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The MBARI Margin Seismology Experiment: A Prototype Seafloor Observatory

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The MBARI Margin Seismology Experiment, conducted from 1996 through 1999, had both technical and scientific goals. The technical goals were to develop new sensors and methods for the development of long-term seafloor geophysical observatories. The scientific goals of the project were to constrain the seismicity of the major faults that crosscut the continental margin of Central California. The 1997 component of this project was MOISE (Monterey Bay Ocean Bottom International Seismic Experiment), an international cooperative pilot experiment that successfully deployed a suite of geophysical and oceanographic instrument packages on the ocean floor using MBARI's ROV *Ventana*, a tethered Remotely Operated Vehicle (ROV). 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. The MOISE instrument suite was a digital broad band seismometer package partially buried within the sediment-covered floor of Monterey Bay. Several regional earthquakes of magnitude 3.5 and larger as well as several large teleseisms were well recorded during the three-month deployment.

The seismic data from MOISE suggest that burial of the broad band sensor package in the continental margin sediments adequately reduces the noise from bottom currents such that both regional and teleseismic events can be usefully recorded, at least in the "low-noise notch" (a frequency band between 5 and 50 sec). Both conventional and well-coupled, ROV-installed, short-period instruments were deployed in conjunction with the MOISE experiment. During 1998, an offshore network of five ROV-installed instruments was continuously deployed for 8 months. These MBARI "corehole" seismometers include short-period geophone packages mounted in an underwater housing that can be inserted into a 2.5" diameter borehole to provide improved mechanical coupling with the seafloor. The results of this field program demonstrate that placing instruments in offshore sites reduces azimuthal

gap, horizontal and vertical location errors, and provides more robust focal mechanism solutions to constrain seismicity on nearshore faults.

1. NEED FOR LONG-TERM SEAFLOOR OBSERVATORIES

The limited distribution of continents and islands around the world precludes adequate coverage by land-based geophysical observatories to address many important scientific issues related to plate tectonics and the deep structure and dynamics of Earth (e.g. [1]). Long-term seismic observatories on the ocean floor are necessary both for global dynamics studies of deep Earth structure and regional active-process studies that focus on the seismicity, tectonics and hydrothermal volcanic activity of Earth's crust (e.g. [2]). Continuous measurements from seafloor instruments also provide the ability to characterize episodic events, such as undersea volcanic eruptions and avalanches, as well as unrecognized linkages with biogeochemical processes which may not be noted with traditional expeditionary oceanographic approaches. Such long-term stations should be as low-noise, multidisciplinary and broad band as possible with deployment periods of at least 5 years (e.g. [3, 4].

Arrays of multidisciplinary sensors that include both short and long-period ocean bottom seismometers placed in accessible near-shore sites can be used to constrain critical regional processes that may have significant impact on heavily populated coastal areas. In northern California, existing public broad band and short-period stations are predominantly located on the eastern side of the North-America/Pacific plate boundary, and the seismic activity on the off-shore fault system related to this plate boundary is very poorly documented. The complex of active faults that crosscut the continental margin is considered part of the San Andreas system or relicts of the pre-San Andreas Oligocene plate reorganization. The San Gregorio (SGF) and Monterey Bay fault zones (MBFZ) are the major offshore faults in central California. Seismic activity along these structures has been correlated with the distribution of benthic cold seep communities [5, 6] and submarine mass wasting events [7]. There is some chance that they could pose an earthquake hazard for the adjacent populations from Monterey Peninsula to Santa Cruz [8].

The estimated location, mechanism and size of moderate to large events associated with the SGF and the MBFZ is biased by the uneven distribution of seismograph stations. The historical catalogue of seismic events suggests that earthquakes of magnitude 4.0 have not been uncommon. For example, a magnitude 6.2 earthquake doublet was recorded for Monterey Bay in 1926. In addition, a recent analysis by the U.S. Geological Survey suggests that the northern San Gregorio is capable of a magnitude 7.0 event [8]. The sparse distribution of seismograph stations near the Monterey Bay combined with the absence of stations on the west side of the faults created large errors in the determination of hypocenters and focal mechanisms for the characteristic moderate to small events ($M<2.0$). In addition, the levels of microseismicity or creep are unknown.

During the 1997~1998 Monterey Bay Aquarium Research Institute (MBARI) Margin Seismology Project, a suite of three-component broad band and short-period seismometers were deployed in Monterey Bay to supplement the measurements made by the onshore seismograph network (Fig. 1). The initial results of this field program demonstrate that placing instruments in offshore sites reduces azimuthal gap, horizontal and vertical location errors, and focal mechanism uncertainties [9].

In addition, the use of offshore stations provides needed phase arrivals for events far offshore, contributes to velocity studies of the SGF and MBFZ [10], and offers unique opportunities for seismological studies that land-based instruments are unable to provide (i.e., studies of T-phase and marine mammal acoustics).

