flow and seismic events. When an event is detected, the MOOS system will trigger the sampler to operate at higher sampling rates

d) Temperature Recorders. A variety of low-temperature and high-temperature probes are available from Deep Sea Power & Light. The sampling rate can be preprogrammed to permit autonomous recording for at least one year. The temperature probes can also be interfaced to the hydrothermal vent packages. These recorders will be deployed in each of the high-temperature vents (Vent 1, Vent 3 and Plume) and at 10-12 sites along the Cleft walls that have significant diffusive effluent.

e) Vent Fluid Flow Measurements. Each of the two vent sites would include at least two flowmeters, to compare diffuse and focussed flow rates. There are two instruments available that may be suitable for this application

- A heat-pulse flowmeter has been developed at the University of Hawaii to determine speeds of fluid flow using a heat-pulse concept in which a grid heats neighboring waters that flow along a tube with several thermistors. The benefit of this instrument is that it can be placed in small cracks and is designed to measure flow rates in the diffusion-to-subtle advection range much below 0.1 mm/s.
- The Medusa autonomous vent fluid sampling system includes a titanium sensor head, which is placed directly upon zones of diffuse hydrothermal flow, and a separate titanium alloy pressure case containing the electronics, datalogger/controller, and power supply. The sensor head contains a titanium-rotor effluent velocity sensor with an optical detector; Type-T and Type-K thermocouples which measure the temperature difference between vent and ambient fluids. This system has been deployed on the MAR, the JdF and the EPR every year since 1994 with variable success. The new generation of Medusa and its successor the DALEX, are being built in collaboration with NASA for the study of life in extreme environments. The gas-tight samplers are especially applicable to microbial studies at vent sites.

A method of measuring diffuse flow using acoustic reflectivity has also been developed at Rutgers and will be considered.

f) Biological Samplers. Samplers for microbial and larval studies are only in the early design stages. Microbial samplers and insitu analyzers would be placed into coreholes in sulfide and/or basalt to assay the species within the seafloor environment. Larval samplers would be deployed on the riser for the MOOS moorings and also on the AUV. Both of these efforts would require significant prototype efforts within Monterey Bay prior to incorporation with the MOOS experiment.

6.2.3.3 Water Column Measurements:

a) Prior to Event Detection. An AUV would be deployed to measure the integrated impact of hydrothermal effluent on the overlying water column. The AUV will measure temperature, chemical, and transmissivity anomalies over the continuous vent sites to complement the benthic instrumentation. AUV instruments would include: ISUS for sulfide, nitrate, organic carbon and bromide, O2, FE osmo-analyzer, HOBOS temperature, autonomous water sampler, osmo-sampler, transmissometer, CTD, ADCP, flow meter, precision pressure gauge. These sensors would be used to constrain the geochemical and microbial impact of the chronic venting. Similar packages, especially the CTDO and current meters would be placed on the mooring cables at 50 and 150 m above the bottom.

b) AUV missions would be run to detect a megaplume event. Detection of temperature and particulate changes, indicating onset of an event, would be made with a CTD and a transmissometer.

c) Continuous missions would be run on the order of once a week. The spatial extent of the continuous mission is approximately 10km by 20km. A single lawn mower pattern at a depth of between 50 to 200 meters above ocean floor with transects spaced every 3.3 km across the ridge axis would give a mission length of 100 km (4 legs * 20 km/leg + 3 legs * 3.3 km/leg + 10 km return to dock). At 3 knots, this would be a mission length of 18 hours. Assuming a vehicle which requires 250 watts to run and power instruments, this would imply an energy storage capability on the AUV of 4500 watt-hours and a energy recharge source capable of delivering a continuous 30 watts to the vehicle to meet the desired 1 week mission period ((18 hours * 250 watts) / (168 hours – 18 hours)).

d) After an Event Detection. Following an event detection, the AUV's will extend water column measurements to include much of the segment (up to 50 km long by 10 km wide by 1 km of depth) to monitor the formation and dissipation of the hydrothermal plume.

e) This mission would require an energy storage capability on the AUV of 9700 watt-hours assuming that only one AUV is available for this mission. Adding a second AUV, especially one dedicated to event response, would reduce the required storage capability. Adding a third mooring in the northern end of the survey array would similarly reduce the power storage requirement.

f) In addition, once the plume has been located, the required survey area would be greatly reduced as the observed megaplumes have been only 5-10 km in diameter.

g) The observed plumes have formed and dissipated in less than three weeks, so that the mission requires 2-3 surveys during that period of time. The current meterings on the mooring cables will assist in tracking the movement of the plume once it is located.

h) General Both mapping capabilities would require a navigation accuracy on the order of 10 meters in all three directions to provide adequate map resolution.

6.2.4 Use Scenario 4: Benthic Carbon Cycling

6.2.4.1 General

a) This Use Scenario focuses on differences in carbon cycling by benthic communities in areas near or distant from the influence of organic inputs from the Monterey Canyon system.

b) Measurements will be made to compare carbon availability and its utilization by benthic communities at deep-sea sites influenced by organic inputs from the Monterey Canyon and those distant from the effects of the canyon. The rates of carbon input from surface waters, organic material transported down-canyon during debris flows, and rates of carbon uptake will be measured under various conditions of organic inputs. The studies will broaden understanding of both the role of Monterey Canyon in the nutritional dynamics of deep-sea benthic communities and the strength of coupling between pelagic and benthic systems in the central coast.

6.2.4.2 Science Questions

a) The experiment will address the following science questions:

- *Canyon-based transport of organic debris to deep-sea sites represent a significant (i.e. >50%) contribution to the total carbon budget of benthic communities in the outer reaches of the canyon axis.*
  The relative importance of canyon-based inputs must vary depending upon the distance from shore and the depth. While sinking organic debris degrades rapidly with depth, thereby reducing its value to benthic communities in deeper waters, down-canyon transport of organic debris may result in rapid transport with little deposition, leading to an increased importance at some depths..
- *How does the relative importance of down-canyon transport of organic debris versus phytodetritus from surface waters vary over seasonal and interannual time scales?*
  Winter storms and other events may both increase export of material from nearshore kelp beds and initiate down canyon flux events, leading to temporally varying deposition of organic debris to the deep canyon axis. Seasonal shifts in surface productivity will also modulate carbon input to the benthos. Both sources may change dramatically over interannual temporal scales.
- *How do benthic communities in canyon-impacted and non-canyon sites respond to shifts in carbon availability owing to climate variability?*
  Environmental variability (e.g. ENSO, La Nina, Pacific Decadal Oscillation, Climate Warming), influence greatly the productivity of surface waters and sinking organic flux that sustains benthic faunal communities. Changes in flux related to these events have been measured in the deep-sea, but have not yet resulted in detectable shifts in community dynamics off this coast. Long term monitoring of community patterns and carbon cycling will allow evaluation of the strength of coupling between benthic and pelagic / canyon carbon production.

6.2.4.3 Experiment Sensor and Instrumentation Requirements

a) Sinking Particulate Carbon Flux. The rain of organic debris will be measured using sediment traps deployed on surface or subsea moorings, used to measure flux at 50 m above the bottom and a minimum of 200 m above the bottom. Within 50 m of the bottom, resuspended material is usually collected in traps and does not estimate the magnitude of flux sinking from the surface.

The shallower trap will be used to estimate euphotic zone carbon export. Sediment traps with rotating collection cups will be used to capture the sinking flux of material beneath the euphotic zone and within the benthic boundary layer. Each trap could be a 'free vehicle' or could be integrated with MOOS to allow for cup rotation at any time, by user intervention.

b) Boundary layer conditions**.** Optical instrumentation (in situ fluorometers [ISF] and optical backscatter sensors [OBS]) will be deployed on benthic landers or moorings to monitor suspended material near the bottom. Turbidity flows are expected to have high backscatter, but low fluorescence, while sinking events will have relatively high fluorescence. Current meters deployed near the sea bed will monitor local current speed and direction, and detect advective events. Instrumentation will include:

- Current Meter – S4 current meter will suffice
- Optical Backscatter / In situ fluorescence. Plan to purchase several "hydroscat II" which have backscatter (OBS) and fluorescence, with internal data loggers and power. These instruments could be 'stand alone' or integrated with MOOS communications to allow for real or near-real time data capture.

c) Benthic Community Characterization. Community structure will be characterized using video transects and sediment core sampling by ROV. Activity patterns and visual changes in the character of the sea floor environment will be monitored using a benthic camera system, linked to shore or a local image storage device. Measurements of species abundance and distribution will be made with:

- ROV Video Transects: analysis of benthic megafaunal patterns
- ROV Sediment Cores: analysis of infauna organisms.
- Digital Imaging System: deployed on benthic lander, integrated with MOOS for real / near-real time image capture (e.g. 1/ day).

d) Benthic Respiration Measurements. Carbon cycling will be measured using benthic chambers with oxygen sensors to monitor oxygen consumption (respiration rates will be converted to carbon demand). Initially, these measurements can be made using ROV deployment and recovery of respiration systems. Development of a benthic ROVER will allow time series measurements of oxygen consumption and other parameters without the need for heavy ROV use. Instrumentation requirements include:

- Benthic Chambers: Presently chambers are deployed by ROV, and are useful for a single measurement of sediment community oxygen consumption (SCOC).
- Benthic ROVER: - MOOS technology development will include a benthic ROVER (similar to Smith et al.1997), a free-vehicle lander with limited mobility to crawl over the bottom after each SCOC measurement to allow sampling of undisturbed sea floor. Distance traveled between measurements is approximately 10 m. ROVER instrumentation can initially include benthic chambers, current meters, and limited mobility, but can be expanded to include several other sensors / samplers (imaging system, oxygen / pH profilers, sediment samplers, etc.). The ROVER can be a free vehicle or integrated with MOOS communications and telemetry for greater programmability and event response.

6.2.4.4 Site Location.

a) Study sites for this project will include at least two sites in or near the base of Monterey Canyon and two control sites, distant from the influence of down-canyon debris flows. Several potential study sites for this project are shown in Figure 1 in Appendix 4. Although the Monterey Canyon sites are positioned presently near the outlet of Monterey Canyon to the abyssal plain, additional sites within Monterey Canyon would benefit this program. Three sets of sites are marked on Figure 1, ranging from relatively shallow (1500 m), 3000 m and deep (3300 m). Canyon sites have been chosen in areas with the broadest canyon base available for the depth selected. Control sites are located principally to the south of Monterey Canyon to the west of the Pt. Sur region where no submarine canyons bisect the continental slope.

7. Portability

a) There is a requirement for system portability so that the entire MOOS system, or MOOS sub-systems, can be configured and deployed for scientific missions at different sites using an acceptable level of resources.

8. Configurability

a) The MOOS system is required to support a broad range of scientific experiments with different mooring hardware configurations, sampling strategies and instrumentation. The system is required to be easily configurable to these various configurations.

b) The MOOS system will be designed to allow deployment of combinations of sub-systems. Such combinations include the options in Table 1.

9. Expandability

a) The MOOS system will be developed and deployed incrementally over an extended period. It is required that the system be designed to allow a ready upgrade path for accommodating future advancements in measurement and sub-system capabilities.

10. Data Collection

10.1 Local Storage Capacity

a) MOOS deployment locations that are reachable with VHF band packet radio data links, such as Monterey Bay need enough local storage to retain data for several weeks in case of radio link failure. For deployments outside of packet radio range the local storage capacity required should allow data logging for instruments that do not store their data internally for a minimum one year nominal time between mooring system maintenance cycles. This allows the capture of more data than can be transmitted in real-time or near-real-time back to shore as well as full data recovery during a normal maintenance cycle if the instrument-to-shore data link becomes unreliable.

10.2 Real Time Data Requirements

a) There is a need for near real-time (1-4 hrs) bi-directional data to notify shore of the onset of an episodic event, and to receive subsequent mission commands from shore (see Section 5).

b) There is a need for near real time (1-4 hrs) data for engineering health monitoring of the MOOS mooring and sensors.

c) A minimal data set, such as daily averages, still visual images, event logs, or event "snap-shots" are required and the observational science capabilities improve with increased data rate.

11. Data Management and Representation

a) The data processing requirements range from "production" processing of standard data types such as CTD data to highly customized processing for more specialized data sets such as chemistry instrumentation data. For specialized data sets the system is required to pass through raw data to the end user in a form that can later be correlated with the standard data sets. The functional requirements for both standard and specialized data sets and will be determined in the "MOOS Data Management" project workshop scheduled for March 2000.

b) All data must be stored locally.

c) Specific functional requirements will be developed in the following areas:

- Processing
- Quality control
- Quality identification
- Archival
- Representation

12. System Cost

a) The MOOS system must provide an affordable mooring based system with consideration given to balancing the initial cost, installation and maintenance costs.

Appendix 1: MOOS Use Scenario 1: MOOS Sampling Requirements and Use-Scenarios for Investigating Multi-Scale Oceanographic Processes (DRAFT)

Michael B. Matthews
March 21, 2000

1 Introduction

We investigate the MOOS sampling requirements and system usage scenarios for studying oceanographic processes of interest to the *MUSE* Group. This group represents a cross-section of scientists at MBARI who are interested in biological, chemical, and physical processes in the water column. We present our results in geometrical terms and make no attempt to specify an observing system that would satisfy the requirements. Such a system may be only partially realizable given the projected support for the MOOS system. Engineering tradeoffs and economies of scale must be considered.

In defining the sampling requirements for MOOS, we consider the sampling problem not only in the sense of estimating a random field with minimal error, but also in the sense of acquiring sufficient information to answer important science questions. Why sample a process in the sense of a sampling theorem – i.e., in the sense of the perfectly reconstructing a random field from the samples - when perhaps only a few points are sufficient to answer the question?

We begin by discussing in Section 2 the oceanographic and atmospheric processes of interest to MBARI scientists, and, at the end of Section 2, we generate a list of science questions for small-scale episodic processes. In Section 3.1, we pose hypothetical field experiments for investigating these science questions, and examine the sampling requirements of said experiments. From this, we identify in Section 3.2 four basic MOOS functional requirements for studying episodic processes: (1) event detection, (2) event characterization, (3) frontal boundary characterization, and (4) large-scale and meso-scale context assessment. Finally, in Section 3.3, we propose sampling topologies that satisfy the requirements.

