Deep-Sea Research II 56 (2009) 1754–1762

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Deep-sea benthic boundary layer communities and food supply: A long-term monitoring strategy

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ARTICLE INFO

Available online 28 May 2009

Keywords:
Deep-sea communities
Benthic observatory
Time-series studies
Benthic community
Deep-sea instrumentation
Pelagic-benthic coupling

ABSTRACT

Long-term monitoring of deep-ocean processes is essential for understanding the potential impacts of climate variation on the deep sea. A suite of autonomous and cabled instrumentation has been developed to allow continuous measurements of food supply availability, species composition and abundance, and organism activity. A sedimentation sensor combines a traditional sediment trap configuration with a digital-imaging system and fluorometer to monitor food supply. A digital time-lapse camera system captures high-resolution images of the sea floor to monitor benthic fauna and sediment processes. A bottom-transiting vehicle conducts photographic transects across the sea floor and measures sediment community oxygen consumption at multiple sites. An upward-looking acoustic array measures backscatter targets, pelagic fauna, passing through an insonified field above the sea floor. Although these instruments can be deployed autonomously, cabled observatories can now provide continuous power and real-time communications for sustained monitoring of deep-sea benthic boundary layer communities.

1. Introduction

Impacts of global warming on ocean processes are obvious not only in surface waters but also at greater depths in the water column and on the deep-sea floor. Stratification increases as ocean surface temperatures warm, restricting the exchange of nutrients from deeper water to primary producers in surface waters. Limited nutrient concentrations result in shifting communities of primary producers from diatoms to smaller species, affecting the export of particulate organic carbon (food supply) to the deep sea (Huisman et al., 2006; Buesseler et al., 2007). These climate-related variations in food supply are correlated to changes in species composition and abundance of deep-sea benthic communities (Ruhl and Smith, 2004; Ruhl et al., 2008; Smith et al., submitted).

Biodiversity enhances ecosystem stability in the ocean but can be very susceptible to stresses related to climate change (e.g., Worm et al., 2006). The number of species in the deep sea is largely unknown, but estimates of unidentified species reach as high as 10,000,000 (Grassle and Maciolek, 1992). This vast gap in our knowledge on deep-sea biodiversity, combined with the unknown impacts of climate change and ocean acidification (Barry et al., 2005), makes this problem even more critical to resolve in a timely manner before species go extinct and their influences on deep-sea ecosystems go unrecorded.

Long time-series studies are essential to monitor the stability and health of deep-ocean communities, especially as climate change and anthropogenic impacts exert increasingly more influence on the deep ocean. Monitoring of upper-ocean processes associated with the production and cycling of organic matter is currently being conducted using technologies such as remote sensing by satellites (Behrenfeld et al., 2005), moored instruments with continuous sampling, and intense but discontinuous sampling from surface ships (e.g., Karl and Michaels, 1996; Siegel et al., 2001). However, technological and logistical constraints have limited similar long-term studies in the deep-water column and sediments from shelf to abyssal depths (e.g., Biscaye and Anderson, 1994; Smith et al., 1994, 2001; Sayles et al., 1994; Karl et al., 2003). With the advent of miniaturization of computers with low power requirements combined with digital photography and increased data storage, long-term monitoring of deep-sea communities has become a reality. Further developments with acoustic links to the ocean surface and cabled networks to shore now permit the ability to collect and analyze data and to alter sampling frequencies in real time. Here we describe new instrumentation and installations that will allow monitoring of benthic boundary layer communities with the spatial and temporal resolution necessary to evaluate changes resulting from global warming and other anthropogenic perturbations.

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doi:10.1016/j.dsr2.2009.05.020

2. Instrumentation design and development

2.1. Measuring food supply (water column)

Sediment traps have been an effective means of measuring food supply in water columns; however these instruments require servicing with a ship to collect the captured samples. Since sediment traps have a fixed number of collection cups, extending the length of the deployment results in lower temporal resolution. On the other hand, the investment of resources to conduct ship-based servicing of sediment traps can be significant. We have developed a modified sediment trap for deployment on cabled observatories, referred to as a sedimentation sensor, which uses remote sensing and imaging to measure food supply without requiring routine servicing (Fig. 1).

The sedimentation sensor consists of a vertically mounted collection funnel, with a 0.5-m^2 mouth opening (Figs. 1A and B). The tapered base of the collection funnel is secured to an upper, stationary, delrin disk that supports a fluorometer and camera above an offset, rotating, collection disk below with a geared circumference. A drive motor rotates the collection disk and is attached to the underside of the stationary disk. The rotating collection mechanism is a modification of a proven design used worldwide on long-term, sequencing sediment traps (Honjo and Doherty, 1988). The rotating collection disk has a polished glass plate forming the bottom of a cylindrical opening at the periphery of the lower disk (Fig. 1C) to retain the sample during examination. Another cylindrical opening in the collection disk without a glass plate is placed on the same radius to follow in each alignment position. As the rotating disk is driven counterclockwise, the glass sample plate becomes aligned with four different positions (stations).

In the collection position, *station* 1, the sample plate is aligned with the base of the collection funnel and sinking particles settle on the glass surface. The sampling frequency is programmable at desired intervals to minimize the occurrence of overlapping particles and optimize individual particle examination on the glass plate. After the collection/sampling period, the collection disk with glass sample plate is rotated to the next station, *station* 2, aligning with an optical window in the upper stationary disk through which a fluorometer measures the fluorescence of the particles on the sample plate. The fluorometer excites the phytopigments on the collection plate at wavelengths characteristic of chlorophyll (chl-*a*, 470 nm) and phycoerythrin (PE, 540 nm), as indicators of fresh phytodetritus (Hewes et al., 1998; Kolber et al., 1998; Rottgers, 2007).