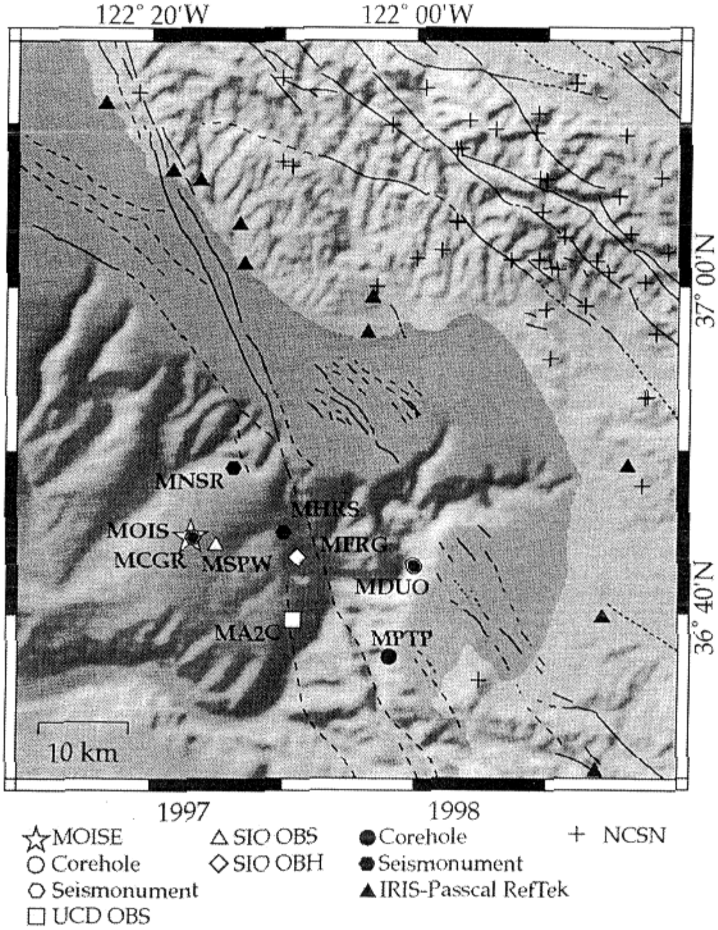


Figure 1. Bathymetric map of the Monterey Bay area showing the locations of instruments deployed during the MBARI Margin Seismology Program in 1997 and 1998. The MOISE instrumentation, including the broad band seismometer, EM sensor package and current meter/pressure gauge were deployed at a depth of 1015 m at the site indicated by the star, the station MOIS. Other instrumentation was placed near MOIS during 1997 to facilitate instrument comparisons (MA2C, MFRG, MSPW, MDUO, MCGR). During 1998, the short-period array was consistently reoccupied at

select sites (MDUO, MCGR, MHRS, MNSR, MPTP) to attain better azimuthal control over the known fault segments.

2. INSTRUMENTS AND METHODOLOGY

Although the scientific need for time-series data from seafloor instruments has been recognized for at least a decade, the technical limitations have proven to be daunting. Technical challenges common to different types of seafloor observatories include: (a) the optimal installation of sensors to maximize signal to noise; (b) a source of power for months to years of operation; (c) timely data retrieval for confirmation that the instruments are properly functioning. Conventional seismometers are deployed by releasing them over the rail of the ship, with minimal control over the specific site or attitude. This type of instrument requires an acoustic release and flotation for autonomous retrieval, both of which compromise the data quality by reducing the mechanical coupling between the seafloor and the instrument. Periods of observations are frequently limited to the duration of a single expedition or to the life of the batteries deployed with the instrument. Deployments longer than a few months are the exception. Longer deployments incorporate increasing risk as instrument malfunction will be undetected until the completion of the experiment. As a result, baseline phenomena are assumed to be extrapolations of results from limited observation periods. Major catastrophic or episodic events may remain completely undetected between the finite windows of observation.

2.1. The MOISE methodology

MOISE [11, 12] was the centerpiece of a series of proof-of-concept experiments conducted in Monterey Bay to develop an enhanced methodology for seafloor installations that exploits the capabilities of tethered ROVS. Although the instrumentation was deployed only for a few months, the strategies invoked for their installation emulated those required for a permanent deployment. These included: *in situ* assembly of instruments using underwater connectors manipulated by submersibles, improved coupling of sensors by burial or installation into boreholes, repeated access to sensor data during the experiment, and the addition of external battery packs to extend the instrument deployment period [13].

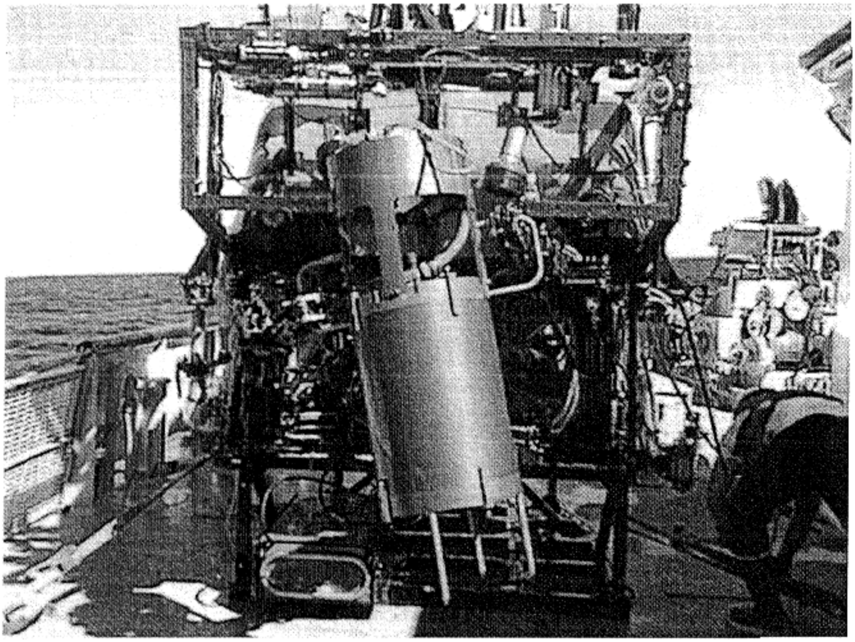
The most complex instrument deployed for the MOISE experiment was a three-component broad band seismometer system, based on a Guralp CMG-3T, modified for this experiment by DT/INSU (Division Technique, Institut National des Sciences de l'Univers, Paris). Broad band seismic sensors require very precise leveling and can be damaged by rough treatment. The MOISE package contained the sensors on leveling gimbals, a small cpu with a 16-bit A/D and clock module, and a rechargeable battery (Fig. 2a). The sensor could be initially leveled via commands from the ROV and new software developed for this experiment re-centered the sensors autonomously. The housing included the male side of an 8-pin Nautilus underwater connector. The ROV was used to sink a 55-cm diameter PVC caisson by suctioning mud from the center, a technique adapted from Duennebier and Sutton [14]. The result of this procedure was a hole that was approximately 50 cm deep into the cohesive, organic-rich mud typical of the California continental margin. The ROV then carried the sensor to the seafloor and placed it into the prepared site.

