Multidisciplinary Observatory Development in Monterey Bay

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Abstract. The Monterey Bay Aquarium Research Institute has several ongoing, parallel development efforts that have a common goal of providing long-term multi-sensor measurements of ground motion and fluid flow on the seafloor. Instrument packages are being designed to operate in a low-power, autonomous mode, but a planned logger/controller will provide Ethernet connection to available cables to either a shore-based laboratory or a telemetered mooring. We describe here instrument deployments that have taken place in the last four years (corehole and broadband seismometers and chemical sensors) as well as plans for the immediate future.

Corehole seismometers

Seismometer development was initiated at MBARI in 1996 with the development of a short-period corehole seismometer, designed and fabricated by the JPL Microdevice laboratory (Stakes et al., 1998). This sensor package uses three standard 4.5-Hz geophones with an extended flat response to about 0.8 Hz. The sensor package is placed into 2.5 inch diameter boreholes drilled into basement outcrops to provide superior coupling and greatly reduced noise. A new low-power datalogger, the GeoSense LP1, developed in 1997, can provide more than 24 GB of storage using less than 0.3 watt of power, easily supporting a 12-month deployment.

During 1998, as part of the MBARI Margin Seismology Project, an offshore network of five ROV-installed instruments was continuously deployed for 8 months. The corehole sensors were placed into holes in granite outcrops drilled by the ROV diamond coring system. On sediment-covered seafloor, the instruments were deployed within low-profile cement "portable" boreholes. The data from these extended deployments have constrained the distribution of seismicity on the off-shore segments of the San Gregorio fault (Fig. 1), identifying the northern San Gregorio as a zone of anomalous high seismicity (Begnaud and Stakes, 2000) with dominantly thrust focal mechanisms. An improved local crustal velocity model permitted the relocation of all moderate events dating back to 1926 (Begnaud et al., 2000). Based on these results, the southern San Gregorio is apparently aseismic.

Because of their improved mechanical coupling, the MBARI/JPL seismometers collect data in which the S-wave arrivals are resolvable for both large and small events. The capability to resolve the horizontal shear waves as well as the vertical compressional waves is critical to constraining the depth of the events, especially for offshore events that typically have large azimuthal gaps in coverage. Accurate direct measurement of the sensor orientation by the ROV combined with the well-displayed shear wave data permitted consistent rotation of the horizontal channels into radial and transverse components. This allowed for more accurate shear wave arrival picks, added phases for event relocations, and leads to more detailed waveform analyses (Stakes et al, 2001) (Fig. 2).

During 2001-2, three of these corehole instruments will be deployed to both supplement data from the land-based array and to provide developmental sites for a planned logger development (the LP2). The deployment sites include 1) the original MOISE site on the center of the sediment-covered Smooth Ridge; 2) the site MDUO where two boreholes are available in extensive outcrop of Salinian granitic basement; and 3) a new site southwest of Point Lobos and Carmel Bay (Fig. 1). The additional data from these instruments will be useful to characterize any microseismic activity from the southern segment of the San Gregorio Fault Zone just offshore of the Big

Sur coast. We also hope to be able to refine the locations and seismic activity of poorly constrained segments of the Monterey Bay Fault zone just offshore of MBARI.