The collection disk then rotates to the next position, *station* 3, where a downward-looking digital camera photographs the collected particles using backlighting through the bottom of the glass plate, which is etched with a scale marker. At this same time, the fluorometer aligns with fluorescent solid standards embedded in the rotating disk to provide calibration of the previous measurement. The collection disk then rotates to the last position for cleaning, *station* 4, where a cam engages a lever arm on the hinged sample plate, releasing the collected particles as the plate falls to a vertical attitude (Fig. 1C). As the rotation continues back to the collection position, *station* 1, this sample plate passes by a stationary brush that cleans the glass surface before it springs back to a horizontal position beneath the collection funnel to continue the sampling and examination process. The elapsed time from the collection station, through the examination stations, and back to the collection station is less than 2 min.

The sedimentation sensor is combined with a time-lapse camera system and mounted onto a titanium tetrapod framework (Fig. 1A). The square frame base is 2 m on a side and 2.3 m high. The cameras are mounted on the apex of the framework with the lens 1.85 m off the sea floor. The camera system consists of two cameras both imaging separate 20 m^2 areas of the sea floor and eight strobes. This camera and strobe setup is identical in function to the time-lapse camera described in Section 2.2.1 except that there are two cameras (pointed in opposite directions) and four strobes per camera for redundancy. All components are mounted on the frame, along with a current meter and pressure housings for electronics and batteries. This system will be deployed on a cabled observatory providing real-time data transfer of images back to shore for analysis. Alternatively, this system can be deployed autonomously, with the image data stored on local memory and power provided by a battery pack.

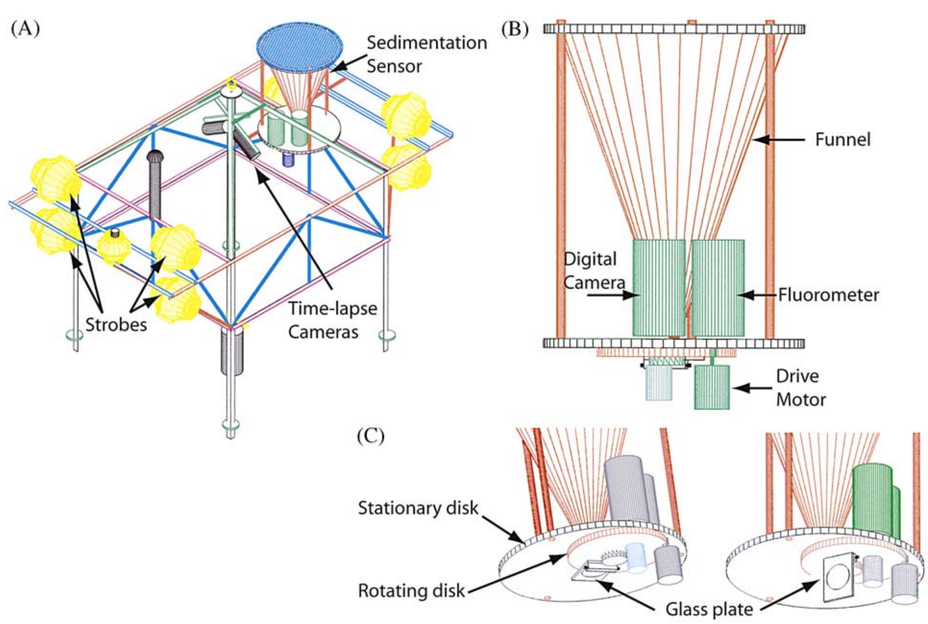

Fig. 1. (A) The sea floor monitoring system includes a sedimentation sensor mounted on a titanium frame, and two digital time-lapse cameras. (B) A digital camera and fluorometer are used to image sediment collected by the sediment trap and measure its fluorescence. (C) The sediment is collected on a glass plate and moved between different measurement stations on a rotating disk.

2.2. Measuring food supply (sea floor)

2.2.1. Time-lapse camera

A time-lapse camera system was developed as part of a long-term monitoring study at Station M (Smith et al., 1993). This is a battery-powered autonomous imaging system programmed to capture images at pre-determined intervals. During routine deployments the system captures a 20-m^2 image of the sea floor every hour over periods of 3–4 months between servicing. This time-lapse system with film camera has been deployed for 18 years at Station M. The growing requirement for longer deployments and increased data storage capacity prompted a transition from film to digital imaging. The time-lapse camera system was modified to include both the existing film camera and a new high-resolution digital SLR camera (Canon EOS 5D; 12.8 Mpixel). The digital camera is mounted on top of the film camera (Fig. 2A) such that each camera images approximately the same area of sediment. Comparison of the dual-camera time-lapse system shows that the quality of the digital camera images (Figs. 2B and C) is comparable to that of film images (Fig. 2D) with sufficient resolution of sediment processes and biota on the sea floor.

The sea floor is illuminated by two 200-W s strobes. Each strobe consists of a commercially available flash tube and custom charging circuitry mounted in a 33-cm diameter glass sphere (Benthos). The controller for the system and the batteries are in a separate titanium pressure housing. A 2.0 kW-h battery pack (alkaline D-cells) provides sufficient energy to capture images at a rate of one per hour over 3 months. The system is controlled by a microprocessor (Tattletale 3, Onset) and custom electronics that switch power and trigger both the cameras and the strobes simultaneously.