After deployment, the ROV connected the broad band seismometer sensor to an "L-CHEAPO" datalogger (provided by Scripps Institution of Oceanography/IGPP) using an mounted on a metal tripod with supports for three Nautilus connectors. Following a 3-day period during which the sensor was allowed to settle, the ROV returned and filled the annulus between the sensor housing and the caisson with glass beads. The ROV then re-connected to the datalogger. Commands sent from the surface ship to the datalogger via the ROV were echoed to the sensor package for unlocking and leveling the sensors. Once the sensors were levelled, the data collection was initiated. The ROV monitored the initial data stream as it was recorded on board the datalogger to confirm proper operation of the system. The ROV disconnected at this point and left the instrument to collect data for 1 week.

After this period, the ROV returned to the site and connected a second Benthos sphere (without disturbing the sensor) with additional lithium batteries to power the instrument for a total deployment period of up to 100 days. Reconnection to the datalogger permitted daily examples of the background noise and one event to be downloaded from the logger hard-drive simultaneous with monitoring the real-time data from the sensor package. The instrument was visited again after 1 month and the data download procedure was repeated. The sensors were also re-leveled by a few degrees during this visit to return them to the mid-point of their dynamic range. Such re-leveling is necessary for instruments installed in sediments because of gradual compaction and settling. In September, at the end of the deployment period, the ROV re-connected and commands were sent to shut down and lock the sensor package.

During the first week of the broad band seismometer deployment, other instruments were placed on the MOISE site to collect contemporaneous data. Collaborators from Laboratoire de Geophysique at Université de Bretagne Occidentale (UBO) provided an electromagnetic sensor package to monitor the co-variation of the magnetic field and seismic events. The EM package consisted of a three-component fluxgate magnetometer, Overhauser magnetometer (measuring the total intensity of the earth's magnetic field), and a two-component electric field sensor using a salt-bridge chopper for electrode drift removal. The magnetometer was carried down by the ROV and placed into position to orient the sensors as close to north as possible. To address the question of bottom current and tidal effects, an S4 current meter, a Seagate CTD (conductivity-temperature-depth for salinity measurement), and a Paroscientific pressure gauge, all mounted on a tripod support frame, were placed a few tens of meters from the other instruments. The bottom currents were anticipated to be the most profound marine noise present in the seismic record due to the shear coupling at the sediment water interface [14, 15, 16]. The presence of strong bottom currents at the site induced large seismic and electric noise, that facilitated a correlation between currents, electric field and seismic signal [17].

A variety of conventional and well-coupled short-period seismometers and hydrophones were also deployed as stand-alone, contemporaneous instruments to provide more comparative data for regional studies. These instruments included conventional, surface-ship deployed short period seismometers with either 4.5-Hz or 1-Hz sensors and a single channel hydrophone. In addition, ROV-deployed "corehole seismometers" were installed in small diameter boreholes in the granite walls of the Canyon for most of the experiment. These corehole seismometers were the instrument packages used to extend the seismic measurements through repeated deployments during 1998 as the continuation of the MBARI Margin Seismology Project. In addition to the ocean-bottom deployments, ten IRIS-Passcal RefTeks were placed along the Monterey coast to increase the density of land-based instruments in the area (Fig. 1).



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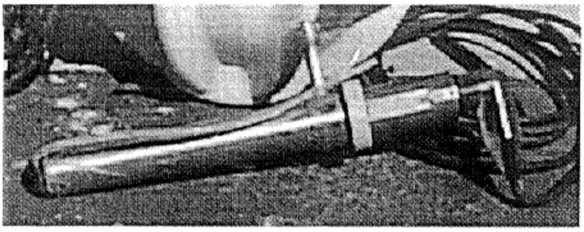


b)

Figure 2. (a) The ROV *Ventana* holding the Guralp broad band sensor package just prior to deployment. The housing contains the three sensors on gymbals in a locked position; a small computer with an independent clock and a 16-bit A/D connected to a rechargeable battery. The housing was carried to the seafloor by the ROV and placed into the prepared site (adapted from Dawe et al., 1998). (b) The MBARI short-period corehole sensor sitting adjacent to the Benthos sphere containing the datalogger and Li-batteries. The sensor can either be carried down attached to the datalogger or these can be connected in situ. The ROV maintains a communication link with the logger until the successfully installation is confirmed. Visual confirmation of sensor leveling is confirmed by the LEDs in the vertical handle (adapted from Stakes et al. [12]).

2.2. The MBARI Corehole Seismometers.

The three-component, wide response (1~90 Hz), miniature sensor package mainly used for the MBARI Seismology program was developed by the Jet Propulsion Laboratory in collaboration with MBARI (Fig. 2b). The sensor technology and instrument response characteristics are described in Stakes et al. [12]. These short-period geophone packages are mounted in an underwater housing which can be inserted into a 2.5" diameter borehole to provide improved mechanical coupling with the seafloor. These small diameter boreholes (dubbed coreholes) have been drilled into the vertical walls of Monterey and Carmel submarine canyons for the seismometer deployment using an underwater diamond coring system mounted on the ROV *Ventana* [18]. Accessible sites west of the SGF are all sedimented, requiring a "portable corehole" a cylindrical hole within a low-profile cement block dubbed a "seismonument". Waveforms for these instruments compared to several traditional ocean floor seismometers [19] show them to have higher signal-to-noise ratios and lower environmental noise (such as bottom currents), features that enhance their capabilities in recording small near-shore seismic events (Fig. 3). The sensor packages and dataloggers were repeatedly deployed and recovered during 1998 using one of the MBARI ROVs. The robotic arms of the ROV placed the sensor packages into the coreholes and rotated them until they were properly leveled, as indicated by an LED on the handle. The seismonuments were carried to the seafloor by the ROV and similarly positioned by the manipulator. Low-power dataloggers were connected to these sensor packages, either on the surface prior to deployment, or *in situ* after the sensor packages were deployed. The loggers' electronics and their Li-battery packs were housed in Benthos spheres anchored several meters from the sensor packages. The deployment period for each instrument varied from 6 to 12 weeks. Timing for each instrument was maintained by an onboard temperature-compensated crystal oscillator with a rated drift of 1.5 sec/year.