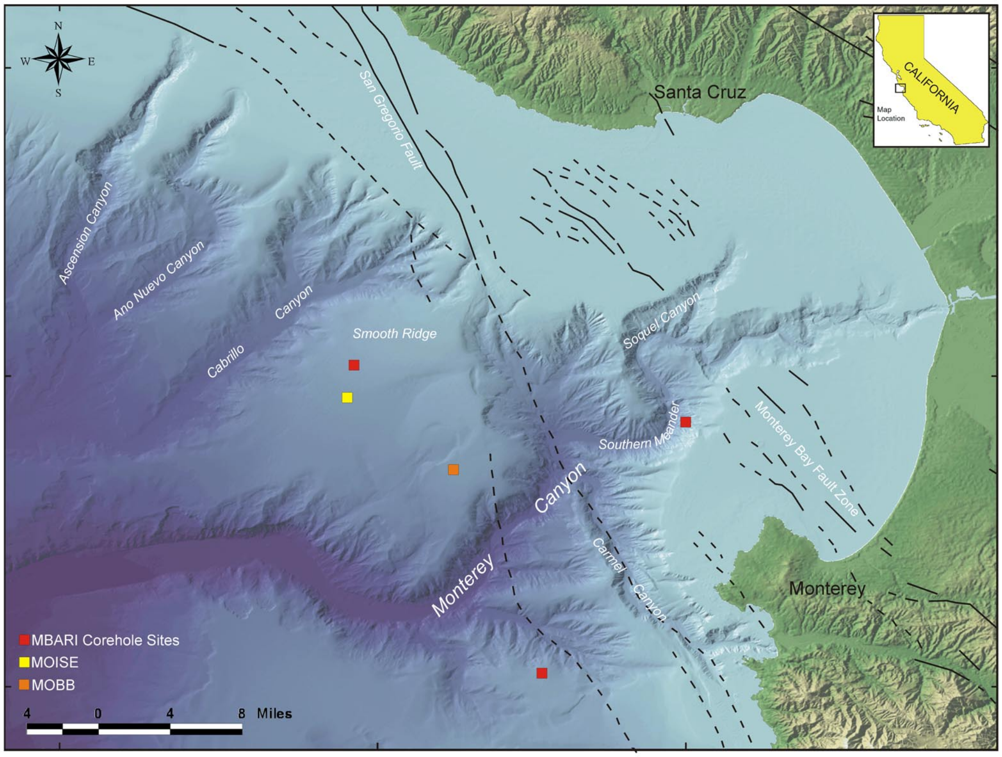

Figure 1. Monterey Bay offshore of central California provides a unique site for testing long-term instrumentation. Short-period corehole seismometers will be deployed during 2001 at three permanent sites. A new broadband observatory will be established on Smooth Ridge, designated as the MOBB site. Chemical sensors and samplers have been deployed in the upper water column of Monterey Bay to characterize seasonal upwelling events.

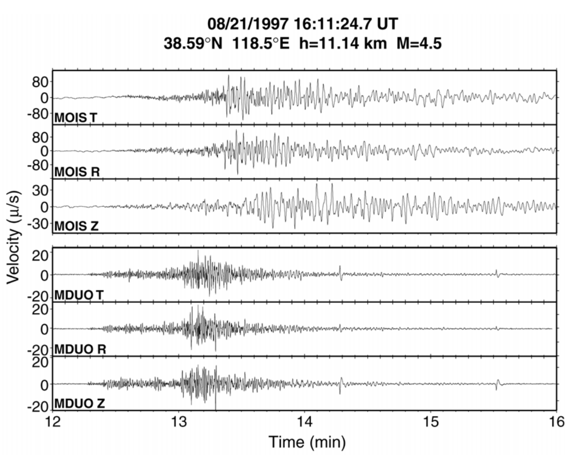

Figure 2. Example rotated waveforms for a regional teleseismic event from the short-period sensor (MDUO) and the broadband seismometer in Monterey Bay. The MDUO corehole instrument is deployed in granitic basement rocks within the walls of Monterey Canyon. The MOISE broadband sensor was partially buried in the sediment of Smooth Ridge west of the San Gregorio fault.

The corehole instruments will continue to be deployed as autonomous packages until a) the LP1 is upgraded and b) a permanent cable or mooring is placed into Monterey Bay. Until a real-time connection is realized, the data from the instruments will be recovered via ROV on a regular basis, downloaded by MBARI and added to the public domain database. The data from multiple short-period instruments is useful for regional and local tectonic studies such as these. The data become more useful when used in conjunction with data from truly broadband sensors.

Seismic Broadband sensors on the ocean floor

Methodology to deploy broadband seismic sensor packages has been developed in collaboration with UC Berkeley. In the summer of 1997, a suite of geophysical instrument packages was deployed on the ocean floor for 3 months using MBARI's ROV

Ventana, under the aegis of MOISE (Monterey Bay Ocean Bottom International Seismic Experiment), an international cooperative pilot experiment between MBARI, DT/INSU,IPGP and UBO (France) and UC Berkeley.