We assume that small-scale processes in Monterey Bay are of essential interest. We discuss several such processes including coastal upwelling and ecosystem dynamics. The choice of Monterey Bay is arbitrary; the point is that we choose a specific geographic area in which small-scale processes of interest exist.

1.1 Glossary of Terms

MOOS	***M***BARI ***O***cean ***O***bserving ***S***ystem
MUSE	***M***OOS ***U***pper-Water-Column ***S***cience ***E***xperiment
AUV	Autonomous Underwater Vehicle
Sampling topology	A geometric configuration of sample points in both space and time
Mulit-scale topology	A sampling topology where the distance between sampling points increase geometrically with distance from the geographic area of interest
Random process	A (possibly multi-dimensional) random function of time
Random field	A (possibly multi-dimensional) random function of space or space-time
Stationary process	A random process with time-invariant statistics
Nonstationary process	A random process with time-varying statistics
Episodic process	A random process with dominant temporal components of well-delineated onsets and terminations
Large-scale process	A process with spatio-temporal scale of thousands of kilometers and hundreds of days
Meso-scale process	A process with spatio-temporal scale of hundreds of kilometers and tens of days
Small-scale process	A process with spatio-temporal scale of tens of kilometers and several days
Stationary sampling	A time-invariant sampling scheme
Dynamic sampling	A time-varying sampling scheme
Adaptive sampling	A time-varying sampling whose topology is a function of the sampled field

1.2 Background

Both natural climatic variations and human influences cause oceanographic processes to vary on a number of different spatial and temporal scales. Hence, the processes of interest are nested spatially and temporally in scale, such that each successively larger scale affects the next smaller scale. Such processes can be modeled in combination as a single multi-scale random process in which the various scales are related statistically.

To understand and resolve small-scale processes, it is necessary to understand and resolve the effects of larger-scale processes. Thus, our effort to define an observing system must take into account this multi-scale concept. Resolving small-scale processes requires a high-resolution sampling topology. Small-scale processes, however, are driven at their boundaries by meso-scale processes, thus implying a meso-scale sampling topology at the boundary. That meso-scale processes are driven at their boundaries by large-scale processes implies a corresponding large-scale sampling topology.

We divide the processes of interest into large-scale, meso-scale, and small-scale processes. Roughly speaking, large-scale processes are those with a spatio-temporal scale of thousands of kilometers and hundreds of days, meso-scale processes have a scale of hundreds of kilometers and tens of days, and small-scale processes have a scale of tens of kilometers and several days (see Table 1).

Process	*Spatial Scale (km)*	*Temporal Scale (days)*	*Examples*
Large-scale	500-5000	30-3000	deep-ocean circulation
Meso-scale	50-500	3-30	oceanic eddies
Small-scale	0.5-50	0.3-3	coastal upwelling

Table 1. Spatial and temporal scales of oceanographic processes

Random processes are typically classified as either stationary or nonstationary. Stationary processes, which include diurnal and annual phenomena, have statistical properties that are independent of time. Nonstationary processes, which include synoptic weather events, upwelling events, and eddies, have statistical properties that vary with time. To the extent that multi-scale processes include both stationary and nonstationary phenomena, we shall to classify them as being nonstationary. In Section 3.3, we introduce the notion that a multi-scale nonstationary process can be resolved sufficiently using a corresponding nonstationary or “adaptive” sampling topology.

An optimal observing system for the aforementioned multi-scale nonstationary processes is based on the concept of a corresponding *multi-scale nonstationary sampling topology*. The large-scale and meso-scale components of a multi-scale process are well resolved by a sparse stationary sampling topology as realized by an array of stationary moorings. Such a topology provides sufficient information to detect and provide context for smaller-scale episodic components in the geographic area of interest. Once detected, an episodic component can be resolved by increasing for a short period of time both the spatial and temporal resolution of the topology. This can be accomplished by increasing the sampling rate of the stationary elements and by deploying mobile sampling elements like ships, AUV's and gliders.

2. Processes of Interest

2.1 Large-Scale Processes

In this section, we discuss several large-scale processes that directly affect meso-scale and small-scale processes in and around Monterey Bay. Recall that a large-scale process is defined as having spatio-temporal scales of thousands of kilometers and hundreds of days.

2.1.1 Deep-Ocean Thermohaline Circulation

[Short description of the energy budget, thermohaline circulation, and local affects.]

2.1.2 Large-Scale Wind Fields

[Similar description of the energy budget, large wind fields, and the local affects.]

2.1.3 Annual, Inter-annual, and Decadal Processes

[Short discussion of processes like El Nino and their affect on local processes.]

2.2 Meso-Scale Processes

2.2.1 Oceanic Eddies

Oceanic eddies are circular flows of water extending throughout the water column with spatial scales of hundreds of kilometers and temporal scales of several months. They are similar to synoptic weather systems in scale with currents that reach tens of centimeters per second. In addition, there exist small-scale (50km) eddies that often do not reach the surface, and large-scale (1000km) eddies sometimes found in the Pacific. Of interest is how such eddies interact with large-scale oceanic circulation patterns and how they influence small-scale processes such as coastal upwelling.

2.2.2 Synoptic Weather Systems

[Short description of synoptic weather systems and their effect on small-scale processes.]

2.3 Small-Scale Processes

2.3.1 Coastal Upwelling Events

During the spring and summer months, the northern California coast is the location of maximum equatorward wind stress over the California Current system. These strong winds, which directly affect the circulation over the continental shelf, are driven by the combined effect of the North Pacific high-pressure system and the thermal low-pressure system that is commonly found over the southwest United States during spring and summer.

Coastal upwelling is a circulation pattern that develops when strong winds transport surface-layer water offshore, resulting in the upwelling of an equal amount of nutrient-rich subsurface water near the coast. Local surface wind shear combines with the Coriolis force to produce a net transport of surface waters in a direction perpendicular to the wind. The affected surface or *Ekman layer* is only several tens of meters deep. The upwelled subsurface water flows horizontally away from the upwelling site in a coherent surface flow. Thus, large-scale wind systems provide the driving force and the large-scale current system determines the water properties (density and nutrient content) for upwelling. The seasonal wind systems provide the mean winds favorable to upwelling, however, it is synoptic weather systems that produce distinct upwelling events.

The time for upwelling circulation to respond to the wind is on the order of the inertial period, which, for the central California coast, is approximately 30 hours. The upwelled water advects southward across the bay and there is a relaxation phase that sets in after three to five days. Frontal instabilities develop along the cyclonic (southern) boundary of upwelling filaments, and strong local upwelling (~30 m/day) occurs in association with these instabilities. Such strong local upwelling along the filament boundary influences significantly the cycling of nutrients and particles within the evolving filament. Because the frontal instabilities propagate westward at approximately 25 km/day, their study requires a sampling topology that accommodates near-real-time remote sensing. During an upwelling event, multiple instabilities exist simultaneously along the southern front with a wavelength of approximately 20 km and a cross-frontal dimension of approximately 10 km. Therefore, the study of filament evolution requires a synoptic sampling topology within the upper-water column across the front in multiple locations. Because upwelled waters are advected with the filament mean flow, the examination of the biological response requires sampling the same instability at least twice over a 2-3 day period.

Recent investigations have demonstrated that the upwelling process entrains not only macronutrients from deeper waters but also iron from the sediments. Other entrainment processes that recruit waters not in contact with the sediments will not have the same nutritional effect on the primary producers. Sediment-laden waters have been observed at a site of active shallow upwelling in northern Monterey Bay. This site is a natural analog to the initial stages of the iron fertilization experiments carried out in the equatorial Pacific upwelling system. These experiments have greatly furthered the understanding of the influence of nutrient fertilization on phytoplankton physiology and community structure.

Another observable product of the upwelling process is the formation of strong physical and biological fronts between the recently upwelled water and the warmer surface water displaced by upwelling. Interest in these frontal regions is two-fold. First, a significant proportion of the upwelled water and nutrients is likely mixed laterally along these edges rather than being advected downstream and offshore. Second, the nutrient fertilization, together with physical phenomena like convergence and increased stratification, make these frontal regions areas of increased biological activity. The biological consequences may make these regions more important to the coastal upwelling ecosystem than one might presume from their areal extent.

2.3.2 Ecosystem Population Dynamics and Distribution

The physical and chemical properties of the ocean as well as the dynamics of predation determine upper-ocean ecosystem productivity and structure. Variations in ecosystem structure and production propagate through the water column to both mid-water and benthic communities. Because the physical and chemical sources of primary production are spatially and temporally uncoupled from the biotic sinks, understanding the processes that control ecosystem productivity and structure requires an observing system that monitors variation in both space and time.

Of particular interest are the spatio-temporal regulation and distribution of heterotrophic and phototrophic picoplanton (0.2-2 microns) and their succession along upwelling fronts. Because the doubling time of such organisms is on the order of several days, a system for observing picoplanton population dynamics requires a temporal resolution of tens of hours. However, since the regulation and distribution of picoplanton is dominated by the concomitant physical and chemical processes, a system that observes sufficiently such processes is also sufficient for observing picoplanton population dynamics

2.3.3 Seafloor Venting

Seafloor venting from a stable gas hydrate field in the Guaymas Basin has been recently reported. Water-column plumes as high as 900 meters were detected using acoustic measurements. Although it is unknown whether these plumes are composed of gas bubbles, gas-hydrate-armored gas bubbles, or gas hydrate crystals, it is clear that they represent upward gas transport from the seafloor. Of interest is the nature and composition of the water-column plume and the processes by which gases are transported from the seafloor to the surface. Of particular interest is the fate of gas in the rising plume. One hypothesis is that the gas hydrate will rise to the top of the gas hydrate stability zone and decompose in the water column, leaving a methane-rich layer at this water depth.

Investigating such venting phenomena requires an observing system that is capable of actively searching for and characterizing distinct vents and plumes. This contradicts the typical MOOS system paradigm, which depicts a static passive system that can adapt itself in response to a detected event. Here, an active MOOS system would establish a 5×2.5-km surveying pattern with a horizontal resolution of 500m and a vertical resolution of 250m to a depth of 1500m. Finally, we assume that such seafloor venting is a steady-state phenomenon; therefore, we impose no temporal constraints on the aforementioned survey.

3. MOOS System Functional Requirements for Sampling

3.1 Science Questions

Scientists in the *MUSE* Group wish to observe the aforementioned processes to answer a number of import questions concerning the biological and chemical response to the physical phenomena. The following is a list of questions that are under discussion within the context of MOOS. In this section, we discuss the significance of these questions on the MOOS sampling requirements. Table 2 summarizes the sampling and sensor requirements for each question.

1. Are nutrients resuspended during coastal upwelling?
2. How far are nutrients transported offshore during upwelling?
3. What processes force along-front flow, cross-front exchange and enhanced vertical flow at fronts, and what are the consequences of these processes?
4. What is the biological response to upwelling?
5. What and where are the major sources and sinks of nutrients, primary productivity, and zooplankton?
6. What is the impact of climate variability on the above questions?

3.1.1 Are nutrients resuspended during coastal upwelling?

The question of nutrient resuspension can be answered conclusively by detecting the presence of nutrients in upwelled water. Using dominant physical indicators like temperature and current, the observing system must detect the onset of an upwelling event with an error probability of less than 10%[1] and a notification delay of less than twelve hours[2]. A high-resolution (6 hours) time series at a single stationary location within the mean area of historical upwelling is sufficient for event detection. The periodic sampling of the same area along the 10-km trajectory of a mobile platform is also sufficient. Nutrients of interest include micro-nutrients (iron and aluminum) and macro-nutrients (nitrate, silicate, phosphate, and particles). Measuring these nutrients upon event detection is sufficient to answer the above question. Necessary sensors include iron, CTD, ADCP, fluorometer, and transmissometer or OBS.

3.1.2 How far are nutrients transported offshore during upwelling?

During upwelling, nutrients are transported perhaps as far as 100km along shore and 200km offshore over a period of several weeks. Investigating such transport mechanisms requires a combination of water-mass tracking, synoptic maps, vertical sections, and time series. Event detection is also required detect the large-scale jets that affect the transport question out to 200km. Water-mass tracking involves making periodic high-resolution measurements (4 hours, 1km) for the purpose of maintaining the position of a mobile observing platform within the water mass. Synoptic maps with a temporal resolution of less than 24 hours are required. These maps must adapt their scale from 20-200km and resolution from 1-10km as the water mass spreads from the upwelling source to the outer regions. Vertical sections to 200m with resolutions of 2m (0-30m depth) and 10-25m (30-200m depth) are also required. Finally, a 2- to 4-week time series at a single location within the trajectory of the upwelling plume with a resolution of 2-4 days is required. Necessary sensors include iron, CTD, ADCP, fluorometer, CO2, nitrate, and transmissometer or OBS.

3.1.3 What processes force along-front flow, cross-front exchange and enhanced vertical flow at fronts, and what are the consequences of these processes?

Convergence at fronts enhances horizontal and vertical flows and concentrates marine life. Instabilities that develop along the fronts enhance cross-frontal exchange and vertical flow. These dynamical variations influence cycling of nutrients and particles, and hence biological processes at fronts. Resolution of frontal flow patterns can be achieved at a basic level by synoptic 10-km vertical sections of the upper 100m across the front at a horizontal resolution of less than ½ km and a vertical resolution of less than 5m. Because of the rapid evolution of frontal structure and processes, synoptic in this case would mean performing sampling pattern in less than six hours. Understanding the processes and their integrated effects, however, requires the synoptic resolution of a volume. Furthermore, the sampling effort must also resolve propagating processes. Volume resolution can be achieved through a series of parallel cross-frontal sections. The required along-front horizontal spacing of transects is 1 km or less over an along-front horizontal scale of 10 km, and the required synopticity is less than one day. To define evolution

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[1] This includes both false positive and false negative detections.
[2] Notification delay is defined as the time between the actual onset of the event and notification of the responsible researcher. This term includes eventual processing and communication delays.

of a propagating frontal process, volume-resolving sampling must be repeated at least twice at a temporal resolution of a few days. Required sensors include CTD, ADCP, fluorometer, OBS, CO2, iron, and nitrate.