The MBARI/JPL seismometers, because of their improved mechanical coupling, 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 a large azimuthal gap. Traditionally deployed ocean-bottom seismometers can display high background noise levels for the horizontal channels due to non-linear coupling between the geophones and Earth [14, 20, 21] and from ocean floor currents. 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 (Fig. 4).

The seafloor deployment sites for 1997 and 1998 of MBARI's "Margin Seismology Project" are shown on Fig. 1. During 1997, the corehole deployments were geographically limited to facilitate instrument comparisons during MOISE. Much of the development and the most continuous data have been obtained from site Duoseismo (MDUO) where two coreholes were placed 17 m apart in Cretaceous granitic basement for side by side comparisons [19]. A comparison of data from MOIS (the broad band site) and MDUO (the corehole site within the granite) is provided in Fig. 5.

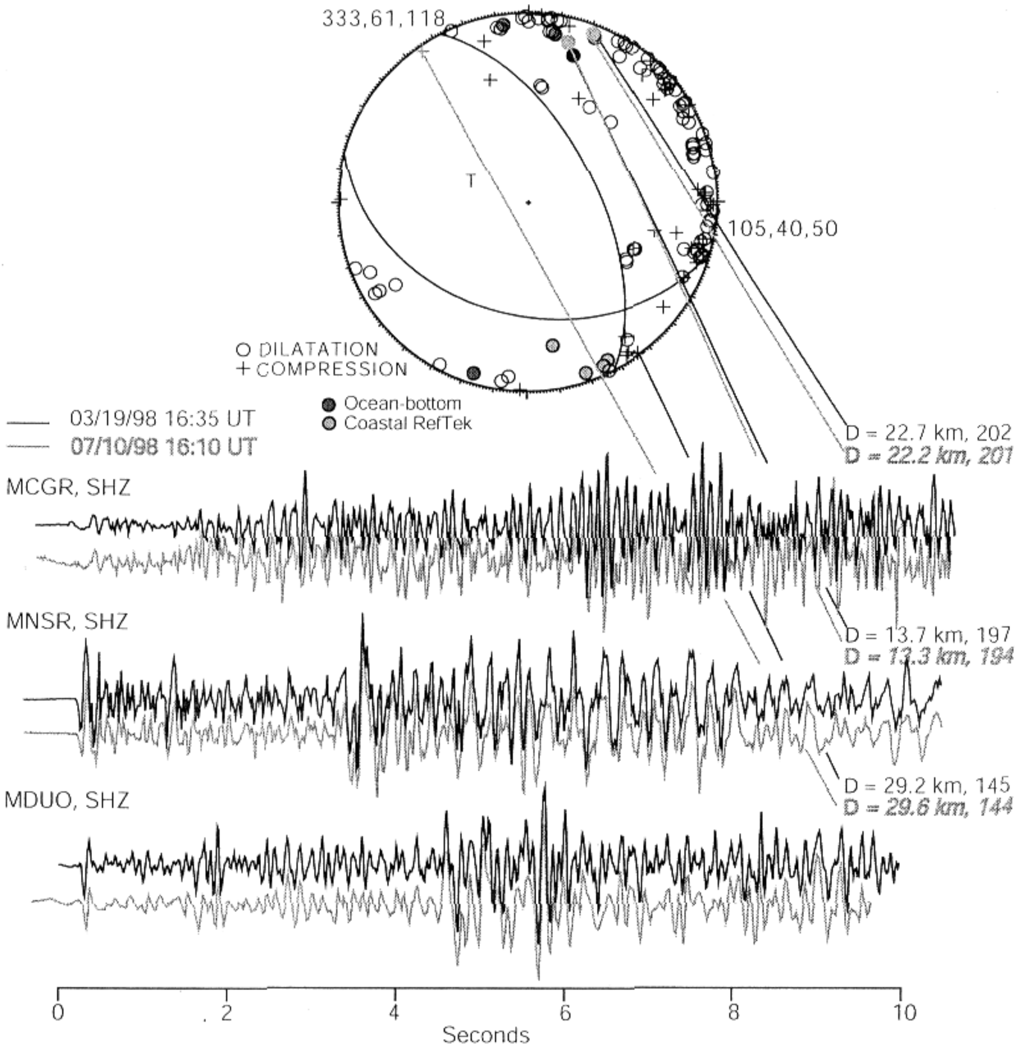


Figure 3. Two events recorded in 1998 were co-located within a few hundred meters of each other. Waveforms for the two events recorded at each of three seafloor short-period seismometer sites show good correlation due to the high fidelity of the digital instruments, both for corehole (MDUO) and sedimented seismonument sites (MCGR, MNSR).