The cameras are mounted on a titanium angle framework (Fig. 2A). The film and digital camera lenses are mounted 2.1 and 2.3 m off the sea floor, respectively. The two strobes are positioned approximately 4 m apart on either side of the camera.

Sample images were taken with the digital camera in June (Fig. 2B), and July (Fig. 2C) during a 3-month deployment at Station M (4100 m depth) in 2007. The most notable difference between the images is a detrital aggregate settlement event in July illustrating the seasonally fluctuating food supply to the benthic community.

2.2.2. Bottom-transecting vehicle

The Benthic Rover is a bottom-transiting vehicle capable of long-term monitoring of the benthic community (Fig. 3). This instrument platform is 2.6 m long, 1.7 m wide, and 1.5 m high. Benthic Rover is designed for deployments to 6000 m depth, and has been routinely deployed to 4000 m. The vehicle propulsion system is comprised of two 46-cm-wide lugged tracks (Fig. 3) driven by two brushless motors (Model EC 60, Maxon Precision Motors) mounted in pressure-compensated oil-filled housings. Vehicle buoyancy consists of 13 blocks of syntactic foam, as well as six bored prolate spheroid syntactic floats. A cylindrical steel ballast weight (113 kg) is suspended between the tracks. One end of a sling bearing the weight of the ballast is attached to a lever, held in place by a second lever, which in turn is held captive by a burnwire loop. An acoustic command from the surface initiates the release of the drop weight by applying an electrical current to a burnwire that corrodes, thus releasing the sling holding the weight.

On deployment the Benthic Rover with ballast weighs 1136 kg in air and 68 kg in water. On release of the ballast, the instrument has a positive buoyancy of 45 kg. A two-dimensional acoustic current meter (2DACM, Falmouth Scientific Inc.) is mounted on the top of the Rover (Fig. 3A). In the front of the vehicle are two vertically mounted instrument racks located port and starboard. A respirometer chamber is mounted on each rack and moves up

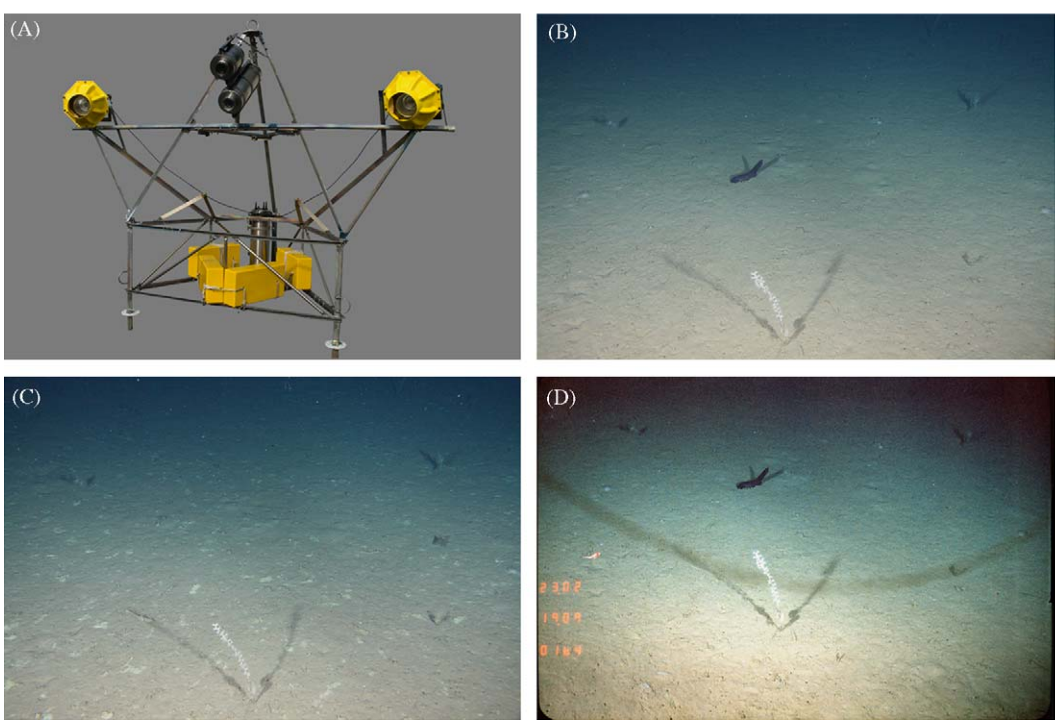

Fig. 2. (A) The time-lapse camera consists of the digital camera housing (top) mounted above the film camera housing, with two strobes on horizontal struts providing illumination. (B) An image captured by the deep-sea camera tripod on 9 June 2007 at Station M, at a depth of ~4000 m. A deep-sea holothurian (*Psychropotes longicauda*) is visible in the center of the frame. (C) In an image collected on 8 July 2007, the same patch of sea floor is now covered by phytodetritus after a large aggregate settlement event. (D) An image from the film camera, taken on 9 June 2007 (the same time as the digital image in panel b), illustrates that the resolution is comparable between the two cameras.