3.1.4 What is the biological response to episodic events?

In this discussion, we shall use an algal bloom as an example of scale. The requirement for event detection is the same as that in Section 3.1.1; however, the locations of the different types of events (e.g., algal blooms, upwelling events) do not necessarily coincide. Water-mass tracking on a scale of 5-10km with a spatio-temporal resolution of 1km and four hours is also necessary. As in Section 3.1.2, daily 10km×10km synoptic maps with a resolution of ½ km are required over a period of several weeks. Required sensors include iron, CTD, ADCP, fluorometer, nitrate, transmissometer or OBS, and Genosensor. Water samples and meteorological measurements are also required.

3.1.5 What and where are the major sources and sinks of nutrients, primary productivity, and zooplankton?

This question can be addressed in a manner similar to those in Sections 3.1.2 and 3.1.3.

3.1.6 What is the impact of climate variability on the above processes?

The following four system components are necessary to approach the above question: (1) a short-term, high-resolution system response to episodic events, (2) a stationary observing topology for long-term time series, (3) a remote sensing capability to augment the first two components, and (4) a modeling capability to interpolate between components (1) – (3).

Investigating the impact of climate variability on episodic processes requires first a high-resolution investigation of the processes themselves, which has been addressed in Sections 3.1.1 – 3.1.5. To the extent that it is impossible for the system to respond with equal intensity to every detected event, we accept the periodic deployment of the system – perhaps only once or twice a year - to investigate only representative events. To approach the above question, these singular investigations need to be tied together in a long-term context, which underscores the necessity for a sparse, stationary observing topology for long-term time series. By sparse topology, we mean a geometrically progressing topology on an order similar to that illustrated in Figure 2. Tying together high-resolution episodic investigations with a spatially sparse time series requires the additional spatial and temporal information provided by remote sensing. Although limited in the number of measured properties and degrees of freedom, remote sensing can provide large-scale daily synoptic maps that include those events not investigated by the observing system. Furthermore, remote sensing provides high-resolution information on both boundary conditions and forcing functions for model studies. Finally, to the extent that modeling provides a theoretically based interpolation of the remaining "dimensional holes" in the larger long-term picture, model studies can augment the interpretation of the aforementioned processes and aid in characterizing their long-term variation.

3.2 Functional Requirements

Our discussions in Section 3.1 identified four basic MOOS functional requirements for sampling episodic processes: (1) event detection, (2) event characterization, (3) frontal boundary characterization, and (4) large-scale and meso-scale context assessment.

3.2.1 Event Detection

Because dynamic sampling schemes for characterizing episodic processes must be referenced to a fiducial point of the process, the ability to detect episodic events is a basic functional requirement. Event detection schemes for such processes are typically based on pattern recognition. However, if we model the process as a temporally expanding ellipsoid with sharp frontal boundaries, we can derive a detection algorithm based on a spatially sparse, temporally dense sampling topology. The criteria for event detection of episodic processes include a detection error probability of less than 10% and a notification delay of less than twelve hours. The episodic events of interest include coastal upwelling events as well as phytoplankton and algal blooms. Upwelling events in the vicinity of Monterey Bay occur primarily along the coastlines off of Davenport and Pt. Sur. Phytoplankton and algal blooms occur at various places both inside and outside the bay. A sufficient stationary sampling topology for the detection of these episodic events of interest is shown in Figure 1.

3.2.2 Event Characterization

The ability to characterize both the extent and composition of an episodic process is a second basic functional requirement. By characterizing the extent, we mean estimating the dominant spatial boundaries of the process as a function of time. By characterizing the composition, we mean estimating the property fields of the process over space and time. The nonstationary nature of the process indicates a dynamic sampling scheme; the large ensemble-to-ensemble variations in the random field further indicate an adaptive sampling scheme. The exact sampling scheme for an episodic process depends on the acceptable amount of error that results from estimating the random field using sampled data. As suggested error criterion for event characterization is an overall estimation error of less than 20%.

3.2.3 Frontal Boundary Characterization

The ability to characterize the frontal boundaries of an episodic process is a third functional requirement. By characterizing a front, we mean determining its precise location and properties (e.g., gradients and fluxes). This requires a dynamic sampling scheme, in which the sampling resolution normal to the front is several orders of magnitude higher than that parallel to the front.

3.2.4 Large-Scale and Meso-Scale Context Assessment

The ability to provide large-scale and meso-scale context for small-scale processes is a fourth functional requirement. By context, we mean an estimate of the corresponding random fields over the small-scale period of interest. Since the time scales of large-scale and meso-scale processes are much longer than that of small-scale processes, we assume that this context is stationary during the course of a small-scale episodic event.

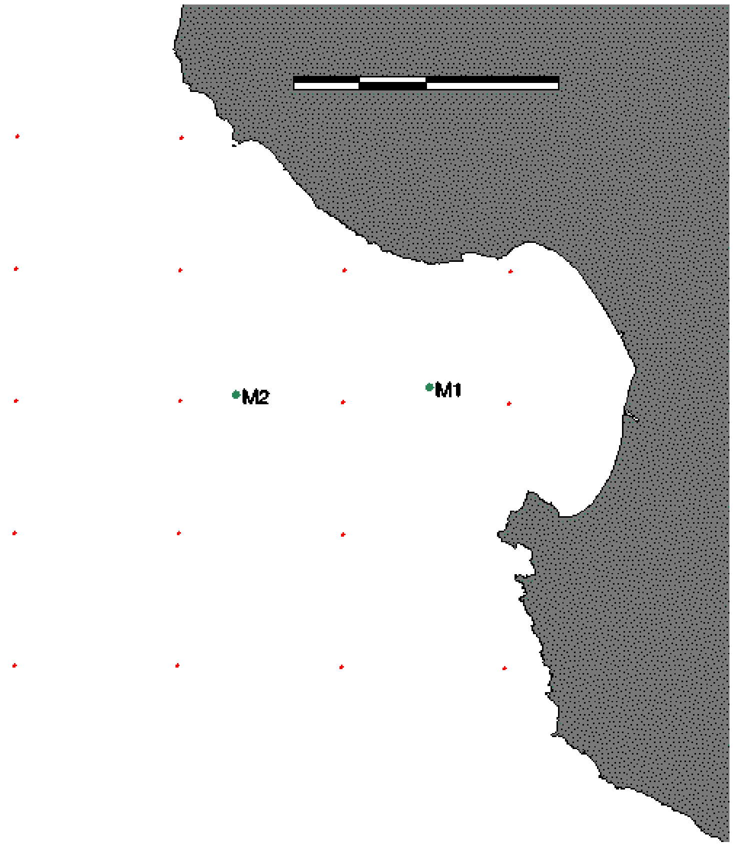


Figure 1. Example of a MOOS event-detection topology for coastal episodic events. The topology is shown in relationship to the current M1 and M2 moorings.

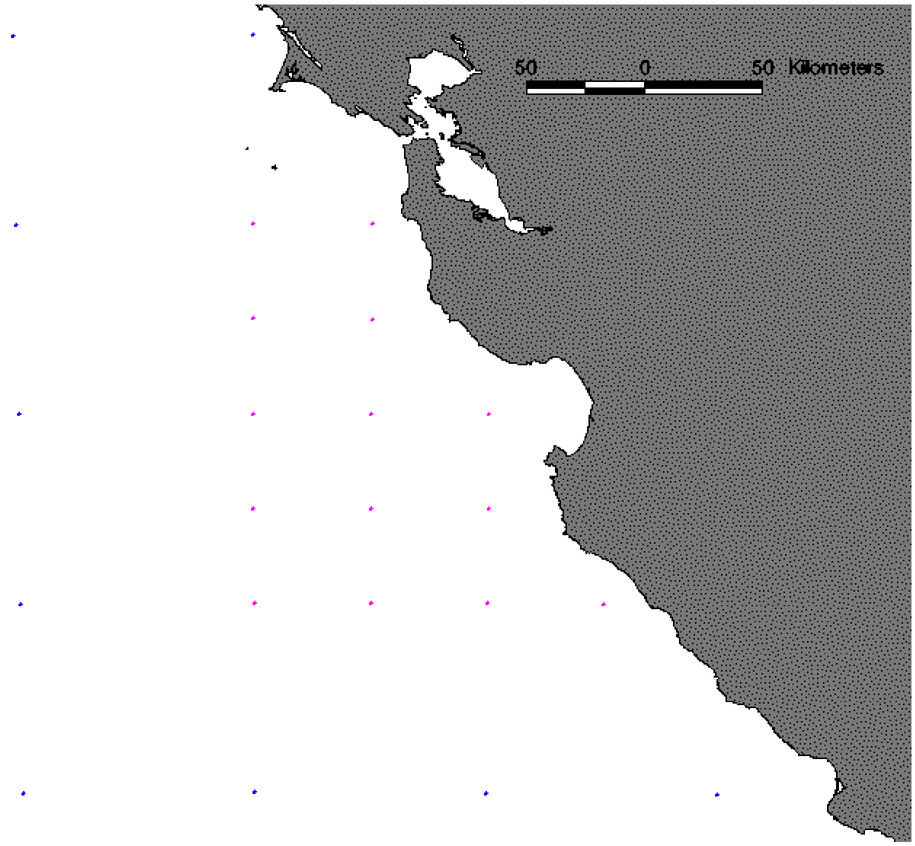


Figure 2. Example of a stationary time-series sampling topology for MOOS with a geometrically increasing scale of 40km and 80km.

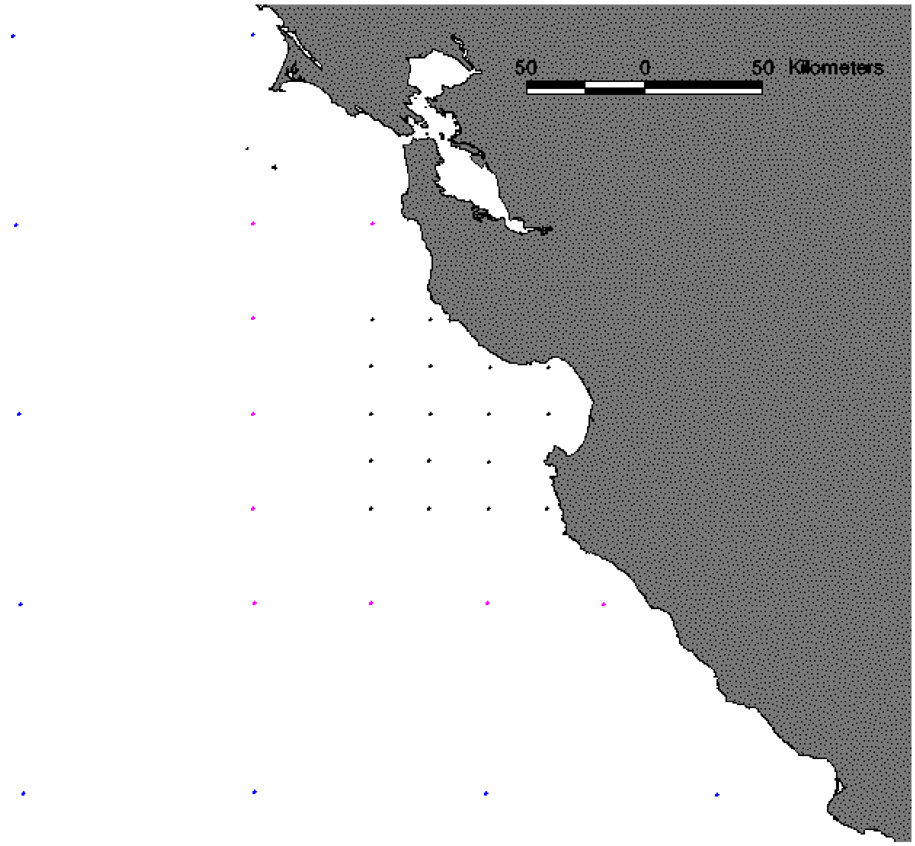


Figure 3. Combined event-detection and time-series topology for MOOS

Appendix 2: MOOS Use Scenario 2: Canyon Processes

1.0 Introduction

This document will describe a typical "use-scenario" for the MOOS technology currently being developed at MBARI. This scenario is an example of how the Monterey Canyon Dynamics experiment currently being discussed in the Benthic MOOS working group might make use of the capabilities envisioned for MOOS. Since the experiment is only in the initial planning stage this use-scenario is, of course, only an example and will require additional work to completely define the experiment requirements. A precise description of the experiment will be presented in the proposal.

The second section of this document provides and overview of the experiment and is taken directly from the preliminary draft proposal. The third section is an attempt to outline a specific set of requirements that this experiment might require from the suite of capabilities that have been discussed for MOOS.

2.0 Monterey Canyon Dynamics: Tracing Sediments from Source to Sink

We propose a systematic study of the physical processes that occur in the axis of Monterey Canyon. The intention is to establish the significant processes that excavate submarine canyons, to determine the rates of these processes, to understand the role of submarine canyons as conduits for transporting materials from continents to the deep-sea, and to assess the importance of submarine canyons in moving carbon to the deep-sea. While the flanks of submarine canyons have been extensively sampled and studied, the axes have been neglected because appropriate technology to investigate them has not existed until now. The axis is where the major sediment transport and erosion processes are focused.

A three pronged approach is proposed: (1) Instrument the canyon floor to establish time series measurements that define the range of near-bottom current and suspended sediment conditions that occur within the axis of the canyon. (2) Sample the sediments on the floor of the canyon and establish both when they were deposited and by what processes. (3) Repetitive mapping of parts of the canyon floor to determine the changes in its shape that occur over time in response to the measured energy conditions. Because of MBARI's unique assets, commitment to seafloor observing technology, and close proximity to the canyon, this package of coordinated experiments could not be efficiently conducted by any other organization in the world. Support to pursue approach 1 is being requested here as part of the MOOS effort. Approach 2 is independently being pursued as part of the existing Continental Margin Fluids and Gases and the Convergent Margin projects. Approach 3 will commence when detailed mapping capabilities become available.

<u>Background and State of the Knowledge</u>
The existence of submarine canyons has fascinated man since their discovery over 100 years ago. Part of the original fascination stemmed from the once radical suggestion that deep-sea processes are as or more energetic than those which occur on land.