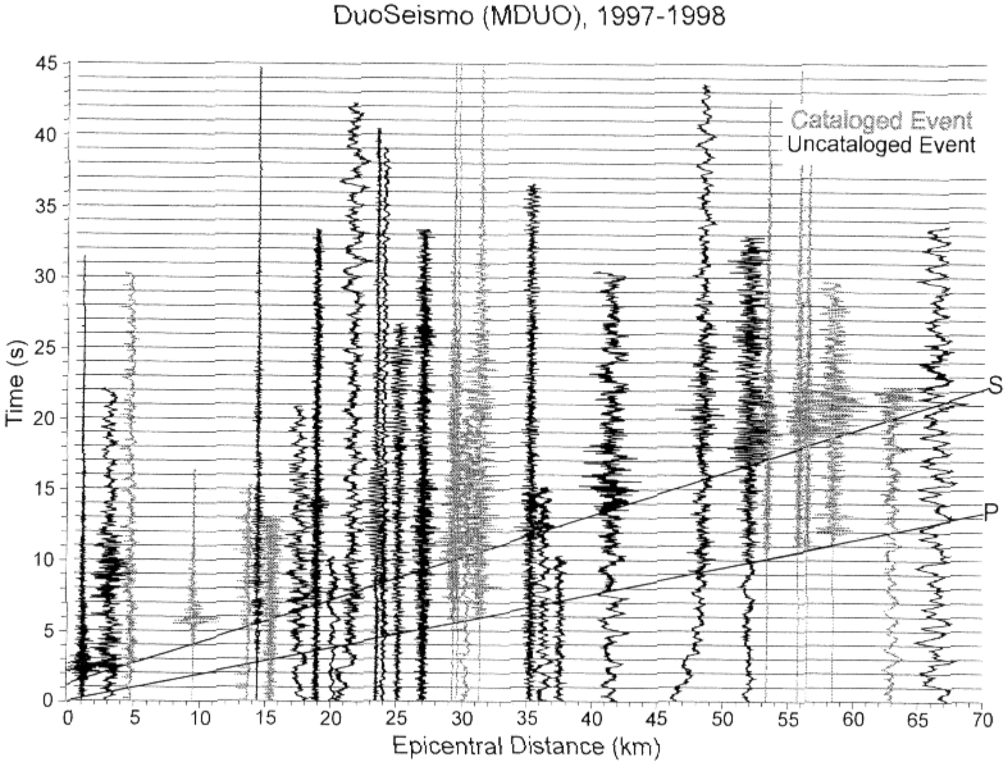


Figure 4. Unfiltered record section for short-period corehole instrument at site DuoSeismo (MDUO). The high fidelity of the digital instruments and control of the sensor orientation permitted consistent rotation of the shear waves into radial and transverse components. Use of both horizontal and vertical components resulted in better constrained focal mechanisms. The grey waveforms are associated with events cataloged by the Northern California Earthquake Data Center. These waveforms were used to estimate P and S travel time curves for MDUO. Many uncataloged events were detected at MDUO with their associated waveforms shown in black. The travel time curves were used to help constrain the epicenter distance of the uncatalogued events.

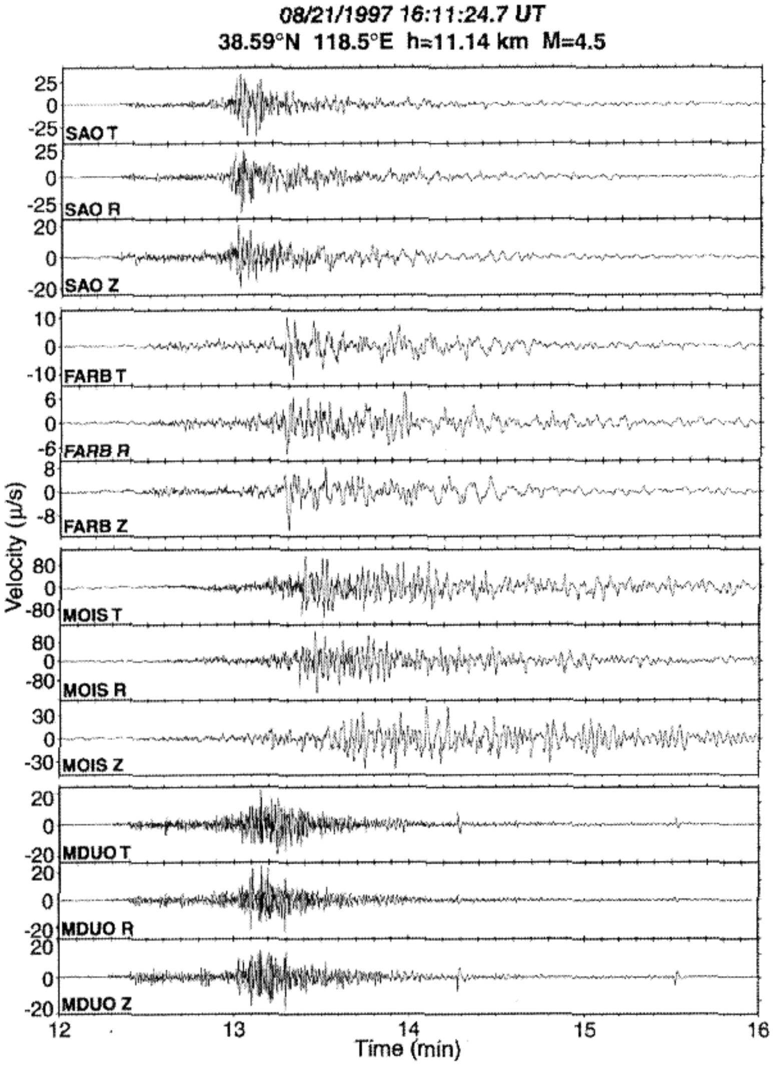


Figure 5. Comparison of broad band data for a regional earthquake (Nevada, distance ~ 400 km) recorded at MOIS and MDUO, a nearby continental station, SAO, and an adjacent island station FARB. The data have been high band-pass filtered at 50 sec (modified after [12]).