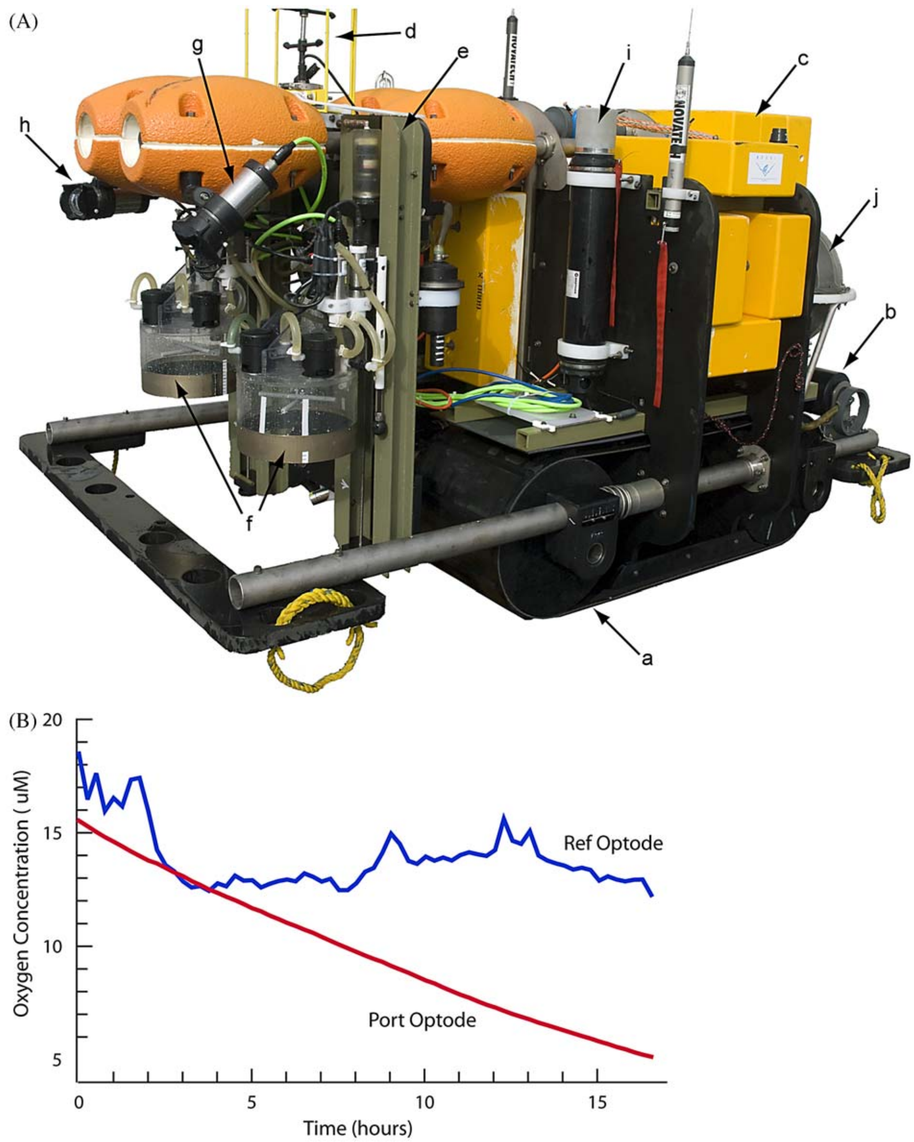

Fig. 3. (A) A side view of the Benthic Rover shows: (a) the treads that are part of the propulsion system, (b) one of the two propulsion motors housed in oil, (c) syntactic foam used for floatation, (d) the current meter used to ensure the Rover is driving up current, (e) the instrument rack, which lowers and inserts the respriometer chambers, (f) the respirometer chambers, which measure sediment community oxygen consumption, (g) the high-resolution digital camera aimed at the sea floor, (h) a 200-W-s strobe to illuminate the still images, (i) the acoustic modem that can release a drop weight, and (j) one of two titanium pressure housings used to carry batteries and electronics. (B) A plot of oxygen concentrations recorded from the reference optode (blue) and the port chamber optode (red) during a standard incubation. These data were collected in the Monterey Bay, at a depth of 900 m, during an experiment lasting ~17 h. During this time, the ambient concentration of oxygen fluctuated with tidal currents. The oxygen concentration in the respirometer chamber steadily decreased as a measure of sediment community oxygen consumption (SCOC).

and down on a carriage driven by a lead screw geared to a brushless DC motor. The acrylic cylindrical respirometer chambers are 30 cm in diameter and 20 cm high with a Teflon-coated titanium knife edge attached to the open bottom rim. In the center of each chamber is a stirrer driven by a magnetically coupled brushless motor. The stirrer runs continuously during incubations to circulate the chamber water. The oxygen concentration in each chamber is measured by an optode (Model 3830, Aanderaa Data Instruments). In addition to one optode in each chamber, there is a third optode, mounted externally, providing a reference measurement in ambient seawater (Fig. 3B). Each respirometer has three pump-actuated valves (Model 5T, Sea-Bird Electronics, Inc.) that open when the chamber is inserted into the sediment to prevent a bow wave, and then close to seal the chamber during incubations. Two video cameras (Nova model, Insite Pacific Inc.) are directed at the sediment surface where the port and starboard chambers are inserted. A high-resolution digital survey camera (5 Mpixel color CCD; Model GC2450, Prosilica Inc.) is mounted on the front port side of the vehicle and captures still images of the sea floor as the vehicle is transiting between sites. A 200 W s strobe (Model YS-250Pro, Sea&Sea in custom titanium housing) mounted on the starboard side of the vehicle provides sea-floor illumination during transits. When the vehicle is deployed autonomously the only means of communication from the surface ship is by acoustic modem (Model ATM-887, Teledyne Benthos). The modem sends status messages on Rover performance to the surface ship and also serves as the communication link to release the ballast weight. Batteries to power the Rover and control electronics are housed in two 43-cm diameter, spherical titanium pressure housings, one located forward and one located aft on the vehicle (Fig. 3).