The geologic record leaves little question that submarine canyons are major conduits for sediment transport. Both their general shapes and the exposure of outcrops of old material on their flanks makes it obvious that the canyons have been carved into the continental margins by erosion. The occurrence of huge volumes of materials derived from the continent within deep-sea fans that emanate from the lower canyon attest to the scale of canyon processes (Normark and Gutmacher, 1989). However, we know almost nothing about the actual transport processes that occur within the canyons and rates of sediment transport down the canyon system.

While all workers now agree that submarine canyons are major conduits for material transport from the continent into the deep-sea, numerous basic questions about the character, rates, and frequency of the transport events that occur in submarine canyons remain unanswered. Opinions vary enormously as to how frequently canyons are active, the importance of the various transport processes, and the nature of the materials that canyons carry. These views can be grouped into three basic categories:

(1) Some researchers believe that the axes of canyons experience sufficiently energetic conditions to transport large volumes of sediment on a regular basis. Regular tidal movement and internal wave pumping may be continuously moving material within the axis of the canyon system (e.g., Shepard et al., 1979; Hughes et al., 1990; Klinck, 1989). Interestingly, these models suggest the *net* transport of suspended material is up-canyon.

(2) A more moderate view is that fine-grained sediment which collect continuously in the upper canyon are destabilized during high energy storm events forming turbid (thus dense) water masses that drain down the canyon. Thus, transport events are predicted to correlate with major storms and should occur on a roughly seasonal cycle (Shepard and Emery, 1941; Olivier, 1972). Some data from moorings in Monterey Canyon support this assertion (Kinoshita and Noble, 1995).

(3) Finally, the extreme view is that the only significant events that influence canyon evolution may be associated with infrequent but catastrophic failure of the canyon walls (Normark and Gutmacher, 1988; Garfield et al., 1994). Material from periodic slumping of the canyon walls, perhaps stimulated by earthquakes or basal seepage, may enter the canyon at any place along the canyon axis, and not just at the canyon’s head. While it is clear that the sides of Monterey Canyon are heavily scared by slumping events, it is unclear as to whether slumps are a major sediment source or simply a consequence of canyon enlargement associated with other erosional processes. These predictions imply that turbid flows may enter into the upper canyon at any place along its axis.

Which of these processes dominate has enormous implications as to the sources and types of material that move through the canyon and to the ecology of organisms that depend on this transported material. While we cannot realistically expect to place sensors in the canyon capable of capturing the rare catastrophic events, we can deploy instruments in the canyon which will assess the role of both daily (#1) and seasonal (#2) events. However, the parallel efforts to sample the deposits on the canyon floor will provide ground truth as to whether the deposits that are on the canyon floor could have been deposited under the conditions that occur over the time period that the canyon is monitored.

Historical Reasons for Lack of Data on Submarine Canyon Processes

For most of this century the lack of data on submarine canyon processes has persisted because of a number of largely technical reasons:

• The rough and complicated topography associated with submarine canyons has historically hindered detailed seafloor surveying efforts. The only systems that provide access to canyon floors for detailed studies are submersibles and ROV's. However, except for in Monterey Canyon these efforts have been largely restricted to individual expeditionary efforts.

• Until recently the quality of the navigation has been too poor to even provide good maps of submarine canyons. Before GPS, it was difficult to confidently find the axis of a canyon, let alone to reoccupy it to deploy instruments or to sample it with wire-line tools. Surface ship multi-beam data (e.g., EM-300) now make it possible to accurately image the canyon floor. However, such surveys do not have high enough resolution to make repeat surveys productive.

• Traditional wire-line corers do not penetrate into sand and the canyon axes are believed to be sand floored. However, the sides of canyons are relatively easy dredging targets. As a consequence there are numerous samples from the walls of submarine canyons, while almost no samples from the canyons axes of submarine canyons have been obtained. However, the development of a vibracoring system at MBARI that can be deployed from the *Ventana* will now make it possible for us to collect precisely located cores from sand-rich deposits along the axis of Monterey Canyon.

• Access to most submarine canyons has been rather limited. For example, all the major U.S. East Coast canyons are a considerable distance away from an oceanographic port facility. However, the head of Monterey Canyon is within 5 minutes of Moss Landing Harbor, and large sections of the canyon axis are easily accessible for observation and sampling with the *R/V Point Lobos/Ventana*.

• Until recently sensors capable of monitoring physical conditions within a submarine canyon did not exist. While there are now sensors that are now capable of this challenge (e.g., ADCP, Transmissometers), data storage and power restrictions make it difficult to collect adequate amounts of data to resolve the various transport mechanisms with the benthic mooring systems in common use today.

• Funding agencies have been reluctant to place much instrumentation in the axes of submarine canyons for fear that the instruments would be lost during sediment transport events. Submarine canyons have a bad reputation for the loss of equipment based on anecdotal evidence. It is easiest for those who have lost gear in and around canyons to explain this as a consequence of the environment. However, the alternative explanation is our technology to relocate and recover instruments in this complex topography has been inadequate. We wish to point out that MBARI's M1 buoy has been moored in the axis of the canyon for a decade. Moreover, we suggest that the flanks and floor of the Monterey Canyon may actually be a safer environment to place instruments that are connected by seafloor cables than the smooth intercanyon areas because intense commercial fishing efforts scour the bottom in these smoother areas regularly.

• Financial and infrastructural commitments involved sustaining a monitoring effort for a long enough period of time to construct a meaningful data set have been difficult to obtain. However, developing the appropriate technology to make the basic measurements that will allow us to monitor transient events is at the core of the MBARI/MOOS effort.

Approach
Three parallel approaches are proposed to collect the basic data necessary to define the processes that occur in submarine canyons. They are: (1) Deploy a MOOS mooring to establish energy conditions on the floor of canyon and to determine the potential for sediment transport and erosion. (2) ROV sampling of the channel floor to establish the stratigraphy of the most recently deposited channel floor materials. (3) Repeat mapping of the channel floor at the highest resolution possible, to determine the changes that occur in topography of the channel floor. The first effort is being proposed here. Efforts # 2 is underway. Effort #3 is coupled with the development of a high-resolution multi-beam system that is independently being proposed.

#1 MOOS Monitoring – Canyon Array
We propose to monitor the physical conditions (near the floor of Monterey Canyon to better define the processes associated with sediment transport along the canyon axis and the rates and frequency at which episodic sediment transport events occur. To do this we will deploy five near-bottom instrument packages at varying water depths along the axis of Monterey Canyon, and one instrument package outside the canyon system to provide background information (see figure 1). Collectively, these instruments will form an array that will allow the passage of energy and material to be tracked along the canyon axis with synchronous time series data on the current structure and suspended sediment content in the lower 100 meters of the water column above the canyon floor.

Each station in the array will be designed to capture the current structure and sediment suspended sediment load from the seafloor upwards to ~80 m off the bottom. All the previous measurements of currents in submarine canyons have been placed at 50 to 100 meters off the bottom and those that contained ADCP's had the instruments looking upwards away from the benthic boundary layer. Thus, such measurements have never been systematically made that are fundamental to understanding the dynamics of submarine canyons worldwide.

Each station will have: (1) a near bottom mounted upward-looking ADCP which will outline the current structure thorough most of the benthic boundary layer, (2) a near-bottom transmissometer to quantify near bottom sediment loading, (3) a near-bottom conductivity and temperature sensor to track hydrographic changes in the benthic boundary layer, and (4) a near bottom current meter to assure a current measurement in the benthic boundary layer. This array will be configured to define both the ambient conditions and to track the initiation and evolution of individual flow events along the canyon's axis.

The five monitoring stations will be approximately equally spaced along the canyon floor between ~250 and ~2250 m water depths. At each station the current velocity profile will be measured from the seafloor up to about ~80 meters above the bottom. The 250-2,250 meter depth range has been selected for the following reasons: (1) The instruments will be close to MBARI. (2) It provides dense enough coverage to unambiguously capture the events within one relatively short section of the upper canyon. (3) The instrument array will start near the canyons head, thus the data will be relevant to issues as to what proportion of the materials enter the canyon near its head rather than being captured along its path. (4) The array straddles the depth where the energy dissipation caused by tidal intensification associated with canyon narrowing and impinging internal waves is greatest (500-2,000 m). Thus, this is the depth zone in which ambient currents would have the greatest sediment transport potential. The sixth station needs to be up off the canyon floor to obtain background data.

The benthic instrument arrays must to be capable of collecting data frequently enough (~ every 20 seconds) to detect the onset, passage, and decay of periodic flow events. Power and data requirements for these instrument arrays can be satisfied using benthic cables that run from a mooring on the flanks of the canyon.

#2 Stratigraphy and Sedimentology of Monterey Canyon Floor

Each of the various processes that have potential significance for transporting material through submarine canyons should result in distinctive sediment deposits. For example, major events will produce thick deposits that are either very poorly sorted or contain relatively thick beds of coarse sand. However, at the other extreme, deposits produced by regular or tidal events will be composed of numerous fine oscillations in grain size and material. By sampling the deposits that are presently on the floor of the canyon we will be able to obtain independent data for assessing which sediment transport processes are most important. Moreover, by integrating observations from the physical sensors and material sampling we will be able to document the response of the canyon floor to the measured physical conditions.

The vibracoring system that is being developed at MBARI will allow us to sample the upper ~2 meters of the canyon floor. With this data we should be able to map the sediment facies that occur on the channel floor. Ultimately, the objective is to compare whether the conditions that are monitored during the deployment of the sensors are capable of creating the deposits that occur *in situ.*

We also plan to track sediment movement in the canyon using various chemical, isotopic, mineralogic, and textural tracers. For example, DDT is being carried on the fine sediments that are carried by our local rivers out of the adjacent agricultural lands into the bay. The land is one of the major sediment sources for materials that may be moving down the upper canyon. Our contention is that DDT and its decay products are useful tracers for material that has been transported offshore in the last ~50-60 years. This is because DDT use started after World War II and DDT was presumably only sprayed on land. Thus, the presence of trace amounts of DDT in marine sediments labels the sediments that were transported from land within this time span. We believe that detectable levels of DDT should form a tongue that extends some distance down the axis of the canyon. The characteristics of this tongue will define the extent of sediment transport in the canyon. We can independently identify sediments that were deposited within this same time period using ^{137}Cs, a bomb-produced isotope that is detectable in essentially all sediments that were deposited since 1945.

#3 Repeat Mapping of Sections of Monterey Canyon Floor

Our continuing ignorance about the nature of submarine canyons persists in part because we have not been able to study the dynamics of the canyon floor in ways fluvial systems are examined on land. We have a substantially more complete view of terrestrial fluvial dynamics based on studies of the shape and position of sand bars, the nature of near-surface materials, and measurement of changes in these features from repeated observations (Leopold et al., 1968). Unfortunately, this type of information is not available for any submarine canyon. Thus, producing detailed maps of sections of the main channel of Monterey Canyon and repeating the mapping process after distinct events have occurred would constitute a major milestone in submarine canyon research. The MOOS mooring system is a critical element in identifying when substantial sediment transport events have occurred and allow us to determine when to repeat the morphologic measurements.

Moreover, it is possible to determine whether the geomorphology of fluvial systems represents a response to current conditions or a relict of former conditions, based on whether their central channels are in dynamic equilibrium or out of equilibrium with ambient conditions (i.e., accreting or eroding).

Repeated surveys of sections of the main channel in Monterey Canyon (on either seasonal or longer time scales), would define rates of accretion or erosion in this system. Thus, we could establish whether ambient conditions are responsible for the observed canyon morphologies, design appropriate experiments, and begin to construct a sediment budget for the canyon system.

A mapping tool that is able to map the canyon floor at very high resolution (ideally ~25 cm contour resolution) is needed. This system must be navigated at an accuracy that allows repeat surveys at a similar resolution. The tool must be capable of operating within the complicated topography associated with the canyon walls. We envision that such a tool could be deployed from either an ROV or AUV.

3. Observing System Requirements

The purpose of this section is to extract from the previous experiment description the technical requirements for the observing system. This section is broken up in several categories, the first is a description of the expected operating environment. The remaining sections describe the technical requirements for the system. They have been broken up into sections that can be considered as components of the MOOS suite of capabilities, e.g., the MOOS mooring, AUVs and ROVs.

3.1. Operating Environment

The operating environment is the typical conditions for the Monterey Bay area. Environmental data from the MBARI M1, other permanent monitoring stations in and around the bay and previous studies from various research groups can be used to give a complete description of the environmental conditions e.g., sea state, current, wind speed and direction required for design of the system components.

3.2. MOOS Mooring Measurements

The current experiment looks like it can be supported with one mooring with one multi-port benthic node.

3.2.1. MOOS Mooring Surface Node Measurements

Only the telemetry capability of the MOOS Mooring will be required at the surface node. Surface environmental data can (and will) be acquired by the M1 mooring and other permanent monitoring stations around the bay including USGS stream monitoring stations. If other uses for this deployment require sensors on the surface node, we will of course include the data in our measurements.

3.2.2. MOOS Mooring Water Column Measurements

No water column measurements are required at the MOOS mooring

3.2.3. MOOS Mooring Benthic Node Measurements

This is where the majority of activity in this experiment occurs. The current plan suggest that one benthic node can effectively support the required 6 remote instrument suites.

3.2.4. Spatial Coverage

The benthic node can be placed at what looks to be a suitable site that puts it roughly within 10 km of all 6 of the currently selected remote sites. The instrumentation planned for each of the remote sites will extend less than 2 meters above the bottom.

3.2.5. Remote instrumentation suites

An important aspect of the remote instrumentation node design is the requirement to survive a significant sediment transport "event". This requirement will have a strong influence on the node design and selection of node instrumentation. Each of the remote nodes will consist of the following instruments

3.2.5.1. ADCP

A RDI Workhorse Sentinel (or similar) ADCP will be bottom mounted and upward looking to measure current profile in the first 80 (or so) meters above the bottom. In addition, the acoustic return from each of the ADCP measurement bins can be used to estimate sediment concentration. This ADCP generates roughly 750 bytes of data and requires XX watt-hours per measurement. We would like to make measurements every 10 minutes.