3. RESULTS

The results from MOISE are both technical and scientific: the successful strategy for deployment of a broad band sensor package into soft sediment and correlation of seismic and electromagnetic data with physical oceanographic information. In addition, data from MOISE have been incorporated into the MBARI Seismology Program database and used to accurately determine hypocenters and mechanisms for the offshore faults. Details of these results are provided by: Romanowicz et al. [11], Stutzman et. al. [17], Stakes et. al. [12], Begnaud and Stakes [9] and Begnaud et al. [10]. The instrument sites at 800~1000 m depth were well within the SOFAR channel as well as being within a marine mammal sanctuary. This location was the deepest site easily accessible to the ROV *Ventana* operating on a daily basis from Moss Landing. As a result, there are large numbers of marine mammal calls and T-phase arrivals (water carried acoustic signal) found within the seismometer data records [22]. The continental margin seismometer sites provided records of T-phases prior to their complete conversion and recording by land-based stations.

3.1. Correlation of noise and currents

The deployment of the broad band sensor package was successful, though less than perfect. Although the sensors and gimbals were completely buried in the sediment and stabilized by the glass beads, the upper third of the housing and the support for the connector were exposed to highly variable bottom currents. In spite of the less-than-optimal installation, we were able to identify all large teleseisms (M>6.0), for which 30~50 sec surface waves were prominent, as well as numerous regional M>4 earthquakes in the continuous data recorded by this instrument.

Three component broad band seismic data were acquired continuously on the MOISE Broad band package from 21 June through 11 September 1997, at a sampling rate of 20 samples/sec. Several regional earthquakes of magnitude 3.5 and larger as well as several large teleseisms were well recorded during that time period. Comparison of the records obtained at the ocean-bottom site (station name: MOIS) with those of nearby land sites of the Berkeley Digital Seismic Network (BDSN) and of the Geoscope Network (SCZ) provide useful insight into the quality of the data (Fig. 5). The teleseismic events are band-pass filtered between 5 and 50 sec, a frequency band of minimum noise (or low-noise "notch") as consistent with previous seafloor experiments (e.g. [23, 24, 25]). Background noise levels were found to fluctuate in this period band (Fig. 6), and the best recordings were obtained during the quietest periods, when noise in the minimum noise window was comparable to that observed commonly at nearby land sites [12]. Investigation of the source of the large noise fluctuations at station MOIS in the low-noise window was made possible owing to the contemporaneous recording of physical oceanographic data. In the period band 10~50 sec, background seismic noise is often strongly correlated with the bottom current velocity, which exhibits large fluctuations that in general can be related to tides [12, 17].

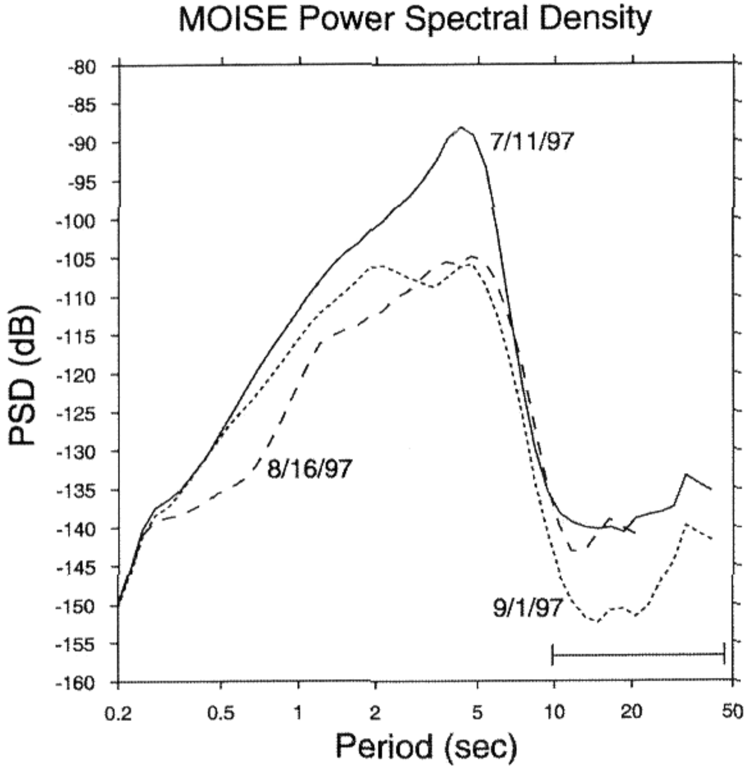


Figure 6. Comparison of noise power density spectra on the vertical component of MOISE, computed on 3 different days, using 8 hours of data starting at 0 hours GMT. Depending on the date and the time of day, noise fluctuated by over 20 dB both in the microseismic band (due to atmospheric conditions) and in the low-noise notch between periods of 10 ~50 sec (due to tidal currents).

3.2. Hypocenters and mechanisms for offshore faults

During the 1997~98 MBARI ocean-bottom instrument deployments, 30 local Monterey Bay seismic events were listed on the Northern California Earthquake Data Center (NCEDC) catalog [26]. Phase data for these events were obtained from the NCEDC and combined with the MBARI phase data. The majority of Monterey Bay events detected in 1997~98 were in the 1.4~2.5 magnitude range. The 65 best constrained recent and historical events (denoted "master events") were used to develop an improved 1-D crustal velocity model. The relocated master events and their composite mechanisms are shown on Fig. 7. This improved 1-D model was used to relocate all major events within the historical seismic catalogue [10] using the HYPOINVERSE location program [27]. Much of the observed offshore seismicity in 1997~98 occurred on the northern SGF, but there were important events on the MBFZ (Fig. 7). The MBARI ocean-bottom dataset collected in 1997 also included 79 seismic events not catalogued by the NCEDC. There were many additional events observed on single instruments that could not be confirmed as seismic. Similar small events were observed for the seafloor deployments in 1998. Even with the addition of these smaller events, there were no recorded events on the southern SGF that defines the Carmel Canyon off Pebble Beach and Carmel Bay. Events observed on the MBFZ varied in depth and magnitude. Events on the northern SGF show a depth distribution consistently deeper on the eastern side. This suggests a fault plane that dips to the east offshore of Santa Cruz.