The goal of MOISE was to advance the global Seafloor Observatory effort through the development and installation of a prototype suite of instruments placed on the western side of the San Andreas fault system offshore of Central California (Stakes et al., 1998; Romanowicz et al., 1998). The centerpiece of the MOISE instrument suite was a digital broadband seismometer package partially buried within the sediment-covered floor of Monterey Bay.

The deployment site was in Monterey Bay, 40km offshore and 10km west of the San Gregorio fault at a water depth of 1015m (Fig. 1). The instruments deployed included: a three-component Guralp CMG-3T broadband seismometer system, mounted on leveling gymbals, with a self-recentering program designed by DT/INSU. The sensor package was half buried in the sediments. The broadband was connected on the seafloor by the ROV to an L-CHEAPO recording system (designed by Scripps/IGPP and modified by MBARI) and to an external battery pack. A CTD/Paroscientific pressure gauge package and an S4 current meter were placed nearby to measure local bottom currents. A stand-alone electromagnetic sensor package, contributed by UBO was also deployed by the ROV and recovered via elevator. In addition, two MBARI well-coupled corehole seismometers were deployed at adjacent sites along with a variety of conventional short-period seismometers and hydrophones deployed as stand-alone, contemporaneous measurements. On three separate dives a connection was made from the ship to the L-CHEAPO via the ROV RS232 with command and data links through the datalogger to the seismometer package. Through this link we were able to a) successfully level and initiate the data collection and recentering routines, b) extract samples of both historical and real-time data to the state-of-health of the system and c) re-level the seismometer sensors. This experiment was, in particular, a successful feasibility test for ocean floor deployment of broadband sensors using an ROV.

The seismic data from MOISE suggests that burial of the broadband sensor package in the continental margin sediments adequately reduces the noise from bottom currents. Both regional and teleseismic events were usefully recorded (Romanowicz et al., 1998) at least in the "low-noise notch" (a frequency band between 5-50 seconds) (Fig. 2) The contemporaneous logging of pressure and current velocity documents that, during periods of low bottom currents, the instrument noise is comparable to land-based stations.

Chemical Sensors

Chemical sensor systems with long-term (order 1 year) endurance and stability now exist for several chemicals of relevance to hydrothermal systems including sulfide, bromide and iron. These systems can be deployed in an observatory network to couple seismic, heat flow and chemical observations in an integrated study of the processes that transport and transform mantle energy into hydrothermal ecosystems. For example, osmoanalyzers (Jannasch et al., 1994) configured to determine dissolved iron have been successfully deployed on Axial Seamount, monitoring Fe-variations in vent fluids (Fig. 3). These systems have been deployed for time periods in excess of one year. New generations of instruments, such as the In Situ Ultraviolet Spectrophotometer (ISUS) are in development and will greatly extend the range of chemicals that can be detected in hydrothermal systems.

Chemical sensors will be supplemented by conventional physical sensors to measure temperature and particulates adapted to the extended periods of observation. In addition, sampling devices will be used to collect material for analyses that cannot yet be performed in situ. These instruments include the Osmosampler (Wheat et al., 2000), which collects small volumes of fluid into capillary tubes and provides near daily resolution for time periods up to

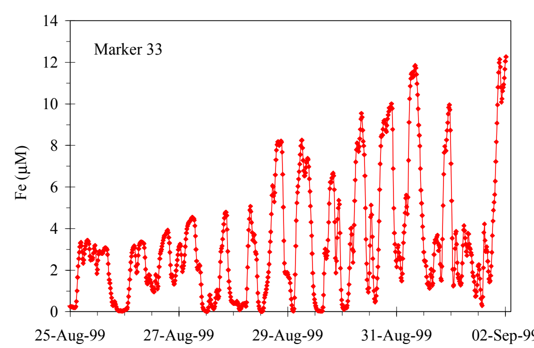

Figure 3. An Fe-Osmoanalyzer was deployed at ambient temperatures on Axial Seamount on the Juan de Fuca Ridge with its intake (~2m long) positioned about 40 cm below the surface inside the hydrothermal vent near "Marker 33" (~1500m). The Fe-OsmoAnyalzer provided continuous analysis of Fe concentrations with readings recorded every 15 minutes. The analyzer self-calibrated itself by analyzing known standards every 10 days, and operated continuously from June 1999 until June 2000. The main variability correlates with tides (Jannasch et al., 2000).

five years. Other, more complex, fluid and microbial samplers have yet to be adapted to seafloor deployments.