3.2.5.2. Transmissometer

A TBD transmissometer will be rigidly mounted about 2 meters above the bottom to measure sediment concentrations, which may hug the bottom below the first bin of the ADCP. A similar transmissometer my be required roughly in the middle of the first or second measurement bin of the ADCP for comparison and calibration purposes. Each of these devices will generate roughly 20 bytes of data and require XX watt-hours per measurement. Again, we would like to make measurements every 10 minutes

3.2.5.3. Conductivity/Temperature

A TBD CT sensor will be rigidly mounted to the remote node to provide benthic contextual data. The CT sensor will generate roughly 100 bytes of data and require XX watt-hours per measurement with measurements every X hours.

3.2.5.4. Boundary layer current meter

A physically robust current meter, potentially an Interocean S4, will be rigidly mounted 2 meters above the bottom for current velocity measurements below the lower limit of the ADCP. This device generates about 100 bytes and requires XX watt-hours per measurement with measurements every 5 minutes.

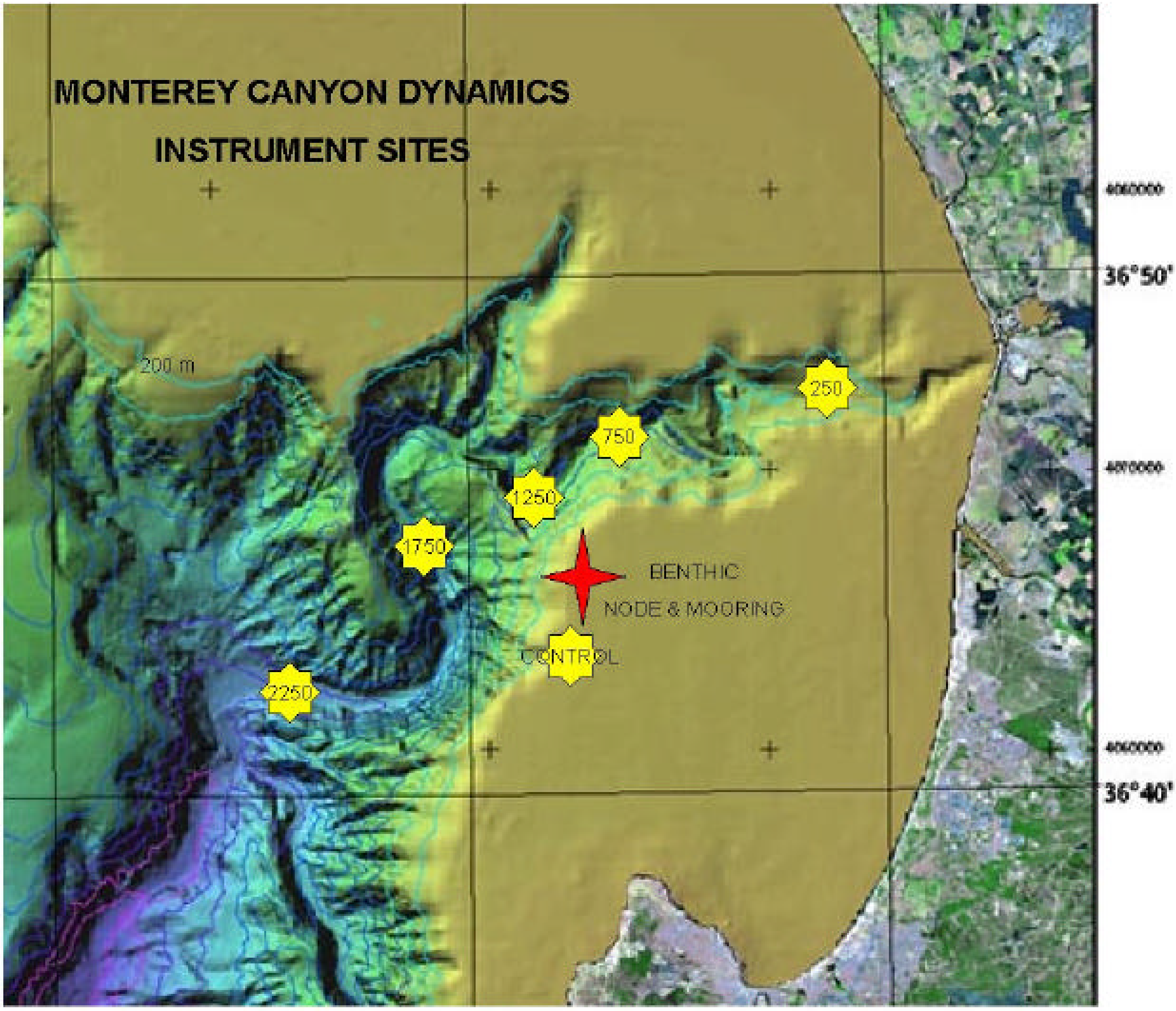
3.3. ROV Measurements

Two kinds of measurements suitable for ROV operations are required. The first is precision bathymetric mapping of approximately 10 sites where significant geomorphic changes may occur. This would require bathymetric measurements over a spatial extent of approximately 400 meters by 200 meters with 2 meter resolution horizontally and .2 meter resolution vertically. A thorough baseline map would be generated at the beginning of the experiment with periodic re-surveys at the beginning and end of each storm season for the 3 year duration of the experiment. These re-surveys would only be required over areas that significantly changed from previous measurements. The degree of change could be determined either visually by comparing real time video while re-visiting the site with previous videotapes or by mapping a small subset of each site and comparing with previous surveys. In addition to these periodic measurements, we would like to be able to respond to significant events as identified in real time at the remote instrument sites. An event response would be similar to the re-survey described above. The ROV would visit some subset of the survey sites that may have sustained geomorphic change and, based on the current condition, resurvey some or all of the baseline map at each of the selected sites.

The second ROV measurement is sampling the sediment in the identified sites of interest using the current ROV techniques (push cores, grab samples, etc.) and those under development (vibro-cores, box cores, etc.). Again, this would be done to generate the baseline map and when changes are detected either during the periodic return visits or event response visits.

3.4. AUV Measurements

It may be possible to do the mapping measurements described in the ROV measurements sections using an AUV. At this point, the choice of AUV versus ROV mapping appears to be a function of which platform is the best choice for engineering, schedule and risk mitigation reasons. It may be that this choice is made primarily by the Engineering staff with minimal input from the science users beyond specifying the requirements and understanding the performance trade off between the two platforms.


MONTEREY CANYON DYNAMICS
INSTRUMENT SITES
200 m
250
750
1250
1750
2250
BENTHIC
NODE & MOORING
CONTROL
36°50'
36°40'

Appendix 3: MOOS Use Scenario 3: Active Mid-Ocean Ridge Processes

1.0 Introduction

This document will describe a typical "use-scenario" for the MOOS technology currently being developed at MBARI. This scenario is an example of how a long term observatory using MOOS technology might be implemented on an active mid-ocean ridge segment such as the Southern Cleft of the Juan De Fuca ridge. Since the experiment is only in the initial planning stage this use-scenario is, of course, only an example and will require additional work to completely define the experiment requirements. A precise description of the experiment will be presented in the proposal.

The second section of this document provides and overview of the experiment and is taken directly from the preliminary draft proposal. The third section is an attempt to outline a specific set of requirements that this experiment might require from the suite of capabilities that have been discussed for MOOS.

2.0 The Problem Addressed-Temporal Dynamics of Ocean Crust: Development of a Long-Term Observatory on an Active Mid-Ocean Ridge Segment

Statement of the problem

The formation of the oceanic lithosphere at the mid-ocean ridges results from complex interactions among volcanic, tectonic, and hydrothermal processes. Biologic processes are also coupled with this phenomenon as subsurface flow of nutrients sustains a recently recognized microbial community as well as the surficial oases of vent animals. These processes, and the observable phenomena they produce, are operative on time scales that range from days to decades. The specific linkages between this diverse phenomenon are relatively unconstrained because of the absence of an experimental methodology that will permit continuous, long-term observations of active processes on the seafloor. We propose to build a suite of sensors and samplers appropriate to address fundamental hypotheses on the coupling between volcanic, tectonic, hydrothermal and biological processes during the formation of oceanic crust. In addition, this project will provide an engineering laboratory to develop the communication and control tools required to provide continuous access to the most remote sites on the ocean floor.

We propose to make long-term (at least 3 years) observations of surficial geological changes, microseismicity, hydrothermal and biological activity on a representative segment of mid-ocean ridge crest with an active hydrothermal system. We will use the Cleft Segment of the Juan de Fuca Ridge as the example, both because of its logistical proximity (630 n.m. from Moss Landing) and its similarities to both fast and slow spreading ridges. The Cleft segment has characteristics typical of intermediate to fast spreading ridges, including evidence for a magma chamber, terrain dominated by volcanic flows, evidence for tectonic fissuring, and active and extinct hydrothermal vents, and conspicuous bacterial flocculent associated with vent sites. Event detection records on the Juan de Fuca/Gorda Ridges demonstrate that both magmatic and tectonic processes take place on a measurable time scale. These geological, geochemical, geophysical and biological observations will comprise the first detailed examination of intermediate-scale temporal variations in the crust-forming processes. This experiment is proposed initially for the Juan de Fuca Ridge because of its proximity to the West Coast of the U.S., the community interest deriving from the proposed Neptune seafloor cable and the presence of other geodetic experiments at this site. The experiment is appropriate for the northern East Pacific Rise also, whenever this latter target becomes more logistically attractive and appropriate for the MBARI resources.

Why it is important

The existing paradigm for mid-ocean ridges proposes that their observed morphology and hydrothermal activity are a result of the balance between magmatic supply and tectonic extension. On faster spreading ridges the dominant features are controlled by volcanic eruptions, whereas on slower spread ridges episodic eruptions are followed by long periods of amagmatic extension. The presence of an axial magma chamber likely controls the depth of the brittle-ductile boundary, the depth and distribution of major faults and the depth of hydrothermal fracturing that penetrates into the high-temperature reaction zone (Alt, 1995; Von Damm, 1995). Dike injection into the upper crust or magma recharge into the lower crust create short-term perturbations in the hydrothermal system and the nature of local tectonic activity. The earliest phase of tectonic extension has also been associated with voluminous outpourings of bacterial debris presumed to be artifacts of a crustal biosphere that populates the crust during some phase of the volcanic-tectonic cycle. The return of a ridge segment to its equilibrium state after an eruption or dike injection probably takes place over a few years, and is amenable to long-term observations (months to years). Our understanding of the specific linkages between these processes and the frequency or rate of perturbation and recovery have been limited to serendipitous discoveries or short observational windows.

The major scientific theme addressed here is the temporal and spatial variability of the hydrothermal cooling and tectonic fracture that occur during the formation of oceanic crust. The hydrothermal effluent impacts the chemical composition of the overlying water column and modulates the environment for microbiol and macrofaunal species. Both surface and subsurface processes will be mapped and measured with a multidisciplinary experiment on a single ridge axis. We will try to quantify the subsurface processes by the deployment of an innovative suite of instruments and samplers networked via two MOOS telemetered moorings. Continuous measurement of ground motion, fluid flow, and fluid chemistry combined with field evidence of persistent diffusive flow and active extension might enable linkages to be resolved and from these infer the depth and progress of a brittle fracture horizon beneath a ridge hydrothermal system. By assessing the changes in the microbial community in concert with the geochemical processes we hope to determine the species distribution, abundance and habitat distribution for the "crustal biosphere" during various phases of the evolution of the hydrothermal system.

The development and deployment of such a ridge crest MOOS seafloor observatory has been a primary component of both national and international scientific programs. There have been at least six major workshops to design both the scientific goals and infrastructure for such an observatory. Unfortunately few of these plans have come to fruition, as the technical and scientific requirements have proven to be daunting.

Present state of art/understanding

Volcanic eruptions, or their manifestations, have been observed on three different sites on the Juan de Fuca Ridge / Gorda Ridge system. These sites are the northern Cleft site during the mid 1980's (e.g., Chadwick et. al., 1991), the Co-Axial Segment in 1993 (Embley et al., 1995), and the northern Gorda Ridge in 1996 (Embley et al., 1996). The large number of detected eruptions in this region is a direct result of monitoring the SOSUS arrays that can remotely detect seismo-acoustic energy and distinguish between eruptive and other events (Fox et al., 1995). The proximity and real-time SOSUS monitoring also enable rapid response to capture events in the early stages of activity. Other intermediate to fast spreading centers likely erupt at least as frequently. The gradual return to a steady state system continues to be observed following the 1991 eruption on the East Pacific Rise at 9°50'N (Haymon, et al., 1993). Repeated annual visits to the eruption site revealed substantial changes in the hydrothermal activity. Von Damm et al. (1995) described fluids that underwent major changes in chemistry for at least three years and some changes that occurred in several months. The most dramatic chemical variations were observed in gases such as methane or helium and in dissolved Fe and chlorinity. The amplitude of variation is decreasing, apparently as the ridge segment returns to equilibrium. Initial high levels of bacterial floc associated with the earliest phases of volcanic intrusion are superceded by the development of faunal communities and presumably a more stable microbial population. On the Cleft Segment an event during the mid-1980’s supported vast fields of tubeworms which had disappeared by 1988 (Stakes and Moore, 1991). The extent of seafloor strain and seismicity that occurs between major episodes is relatively unknown. Local geological changes, such as growth of fissures or collapse of the axial rift walls or cessation of venting is rarely coordinated with data from other sensor and samplers. Continuous monitoring of hydrothermal and biological events, coordinated with studies of crustal deformation, extension and microseismicity, will be broadly applicable to large segments of the mid-ocean ridge system.

We have identified a series of specific scientific hypotheses to guide our selection of field observations, sensors and samplers appropriate for this project. These are:

Hypothesis 1. The microseismic activity of a ridge segment can be correlated with vertical or horizontal deformation, or with the movement of magma prior to an eruption.

Hypothesis 2. Changes in hydrothermal systems are linked to substantial (but not all) earthquakes that alter crustal permeability structure. These changes can occur over short time scales (hours to years).

Hypothesis 3. Temporal changes in the hydrothermal system that are related to either dike injection (new heat source) or evolution of the fluid pathways are recorded within chimney features.

Hypothesis 4. Solid Earth tidal deformations, ocean tides and hydrology within the hydrothermal system are linked and can be distinguished by observing the long-term variations in pressure, flow velocities, temperatures and seafloor deformation .