This tracked vehicle, extensively modified from the original prototype (Smith et al., 1997), is equipped with instrumentation to collect sediment data and analyze bottom water at pre-programmed intervals across the sea floor. After free-fall deployment from a surface ship, a typical mission starts with the Benthic Rover transiting approximately 10 m from the drop zone into the prevailing current to a fresh study site. On arrival, there is a pause in operations to allow ambient environmental conditions to stabilize. After this period, the sediment directly in front of the Rover is photographed after which respirometer chambers are lowered into the sediment. Video cameras capture still frames before and after insertion of the respirometer chambers. These images provide a measure of the chamber insertion depth and also record enclosed sediment structures and fauna.

The abundance and size of detrital aggregates on the sea floor, evidence of food supply, are measured from survey camera images taken every meter during each transit between sites, providing an overlapping mosaic (Fig. 4). The resolution of each image is sufficient to identify aggregates on the sea floor as well as the abundant megafauna.

In addition to the transit images, a fluorescence imaging system will be incorporated into the Rover to provide estimates of detrital quality on the sea floor. The fluorometry system consists of a high-sensitivity 1.4-Mpixel monochrome CCD camera (Prosilica, GC1380) and a blue LED light that will mount on the front of the Rover. To capture chlorophyll fluorescence the LED excitation wavelength was selected to be 470 nm. A 665-nm long-pass filter is mounted on the camera. The resulting images will provide a map of the fluorescent material at each measurement site.

2.3. Measuring abundance and species composition (water column)

One of the least studied areas of deep sea is the bathypelagic zone overlying the benthic community. Baited traps have been used effectively to observe and collect the necrophagous species in these deep-sea areas (e.g., Isaacs, 1969; Hessler et al., 1978; Smith et al., 1979; Lampitt et al., 1983; Smith and Baldwin, 1984). Using a wide variety of techniques, including a moored acoustic array, baited traps, and a multiple opening–closing trawl, revealed a large number of undescribed pelagic species of crustaceans, polychaetes, and fishes, which were numerically and gravimetrically dominant (Smith et al., 1992).

2.3.1. Acoustic array

The first moored acoustic array developed to detect deep pelagic animals was a split-beam line array with an omni-directional horizontal disk-shaped beam pattern that was narrow in the vertical axis to monitor the movements of animals across specific depth boundaries (Smith et al., 1989). A more applicable configuration for examining the benthic boundary layer is an upward-looking acoustic array that can insonify a cone of water transcending the bottom 200 m of the water column. Acoustic Doppler current meters have been used to monitor movements of zooplankton (e.g., Liljebladh and Thomasson, 2001) but have limited capabilities in resolving depth intervals (range bins) finer than 8 m. This coarse resolution combines all backscatter targets from each range bin as they originated from a single target. To gain finer resolution, we developed an upward-looking acoustic array with 10 cm-range bins, providing much higher probability of single-target recognition up to 200 m above bottom (Glatts et al., 2003). This split-beam array worked at a frequency of 150 kHz and was capable of resolving targets of >1 cm. Transmission with all four quadrants produced a 5° cone pattern and the receive mode was amplified and stored separately, providing the split-beam configuration.

The upward-looking acoustic array has now been upgraded on a long-term titanium framework that rests on the sea floor with the unobscured, upward-looking transducer (Fig. 5). The

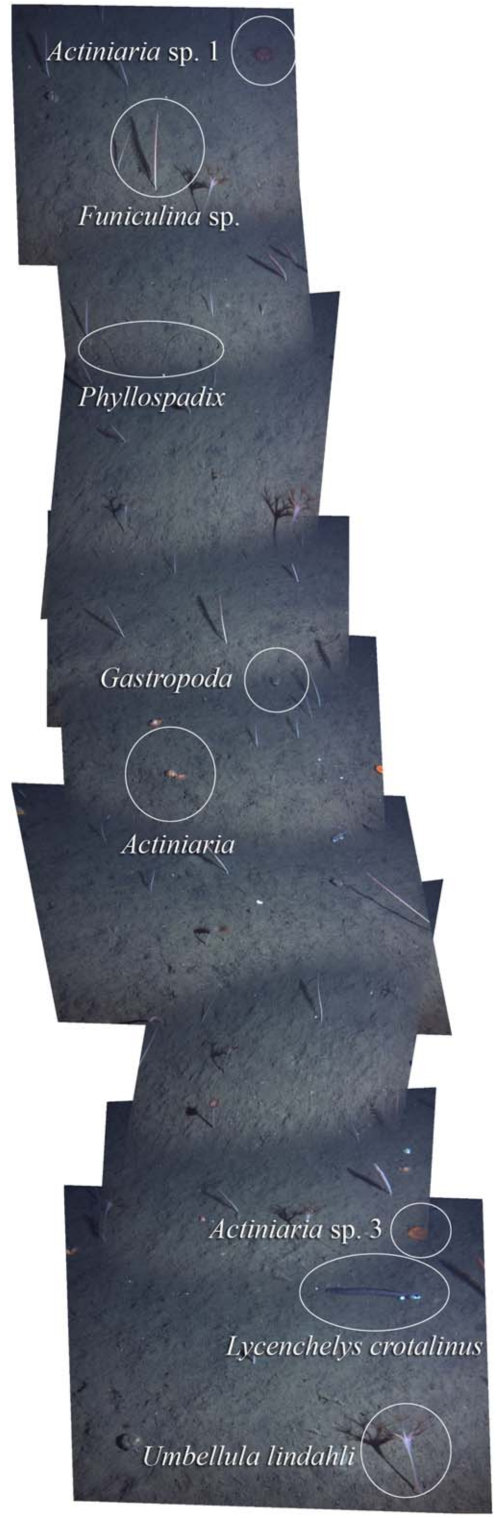

Fig. 4. An overlapping mosaic of nine images captured during a Benthic Rover transit in the northeast Pacific at ~1000 m depth. Several common taxa in this area are identified. The mosaic was created using the software PhotoMosaic 1.1 (H. Singh, WHOI).