The capability to resolve shear waves, as well as compressional waves, is critical to constraining depth and epicenter location which then permit more accurate focal mechanism determination. First-motion focal mechanism solutions (generated by the FPFIT program [28]) were calculated for the well-located master events. The ocean-bottom instrument locations provide key positions on the focal sphere for better constraining the nodal planes, reducing the strike, dip, and rake uncertainties, reducing the number of multiple solutions, and allowing for more consistent mechanisms [9]. Composite focal mechanisms for the master events are provided in Fig. 7. Mechanisms for the MBFZ are consistently strike-slip with fault planes that are near vertical. West of Santa Cruz, the SGF strikes at N $27^{\circ} \pm 3^{\circ}$ W and dips to the east at $61^{\circ} \pm 5^{\circ}$ with primarily thrust motion and a component of right-oblique slip [29]. The discovery of this dipping focal plane and thrust mechanisms highlights a potential hazard for the adjacent populated coastal region.

4. THE FUTURE: MOISE-II AND THE MOOS

Plans are underway to install a permanent broad band sensor in Monterey Bay. This project (MOISE-II) is a collaboration between between UC Berkeley and MBARI. The MOISE-II instrument array will include a CTD, current meter and pressure gauge similar to the original MOISE. However, the sampling rates for the instruments will be better matched to permit some removal of the bottom current noise. The sensor package will also be completely buried to minimize the impact of the tidal currents. The permanent broad band station will be the first seafloor node for the Berkeley Digital Seismic Network (BDSN [30]). Initially, this instrument will operate autonomously with batteries and data transfer conducted during ROV dives. It is anticipated that the MOISE-II 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 mooring (MBARI Ocean Observing System) will provide the data link for the offshore site to provide continuous data on regional and teleseismic events.

The MOOS effort is in a nascent stage, with intense planning only completed in early 2000. Primary components of MOOS are telemetered moorings that can support both upper water column and seafloor experiments (Fig. 8). A suite of seafloor or near-bottom instruments could be networked to a single MOOS junction box for truly multidisciplinary experiments. For the MBARI effort, much effort is being placed on *in situ* chemical and microbiological sensors as well as the low-power electronics to support them. Advanced software protocols will eventually operate within the MOOS central hub to allow *in situ* data processing for event recognition and response. One of the next major operational steps will be to test methodologies for using the ROV to cable instrument packages to a central hub. Autonomous underwater vehicles (AUVs) are expected to play a major role in the MOOS effort, providing three-dimensional surveys around the MOOS moorings for projects as diverse as climate studies or following hydrothermal plumes.

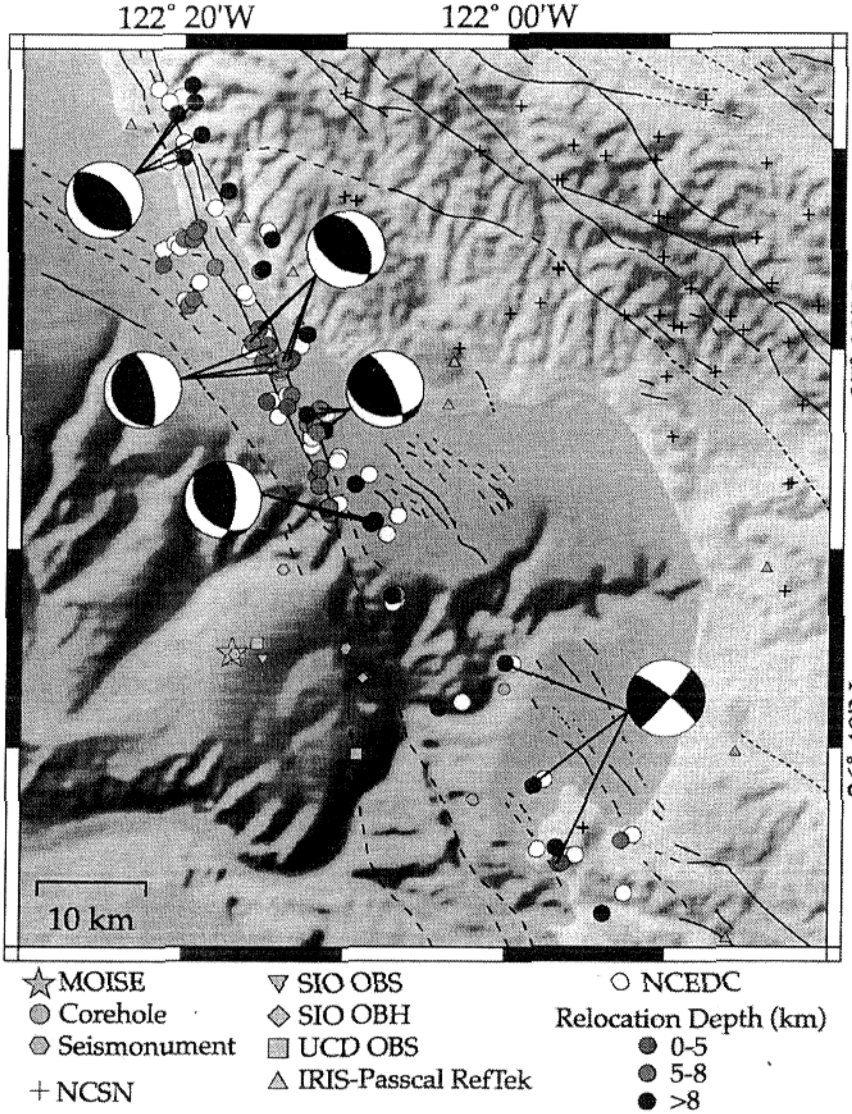
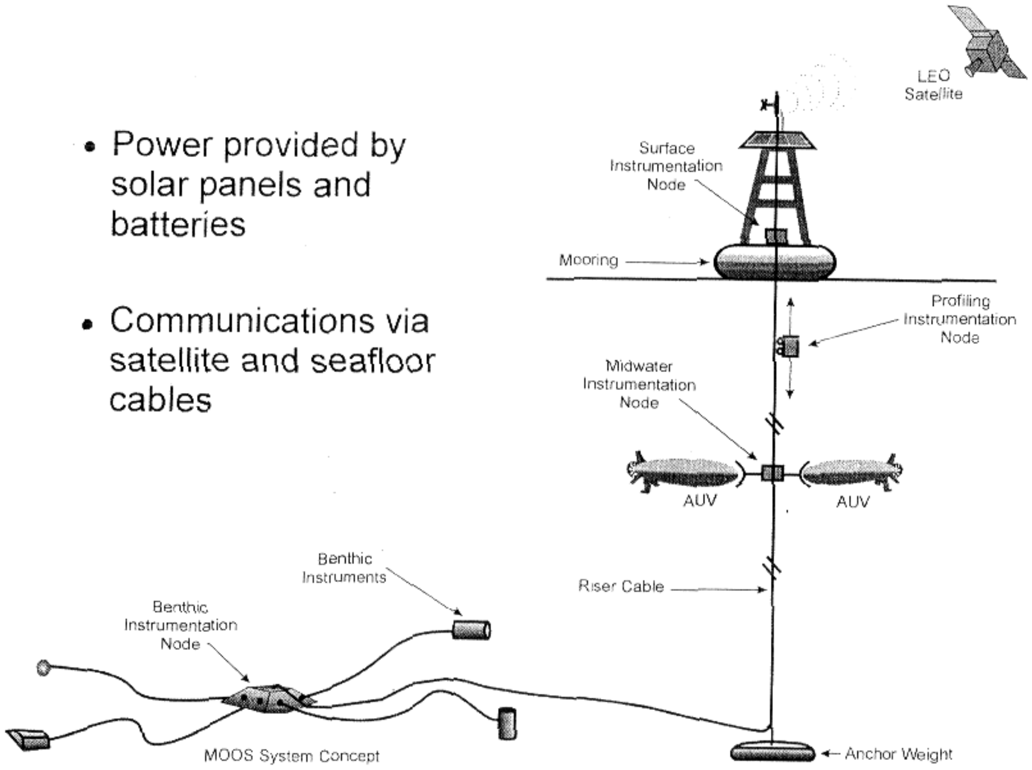