Hypothesis 5. The seafloor sulfide/sulfate deposits and the adjacent oceanic crust at hydrothermal sites with continuous venting harbor a complex, primitive microbial community that not only thrives in the absence of sunlight but also delineates the physical limits of living organisms.

The Cleft Segment of the Juan de Fuca Ridge

The southern Juan de Fuca Ridge segment is about 60 km long, extending north from the Blanco Fracture to the overlapping Vance segment. The Juan de Fuca system offers a variety of volcanically and hydrothermally active sites within a few days from U.S. ports (Newport, Astoria, Eureka). The experiment described here is based on the Cleft hydrothermal systems, however, the MOOS system could be relocated to equally interesting (but more logistically difficult) sites on the northern East Pacific Rise. The types of instrumentation and scales of measurements will be very similar for both Juan de Fuca and East Pacific Rise experiments. On the southern Juan de Fuca Ridge segment, there are two vent areas, North Cleft and South Cleft that are 40 km apart and 20 km from the northern and southern ends of the segment, respectively. The South Cleft vent site is the target of this initial Observatory experiment as the vent areas are the best studied and continue with both robust, high temperature and diffuse, low temperature venting. The south Cleft segment shares many of the traits of intermediate to fast spreading ridges. It exhibits a rather simple linear morphology, three well-defined vent areas (Plume, Vent 1 and Vent 3 from south to north) and has a normal crustal thickness. The "cleft" is a 50 to 200 meter wide fissure that bisects the southern end of the ~3 km wide axial summit crater (ASC). The Cleft segment axial valley is morphologically more like the ASC on the EPR than the axial summit grabens (ASG) characteristic of the rest of the JdF. Like most intermediate to fast spreading ridges, Cleft is underlain by an axial magma chamber (Morton et al., 1987). Further, the Cleft segment exhibits very low seismicity as measured by continental stations and SOSUS observations (Fox, et al., 1995) similar to the EPR and unlike the high seismicity observed on the Endeavour and Co-Axial Segments of the JdF (McClain et al., 1993; Wilcock and Delaney, 1996). An array of several seismometers was placed on the northern Cleft for 11 days in 1990. Significant microearthquakes were detected at a rate of at least one event per two days (McDonald et al., 1994), with swarms of very small events also detected (Sohn et. al., 1995). These latter events are comparable to microearthquakes associated with continental hydrothermal and volcanic systems (e.g. Ward and Bjornsson, 1971; Koyanagi et al., 1972).

Hydrothermal systems along the southern Cleft Segment have been sampled almost yearly since 1984 when three sites (Plume, Vent 1, Vent 3) of active venting were discovered (USGS Juan de Fuca Study Group, 1986; Von Damm and Bischoff, 1987). Each site contains several high-temperature venting orifices as well as areas with diffuse low-temperature venting. Maximum reported vent fluid temperatures for all South Cleft vents are below 350° C (Von Damm and Bischoff, 1987; Massoth et al., 1994; Trefry et al., 1994), but in order to generate the brine-like chlorinities, temperatures in the reaction zone must have been considerably hotter (> 400° C). It is likely that at some time in the past, phase separation was active at South Cleft, producing vapor-dominated fluids at the seafloor while accumulating brines within the crust. Of the three S. Cleft sites, only Vent 1 has fluids hot enough to produce Cu-rich chimneys. With the exception of an approximately 10% change in chlorinity at Vent 1, vent fluid compositions at South Cleft have remained constant to within a few percent. This is in contrast to very large, systematic changes in composition at North Cleft over a time period of 6 years related to fluid evolution following a volcanic eruption (Butterfield and Massoth, 1994).

The intrusion of a dike and subsequent cooling by hydrothermal circulation should be linked to significant fluctuations in hydrothermal properties, such as water temperatures, flow rates, and overall flux and chemistry of the effluent waters. Evidence supporting this prediction is found in observed changes in venting fluids from several ridge segments (Butterfield and Massoth, 1994; Von Damm et al., 1996; Butterfield et al., 1997) as well as in the water column above the Cleft Segment. Baker (1994) found significant variations in water column temperature and light attenuation anomalies during the period 1986-1991 (Figure 2). Although these anomalies form by the integration of oceanographic and hydrothermal effects, they do appear to show a hydrothermal system that goes through up to two cycles of waxing and waning. The anomalies may be related to the eruptive event that took place on the northern Cleft sometime in the 1980's (Embley et al., 1991). Either a second dike intrusion, or an earthquake must have occurred during the period of 1986-1991 to produce a second temperature high during the monitoring period. One possibility is a non-eruptive diking event with black hydrothermal fluid venting from fractures in bare rock on the floor of the cleft, abundant bacterial particulate material, and robust diffusive venting along the west wall of the axial cleft as observed on Alvin dives in 1988 (Stakes and Moore, 1991).

The continuous (or chronic) venting from the South Cleft Hydrothermal sites rise approximately 50 to 200 m above the seafloor. They perturb the lowermost water column and can be measured within the axial summit caldera of the ridge segment (which is two to three kilometers wide). The event plumes associated with either dike intrusions of major tectonic events rise over 1000 meters above the seafloor. These turbulent events disrupt the overlying water column and move away from the vents within a few days to weeks of the event. The two megaplumes measured on the Cleft Segment, were observed displaced several kilometers from the vent sites.

The long term instrument deployments will include geophysical packages deployed in an array around the south Cleft vent sites. The geophysical packages will include short-period seismometers, short baseline tiltmeters, and high resolution pressure gauges. These packages will be used to monitor local and regional ground motion. The hydrothermal vent packages will include chemical samplers and sensors, bacterial samplers, and temperature recorders. An AUV will be exploited to measure the integrated impact of hydrothermal effluent on the overlying water column. The AUV will measure temperature, chemical, and transmissivity anomalies over the continuous vent sites to complement the benthic instrumentation. Following an event, the AUV's will extend their water column measurements to include much of the segment (up to 50 km long by 10 km wide by 1 km of depth) to monitor the formation and dissipation of the hydrothermal plume.

Seismometers. A two-scale experiment has been designed, with two tight internal arrays arranged to detect, locate, and characterize small near-surface microearthquakes along the axis, and an external array designed to distinguish earthquakes over a broad region. The internal array of six packages will be located around the two most hydrothermally active localities in the southern Cleft area (Vents 1 and 3). This small array can be used to distinguish between near surface events and deeper events associated with a cracking front located in the middle crust (depth ~3km.).

The external array of six instruments is designed to discriminate between events located along axis (and thus associated with diking events, the hydrothermal system, or axial tectonic events), and those tectonic events located off-axis). The array will also detect and locate events along the axis but outside the main field area. These packages will be deployed up to 10 kilometers off axis.

A 3D seismic velocity model will be required to precisely locate seismic events detected by the array. This model will be obtained through a seismic refraction experiment involving shooting airgun lines over the MOOS seismometer array. The aray could be augmented with temporarily deployed OBH's to obtain higher lateral resolution. A fairly small airgun array (~500m3) would be adequate for imaging upper crustal structure; a larger array (e.g. R/V Ewing) would be required to image full crustal structure. An upper crustal velocity model would be sufficient for the microseismicity modeling and also would image layer 2A. The formation of the thin (100 m to 400 m) low velocity crustal carapace (layer 2A) is an outstanding controversy. This survey could be done at any time after the deployment of the seismometers and either before or after the deployment of the moorings.

Tilt Meters. A minimum of two short-baseline corehole tiltmeters will be deployed at two sites on opposite sides of the Cleft wall to monitor volcanic inflation or tectonic rotation. The sensor has a resolution of 0.1 microradian and a range of 1.0 degree from sensor null on each of two channels. High resolution Paroscientific pressure gauges will be deployed in concert with the tilt sensors and the seismometers to provide simultaneous measurements of absolute depth as well as to provide pressure data for studies of ocean tides, and pressure and tilt data for measurement of solid earth tidal deformations.

Hydrothermal and Geochemical Samplers. The two most active vent sites as south Cleft (Vent 1 and Vent 3) will be instrumented with a suite of samplers and in situ analyzers to constrain the temporal variability of fluid flow and chemistry. OsmoSamplers will be deployed to provide continuous, although small volume samples. An additional external osmotic pump will be employed to add acid to the sample stream, thus keeping redox sensitive chemical species (e.g., Fe, Mn) in solution. Osmotic Analyzers use the same type of pump system, but analyze for specific ions in situ using standard colorimetric reagents. OsmoAnalyzers for iron are under development at MBARI. Continuous monitoring of the Fe and particulates (via transmissivity) in vent and buoyant plume fluids will become a useful indicator of venting activity. The ISUS system will be deployed to monitor bromide as a monitor of the fluid salinity, as well as sulfide, nitrate, and organic carbon. As other sensors become available (i.e. nutrients, methane, oxygen, silica, microbial assays) these will be added to the vent instrumentation.

A remote large volume water sampler will be proposed by Wheat for development in 2001. This will be a modification of a commercially available trace-metal free sampler that can work at depth. This system (Remote Access Samplers) can collect 48 samples at timed intervals for a period of up to one year, thus providing weekly samples. This sampler can be deployed to collect samples every half hour to examine short-term processes. To take advantage of in situ event detection capabilities that sampler would be networked with the MOOS benthic hub that also monitors temperature, flow and seismic events. When an event is detected, the MOOS system will trigger the sampler to operate at higher sampling rates

Temperature Recorders. A variety of low-temperature and high-temperature probes are available from Deep Sea Power & Light. The sampling rate can be preprogrammed to permit autonomous recording for at least one year. The temperature probes can also be interfaced to the hydrothermal vent packages. These recorders will be deployed in each of the high-temperature vents (Vent 1, Vent 3 and Plume) and at 10-12 sites along the Cleft walls that have significant diffusive effluent.

Vent Fluid Flow measurements. Each of the two vent sites would include at least two flowmeters, to compare diffuse and focussed flow rates. There are two instruments available that we will assess for this application. A heat-pulse flowmeter has been developed at the University of Hawaii to determine speeds of fluid flow using a heat-pulse concept in which a grid heats neighboring waters that flow along a tube with several thermistors. The benefit of this instrument is that it can be placed in small cracks and is designed to measure flow rates in the diffusion-to-subtle advection range much below 0.1 mm/s.

The Medusa autonomous vent fluid sampling system includes a titanium sensor head, which is placed directly upon zones of diffuse hydrothermal flow, and a separate titanium alloy pressure case containing the electronics, datalogger/controller, and power supply. The sensor head contains a titanium-rotor effluent velocity sensor with an optical detector; Type-T and Type-K thermocouples which measure the temperature difference between vent and ambient fluids. This system has been deployed on the MAR, the JdF and the EPR every year since 1994 with variable success. The new generation of Medusa and its successor the DALEX, are being built in collaboration with NASA for the study of life in extreme environments. The gas-tight samplers are especially applicable to microbial studies at vent sites

A method of measuring diffuse flow using acoustic reflectivity has also been developed at Rutgers and will be considered.

Biological samplers. Samplers for microbial and larval studies are only in the early design stages. Microbial samplers and insitu analyzers would be placed into coreholes in sulfide and/or basalt to assay the species within the seafloor environment. Larval samplers would be deployed on the riser for the MOOS moorings and also on the AUV. Both of these efforts would require significant prototype efforts within Monterey Bay prior to incorporation with the MOOS experiment.

The MOOS instrumentation:
The South Cleft hydrothermal sites can be effectively monitored by 1-2 MOOS moorings with benthic hubs and an AUV docking station. The on-axis instrumentation (six seismometers, two hydrothermal packages, one AUV station) will cover an area of five kilometers (maximum) by two kilometers). This will be supplemented by an additional six seismometers that will be deployed up to 10 km east and west of the axis site. These latter instruments could be deployed

to collect data autonomously, be serviced by an AUV acting as a data courier or be networked to the same (or a second) benthic hub.

3. Observing System Requirements

The purpose of this section is to extract from the previous experiment description the technical requirements for the observing system. This section is broken up in several categories, the first is a description of the expected operating environment. The remaining sections describe the technical requirements for the system. They have been broken up into sections that can be considered as components of the MOOS suite of capabilities, e.g., the MOOS mooring, AUVs and ROVs.

3.1 Operating Environment

The operating environment is the Southern Cleft of the JdF Ridge. The expected environmental conditions will be derived from historical data but are known to be significantly rougher than those in the Monterey Bay area e.g., the 90th percentile significant wave height is 15 feet for JdF and 10.5 feet for Monterey Bay. As an example, analysis done during the Western Flyer redesign limits the ability of the Flyer to operate in this area during the winter season to an economically prohibitive small fraction of the time. The accepted weather window for working in this area is July through September. A variety of UNOLS platforms including Jason and Alvin have worked in this area for over a decade with only a few days lost to weather.

3.2 MOOS Mooring Measurements

The current experiment suggests that two mooring will be required to support the number of instruments and the horizontal spatial extent. This may, of course, shrink to 1 mooring or grow to more than 2 depending on the final capabilities of the MOOS equipment. A third mooring would provide especially useful to provide a docking station for AUV surveys in the nothernmost portion of the ridge segment.

3.2.1 MOOS Mooring Surface Node Measurements

Only the telemetry capability of the MOOS Mooring will be required at the surface node. A time synchronization signal will be required. This can be accomplished with a GPS time receiver on the surface node. If other uses for this deployment require sensors on the surface node, we will of course include the data in our measurements. Store and forward data telemetry is acceptable for this experiment (with a reasonable latency on the order of 1 day).

3.2.2 MOOS Mooring Water Column Measurements

Some water column instrumentation similar to the Fe, Temperature, microbial, larval and transmissiometer (similar to the instruments on the AUV described below) may be required in the lower 1000 meters of the mooring riser.

3.2.3 MOOS Mooring Benthic Node Measurements

The current layout plan suggest that two benthic nodes can effectively support the required instrument suites. It may be possible to support the entire suite of instruments with one very capable MOOS Mooring and benthic node but the dynamic environment suggests that two mooring/nodes would provide a highly desirable level of redundancy. The exact configuration of which remote instruments are connected to which mooring will require more thorough discussion to optimize the balance between redundancy, minimum required data set, installation risk and other factors.

3.2.4 Spatial Coverage

Each benthic node can be placed at what looks to be a suitable site that puts it roughly within 10 km of all the currently selected remote sites.