controller, amplifiers, and digital data storage are housed in a titanium pressure cylinder mounted on the frame along with a separate housing with lithium batteries to operate the system autonomously for periods up to 1 year. This instrument is also designed for deployment on a cabled network that provides power and real-time data acquisition to shore with the ability to

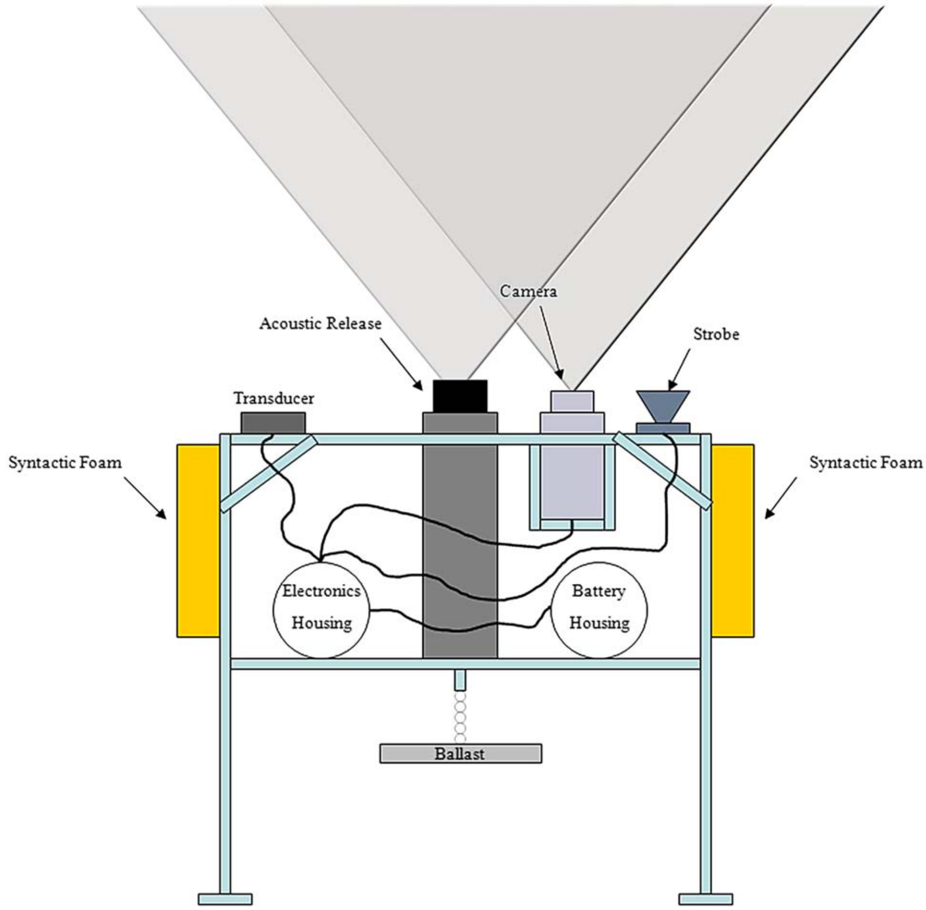

Fig. 5. Upward-looking acoustic array for monitoring backscatter targets in the insonified cone of water reaching from the instrument transducer to 200 m above bottom. The slaved camera can optically image backscatter targets <10 m from the array. The acoustic array can be configured as an autonomous or cabled network instrument.

change sampling frequencies with changing sea-floor conditions (Fig. 6).

2.3.2. Slaved camera

One important problem with acoustic detection of animals is providing reliable ground truth for the detected targets. To address this issue, we have developed a digital camera slaved to the acoustic array. This camera (Canon EOS 5D; 12.8 Mpixel) is mounted with a pan and tilt mechanism to photograph detected targets within a 10-m radius of the insonified cone of the array. When an acoustic target is recorded in the near field (<10 m from the transducer) the camera is positioned to the desired quadrant and strobe (200 W s) and camera activated. The digital images are stored on a 20-gb memory card for autonomous deployments and real-time transmission when attached to a cabled network.

Conventional ground truthing of the acoustic array is also conducted with large trawls and free-vehicle baited trap arrays (Smith et al., 1992; Stein, 1985) to minimize the biases of all these methods to assess the species composition and abundance of this important transitional zone between the midwater and the sediment–water interface.

2.3.3. Autonomous underwater vehicle (AUV)

AUVs have been developed to optically and acoustically image the sea floor (Singh et al., 2004; Bellingham and Rajan, 2007). However these systems can also be configured to image the water column immediately above the sea floor. For example, the acoustic-imaging system used to map the sea floor (Kirkwood, 2007) can be programmed to record the backscatter data between the AUV and the sea floor. These backscatter data can then be analyzed for individual acoustic targets collected in range bins narrow enough to distinguish single pelagic individuals. Similarly, a down-looking camera system (e.g., Singh et al., 2004) can image pelagic species just above the bottom. The AUV can be programmed to conduct long transects, thus avoiding one of the principal biases of moored systems, attraction of mobile fauna. An *in situ* docking station on a cabled network can provide the AUV with battery recharge and data download so that long-term deployments can be achieved (Fig. 6; Bellingham and Rajan, 2007).