The Future

MOBB, MOOS and Neptune

As a follow-up to the MOISE experiment, in a cooperative project between MBARI and UC Berkeley, with complementary support from NSF, we are currently planning the permanent deployment of a broadband, three-component seismometer package in Monterey Bay. The deployment will comprise a Guralp CMG-1T sensor package, a modified LP1 data logger, CTD, current meter and pressure gauges (Fig. 4). The sampling rates for the instruments will be better matched to permit some removal of the bottom current noise (e.g. Stutzman et al, 2001).

The CMG-1T broadband seismometer has a flat velocity response from 360 sec to 50 Hz and lower instrumental noise than the CMG-3T, the sensor used in the 1997 MOISE experiment. It is equipped with a remote automatic mass locking, mass unlocking and centering capability. The Guralp +/-30 degree leveling system is especially designed for use with long-period broadband sensors. The radial and azimuthal adjustments are done until the two-axes inclinometer outputs are brought as close to zero as possible.

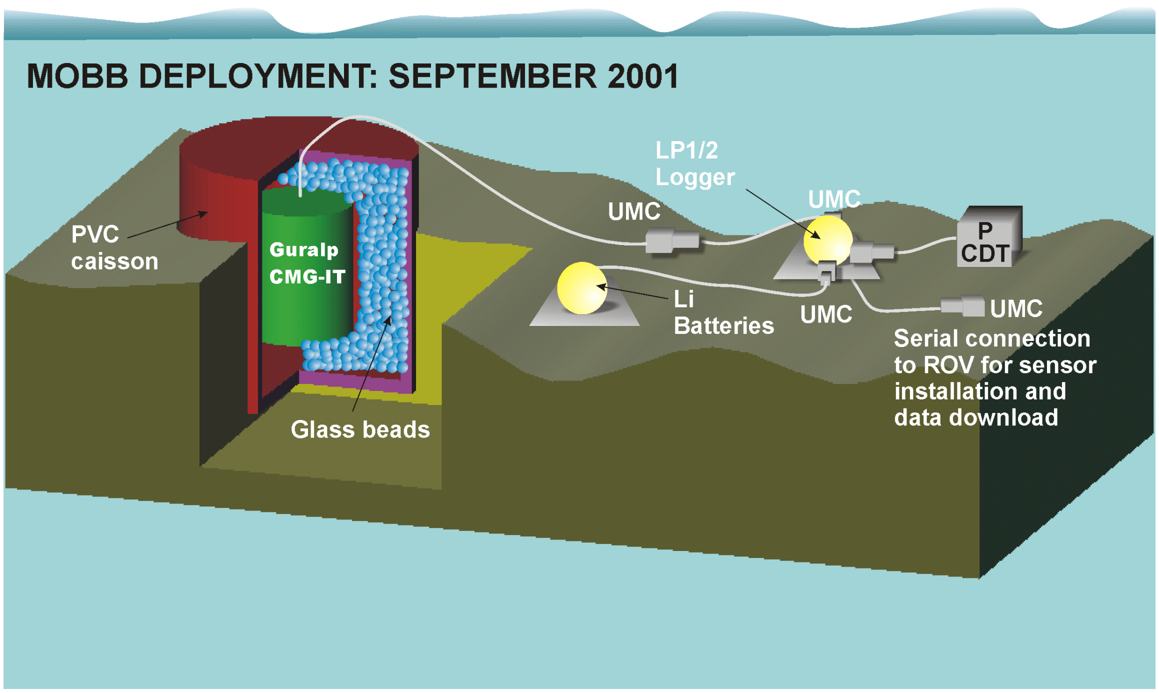

Figure 4. Schematic of the plans for the MOBB deployment site. The Guralp sensor will be fully buried in sediment. Ancillary sensors will include an absolute and a differential pressure gauge.