3.2.5 Remote instrumentation suites

Two kinds of remote instrument suites are planned, a geophysical package and a chemistry package

3.2.5.1 Geophysical package

All 12 of these packages will have one short period seismometer and one high resolution pressure gauge. Two of the 12 packages will also have a short baseline core hole tilt meter that will need to be drilled into a rock face. The data rate for the seismo/pressure package is XXX bytes per day and XXX bytes per day with a tilt meter (approximately 2 GB per month). The units draw 0.3 watts and can be self powered for 12 months.

3.2.5.2 Chemical package

The chemical instrumentation package consists of a variety of sensors, some existing, some modifications of existing equipment and some currently under development. The list of desirable sensors includes: osmo-samplers, osmo-analyzers for iron, ISUS for bromide, sulfide, nitrate, organic carbon, a modified Remote Access Sampler for large volume water samples, temperature recorders, vent flow meters and other sensors for nutrients, oxygen, methane, silica and microbial and larval assays that may become available in the desired time frame.

3.3 AUV Measurements

A continuous and event response mapping capability is required for this experiment. For the purposes of this use scenario, we are assuming that this capability will be served best with an AUV although other platforms should be considered. Both mapping capabilities would require a navigation accuracy on the order of 10 meters in all three directions to provide adequate map resolution.

3.3.1 AUV Instrument Suite

We would like to include instruments from the following list. ISUS for sulfide, nitrate, organic carbon and bromide, O2, FE digiscanner, rapid osmo-sampler, transmissometer, CTD, ADCP. When sensors/samplers become available for microbial or larval determination, these would be added to the package.

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3.3.2 Continuous Mission Profile

Continuous missions would be run on the order of once a week. As described above, most events of interest can be clearly identified for at least 2 – 3 weeks after the event and in some cases several months. For the purposes of this use scenario we are describing the most desirable sample rate. The spatial extent of the continuous mission is shown by the smaller, 10km by 20 km yellow box in Figure 2. A single lawn mower pattern at a depth of 50 to 200 meters above bottom with transects spaces about every 3.3 km across the ridge axis would give a mission length of 100 km (4 legs * 20 km/leg + 3 legs * 3.3 km/leg + 10 km return to dock). At 3 knots, this would be a mission length of 18 hours. Assuming a vehicle which requires 250 watts to run and power instruments, this would imply an energy storage capability on the AUV of 4500 watt-hours and a energy recharge source capable of delivering a continuous 30 watts to the vehicle to meet the desired 1 week mission period ((18 hours * 250 watts) / (168 hours – 18 hours)). For comparison, the current M1 solar panel system provides approximately 5 to 10 watts at the surface as a worst case during the year.

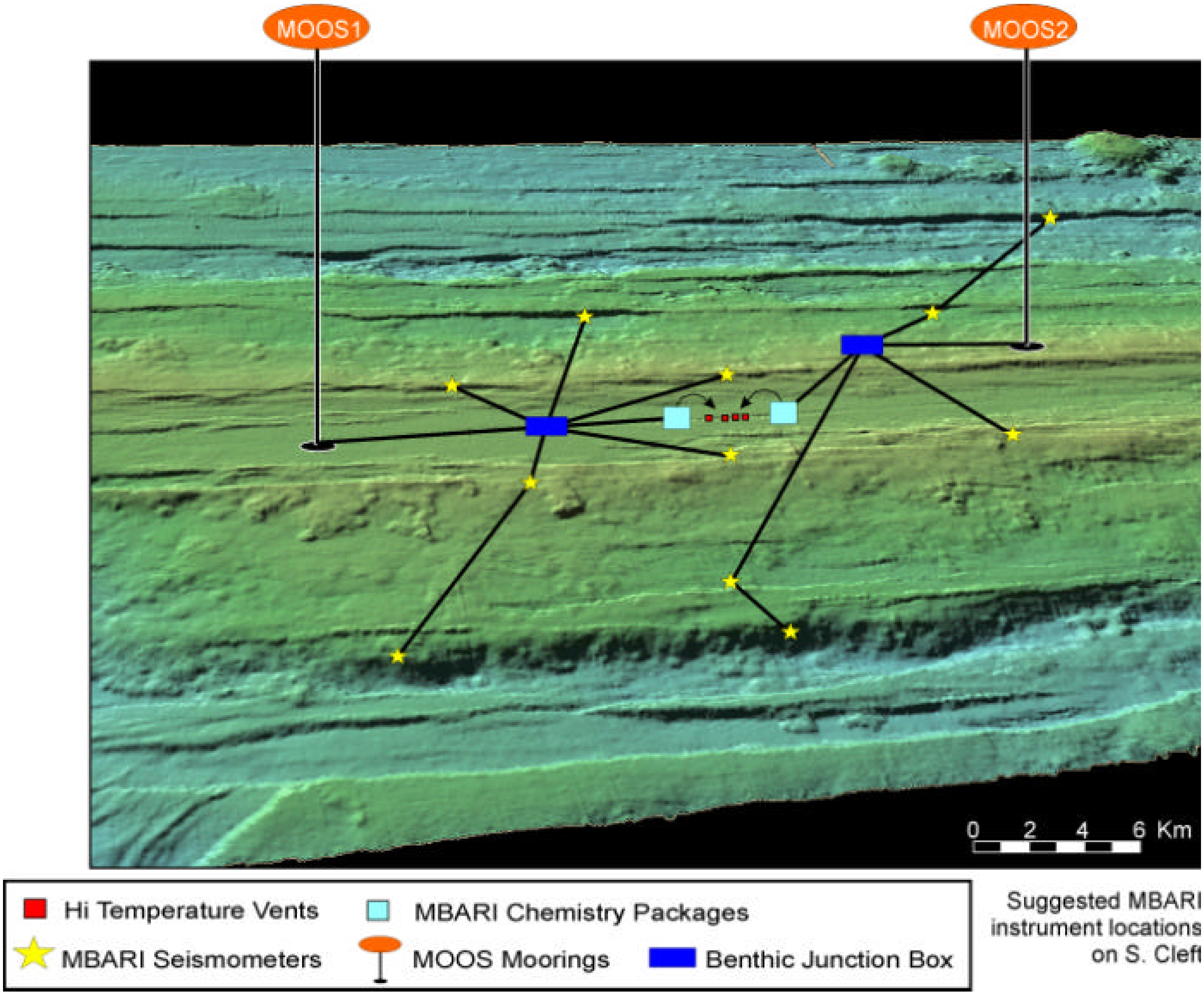
3.3.3 Event Response Mission Profile

An event response mission would require covering the larger black box in figure 2 at 4 discrete depths. The box is 20 km by 60 km with AUV runs at 250, 500, 750 and 1000 meters off the bottom. Using the same lawn mower pattern described above for this geometry gives a 1042km mission length, clearly a challenge for most AUVs (any AUV except ALTEX?) using current technology.

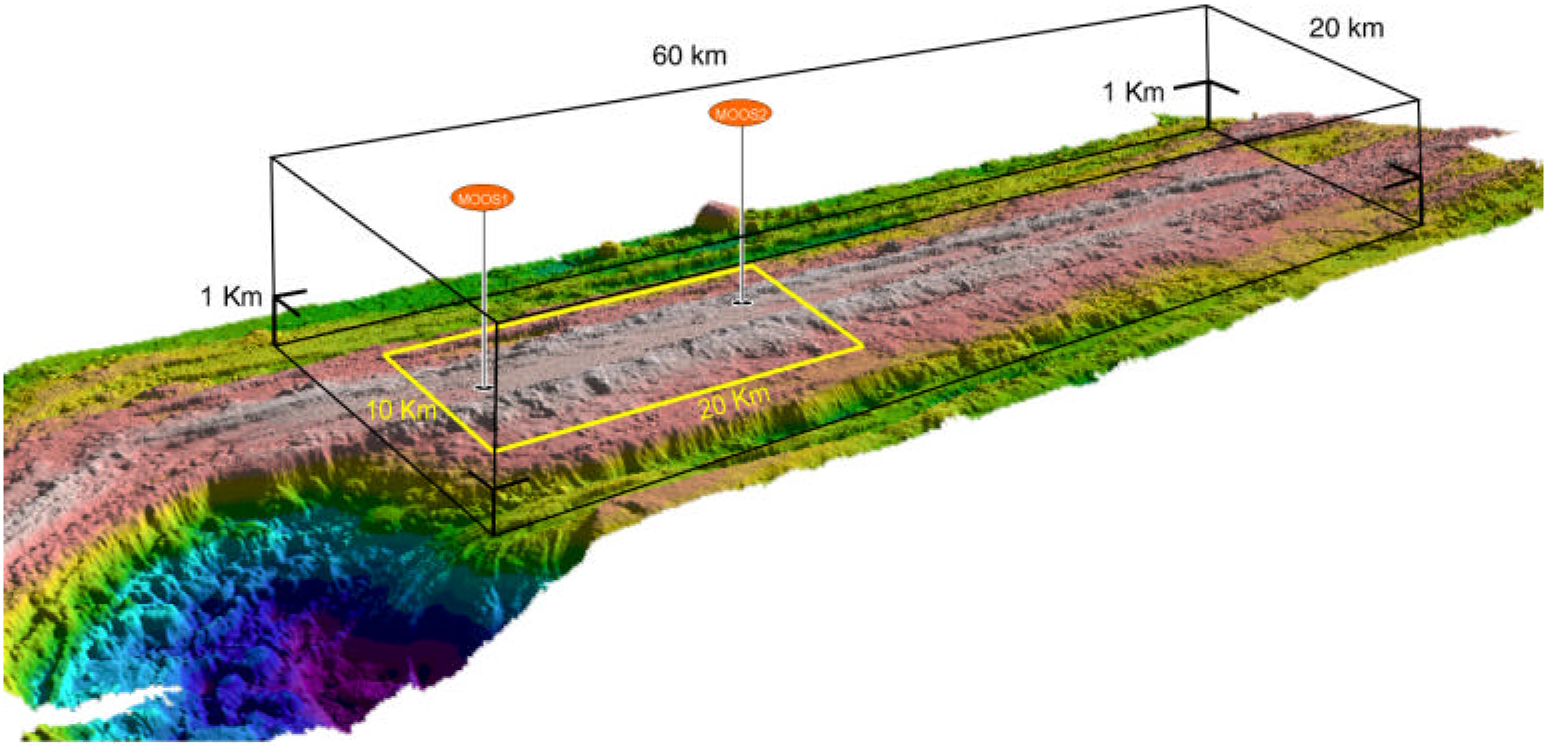
3.4 ROV Measurements

No ROV measurements are planned for this core experiment. Biological sampling of benthic communities or expeditionary observations would of course be valuable supplements to the experiment. Use of the ROV to opportunistically collect macrobiological samples would be desirable. D3pending on the spatial heterogeneity in the faunal composition and in the structure of communities, subsequent experiments will be designed to exploit in situ instrumentation associated with MOOS. A longer-term goal will be to develop an in situ sampler of invertebrate larvae to be deployed on the mooring riser and the AUV. Current efforts are focussed on development of larval sampling devices and molecular based diagnostic markers of constituent species.

In addition, the ROV will be required for the initial instrument installation. Annual maintenance visits will be required to provide fresh batteries, replace non-functioning sensors, and change data-loggers. The ROV may respond to significant events to supplement the insitu measurements.



Suggested MBARI instrument locations on S. Cleft



Yellow box: Area of suggested MBARI instrument deployments

Appendix 4: MOOS Use Scenario 4: Benthic Carbon Cycling Studies

(Draft)

Jim Barry

March, 2000

1. Introduction.

This document describes a potential use-scenario for MOOS technology development in support of studies focusing on the source, flux, and utilization of organic carbon by deep-sea benthic communities. The scenario, which requires greater development prior to submittal as a project proposal, focuses on differences in carbon cycling by benthic communities in areas near or distant from the influence of organic inputs from the Monterey Canyon system.

2. Monterey Canyon Impacts on Benthic Carbon Cycling – *Rates of carbon utilization and community development in relation to sources and rates of carbon input*.

We propose to compare carbon availability and its utilization by benthic communities at deep-sea sites influenced by organic inputs from the Monterey Canyon and those distant from the effects of the canyon, using a variety of in situ sensors, rate measurements, and laboratory analyses. We plan to measure the rates of carbon input from surface waters, organic material transported down-canyon during debris flows, and rates of carbon uptake under various conditions of organic inputs. Results of these studies will broaden our understanding of both the role of Monterey Canyon in the nutritional dynamics of deep-sea benthic communities and the strength of coupling between pelagic and benthic systems in the central coast.

Instrumentation and measurements will planned will include deployment of;

- Sediment traps to sample organic debris sinking from the euphotic zone
- Current meters for measurements of advective patterns and events.
- Benthic landers to measure organic input and utilization (in situ fluorometers, optical backscatter devices, benthic respiration sensors)
- Benthic camera systems to document organic flux events and megafaunal dynamics.
- ROV dives to deploy / recover sediment samples for various analyses (e.g. carbon content, pigments, lipids).

3. Background Information

In nearly all ocean settings deeper than 200 m, sinking organic material from overlying waters fuels the survival, growth, and reproduction of benthic fauna. Various studies throughout the world oceans have documented a relationship between the sinking flux of carbon and the rates of carbon utilization by the benthos. Deeper waters receive less organic carbon than shallower waters, leading to lower standing stocks of biota and lower rates of carbon uptake, compared to shallow waters.

Near continental margins the lateral and downslope transport of organic debris can add to organic inputs from overlying pelagic waters, thereby enhancing food availability for benthic consumers. Jahnke et al. (1987) showed that carbon utilization by benthic fauna near the continental margin is approximately 3 times higher than the sinking flux of carbon from overlying waters, suggesting that material transported laterally must be fueling benthic processes. Smith et al (1992) found that the temporal scale of flux measurements confuses such measures, but also indicated a significant contribution of downslope carbon.

Lateral inputs of organic carbon can arise from near bottom flows of accumulations of organic debris deriving from phytoplankton blooms in surface waters, from nearshore macrophytic debris (e.g. kelp), and from terrestrial inputs. Such materials (especially the latter two) can accumulate in submarine canyons and eventually be transported down-canyon by turbidity flows or other advective events leading to the dispersal of organic debris in the canyon and its outlet.