2.4. Measuring abundance and species composition (benthic community)

Camera systems have been used for decades to record the species composition and abundance of epibenthic megafauna, those organisms large enough to be recognized in photographs (typically >1 cm; Grassle et al., 1975; Smith et al., 1993). Megafauna are primary and upper trophic level consumers that impact the fate of POM at the sea floor directly or indirectly through their feeding activities (consumption and caching) and mixing (bioturbation) of the sediment. Epibenthic megafauna are often surveyed and monitored to evaluate the response and recovery of the benthic community to disturbance (e.g., Jones et al., 2006). In the abyssal NE Pacific, mobile megafauna have undergone changes in community structure over similar long time

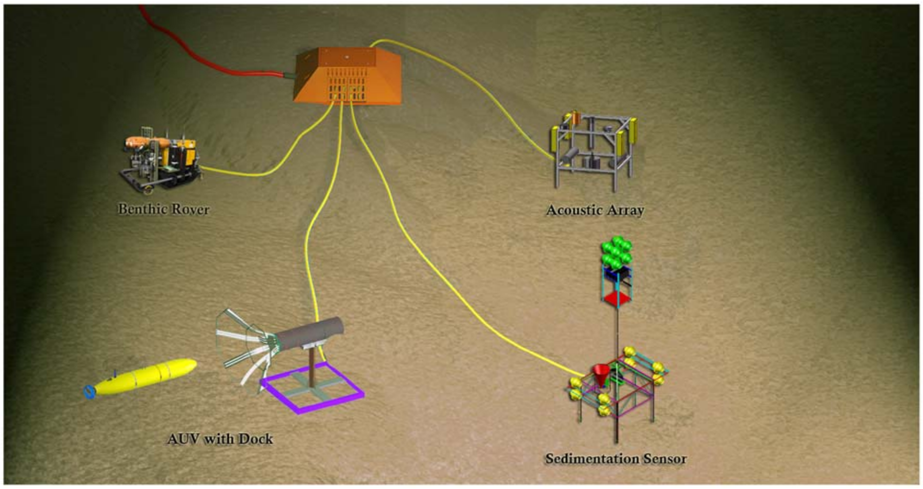

Fig. 6. Illustration of a sea-floor cabled observatory. A cabled node (in orange) provides power and communications to the acoustic array, sedimentation sensor, benthic imaging AUV, and the Benthic Rover.

scales to shifts in the macrofauna community (Ruhl and Smith, 2004; Ruhl et al., 2008). Two strategies exist for optically monitoring the megafauna present on soft bottom substrates in the deep ocean: fixed-point and transect measurements.

2.4.1. Optical fixed-point measurements

Fixed-point measurements have been conducted with time-lapse cameras deployed at a single location on the sea floor (e.g., Isaacs, 1969; Paul et al., 1978; Smith et al., 1993). Such monitoring is very effective at observing both the megafauna species composition and abundance along with the movements of the mobile species. In deep-sea environments, where the abundances of megafauna are reduced compared to shallower areas, a camera system is needed to image a wide area of the sea floor. A time-lapse system with an obliquely mounted camera and side-mounted strobes was developed for imaging 20 m^2 of the abyssal sea floor (Smith et al., 1993).

We have modified this time-lapse camera system to include a digital camera with the capability of programming the time interval of photographs as an autonomous system with battery power sufficient for a 1-year deployment. The capability also exists for this camera system to be tethered to a cable network for real-time data acquisition and programming changes for long-term deployments of years (see Section 2.2.1).

2.4.2. Optical transect measurements

Transect measurements have been conducted using towed camera systems from a ship (e.g., Hersey, 1967; Wigley, 1975; Wakefield and Smithey, 1989; Hecker, 1990). Although this transect method is effective, it is costly regarding the shiptime necessary to conduct such surveys with appropriate temporal resolution. To provide long time-series monitoring of the epibenthic megafauna populations with minimal logistical cost, we have developed a bottom-transiting vehicle (Rover, Fig. 3) that can conduct photo-transects across the sea floor either as an autonomous battery-powered instrument or tethered to a cable network with real-time data acquisition ashore (Fig. 6). The obliquely mounted digital survey camera and strobe on the instrument rack can be activated on every interval >30 s as the Rover transits across the sea floor at a programmed speed. This method can provide overlapping images (Fig. 4) for perspective grid analysis of spatial distribution, abundance, and size (Wakefield and Genin, 1987).

Camera systems on an AUV can also be used very effectively to conduct photo-transects across the sea floor (Singh et al., 2004). AUVs provide the advantage of not disturbing the sea floor while making repeated transits across the same transect to provide valuable insights into temporal changes within the same spatial context. The docking capability to a cabled network, mentioned above, allows long time-series measurements similar to the Rover but without the constraints of a tether.

2.5. Measuring benthic community activity

Measuring benthic community activity over long time series has proven invaluable to evaluate changes in benthic community structure at Station M (Smith and Kaufmann, 1999; Ruhl et al., 2008). The time-lapse camera system has been effective in photographically recording movements of the epibenthic megafauna as an indicator of benthic activity (Smith et al., 1993, 1994). The original Rover proved invaluable in making long time-series measurements of sediment community oxygen consumption (SCOC; Smith et al., 1997), an estimate of the organic carbon utilization rate by the benthic community. These two different measures of activity provide insight into the functioning of the benthic community.