The position detectors are absolute and position information is retained even when the system is switched off. It operates without leveling up to +/-2.5 degrees of tilt. The CMG-1T sensor mass has been increased (compared to the CMG-3T) to 250gm to reduce the Brownian noise of the system. The vertical sensor inertial mass and the inverted horizontal pendulum are both supported with leaf springs with a natural period of about 0.9s. The 24-bit A/D converter module DM24 is mounted on top of the sensor housing and provides standard RS232 output. The internal clock will utilize an external 1 pulse per second signal from the LP1/2 to control the digitizing rate and provide reference for the timestamps.

Although the MOISE instruments were deployed only for a few months, the strategies invoked for their installation emulated those adopted for permanent deployment of the MOBB instrument. These methodologies include: in situ assembly of instruments using underwater connectors manipulated by submersibles, improved coupling of sensors by burial or borehole installation, repeated access to sensor data during the experiment, and the addition of external battery packs to extend the instrument deployment period. The sensor package for MOBB will be completely buried to minimize the impact of the bottom currents. The weighted cable from the sensor will be connected to an LP1 data logger and an external battery pack, both of which will be in trawl-resistant structures (Fig. 4).

The deployment is planned for September 2001. The MOBB site will be prepared by the ROV using a water jet to dig a hole and sink a caisson large enough for the sensor. The instrument will be carried to the seafloor by the ROV with the sensors in the locked position and then placed within the caisson. The data logger and external battery pack will be sent to the seafloor via elevator and connected by the ROV. The sensors will be unlocked and initially leveled manually via the RS232 connection with the ROV. The ROV will confirm proper operation of the system and then the automatic leveling and centering programs will be initiated. During the regular visits, the sensor package will not be disturbed. The data-logger and external battery packages will be replaced by ROV. The permanent broadband station will be the first seafloor node for the Berkeley Digital Seismic Network (Romanowicz et al., 1993). Initially, this instrument will operate autonomously with batteries and data transfer conducted during ROV dives, configured to operate stand-alone for at least 1 year.

It is anticipated that the MOBB will ultimately benefit from other, ongoing MBARI efforts to provide continuous real-time telemetry back to the shore-based laboratory. The connection to a MOOS (MBARI Ocean Observing System) mooring will provide the data link for the offshore site to provide continuous data on regional and teleseismic events. The data will be available through the NCEDC (Northern California Earthquake Data Center) at UC Berkeley. Monterey Bay will also be the site of a NEPTUNE test-bed that will provide a cabled connection to the seafloor instruments networked by ROV-laid fiber. The test-bed will exploit the same mechanical interfaces and data protocols as the proposed cable encircling the Juan de Fuca Plate (Delaney, J.R., et al., 2000).

The LP2 Logger/Controller and Networked "Smart" Experiments.

In 2001, the LP1 will be upgraded by replacing the Motorola 68332 microprocessor with an Intel StrongARM microprocessor. The new logger, called the LP2, will have significantly enhanced processing capability with only a slight increase in power consumption. The LP2 will be able to run complex processing algorithms in situ, such as seismic event detection and location. The LP2 will also have an Ethernet port, which will enable connections to undersea networks and allow rapid downloading of recorded data.

During the next two years our goal will be to interface multiple sensors to the LP2 logger/controller for studies of fluid flow in volcanically and tectonically active sections of the mid-ocean ridge. For our studies of deformation and fluid flow, the contemporaneous measurement of both chemical and seismic activity is essential. We envision the LP2 as the core of a mini-observatory to operate in an autonomous mode or as a multiple-sensor node on a larger, cabled experiment. Advanced software protocols will eventually operate either within the LP2 controller, within the MOOS central hub, or at the NEPTUNE test-bed to allow in situ data processing for event recognition and response. This effort will combine the achievements of the seismology efforts with new chemical sensors developed at MBARI and MOOS. This successful completion of this effort will be a milestone in the establishment of long-term seafloor experiments with real-time connections to land.

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