Figure. 7. Major scientific results of Margin Seismology Project study. Relocated master events define the zones of high seismicity as the northern San Gregorio in Monterey Bay and some strands of the Monterey Bay Fault Zone. The southern San Gregorio appears to be aseismic. Re-location of the full historical seismic dataset follows this same trend (see [9]). On the San Gregorio in northern Monterey Bay, events to east are deeper, reflecting fault plane dipping to east. Composite fault plane solutions show right-lateral strike-slip mechanisms on MBFZ and thrust or oblique mechanism on SGF (figure modified after [29]).



- Power provided by solar panels and batteries
- Communications via satellite and seafloor cables

Figure 8. Schematic of the telemetered mooring that will be the foundation of the MBARI Ocean Observing System. Seafloor instruments would be connected by an ROV to the benthic hub using fiber optic cable. The instruments will be battery powered so that low power electronics are emphasized. Communication with distant instrument sites as well as three-dimensional mapping will be accomplished via an AUV. Local data processing will enable event identification and response for catastrophic events such as volcanic eruptions or mass wasting events. The surface communications will be two-way to permit land-based modification of instrument protocols.

5. CONCLUSIONS

The MOISE experiment was a technological success and demonstrates the feasibility of broad band instruments deployed and maintained by submersible within the sediments on continental margins. MOISE-II will open the door for permanent seafloor nodes that extend land-based seismic arrays. The ROV deployment and subsequent reconnection in mid-experiment has demonstrated that this type of vehicle can install complex instrumentation on the seafloor in a dependable and relatively simple manner. The low level of background noise observed at long periods during intervals of low bottom currents indicates that complete burial of the sensor package in future experiments should result in broad band stations of sufficient quality to usefully complement the land-based stations.

This is particularly encouraging for improving coverage in northern California, where current seismic station distribution is less than optimal for monitoring and understanding strain release and tectonics of this region. Solving the long-term issues of power and data acquisition and retrieval, preferably continuously and in real time [30], through connections to land, should be the focus of the next pilot experiments and is within reach of currently available technology. MOOS will ultimately contribute to the solution to these daunting technical problems.

The scientific results of the MBARI Seismology Project highlight the value of a modest number of offshore stations. Even with a relatively small number of instruments (3~5) and a limited period of observation (less than 18 months) many of the inconsistencies of the historical seismic catalogue have been resolved. The Monterey Bay Fault Zone is clearly active, with the potential of occasional moderate to large earthquakes. The pure strike-slip character of the historical events and the vertical slip planes perhaps limits the potential hazards for the Monterey Peninsula. Evidence within the Monterey Canyon, however, does suggest linkages with mass wasting events that contributes to sedimentary processes. The segmentation of the San Gregorio is apparent within the historical seismic catalogue. The northern segment has a comparatively high level of seismicity, mostly characterized by moderate (*M* 3-5) to potentially large (*M* 6-7) earthquakes. Of greater concern, however, is the consistent evidence of a fault zone that dips to the east beneath Santa Cruz with focal mechanisms that have a significant thrust component. These results clearly demonstrate the importance of extending land-based seismic networks to the seafloor to constrain both regional and global seismic patterns.

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