2.5.1. Time-lapse photography

Mobile species of megafauna move across the sea floor and their speed of movement combined with the area traversed have been effectively used to generate an activity index (Smith et al., 1994). Long time-series deployment of the time-lapse camera has shown strong seasonal, and interannual variation in activity that is correlated with changes in climate indices and food supply (Vardaro et al., in press). These previous measurements were based on 4-month deployments of the camera system that was limited by the roll of film and the battery. Now the new time-lapse camera system is capable of being deployed autonomously for periods up to 6 months with sufficient memory for the digital camera to take a picture every hour (see Section 2.4.1).

2.5.2. Sediment community oxygen consumption (SCOC)

The demand for food by the benthic community can be estimated from the consumption of oxygen in chambers enclosing the sediment and overlying water. The Benthic Rover (Fig. 3 and Section 2.2.2) now has the capability of making long time-series measurements of SCOC with programmable temporal and spatial constraints using real-time communication and data recovery over a cabled network. This important index of activity has been correlated with food supply and climatic indices (Smith and Kaufmann, 1999; Ruhl et al., 2008).

3. Installation

3.1. Autonomous instrumentation

When planning for autonomous instrument deployments, one must consider how to provide ample power for the duration of the deployment, provide non-volatile storage for the data collected, and determine how to equip the instrument with enough intelligence to carry out the required mission.

In the case of the instruments described in Sections 2.1 and 2.2, all can be deployed autonomously, with power provided by alkaline battery packs. In these deployments, the length of the mission is usually limited by the energy available. Other chemistries provide higher energy density, such as lithium batteries, however, at increased cost. Additionally, since batteries require a large volume, increasing the quantity can necessitate additional pressure housings, incurring increased payload. Often energy-saving strategies, such as putting the main processor to sleep between measurements, can result in longer deployments.

As non-volatile storage now exists with larger quantities of memory available in smaller and cheaper packages, recording data and images to disk during autonomous deployments is not a significant challenge. However, developing software with the intelligence to identify fault conditions and recover from errors remains one of the biggest challenges of autonomous instrument deployments.

3.2. Cabled networks

The installation of cabled networks on the sea floor provides new opportunities for long-term monitoring of the deep ocean. Sea-floor observatories such as the ALOHA Cabled Observatory (Duennebier et al., 2008) off the north coast of Oahu, Hawaii, and the Monterey Accelerated Research System (MARS; Etchemendy and Massion, 2008), off the California coast, provide power and Ethernet communications between instruments and a shore-side network. The availability of continuous power on the sea floor enables instruments, whose deployment lengths were previously limited by on-board battery capacity and data storage, to be deployed for indefinite periods of time. Furthermore, the data output can be reviewed on shore in near-real time and can be used to modify the current mission. For instance, if there is an event of interest, sampling rates can be increased or modified accordingly. The ability to communicate with the instruments also relaxes some requirements for on-board software fault tolerance and error detection. The operator can analyze fault conditions and make appropriate decisions. However, there will always be problems not solvable with software modifications, but this risk is not unique to cabled deployments. In general, an instrument needs to be equipped with a modest amount of electronics to interface with the power levels and communication protocols of the observatory. Perhaps a greater challenge is to develop shore-side software to take full advantage of the communication link to the sea floor. Software is needed to upload and manage incoming data and interface with the instrument's controller. Analyzing such large amounts of data provided by the optical and acoustic-imaging systems is a significant hurdle requiring sophisticated image recognition and processing (Jain, 1989; Singh et al., 2004; Radke et al., 2005).

Several of the instruments described in this paper are scheduled for deployment on MARS cabled observatory within the next year (Fig. 6). For example, the Benthic Rover (Fig. 3) will be deployed on MARS and attached to the node through a small-diameter cable, 300 m in length, which is dispensed from a conical mandrel. As the Rover transits from site to site the cable will unwind from the aft end of the vehicle. The sedimentation sensor and time-lapse camera system (Fig. 1A) will be deployed on the MARS node after the Rover. The eventual long-term monitoring strategy will include data collected from a cabled acoustic array as well as images collected from AUV surveys (Fig. 6).

4. Future directions

Long-term monitoring of changes in the structure and activity of deep-sea benthic boundary layer communities is now feasible with new biological sensing systems connected to cabled networks either presently active or planned for installation at a variety of locations worldwide (e.g., Service, 2007). Such long-term monitoring is critical for assessing changes in species composition and abundance of deep-sea benthic fauna related to global warming. Such changes have already been observed at two sites in the northeast Pacific and the northeast Atlantic (Ruhl and Smith, 2004; Ruhl et al., 2008; Smith et al., submitted). We envision benthic cabled observatories, similar to those described above (Fig. 6), being established in critical regions of the world ocean to monitor on-going changes in faunal diversity with temporal resolution coincident with surface ocean conditions.

Acknowledgements

We thank our colleagues F. Uhlman, M. Kirk, and R. Glatts from Scripps Institution of Oceanography, and P. McGill, B. Hobson, J. Ellena, and M. Vardaro from MBARI, who contributed much to the development of the instrumentation described above. We also appreciate the help of Lonny Lundsten, Todd Walsh, and Linda Kuhnz for their efforts on the figures included in this manuscript. This research was funded by NSF Grants OCE0242472 and OCE0638505 and by the David and Lucile Packard Foundation.

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