Although much speculation exists concerning the effects of submarine canyons on carbon transport and benthic carbon cycling, few estimates are available in the literature. Few reports also exist concerning the association, if any, of submarine canyons with enriched faunal communities or rates of carbon cycling. Okey (1997) documented shifts in shallow benthic communities associated with the seasonal flushing or organic debris from the mouth of Monterey Canyon, showing that turbidity flows resulted in disruption of the benthic community persisted in a state of recovery and recolonization between flushing events. Vetter and Dayton (1998) found higher species diversity and higher biomass of benthic fauna to depths of 700 m within submarine canyons off southern California, compared to similar depths on the continental slope.

Because of its size and position, Monterey Canyon may be a very useful model for the effects of submarine canyons on carbon cycling along continental margins. The flux of organic material through Monterey Canyon may be very high and account for a large fraction of the organic carbon budget as distant as the junction of Monterey Canyon and the abyssal plain. Though few estimates exist, Harrold et al. (1998) estimated that drift kelp contributes 20 to 83% of the total particulate organic carbon reaching the sea floor in Carmel Canyon. Although these ROV studies were performed in shallow water (<500 m), they suggest that material can be transported rapidly down-canyon. We have also observed kelp holdfasts at 3000 m in Monterey Canyon, suggesting the importance of down-canyon transport.

Measurements of carbon cycling by benthic communities influenced by Monterey Canyon as well as those near the continental margin, but unaffected by Monterey Canyon, will provide a baseline from which to assess the influence of laterally advected material on benthic carbon cycling in general, as well as broaden greatly our understanding of the role of submarine canyon processes in continental margin biological and biogeochemical processes.

Moreover, because marine benthic communities may account for a large fraction (30 to 40%) of metabolism in the ocean below 1000m, they play a potentially large role in determining rates of carbon sequestration in the ocean and therefore are linked to global climate. Smith's (1999) recent documentation of reductions in sinking flux of organic debris, coupled with constant benthic carbon demand, suggested that the balance between carbon input and carbon utilization in the deep sea in the eastern Pacific is unstable. MOOS studies of benthic carbon cycling present an opportunity to establish a second database monitoring coupling between pelagic and benthic systems along this coast during a period of rapid climatic warming.

4. Scientific Objectives

Several related scientific questions or hypotheses are addressed by these studies, including short and long term results.

a) Canyon-based transport of organic debris to deep-sea sites represent a significant (i.e. >50%) contribution to the total carbon budget of benthic communities in the outer reaches of the canyon axis.

The relative importance of canyon-based inputs must vary depending upon the distance from shore and the depth. While sinking organic debris degrades rapidly with depth, thereby reducing its value to benthic communities in deeper waters, down-canyon transport of organic debris may result in rapid transport with little deposition, leading to an increased importance at some depths..

b) Down-canyon transport of organic debris follows has seasonal peaks.

Winter storms and other events may both increase export of material from nearshore kelp beds and initiate down canyon flux events, leading to temporally varying deposition of organic debris to the deep canyon axis.

c) How do benthic communities in canyon-impacted and non-canyon sites respond to shifts in carbon availability owing to climate variability?

Environmental variability (e.g. ENSO, La Nina, Pacific Decadal Oscillation, Climate Warming), influence greatly the productivity of surface waters and sinking organic flux that sustains benthic faunal communities. Changes in flux related to these events have been measured in the deep-sea, but have not yet resulted in detectable shifts in community dynamics off this coast. Long term monitoring of community patterns and carbon cycling will allow evaluation of the strength of coupling between benthic and pelagic / canyon carbon production.

5. Approach to Benthic Carbon Cycling Studies

a) Sinking Particulate Carbon Flux

We plan to measure the rain of organic debris using sediment traps deployed on surface or Subsea moorings, used to measure flux at 50 m above the bottom and a minimum of 200 m above the bottom. Within 50 m of the bottom, resuspended material is usually collected in traps and does not estimate the magnitude of flux sinking from the surface. The shallower trap will be used to estimate euphotic zone carbon export.

b) Boundary layer conditions.

Optical instrumentation (in situ fluorometers [ISF] and optical backscatter sensors [OBS]) will be deployed on benthic landers or moorings to monitor suspended material near the bottom. Turbidity flows are expected to have high backscatter, but low fluorescence, while sinking events will have relatively high fluorescence. Current meters deployed near the sea bed will monitor local current speed and direction, and detect advective events.

c) Benthic Community Characterization

Community structure will be characterized using video transects and sediment core sampling by ROV. Activity patterns and visual changes in the character of the sea floor environment will be monitored using a benthic camera system, linked to shore or a local image storage device.

d) Benthic Respiration Measurements

Carbon cycling will be measured using benthic chambers with oxygen sensors to monitor oxygen consumption (respiration rates will be converted to carbon demand). Initially, these measurements can be made using ROV deployment and recovery of respiration systems. Development of a benthic ROVER will allow time series measurements of oxygen consumption and other parameters without the need for heavy ROV use.

e) Sediment Tracer Studies

Biomarkers used to discriminate macrophytic debris from phytoplankton-derived organic material will be collected by ROV, or perhaps by ROVER, and analyzed upon recover. Parameters may include pigment analyses, lipids, stable carbon isotopes, etc

6. Study Sites

Potential study sites for this project are shown in Figure 1. Although the Monterey Canyon sites are positioned presently near the outlet of Monterey Canyon to the abyssal plain, additional sites within Monterey Canyon would benefit this program. Similarly, at least 2 control sites would be optimal. Three sets of sites are marked on Figure 1, ranging from relatively shallow (1500 m, shown in green), 3000 m (light blue) and deep (3300 m, dark blue). Canyon sites have been chosen in areas with the broadest canyon base available for the depth selected. Control sites are located principally to the south of Monterey Canyon to the west of the Pt. Sur region where no submarine canyons bisect the continental slope.

7. Observing System Requirements

a) Sinking Particulate Carbon Flux

Sediment traps with rotating collection cups will be used to capture the sinking flux of material beneath the euphotic zone and within the benthic boundary layer. Each trap could be a 'free vehicle' or could be integrated with MOOS to allow for cup rotation at any time, by user intervention.

b) Boundary layer conditions.

Measurements include current speed and direction, particulate loads, fluorescence, to provide information on the conditions during and outside debris flows within the canyon and at control sites.

Instrumentation:

Current Meter – S4 current meter will suffice

Optical Backscatter / In situ fluorescence

We are planning to purchase several "hydroscat II" which have backscatter (OBS) and fluorescence, with internal data loggers. These instruments could be 'stand alone' or integrated with MOOS communications to allow for real or near-real time data capture.

c) Benthic Community Characterization

We plan to measure species abundance and distribution.

Instrumentation:

ROV Video Transects: analysis of benthic megafaunal patterns

ROV Sediment Cores: analysis of infauna organisms.

Digital Imaging System – Deployed on benthic lander, integrated with MOOS for real / near-real time image capture (e.g. 1/ day).

d) Benthic Respiration Measurements

Benthic chambers are used to measure sediment community oxygen consumption (SCOC), which can be converted to estimate carbon demand. *Instrumentation:*

Benthic Chambers: We are presently using chambers deployed by ROV, and are useful for a single measurement of SCOC.

Benthic ROVER: - MOOS technology development will include a benthic ROVER (similar to Smith et al.1997), a free-vehicle lander with limited mobility to crawl over the bottom after each SCOC measurement to allow sampling of undisturbed sea floor. ROVER instrumentation can initially include benthic chambers, current meters, and limited mobility, but can be expanded to include several other sensors / samplers (imaging system, oxygen / pH profilers, sediment samplers, etc.). The ROVER can be a free vehicle or integrated with MOOS communications and telemetry for greater programmability and event response.

e) Sediment Tracer Studies

We plan to use sediment tracers to discriminate between phytoplankton and nearshore-derived organic material. Sediment tracers will probably require collection of sediment samples by ROV or collection and preservation of samples by a ROVER.

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Appendix 5: MOOS Instrumentation

MOOS INSTRUMENT LIST

revision 1.0 2/8/00

Measured Property	Instrument	Principle Data Requester/tech resource	**Sampling** Sampling Period	Vertical sampling interval (meters)	Horizor sampli interv (meter
Surface (<3 meters)					
Physical					
Current velocity	ADCP		1 hr	10	
Temperature	CTD		1 hr	100	
Pressure	CTD		1 hr	100	
Turbulence					
Wave Properties			1 hr		
			1 sec		
Meteorological					
Wind velocity/direction	Sonic?, RM Young				
Air Temperature					
Humidity					
Barometric pressure					
Aerosol	Air filteration	Johnson			
Optical					
Irradiance (Air/water) (downwelling)	Spectral radiometer	Chavez	1 hr		
Radiance (Air/water) (upwelling)	Spectral radiometer	Chavez	1 hr		
Particle density (organ/inorgan)		Chavez	1 hr		
Backscatter	2 Wavelength backscatter and Fluoresence	Chavez	1 hr		
Absorption		Chavez	1 hr		
Chemical					
Conductivity	CTD		1 hr		
CO2 (air/water)	Delta PCO2	Gernot	1 hr		
CO2 (water-column)		MikeGrandpre			
Nitrate	ISUS or DigiScanner or OsmoAnalyzer	Johnson			
O2	Pulsed O2 electrode	Gernot			
Iron	DigiScanner	Johnson			
Iron	Iron OsmoAnalyzer	Johnson/Jannasch	15 min.		
Phosphate	DigiScanner	Johnson			
Silicate	DigiScanner	Johnson			
Total gas pressure	Membrane isolated pressure sensor	Gernot			
High precision PH meter	Injected ISUS	Johnson/Gernot			
Biological					
Chlorophyll	Fluorometer	Chavez			
Zooplankton species/density	Optical plankton counter	Chavez			
Zooplankton species/density	Multi-frequency acoustics	Chavez			
Zooplankton density	ADCP				
Phytoplankton density	Flow Cytometer	Chavez			

Phytoplankton species	Autosampler (Genosensor)	Scholin	
Bioluminescence		Robison/Widder	
Phytoplankton photo efficiency	Fast-rep-rate Fluorometer	Johnson	
Filtered samples	Autosampler (Genosensor)	Scholin	
Water samples	Water sampler (syringe)	Gernot	
Water samples	OsmoSampler	Jannasch	
Object tracking	Acoustic receiver	Robison	
C14 productivity	SID (Submersible Incubation Device)	Johnson	
	Upper Water Column (<500 meters)		
Critical profiling instruments			
Conductivity	CTD		
Temperature	CTD		
Pressure	CTD		
Irradiance (Air/water) (upwelling)	Spectral radiometer	Chavez	1 hr
Radiance (Air/water) (downwelling)	Spectral radiometer	Chavez	1 hr
Additional profiling instruments			
	Deep water Column (Sea Floor to 500 meters)		
Oxygen uptake	In-situ respirometer		
Particle flux	sediment traps or optical particle counter	Barry	
	Benthic		
Canyon Processes Instrumentation			
Current velocity vertical profile	ADCP	Paul/Ussler	
Sediment resuspension	BASS (Benthic Acoustic Stress Sensor)	Paul/Ussler	
Seeps & Seismicity Chemical Package			
Nitrate	In Situ Ultraviolet Spectrometer (ISUS)	Johnson	
Iron	Digiscanner	Johnson/Chapin	
Iron	Iron OsmoAnalyzer	Jannasch	
Sulfide		Johnson	
Sulfate		Stakes	
Bromide			
Organic carbon		Johnson	
Methane	Methane sensor	Paull/Gernot	
Heat flow	Temperature Probe	Paull/Peltzer	
Water samples	MBARI OsmoSampler	Jannasch	
Water samples	Auto Water Manifold	Stakes/Wheat	
Current velocity	Electro-magnetic current meter		
Conductivity	CTD		
Temperature	CTD		
Pressure	CTD		
Oxygen	Oxygen (needs CTD)		
Chlorophyll flux	Fluorometer (needs CTD)		
Optical attenuation	Transmissometer (need CTD)		
Fluid temperature	Thermister or thermo couple probes	Stakes	
Seeps & Seismicity Geology Package			
Seismic waves	Broad band seismo (<1Hz)	Stakes/Caress	
Seismic waves	Short Period seismo (1-100Hz)	Stakes/Caress	
Sea floor displacement	High accuracy pressure sensor	Stakes/McGill	
Sea floor displacement	Tilt meter	Stakes/Clague	

Carbon consumption	mobile respirometer	Chavez			
Bottom Pressure	Pressure sensor				
Biology					
biological activity/dynamics	time lapse imaging	Barry			
	Respirometer	Barry			
POC		Barry			
AUV Instrumentation					
Physical					
Current velocity	ADCP		1 hr	10	
Temperature	CTD		1 hr	100	1
Pressure	CTD		1 hr	100	1
Turbulence				<10	<1
Optical					
Irradiance (Air/water) (downwelling)	Spectral radiometer	Chavez	1 hr	100	1
Radiance (Air/water) (upwelling)	Spectral radiometer	Chavez	1 hr	100	1
Particle density (organ/inorgan)		Chavez	1 hr	100	1
Backscatter	2 Wavelength backscatter and Fluoresence	Chavez	1 hr	100	1
Absorption		Chavez	1 hr	100	1
Chemical					
Conductivity	CTD		1 hr	100	1
CO2 (water-column)		MikeGrandpre			
Nitrate	ISUS or DigiScanner or OsmoAnalyzer	Johnson			
O2	Pulsed O2 electrode	Gernot			
Iron	DigiScanner	Johnson			
Iron	Iron OsmoAnalyzer	Johnson/Jannasch	15 min.		
Biological					
Chlorophyll	Fluorometer	Chavez			
Zooplankton species/density	Optical plankton counter	Chavez			
Zooplankton species/density	Multi-frequency acoustics	Chavez			
Zooplankton density	ADCP				1
Phytoplankton density	Flow Cytometer	Chavez		100	1
Phytoplankton species	Autosampler (Genosensor)	Scholin		100	1
Micronekton species/density	Camera with image recognition	Robison		10	1
Bioluminescence		Robison/Widder		100	1
Phytoplankton photo efficiency	Fast-rep-rate Fluorometer	Johnson		100	1
Filtered samples	Autosampler (Genosensor)	Scholin			
Water samples	Water sampler (syringe)	Gernot			